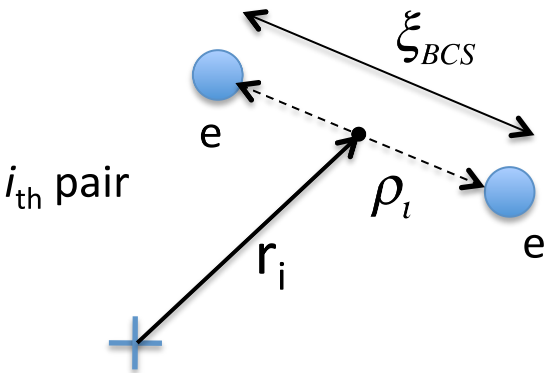
Pedagogical Overview

Unconventional Superconductivity (The Phenomenon)
and
Unconventional Superconductors (The Materials)

- *Conventional Superconductivity*
- *Unconventional Superconductivity and Superconductors*
- *Some Personal Favorites*

The Essence of Superconductivity -- With the Benefit of Hindsight



Superconductivity arises when phases lock

$$\varphi_1 = \varphi_2 = \varphi_3 = \ldots\ldots \varphi_i \ldots\ldots = \varphi$$

$$\Psi_{p_i} = \phi_{\text{int}}(\rho_i)\,\psi_{cm}(r_i) = \phi_{\text{int}}(\rho_i)\,\left|\psi_{cm}(r_i)\right| e^{\varphi_i}$$

Internal structure of a pair

Microscopic Specific Properties

- *q = 2*
- *Pairing symmetry, pair size*
- *Single particle excitations*
- *Density of states*
- *Material parameters of GL theory*
- *The mechanism*

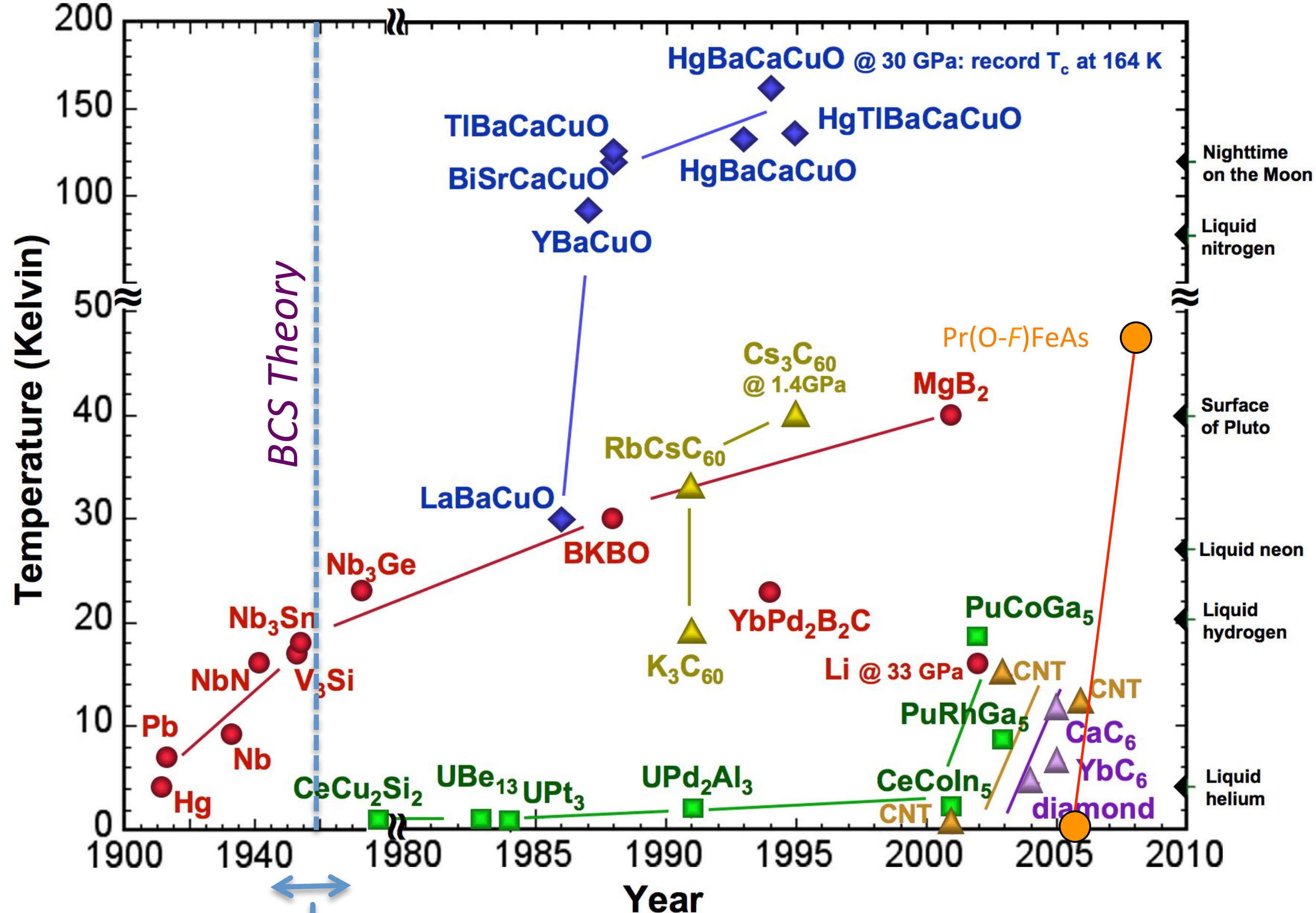
CM wave function of pair

Macroscopic Emergent Properties

- *GL Order parameter/GL theory*
- *R = 0, B = 0,* $\Phi = \Phi_0 = hc/q$
- *Type II superconductivity*
- *Josephson effect*

Some History

Conventional Era *Unconventional Era*



Conventional Superconductivity
GL Theory, BCS, Gorkov and Eliashberg

Adapted from a DoE Report

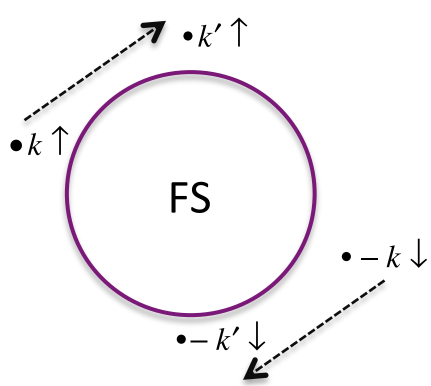
Key Results of BCS Theory

- *Superconductivity arises when electrons bind into pairs and these pairs lock their mutual phases to form a macroscopic quantum state.* $(k\uparrow, -k\downarrow)$

- *The single-particle excitations of a superconductor are comprised of a phase-coherent linear combinations of electrons and holes.* $\psi_k^s = u_k \psi_k^e + v_k e^{i\varphi} \psi_k^h$

