2012 Applied Superconductivity Conference

The Search for New Superconductors from an Applications Perspective

M.R. Beasley
Stanford University

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Objectives of the Talk

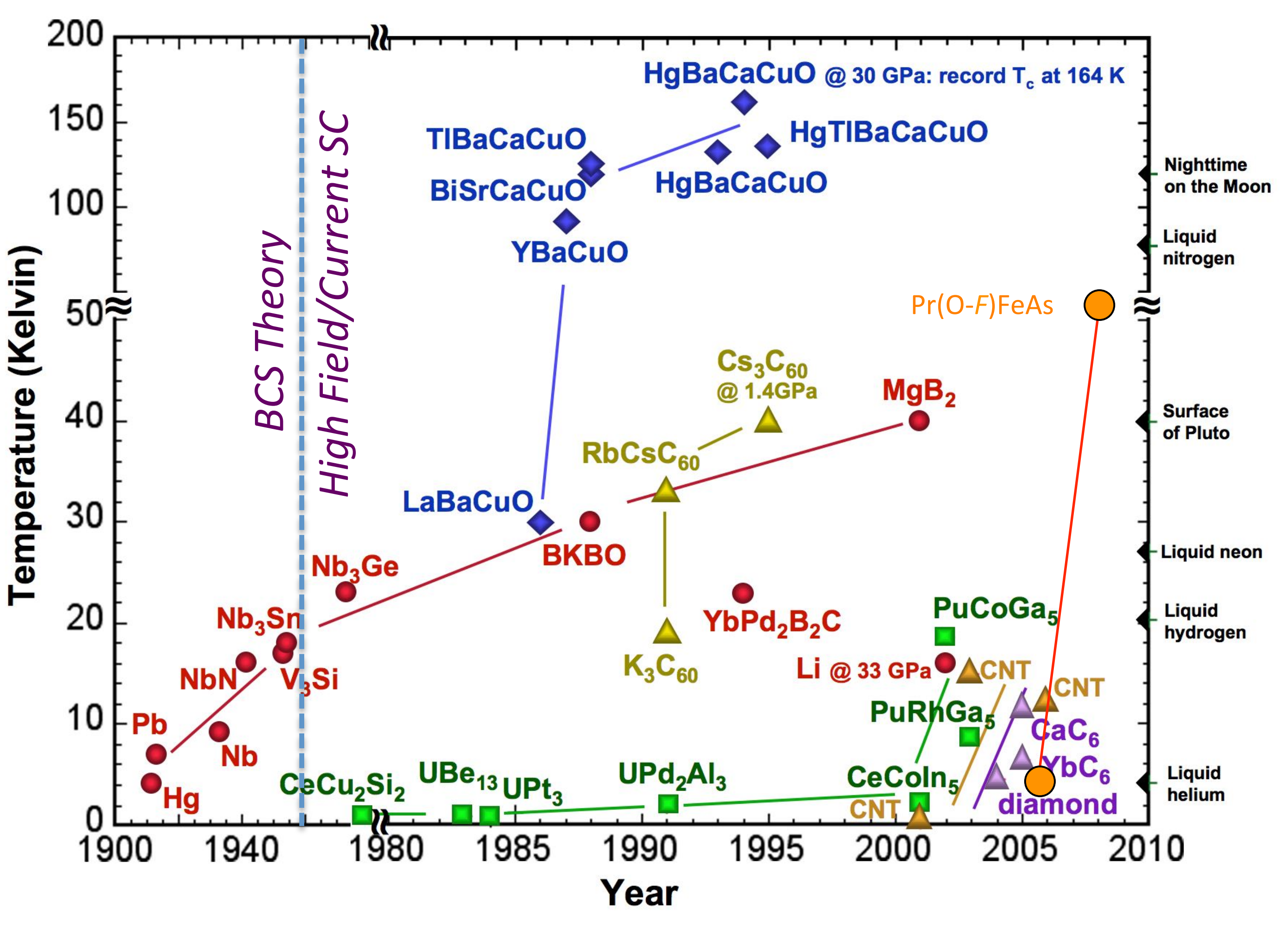
- *Looking back – What have we learned about the nature of very high T_c superconductivity in recent decades?*

- *What does it tell us about the prospects of electric power applications of superconductivity at much higher temperatures?*

