

China/US Joint Winter School on Novel Superconductors
Hong Kong – January 2013

The Search for New High T_c Superconductors from an Applications Perspective

or

*Physical Limits to the Utility and Transition
Temperatures of Very High Temperature
Superconductors*

*M.R. Beasley
Stanford University*

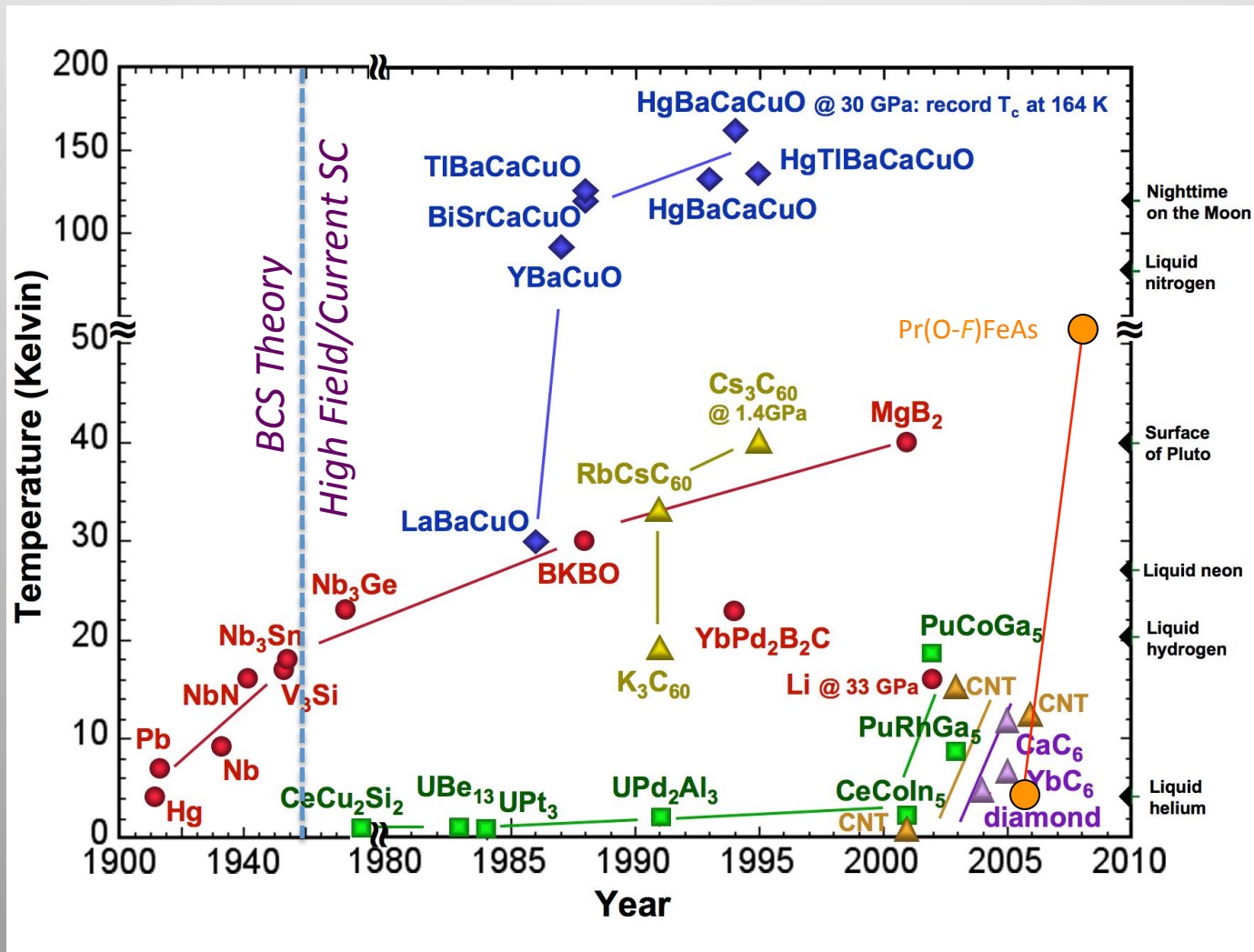
*MRB in Special Issue of the MRS Bulletin on Superconductivity,
MRS BULLETIN 36, 597-600 (2011)*