- $T_c = \Omega_o e^{-1/\lambda}$, *which implies that if no other phases intervene, all normal metals will become superconductors as T -> 0. Here* λ *is the attractive interaction parameter (not necessarily the electron-phonon interaction).*

- *Size of Cooper pair* $\xi \approx \hbar v_F / kT_c$

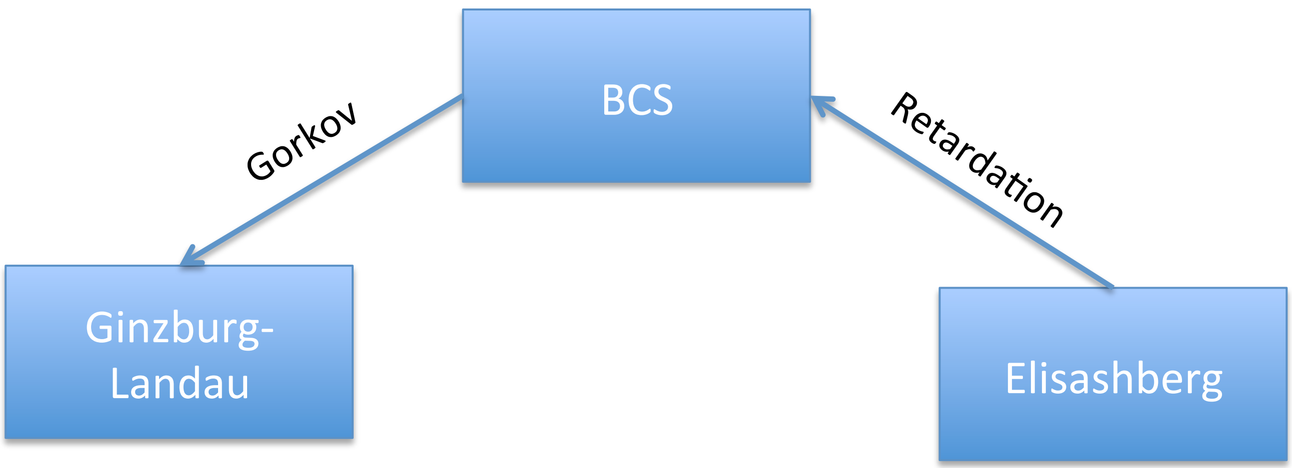


$$(k\uparrow, -k\downarrow) \rightarrow (k'\uparrow, -k'\downarrow)$$

In general, time reversed pairs (Anderson)

The Triumvirate Defining Conventional Superconductivity

A Complete Theory (BCS + Mechanism + Equations for the Material Parameters)



$$F(r) = \int d^3r \left\{ \alpha\left|\psi^2\right| + \frac{1}{2}\beta\left|\psi\right|^4 \frac{\hbar^2}{2m*}\left|\left(-i\nabla - \frac{e*}{\hbar c}A\right)\psi\right|^2 + \frac{B^2}{8\pi} \right\}$$