- *Looking ahead – How might we proceed? Or at least provide some guidance*

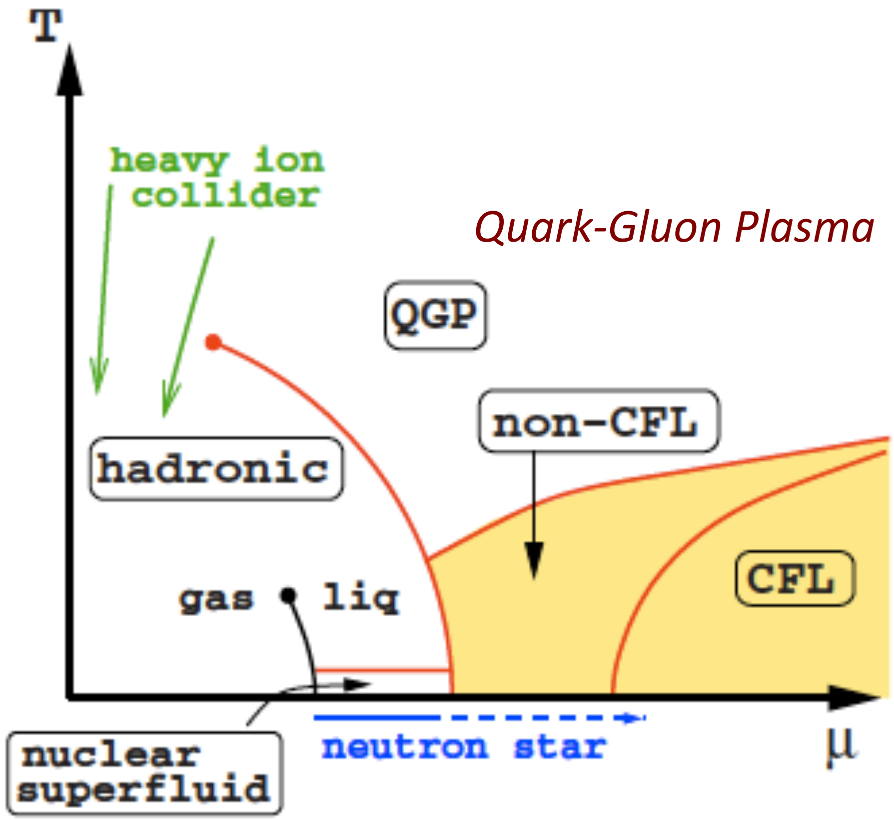
In Search of the Holy Grail

The Quest for a Room Temperature Superconductor



Adapted from a DoE Report

In Nature the Transition Temperature Can Be "Astronomically" High



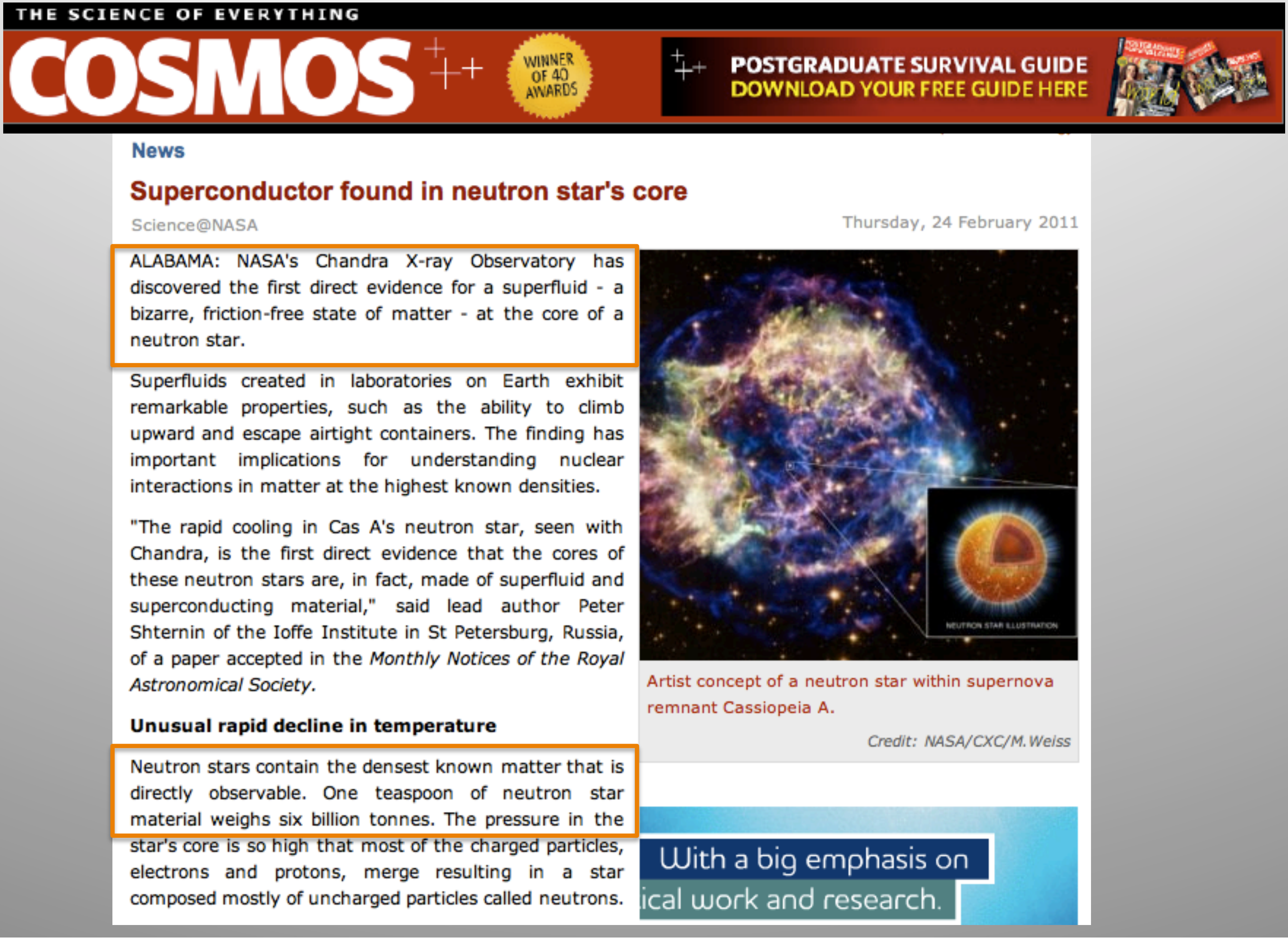
Quark-Gluon Plasma

Color-Flavor Locked Quark Matter

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



THE SCIENCE OF EVERYTHING

COSMOS

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.

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*.

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

Credit: NASA/CXC/M.Weiss

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.

But What About a “Room Temperature” Superconductor?

It must:

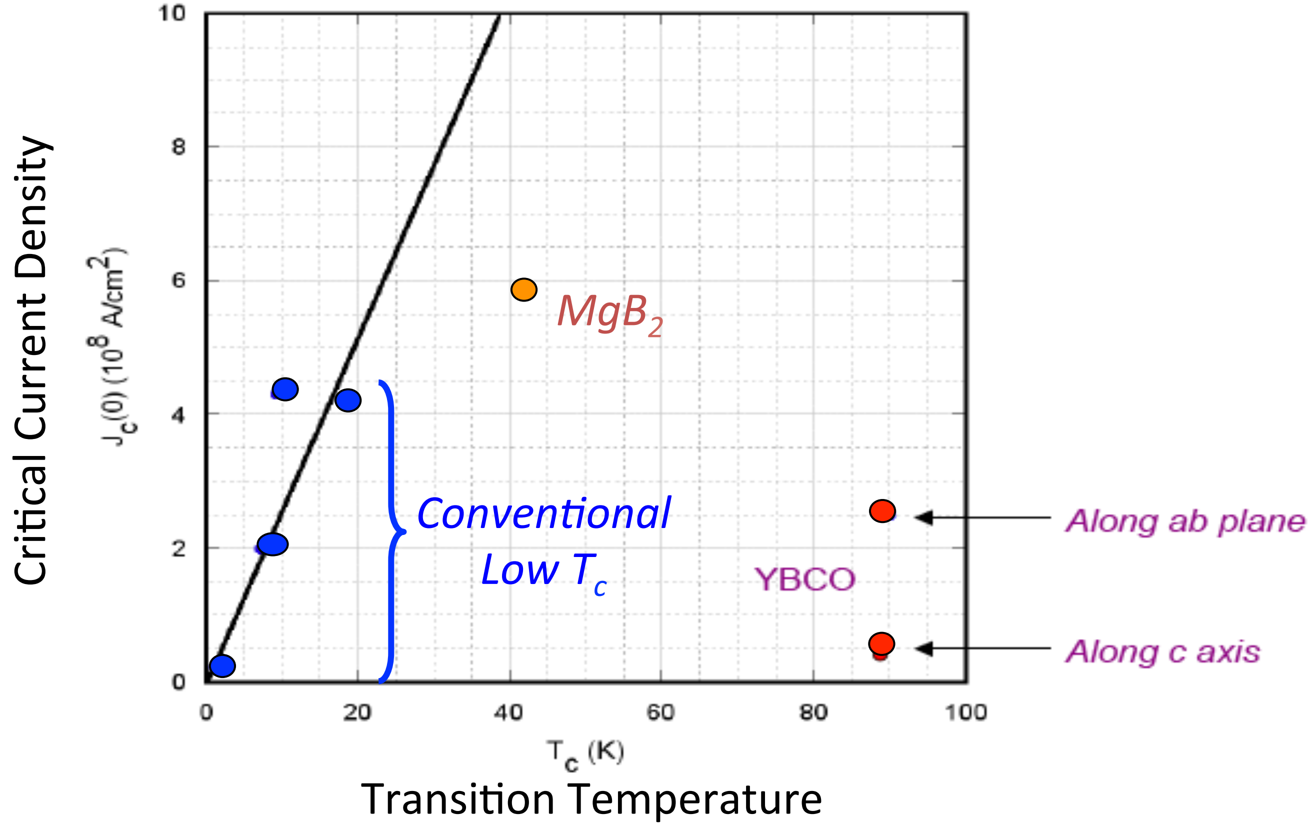
- *Operate in an earthly environment*
- *Be made from earthly forms of matter*
- *And from a practical point of view, exhibit good superconducting properties**

** In the past it has been an article of faith that superconducting properties improve as* T_c *increases*

But Higher T_c Does Not Always Bring Higher J_c

Thermodynamic Critical Current Density of Various Superconductors

The theoretical maximum current density



So What's Going On?

Factors Governing the Thermodynamic Critical Current Density

For any superconductor:

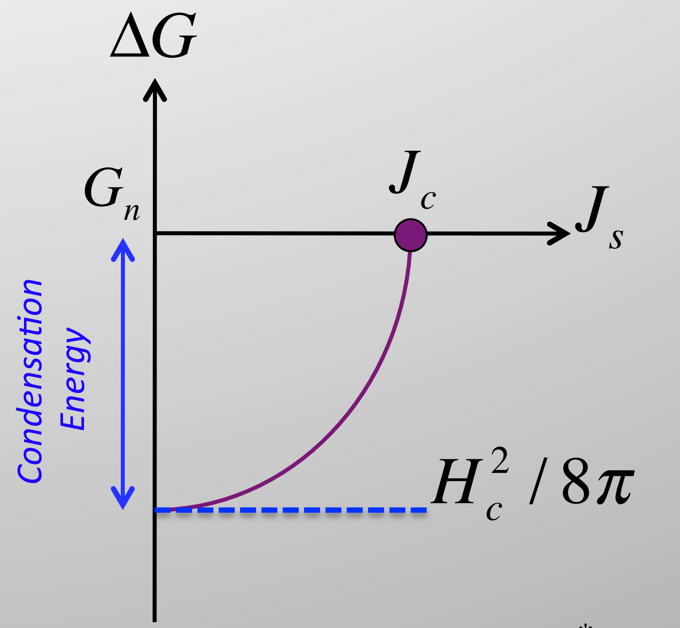
- *The supercurrent density*

$$J_s = n_s^* e^* v_s$$

- *The kinetic energy density*

$$G_K = \frac{1}{2} n_s^* m v_s^2 = \frac{1}{2} \frac{m^*}{n_s^* e^{*2}} J_s^2 = \frac{1}{2} \Lambda_K J_s^2$$

$$\Lambda_K = \frac{m^*}{n_s^* e^{*2}} = \frac{4\pi\lambda^2}{c^2} = Kinetic\ inductivity$$