Objectives of the Talk

- *Looking back – What have we learned in recent decades about the fundamental physics (independent of the mechanism) of very high T_c superconductivity?*
- *What does it tell us about the prospects of electric power applications of superconductivity at much higher temperatures?*
- *What does it tell us about the material characteristics necessary for very high T_c ?*
- *Looking ahead – How might we proceed? Or at least what guidance might we offer?*

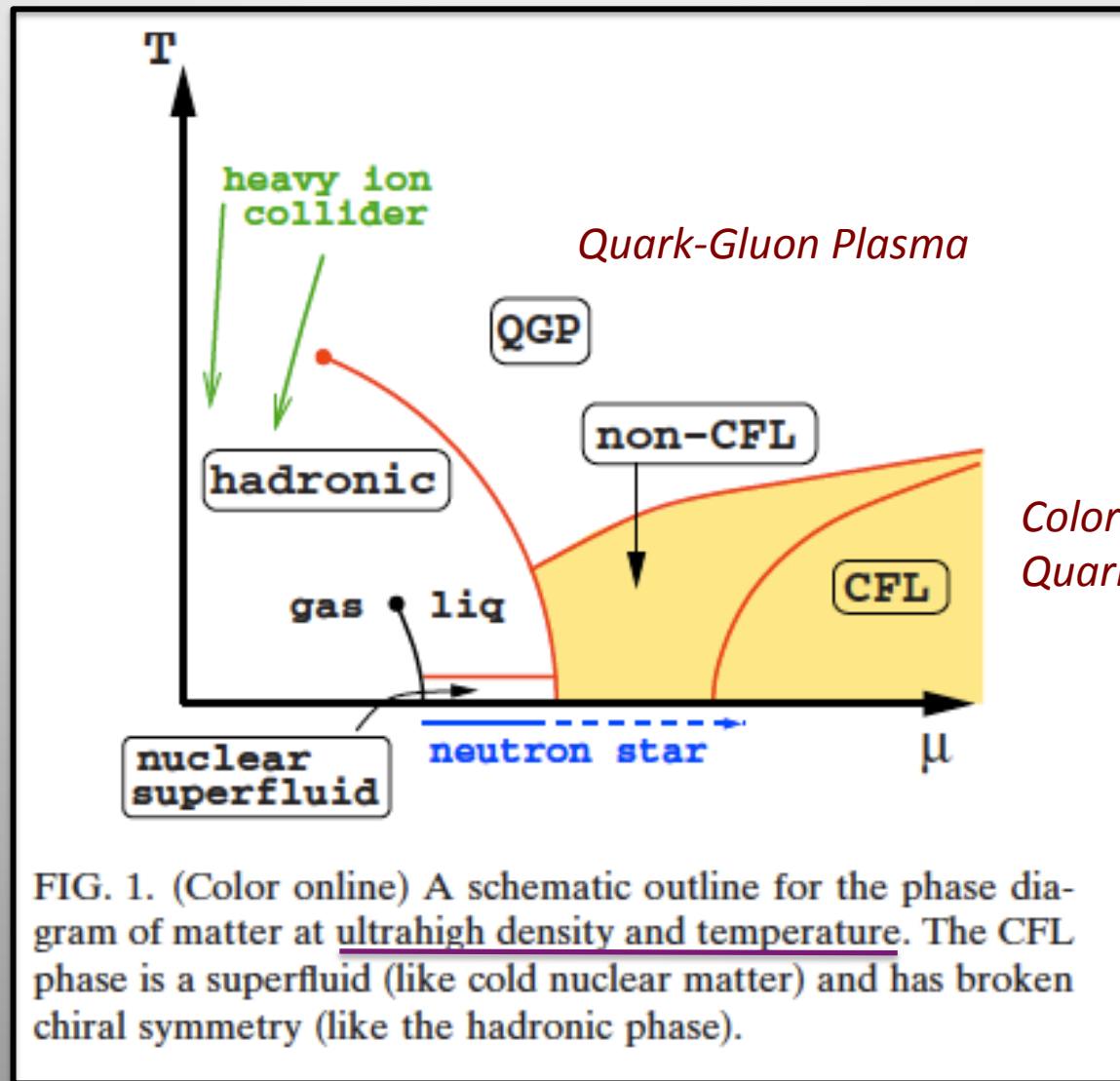
In Search of the Holy Grail

The Quest for a Room Temperature Superconductor



Adapted from a DoE Report

In Nature the Transition Temperature Can Be “Astronomically” High



With Some Experimental Evidence