$$T_c = \Theta_0 e^{\frac{-1}{\lambda-\mu*}}$$

$$\mu* = \frac{\mu}{1+\mu\,\ell n\left(\frac{\varepsilon_F}{\omega_D}\right)}$$

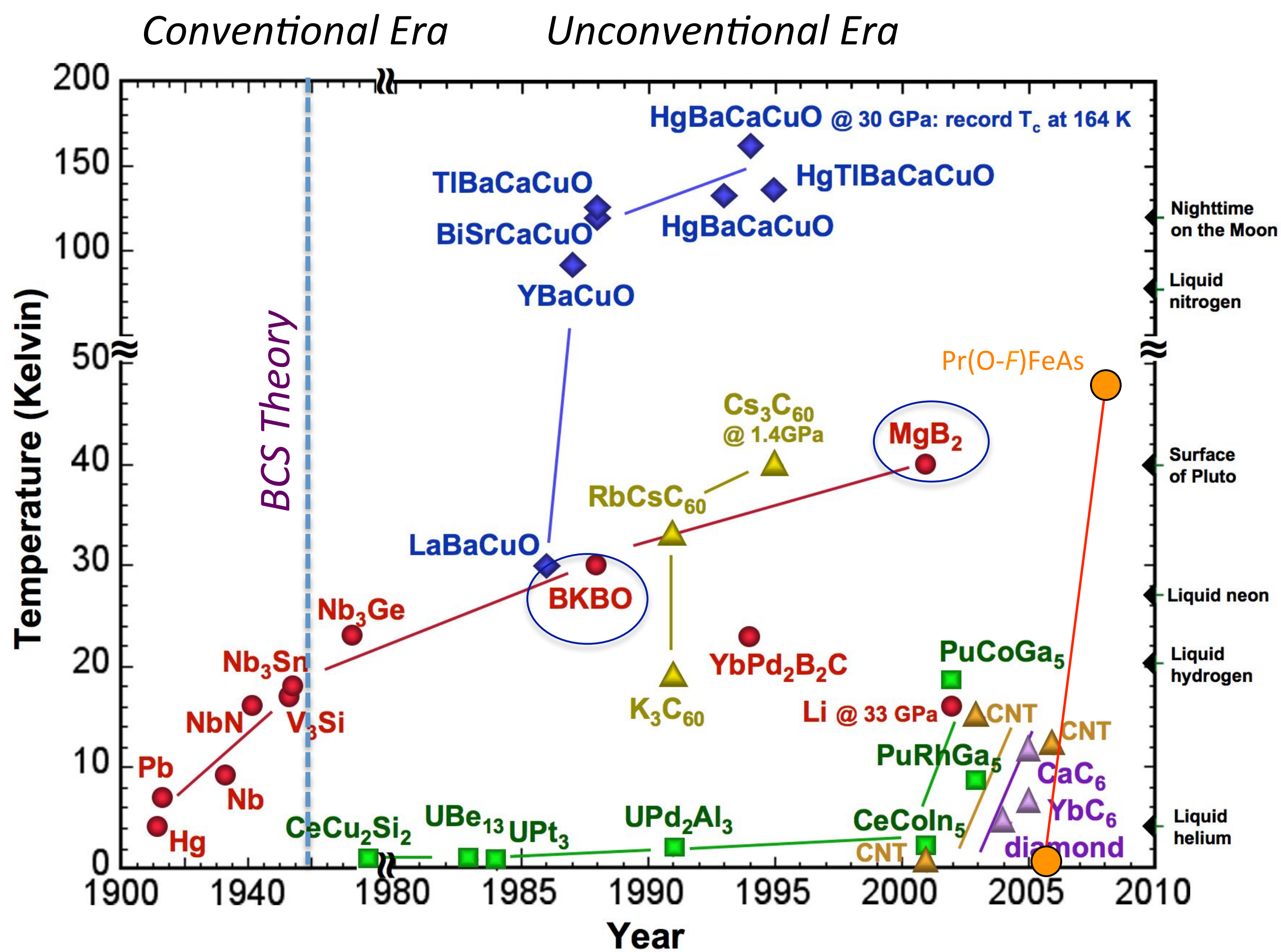
Unconventional Superconductivity

Conventional Superconductivity	Unconventional Superconductivity	Even More Unconventional Superconductivity
Weak coupling λ << 1 $T_c = \Theta_0 e^{-\frac{1}{\lambda}}$	Strong coupling $\lambda > 1$ Maximum in Tc	Very strong coupling λ >> 1 Phase fluctuations – T_c → 0
Mean field theory	Quantum fluctuations when ξ is small $\xi \approx \hbar v_F / kT_p$	Bose metal of pairs? $T_c = \min\{T_\phi, T_p\}$
S-wave singlet Time reversed pairs	Higher angular momentum pairing p, d, …… pairing $\Delta(k) = \int dk^3 V(k,k')\Delta(k')$	S-wave triplet odd-frequency pairing Broken TRS pairs – s + is, d + is, etc
Retarded el-ph interaction $T_c = e^{-\frac{1}{\lambda-\mu^*}}$	Any other mechanism: Electronic interactions -- spin or charge	Non-Fermi liquid in normal state Quantum critical points Competing ordered phases
Anderson's theorem T_c independent of disorder	Enhanced coulomb repulsion due to disorder $T_c = \Theta_0 e^{-\frac{1}{\lambda-\mu^*-\delta\mu^*}}$	Disorder driven Superconductor/Insulator Transition

Unconventional Superconductivity

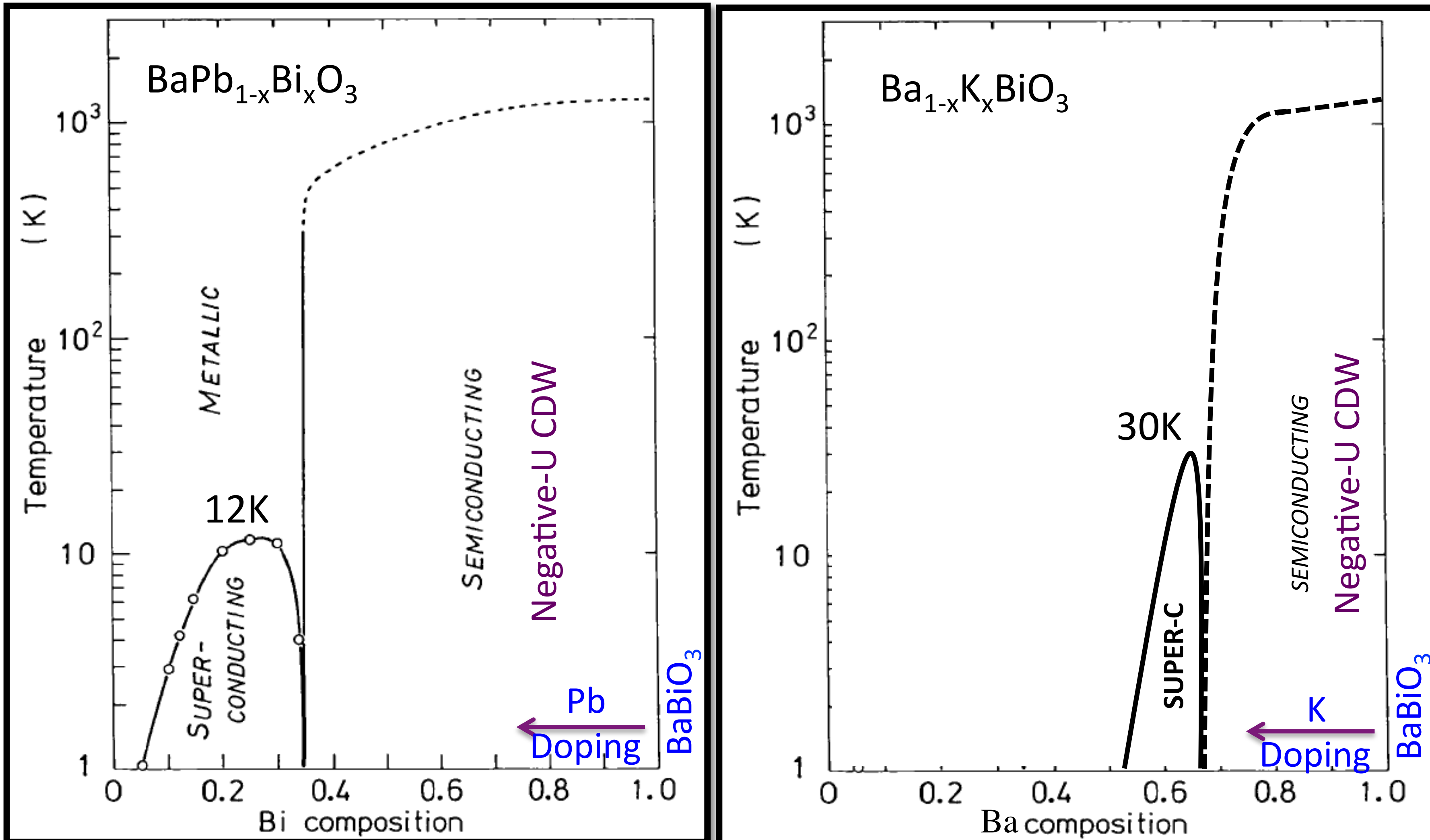
Conventional Classic BCS and Extensions	Unconventional Superconductivity	More Unconventional Superconductivity
Single band superconductivity	Weakly coupled bands/ orbitals	Josephson effects in *k* space
Q = 0 pairing	Finite Q pairing	Pair density waves
Quasi-particles Phase coherent superposition of *e's* and *h's*	SN proximity effect In the presence of a Dirac point	Majorana Fermions
Earthly		Other worldly

Unconventional Superconductivity Along the El-Ph Line



Adapted from a DoE Report

Phase Diagrams of the Superconducting Bismuthates

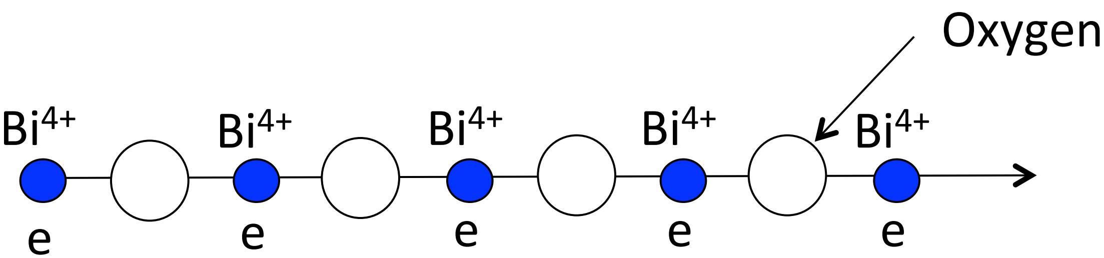


Note similarity to the phase diagrams of the cuprate superconductors but where the ordered insulating state is in the charge sector