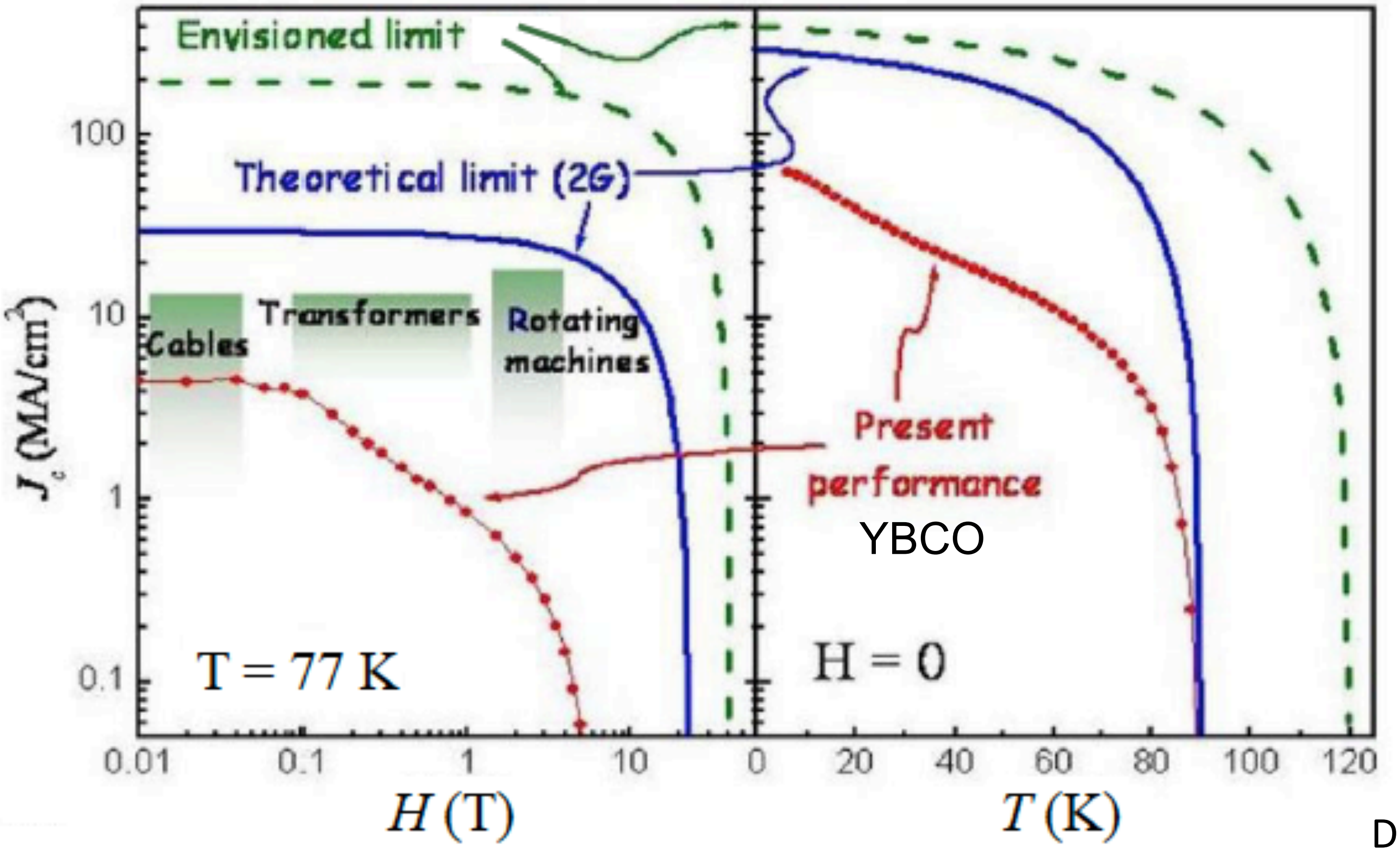


$$J_c = \frac{1}{\sqrt{2}} n_s^* e^* \frac{\hbar}{m^* \xi} \propto \frac{n_s^*}{m^*} T_c$$

where ξ = *size of Cooper pair* ($\xi \propto 1/T_c$)

➡ *Large J_c requires high T_c and high pair density*

And How Good is YBCO for Electric Power Applications?



DoE Report

The Practical Reality

- *YBCO is the best cuprate superconductor for electric power applications (least anisotropic)*

→ *If there are to be commercial electric power applications of superconductivity above 77K, an entirely new superconductor will be required*

→ *We should be looking*

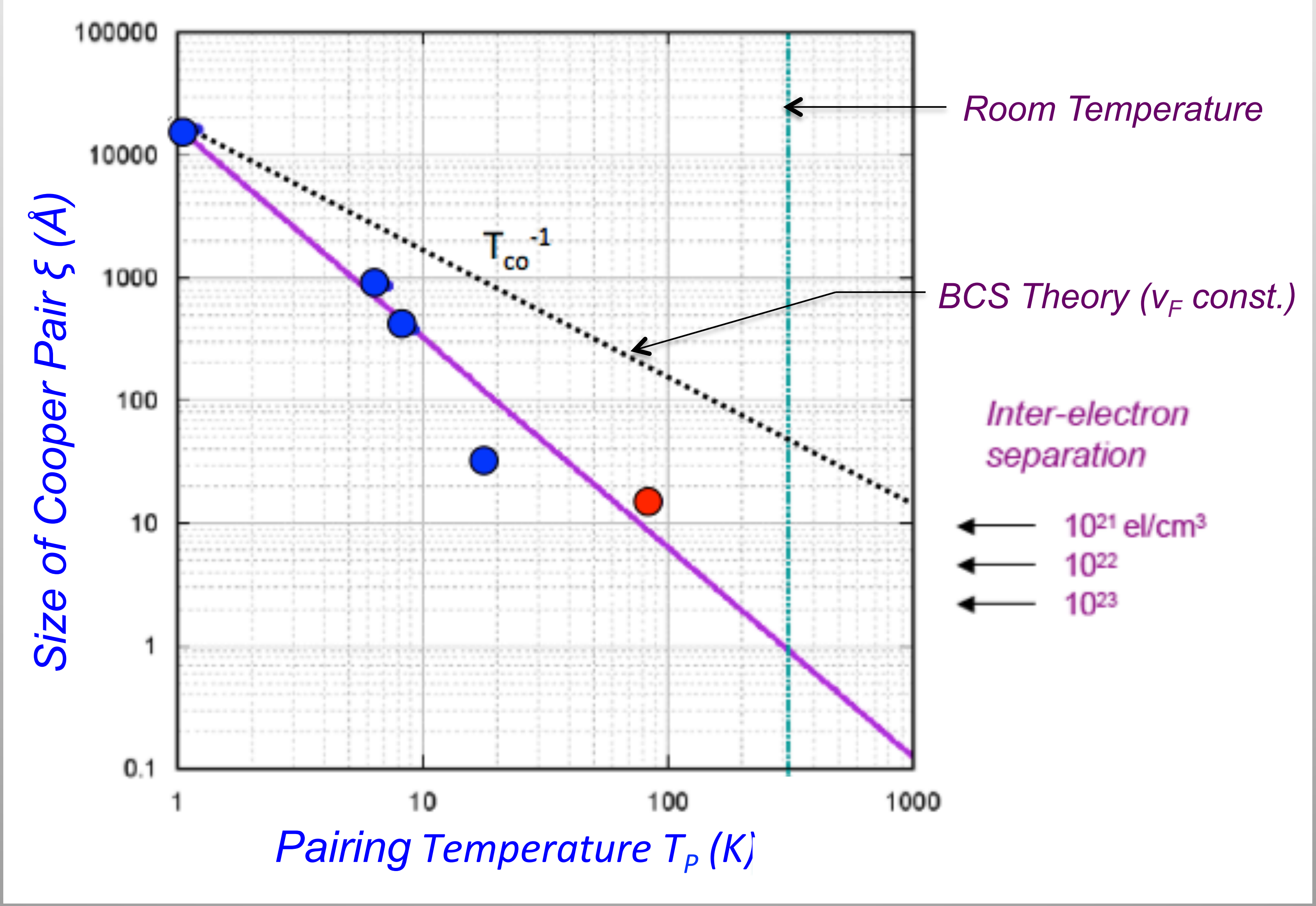
A Primer on The Fundamentals of Very High Temperature Superconductivity