Charge-Disproportionated (Negative U) Superconductors (e.g., $BaBiO_3$)

A Failure of LDA Theory → A new class of correlated insulator

Metal



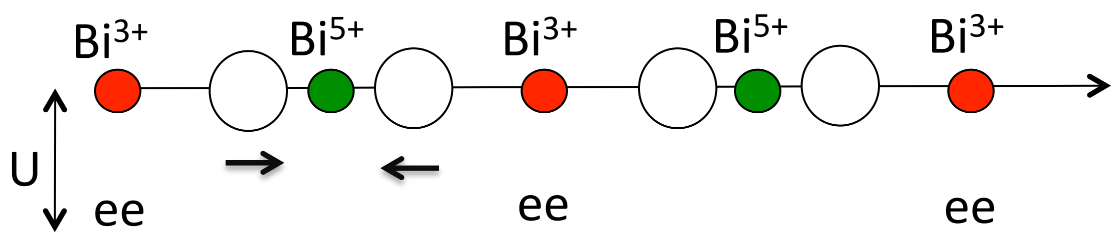
$$2Bi^{4+}(4s^1) \rightarrow Bi^{3+}(4s^2) + Bi^{5+}(4s^0)$$

and

Oxygen atoms move to screen charge (Breathing mode)

Negative U -- Involves both charge and lattice

Insulator



Superconductivity arises upon doping ($Ba_{1-x}K_xBO_3$ and $BaPb_{1-x}Bi_xO_3$)

Disorder in the High T_c Bismuthates

<u>Conventional theory for T_c</u>

- *Clean limit (BCS/Eliashberg):*

$$T_{c0} = \Theta_0 e^{\frac{-1}{\lambda-\mu^*}}$$

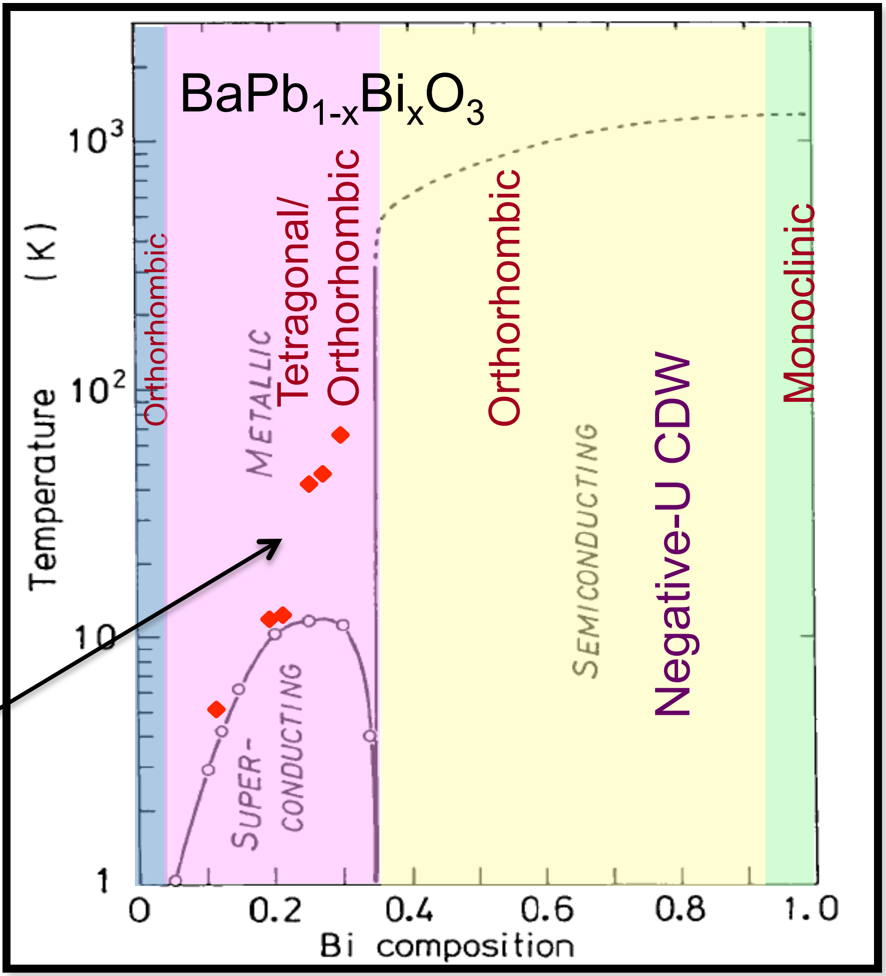
λ = el-ph interaction parameter
μ = retarded coulomb repulsion*

- *Dirty limit (BCS/Eliashburg/Fukuyama):*

$$T_{cd} = \Theta_0 e^{\frac{-1}{\lambda-\mu^*-\delta\mu^*}}$$

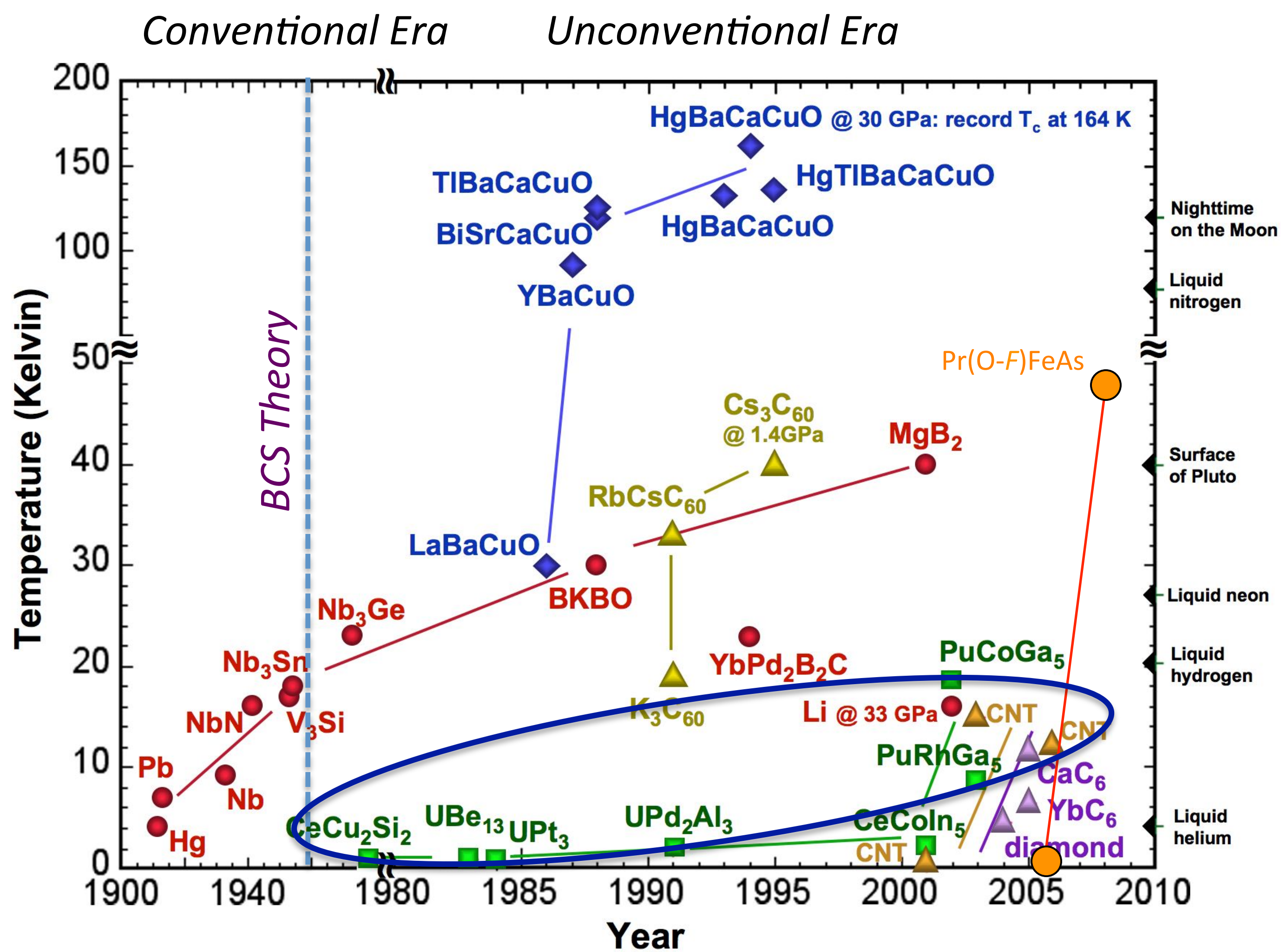
$\delta\mu^*$ = *increase in μ* due to disorder-induced localization*

Measured $T_c = T_{cd}$ and independently estimated $\delta\mu^*$ permits estimate of T_{c0}



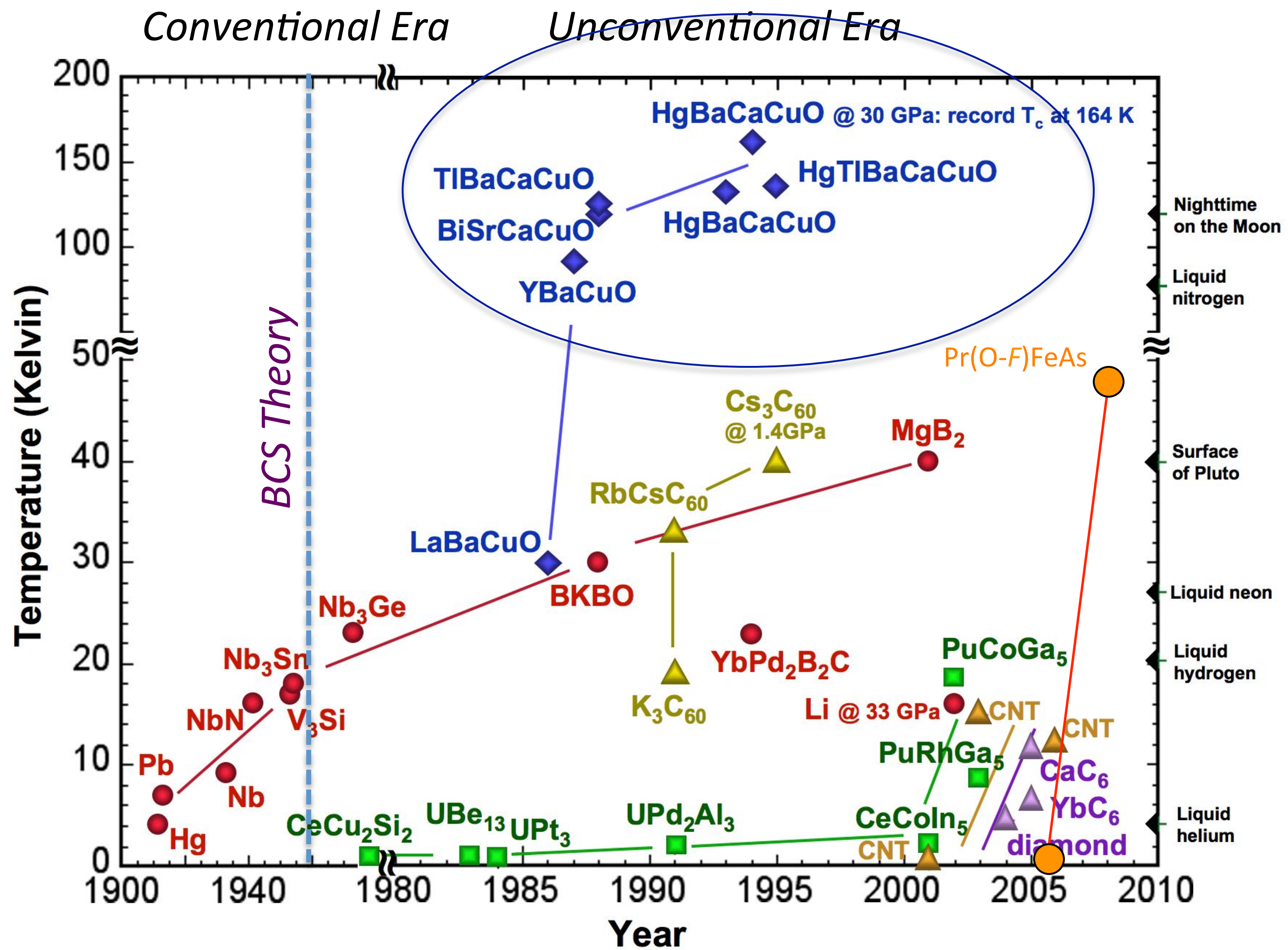
Disorder matters in region of highest T_c

Heavy Fermions and Magnetic Mechanisms



Adapted from a DoE Report

Cuprates and Strong Correlation – A Mixed Blessing



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In Nature the Transition Temperature Can Be "Astronomically" High