- *What would the Cooper pairs be like?*

- *Are there generic (pairing mechanism independent) limits on T_c?*

- *How do these insights square with experience?*

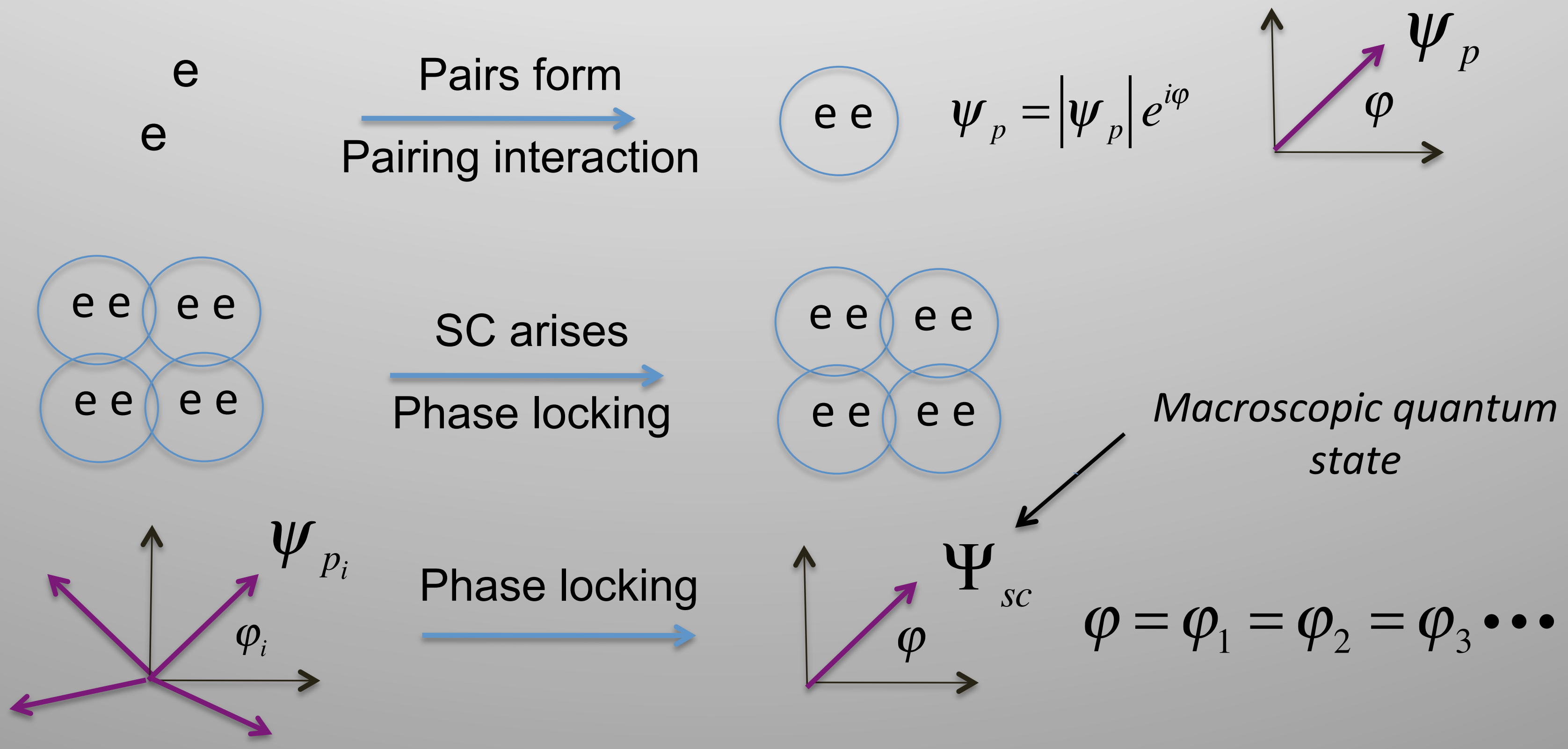
Whatever Else, The Cooper Pairs Will Be Very Small



➡ *The physics of pairing will be local (i.e., real space pairing)*

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.



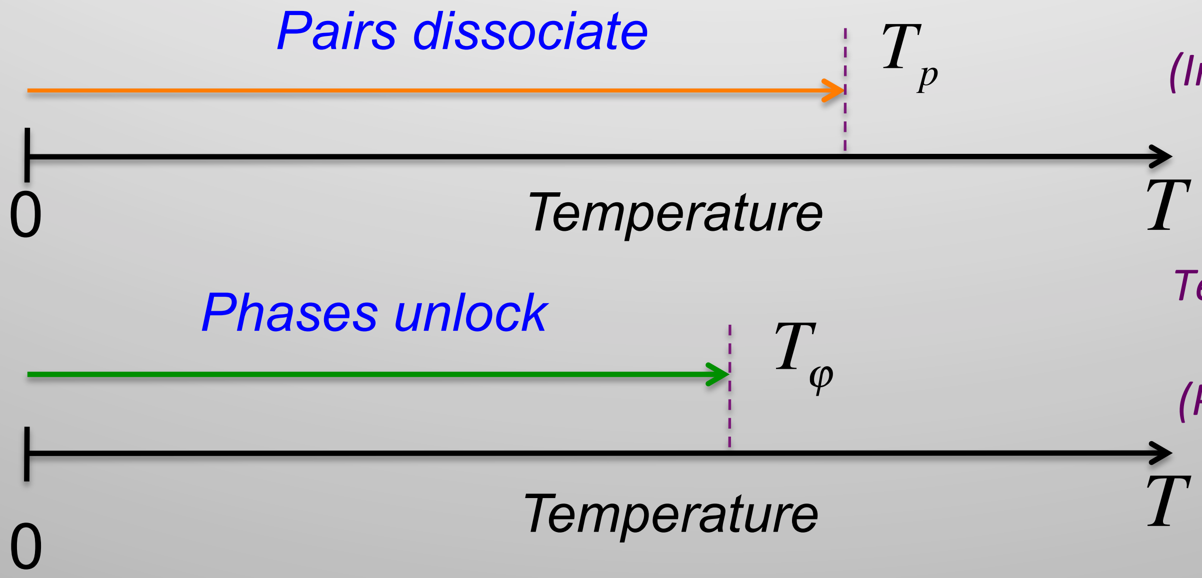
$$\psi_p = \left|\psi_p\right| e^{i\varphi}$$

$$\varphi = \varphi_1 = \varphi_2 = \varphi_3 \bullet\bullet\bullet$$

Each process has its own characteristic temperature

The Actual Superconducting Transition Temperature T_c

The Destruction of Superconductivity by Increasing Temperature



Pairs dissociate

T_p

0

Temperature

T

Binding energy (Interaction strength)

Phases unlock

T_φ

0

Temperature

T

Tendency of phase to fluctuate (Phase stiffness $1/\Lambda_K$)

➡ $\mathit{If}\ T_\varphi < T_p \Rightarrow T_c = T_\varphi$

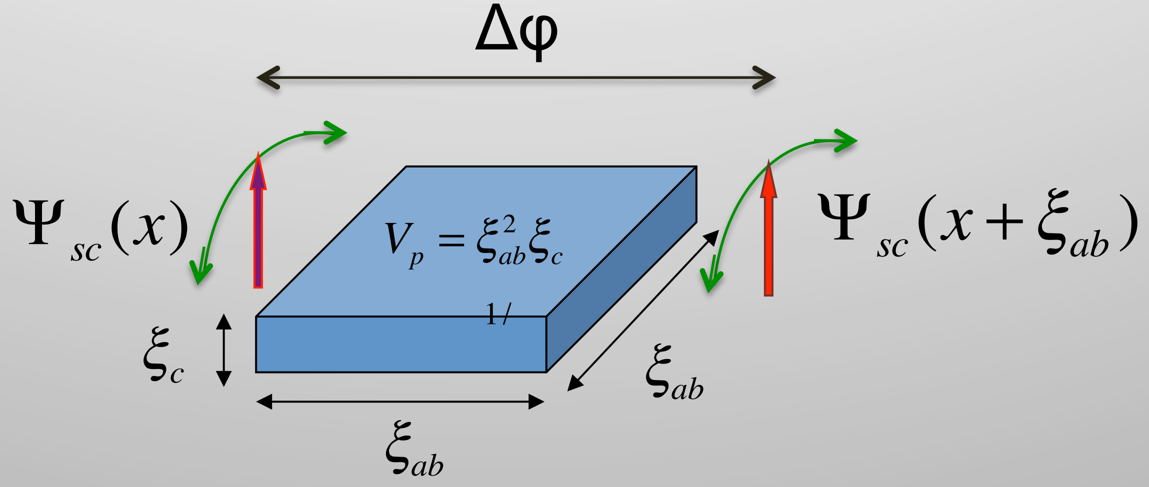
➡ $\mathit{If}\ T_p < T_\varphi \Rightarrow T_c = T_p$

(and T_φ renormalizes down to T_p as in BCS theory)

Thermodynamic Limit to the Transition Temperature Due to Thermal Phase Fluctuations

Independent of the pairing interaction, phase ordering is lost when the RMS phase difference Δφ across a Cooper pair due thermal phase fluctuations is of order π

V_p = Volume of a Cooper pair



Temperature at which thermal fluctuations produce phase unlocking

Energy to twist phase by π

$$\overbrace{\frac{1}{2}\frac{1}{\Lambda_K}(\underset{\frac{\pi}{\xi_{ab}}}{\nabla\phi})^2 V_p}^{\text{Energy to twist phase by }\pi} = k_B T_\phi \Rightarrow$$

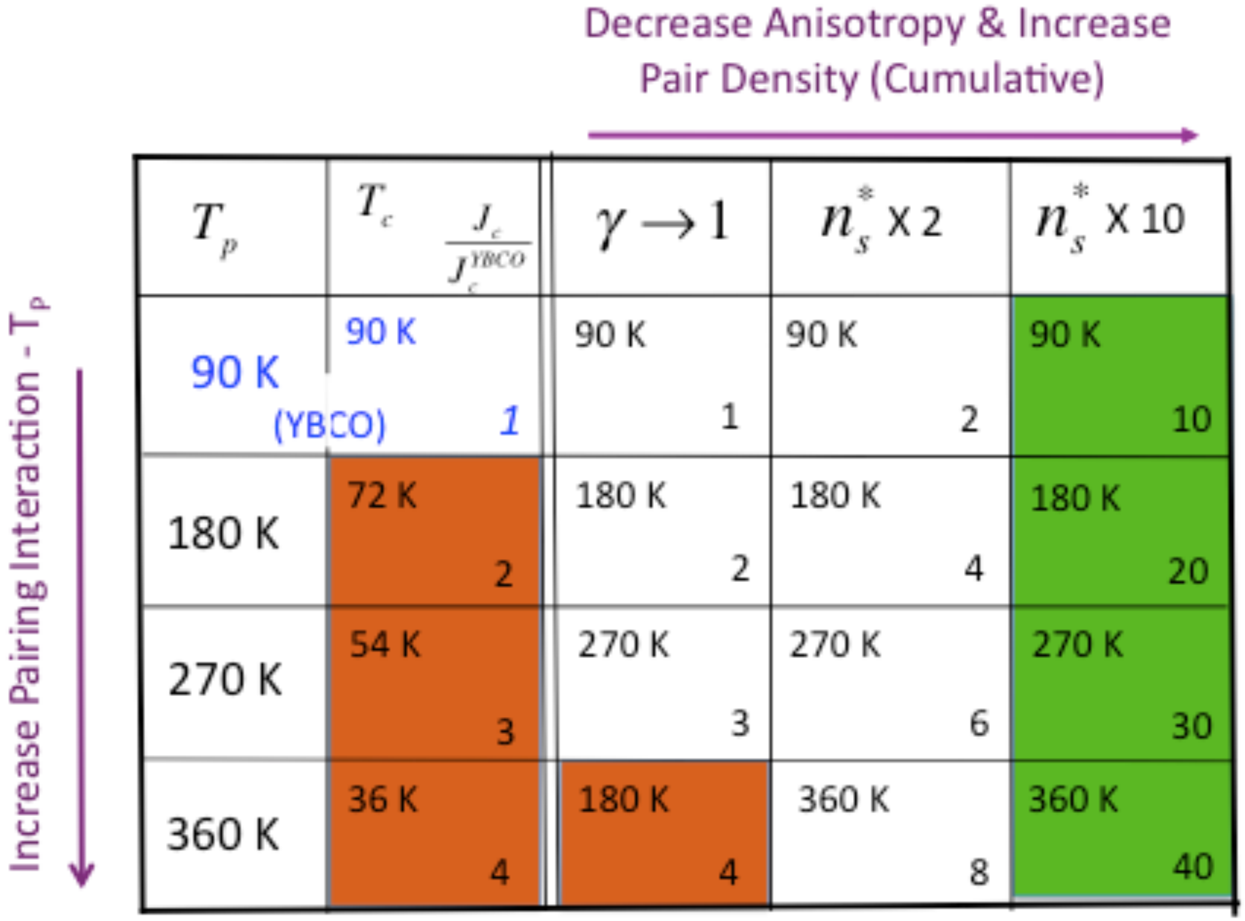
$1/\Lambda_K$ = Phase stiffness

$$\boxed{T_\phi \approx \frac{1}{2}\frac{1}{\Lambda_K}\frac{\xi_{ab}}{\gamma} = \frac{1}{2}\frac{\hbar^2 n_s^*}{m^*}\frac{\xi_{ab}}{\gamma} \propto \frac{n_s^*}{m^*}\frac{1}{\gamma T_p}}$$

$\gamma = (M/m)^{1/2}$ GL mass anisotropy

Is a Room Temperature Superconductor Possible?

Notional High Temperature Superconductors Relative to YBCO (v_F constant)



Decrease Anisotropy & Increase Pair Density (Cumulative)

Increase Pairing Interaction - T_P

T_p	T_c $\frac{J_c}{J_c^{YBCO}}$	$\gamma \rightarrow 1$	n_s^* X 2	n_s^* X 10
90 K	90 K (YBCO) 1	90 K 1	90 K 2	90 K 10
180 K	72 K 2	180 K 2	180 K 4	180 K 20
270 K	54 K 3	270 K 3	270 K 6	270 K 30
360 K	36 K 4	180 K 4	360 K 8	360 K 40

$$\frac{T_\phi}{T_p} \propto \frac{n_s^* v_F}{\gamma T_p^2}$$

$$T_c = \min\{T_\varphi, T_P\}$$

$$J_c \propto n_s^* T_P$$

$$\gamma = \sqrt{\frac{M}{m}}$$

$$\xi \propto 1/T_P$$

Yes, but will require strong interactions, high pair density and low anisotropy

General Considerations *vs* Experience Relevant for the Search for a Room Temperature Superconductor

Commonly Stated Empirical Guidance*	**General Physical Considerations**
Increase interactions	*Increase interactions*
Low carrier density	*High carrier density*
Two dimensional	*Three dimensional*

There is an apparent conflict here

In addition, very small pair size → Local pairing on near atomic level → Must learn to think and calculate in real space more like the chemists do

* Based on the cuprate superconductors

Fundamental Questions

The general physical considerations presented above are derived from thermodynamic reasoning and therefore carry great power

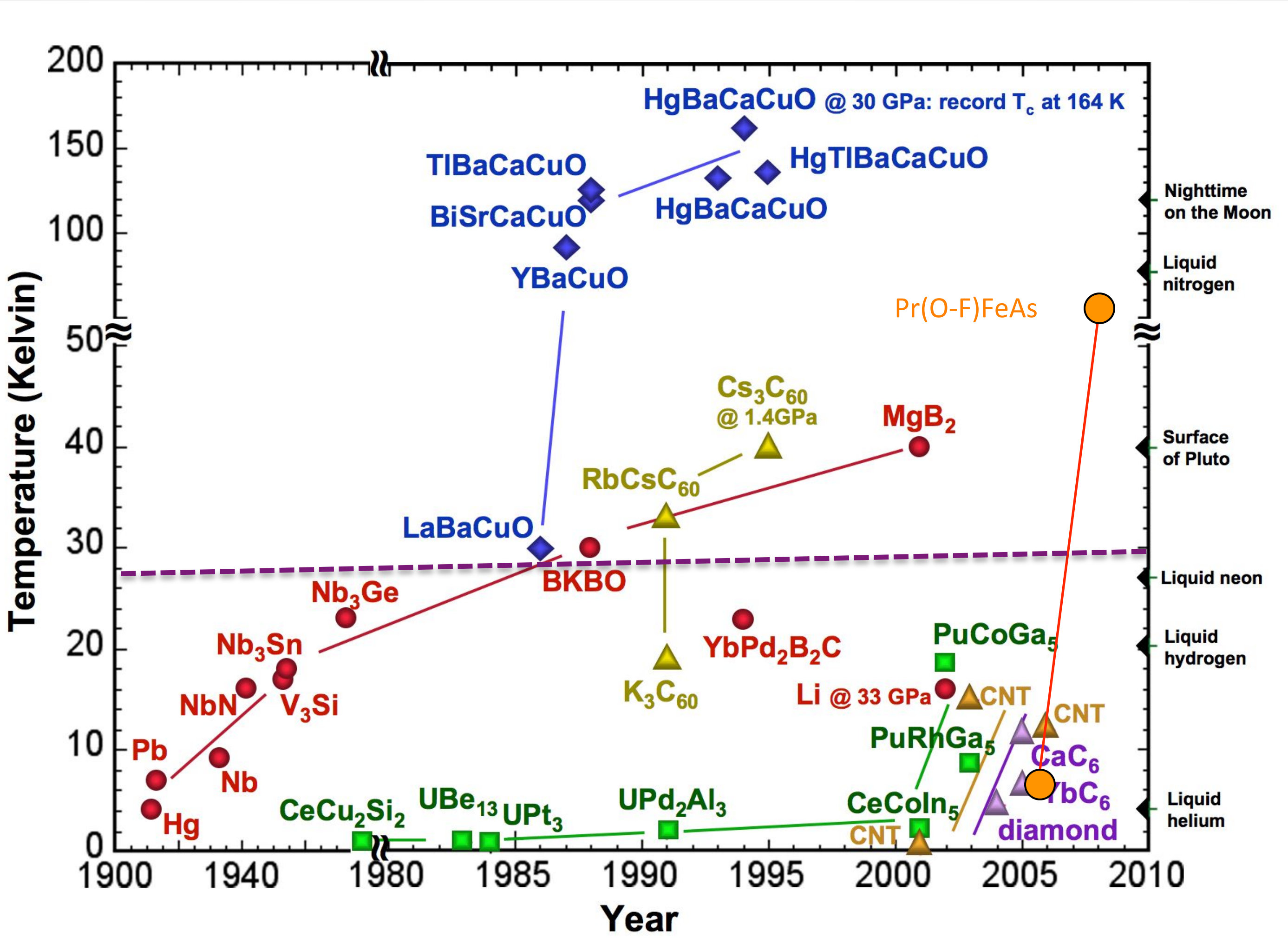
This clearly raises some very fundamental questions:

- *Can strong interactions and high pair density be achieved at the same time? Or are they incompatible? (If the electron density is very high, one may just get a simple metal with weak interactions)*
- *Is reduced dimensionality beneficial (or possibly necessary) for high* T_c*? For example, to weaken an anti-ferromagnetic parent phase through increased fluctuations to allow superconductivity to emerge upon doping*

Now Let's Focus on the Possible Specific Interactions Seemingly Favorable for Very High Temperature Superconductors

- *What do we know empirically?*
- *What can we say theoretically?*
- *What guidance do theory and experiment provide us?*

So What Can We Learn From the Present High T_c Superconductors?