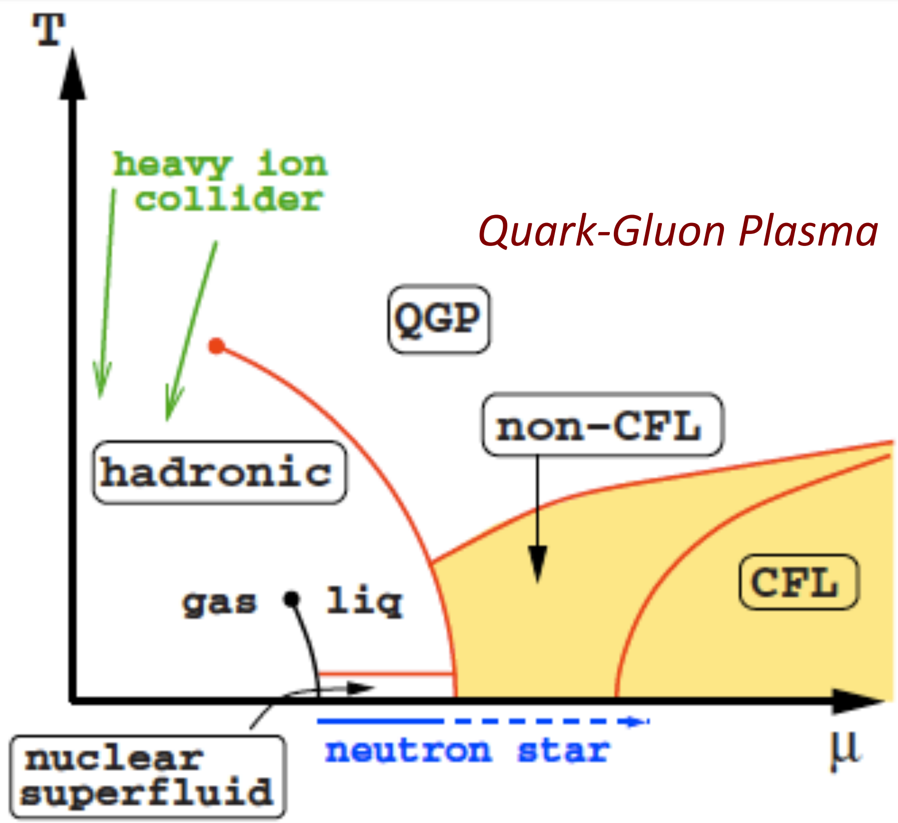


FIG. 1. (Color online) A schematic outline for the phase diagram of matter at ultrahigh density and temperature. The CFL phase is a superfluid (like cold nuclear matter) and has broken chiral symmetry (like the hadronic phase).

Alfred and Schmitt RMP ***80*** *(2008)*

With Some Experimental Evidence

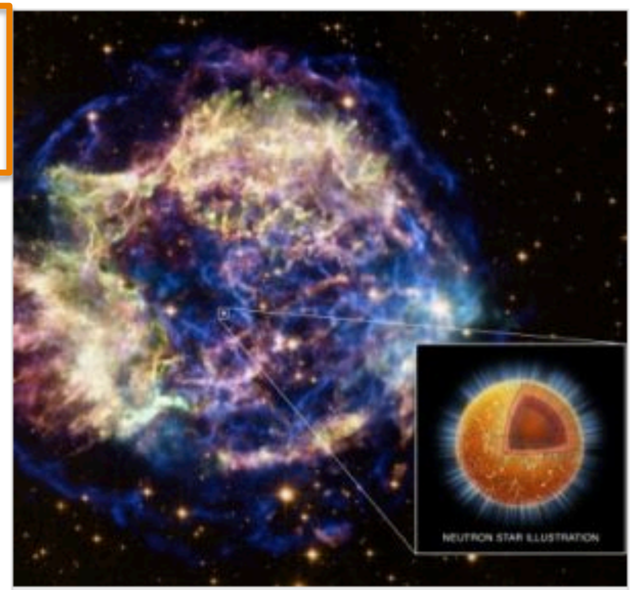
News

Superconductor found in neutron star's core

Science@NASA

Thursday, 24 February 2011

ALABAMA: NASA's Chandra X-ray Observatory has discovered the first direct evidence for a superfluid - a bizarre, friction-free state of matter - at the core of a neutron star.



Artist concept of a neutron star within supernova remnant Cassiopeia A.

Credit: NASA/CXC/M.Weiss

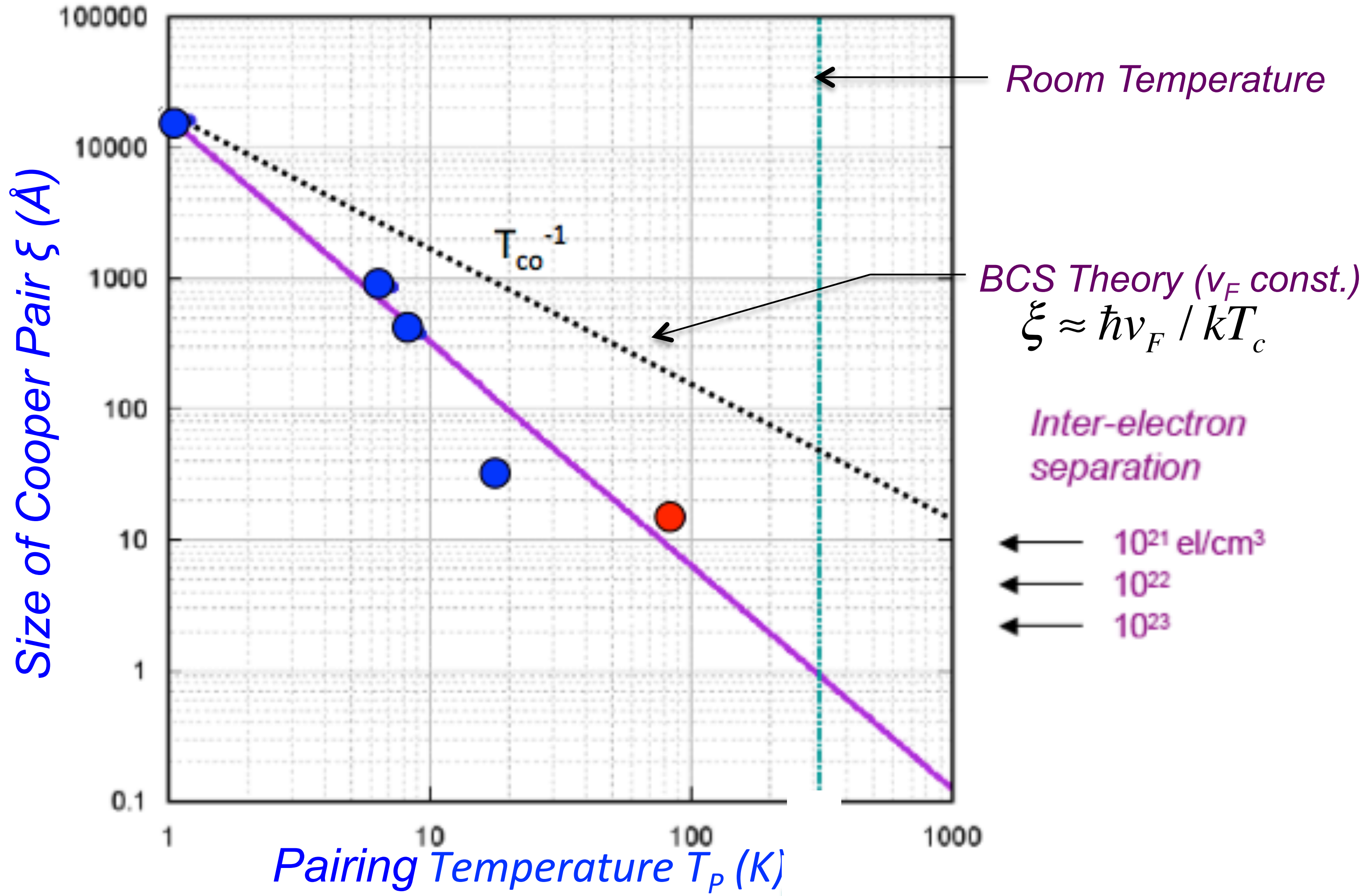
Superfluids created in laboratories on Earth exhibit remarkable properties, such as the ability to climb upward and escape airtight containers. The finding has important implications for understanding nuclear interactions in matter at the highest known densities.