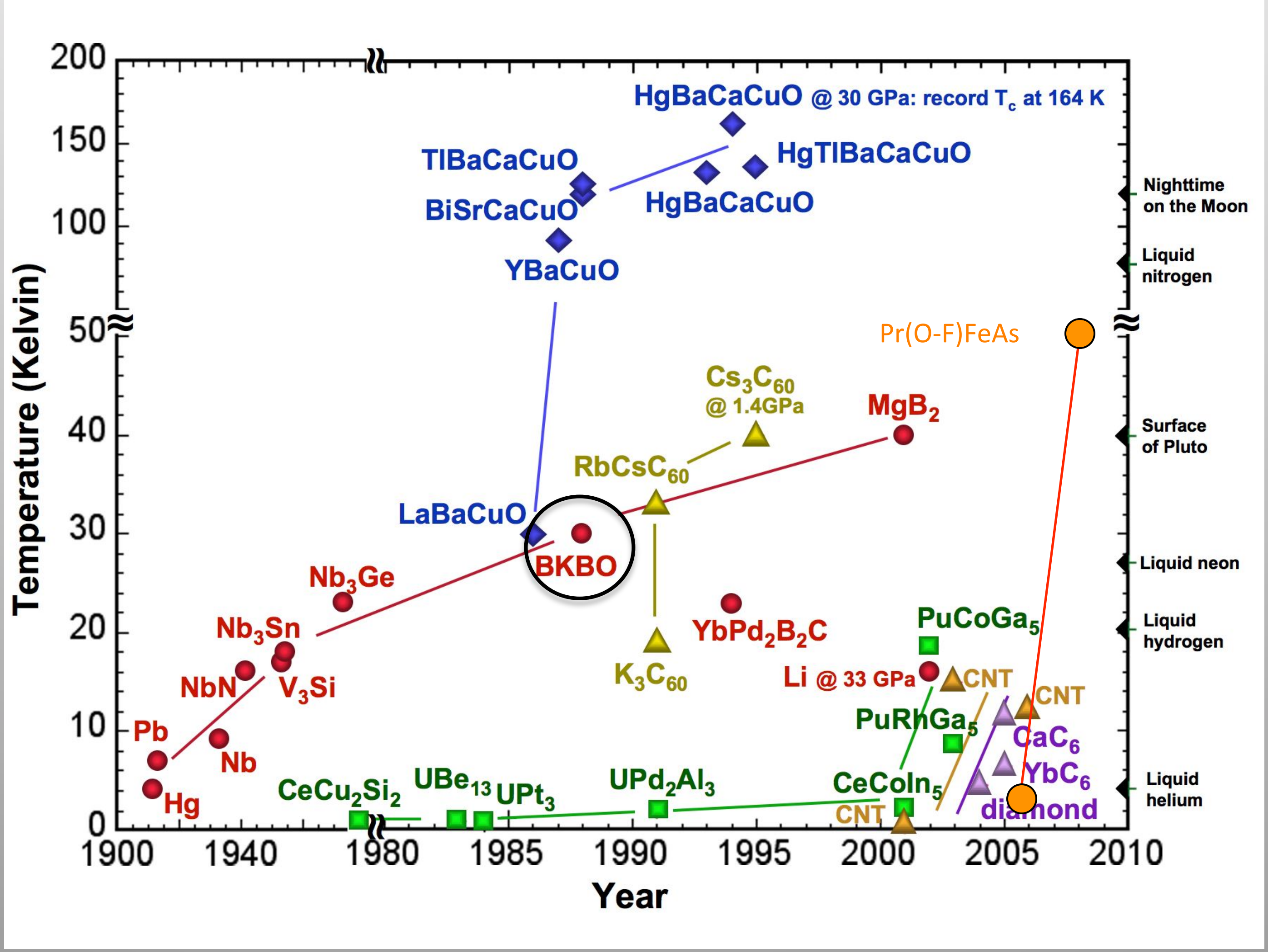
Empirical Guidance on Specific Interactions

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

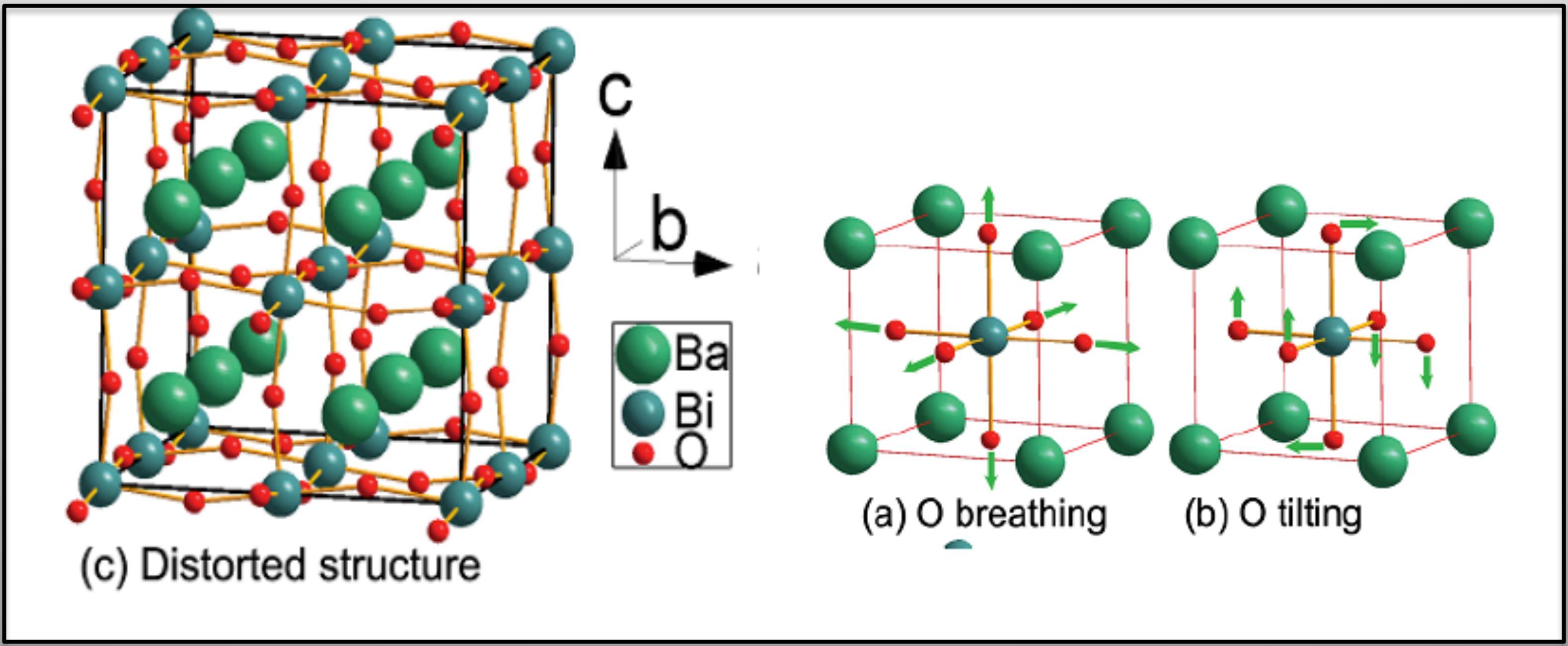
A Case Study – The Bismuthates

Superconductivity in a doped charge-ordered oxide insulator



Crystal Structure of $BaBiO_3$

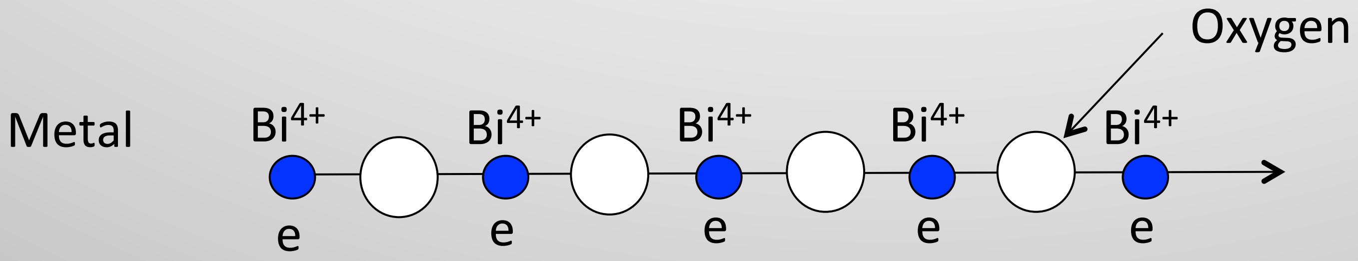
Distorted Perovskite



Note three dimensional structure

Charge-Disproportionated (Negative U) Superconductors (e.g., BaBiO$_3$)

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

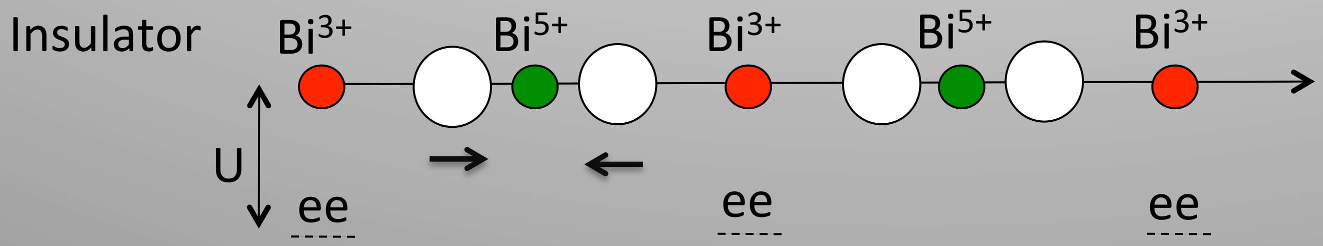


$$2Bi^{4+}(4s^1) \rightarrow Bi^{3+}(4s^2) + Bi^{5+}(4s^0)$$

and

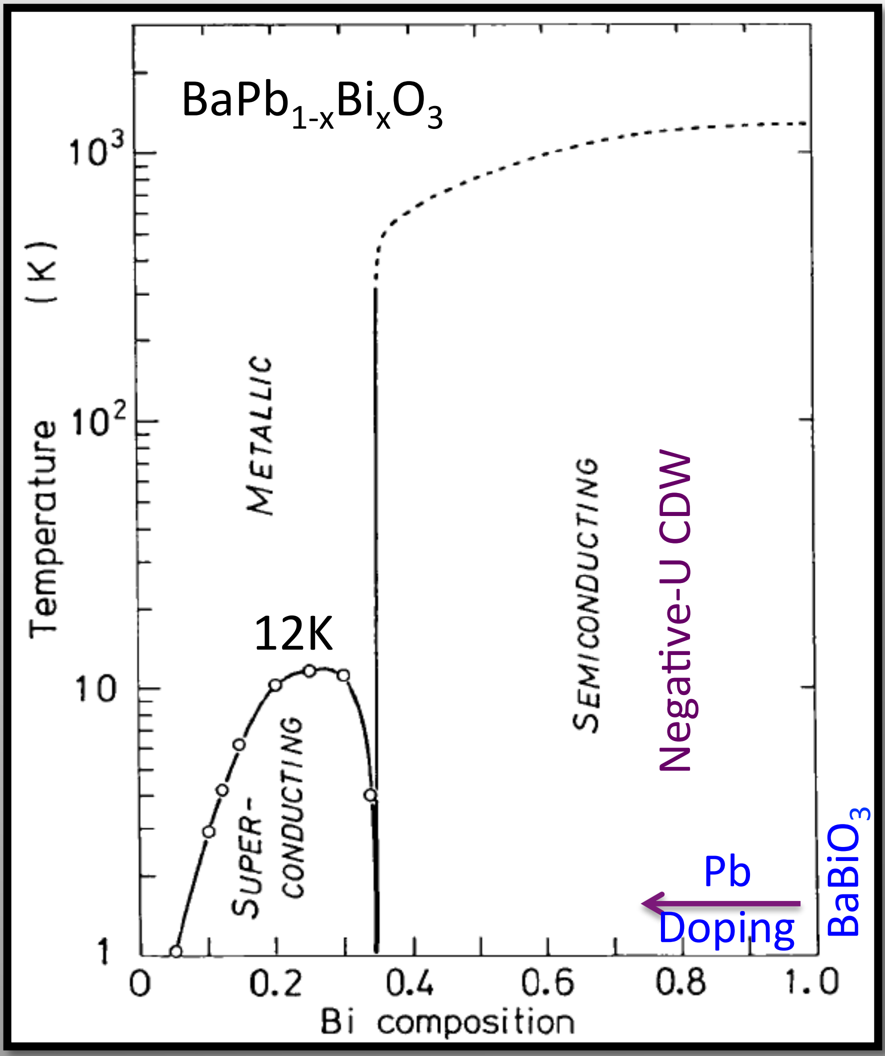
Oxygen atoms move to screen charge (Breathing mode)

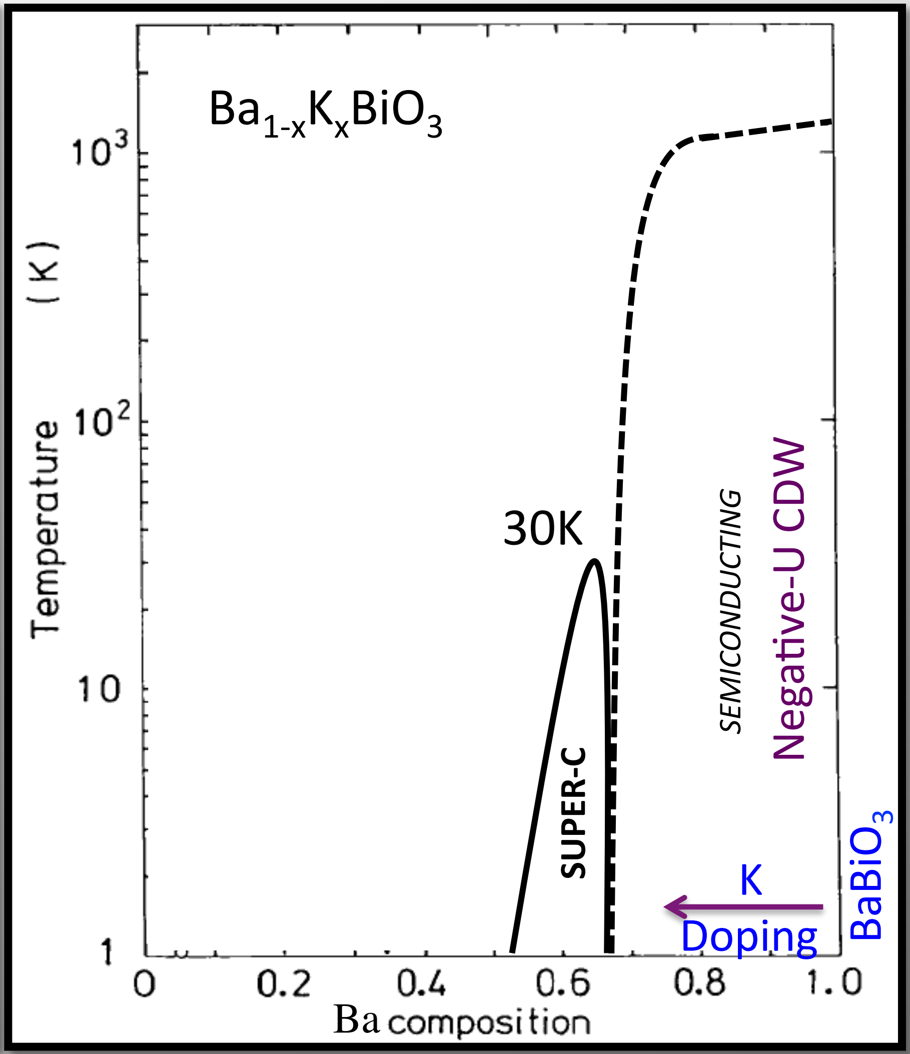
Negative U -- Involves both charge and lattice



Superconductivity arises upon doping (Ba$_{1-x}$K$_x$BO$_3$ and BaPb$_{1-x}$Bi$_x$O$_3$)

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

Optical Properties -- Puchkov et al

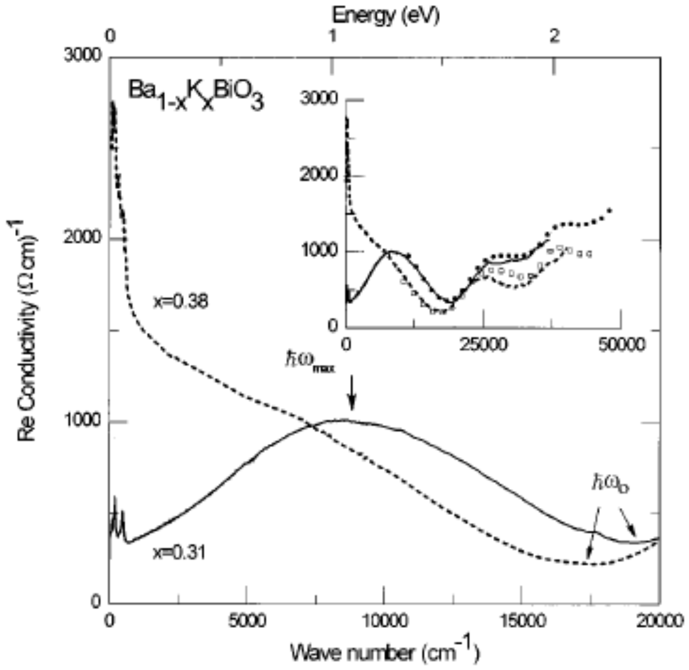


FIG. 1. The optical conductivity of $Ba_{1-x}K_xBiO_3$ just below and just above the insulator-metal transition. The characteristic energies $\hbar\omega_{max}$ and $\hbar\omega_0$, used in the text, are shown. The inset: the lines represent the real part of the optical conductivity obtained from the KK analysis of reflectivity spectra. The symbols show results of ellipsometric measurements.