"The rapid cooling in Cas A's neutron star, seen with Chandra, is the first direct evidence that the cores of these neutron stars are, in fact, made of superfluid and superconducting material," said lead author Peter Shternin of the Ioffe Institute in St Petersburg, Russia, of a paper accepted in the *Monthly Notices of the Royal Astronomical Society*.

Unusual rapid decline in temperature

Neutron stars contain the densest known matter that is directly observable. One teaspoon of neutron star material weighs six billion tonnes. The pressure in the star's core is so high that most of the charged particles, electrons and protons, merge resulting in a star composed mostly of uncharged particles called neutrons.

Any Room Temperature Superconductor Will be Extremely Unconventional



Local pairing,small unit cell and 3D (to minimize phase fluctuations), strong interactions, mean-field breakdown, not a single band.

If you want to find something unconventional, don’t look under the street light.

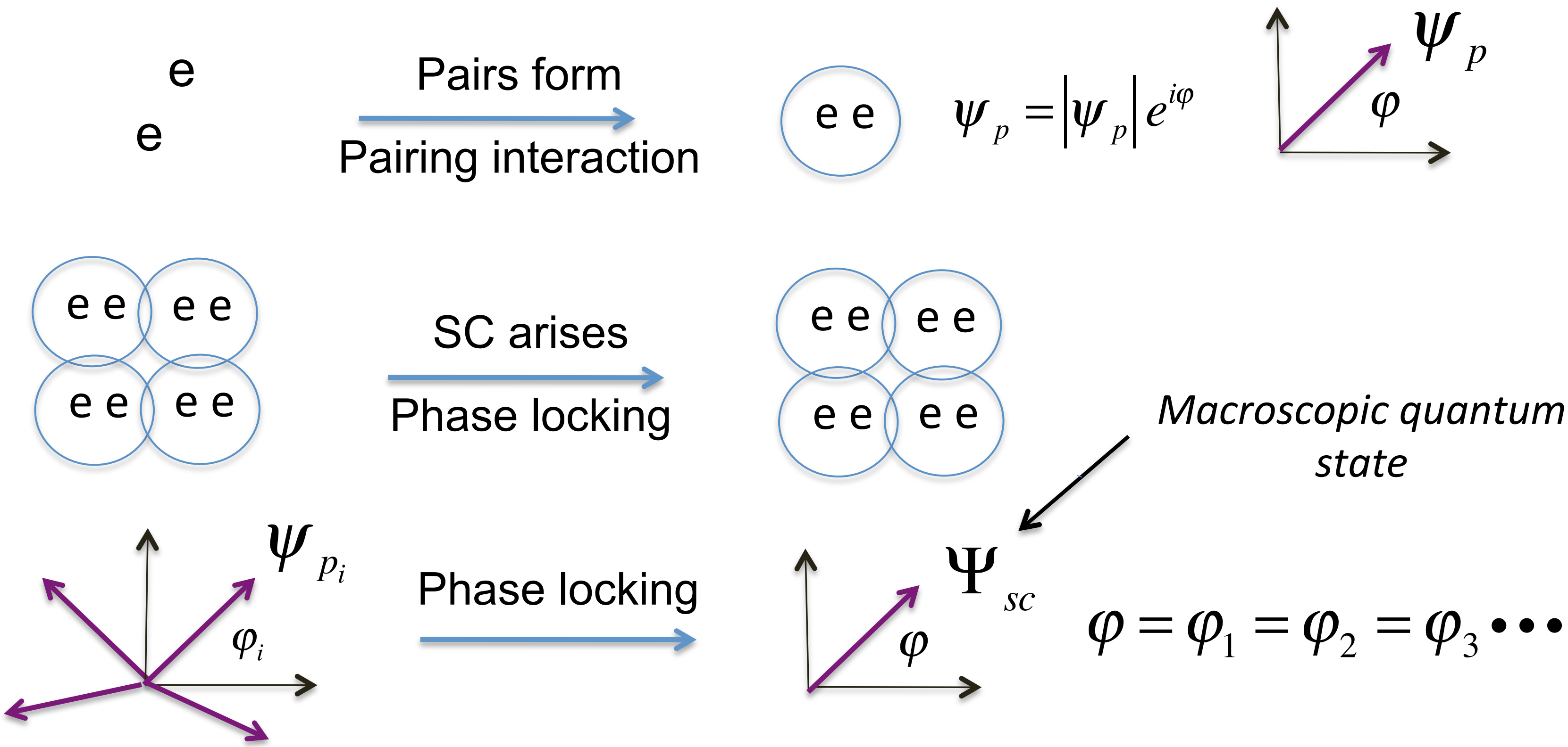
Empirical Guidance on Specific Interactions

Material Archetype	*T_c*	*Interaction*	**Guidance**
Bismuthates (i.e., doped $BaBiO_3$)	30K	Charge + Lattice	*Doped Negative U Insulator*
Cs_3C_{60}	40K	Lattice + Correlation (charge)	*El-Ph Covalent Bonds*
MgB_2	40K	Lattice	*El-Ph Covalent Bonds Prediction*
Fe-Based	50K	Spin	*Antiferromagnetism Multiple orbitals*
Cuprates	130K	Spin	*Doped Antiferromagnetic Positive U Mott Insulator*
Trace High T_c Anomalies	> Room Temperature	?	*Shouldn't Ignore*

→ Electronic (charge and spin) interactions look good

To Determine T_c There are Two Characteristic Temperatures to Consider

Superconductivity arises when electrons (or holes) form pairs and the quantum phases of these pairs order (lock) to form a coherent macroscopic quantum state with a single phase.