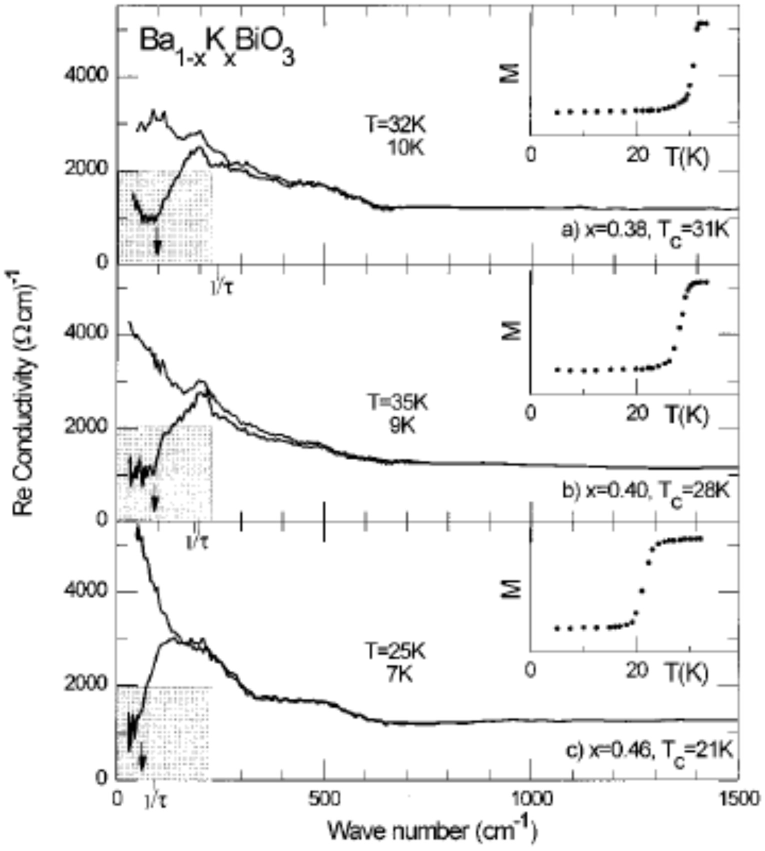
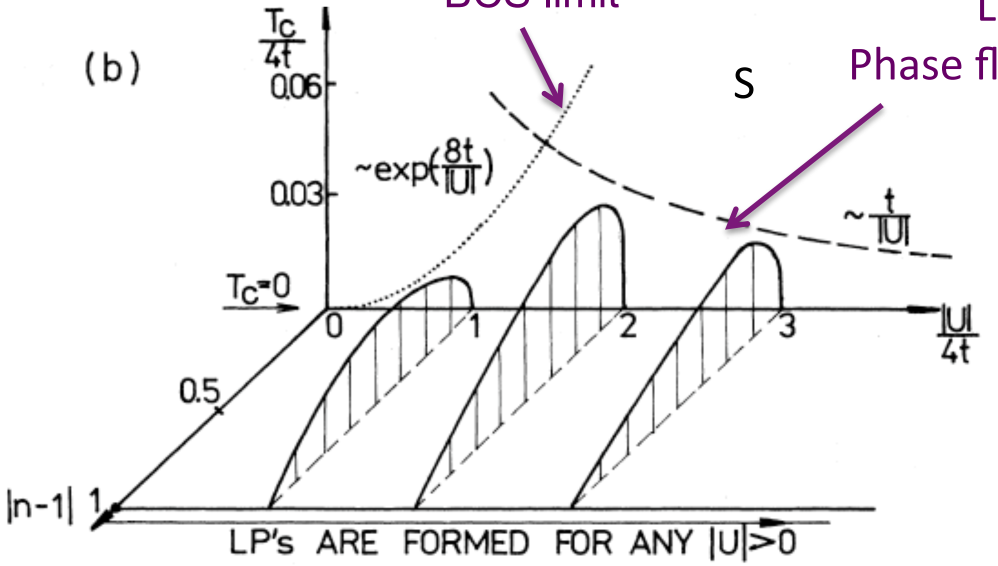


FIG. 4. The optical conductivity of the three metallic samples BKBO in the superconducting and the normal states. The results of magnetization measurements are shown on the insets. The scattering rate values $1/\tau$ in the normal state are shown on the frequency axis for all three samples. The shaded squares represent the spectral weight of the superconducting carriers. The London penetration depth λ_L is inversely proportional to the side of the square. The position of the superconducting gap energy $2\Delta_s$ is shown by the arrows.

- Only 3 x 10^{20} carriers in Drude Peak and little change with x.
- Strong MIR peak

Illustrative Theoretical Phase Diagram

(Numerical Solution to the Negative-U Hubbard Model)



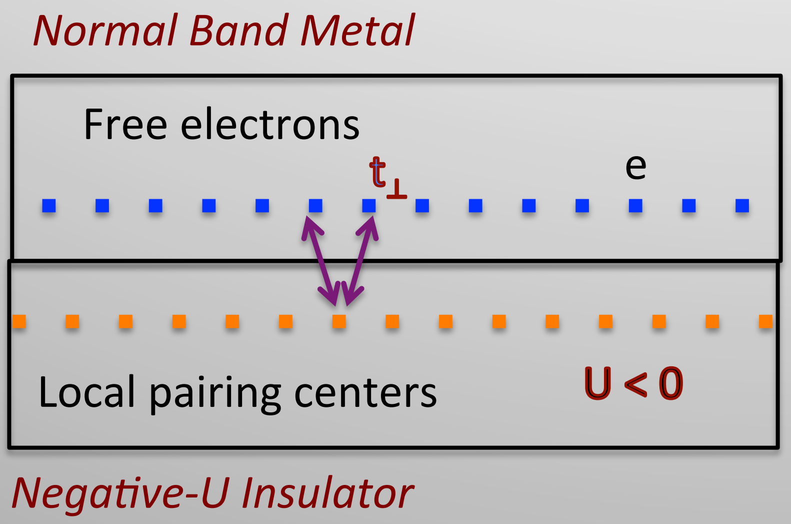
Weak Interactions
Itinerant
BCS limit

Strong Interactions
Localized
Phase fluctuation limit

Max T_c occurs at crossover between weak and strong coupling – Seems to be a generic feature of strong interactions (including the el-ph interaction)

A New Theoretical Concept

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



Normal Band Metal

Free electrons

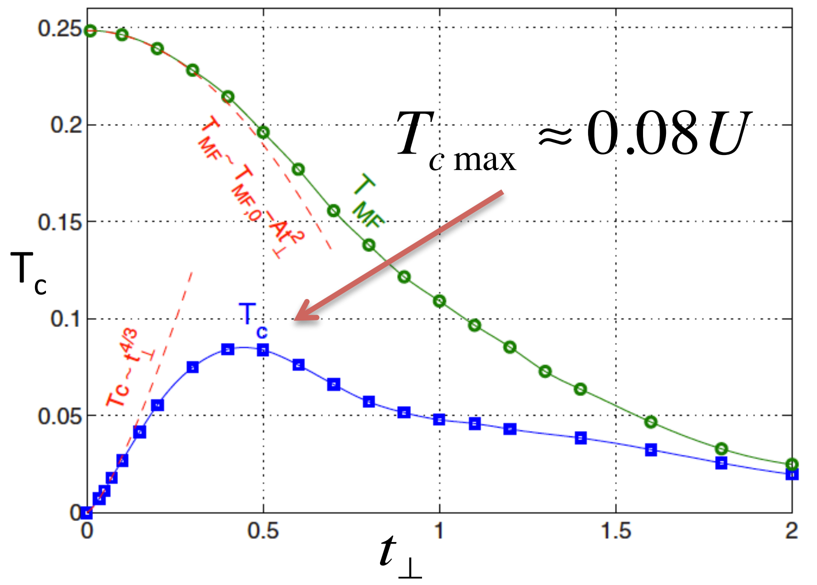
$t_\perp$

e

Local pairing centers

U < 0

Negative-U Insulator



$T_{c\,\max} \approx 0.08U$

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.

Electrons coherently hop on and off the pairing centers to induce superconductivity in the normal metal

A key element here is the role of two distinct sets of electrons that are separated in space

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

So Where Do We Stand in our Quest for a Useful Room Temperature Superconductor?

- *There are generic limits to* T_c
- *But they do not preclude a room temperature superconductor, if the anisotropy is low and the carrier density high*
- *The challenge will be to achieve strong interactions under these conditions; there are some new ideas how to do this*
- *And we must learn how to deal with very small Cooper pairs*
- *The conditions necessary for room temperature superconductivity are consistent with those needed for good practical performance*

Wish Good Luck to Those Willing to Try
(and those that fund them)