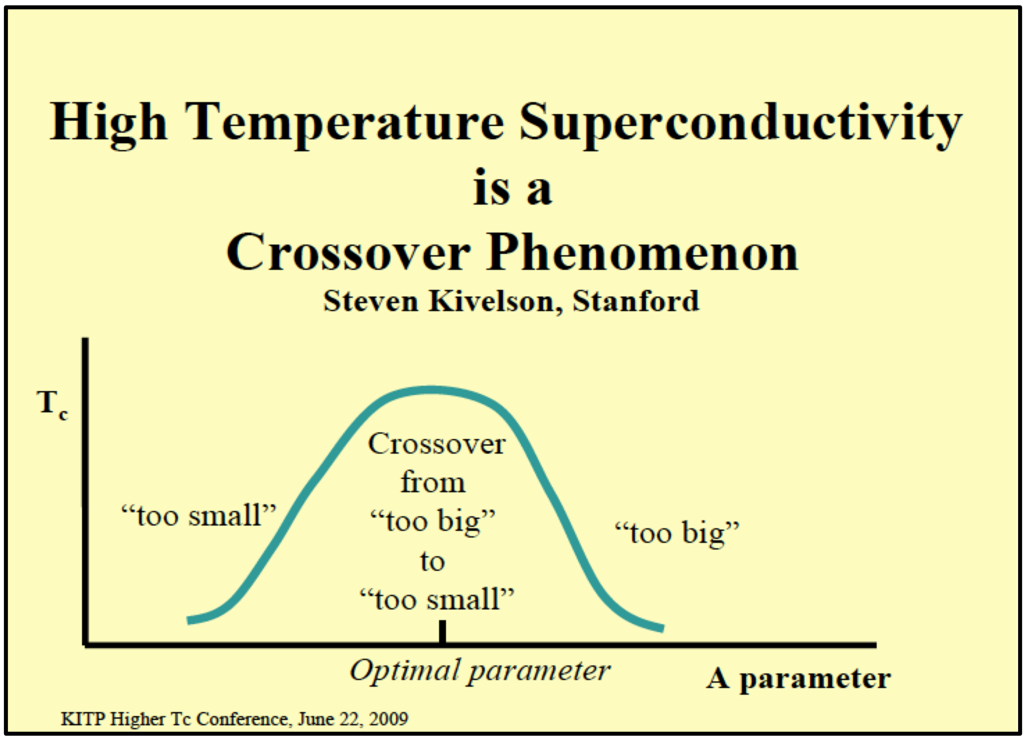


Each process has its own characteristic temperature

Theoretical Guidance

An always controversial subject

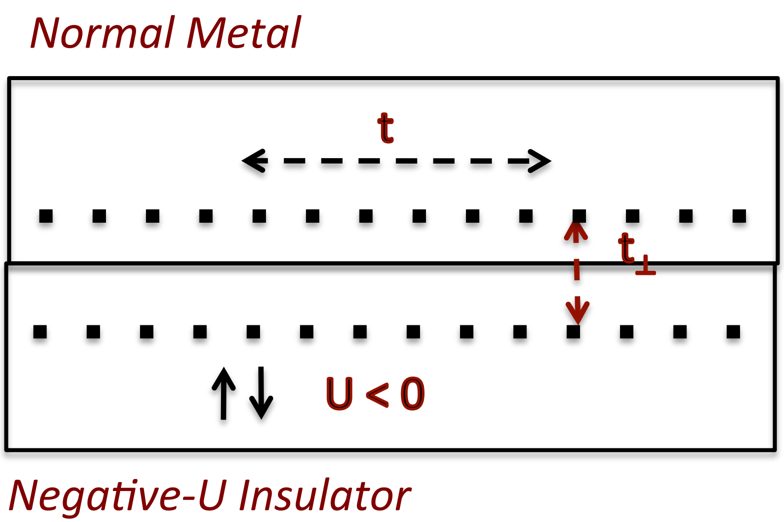
- How to optimize the el-ph mechanism – Modern electronic structure calculations (It is clear that theory could have predicted the high T_c superconductivity of Mg B_2)
- New mechanisms
- Electronic structure calculations as a tool in the search
- Strong interactions, but honor the "Goldilocks Principle"



E.g., from weak coupled BCS (delocalized) limit to strong coupled (local) limit. Typically also for doping.

…. And Maybe We Can Have Our Cake and Eat It Too

High T_c and High Pair Density Superconductor Using a Normal Metal/Negative-U Insulator Proximity Effect:



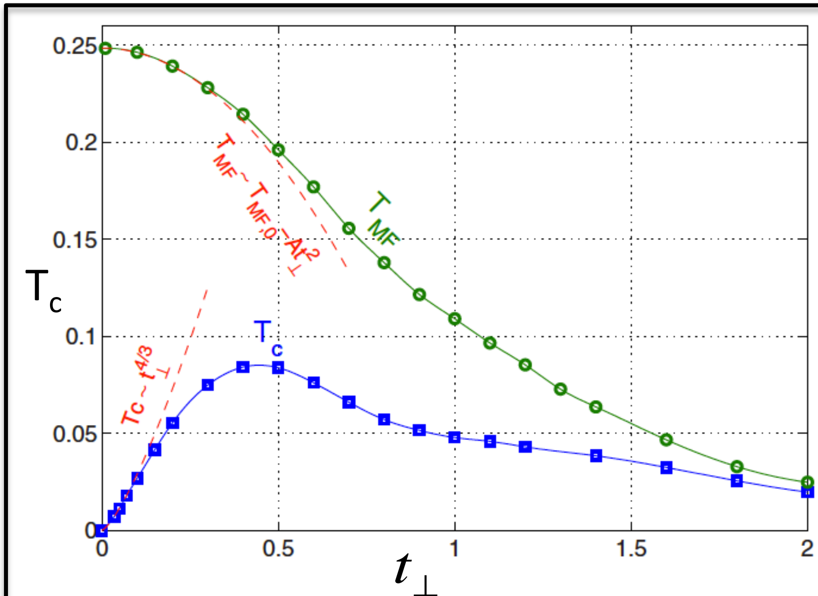


FIG. 1. (Color online) T_c (□) and T_{MF} (◯) obtained from solving Eqs. (6)–(9) numerically for $n=1.5$, $t=1$, $U=1$ as a function of $t_\perp$. The dashed curves are fits to the data according to Eqs. (13) and (15). $A=0.235$ was used in the fit.

$$H = -t\sum c_m^\dagger c_m - U\sum n_{p\uparrow} n_{p\downarrow} - t_\perp \sum c_m^\dagger c_p$$

Berg, Orgad and Kivelson PRB 78, 094509 (2008)