THE SCIENCE OF EVERYTHING

COSMOS

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News

Superconductor found in neutron star's core

Science@NASA

Thursday, 24 February 2011

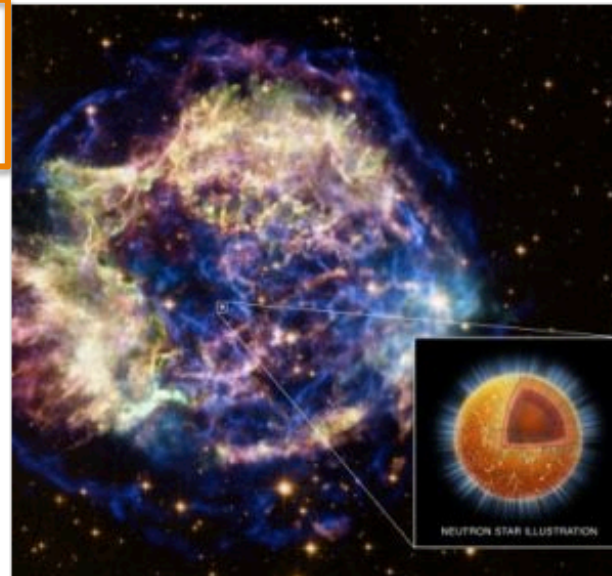
ALABAMA: NASA's Chandra X-ray Observatory has discovered the first direct evidence for a superfluid - a bizarre, friction-free state of matter - at the core of a neutron star.

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*.

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.



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

Credit: NASA/CXC/M. Weiss

With a big emphasis on
ical work and research.

But What About a “Room Temperature” Superconductor?

It must:

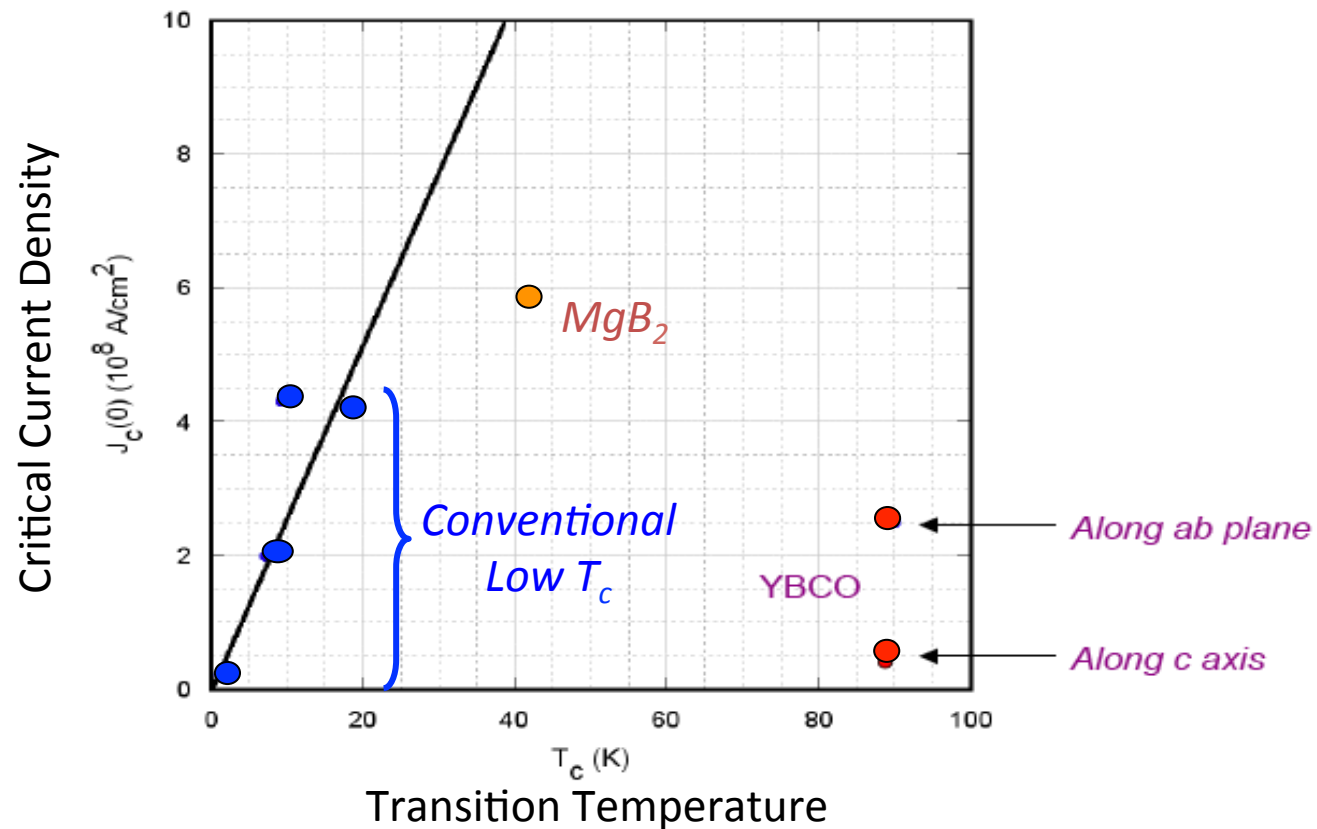
- *Operate in an earthly environment*
- *Be made from earthly forms of matter*
- *And from a practical point of view, exhibit good superconducting properties**

** 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:

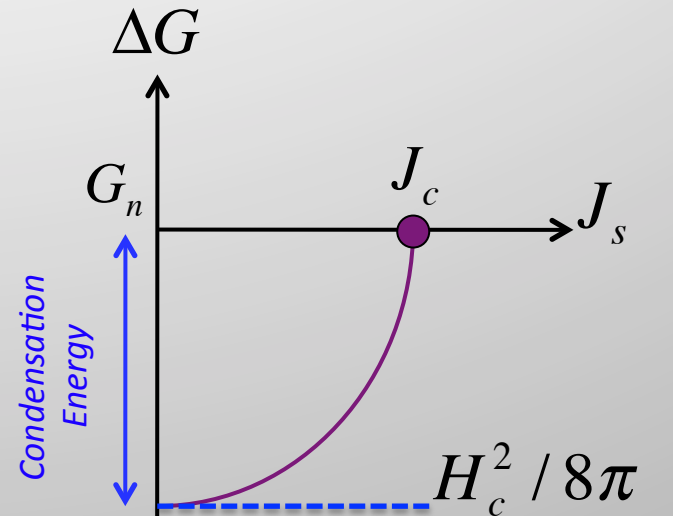
- *The supercurrent density*

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

- *The kinetic energy density*

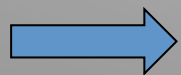
$$G_K = \frac{1}{2} n_s^* m v_s^2 = \frac{1}{2} \frac{m^*}{n_s^* e^{*2}} J_s^2 = \frac{1}{2} \Lambda_K J_s^2$$

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



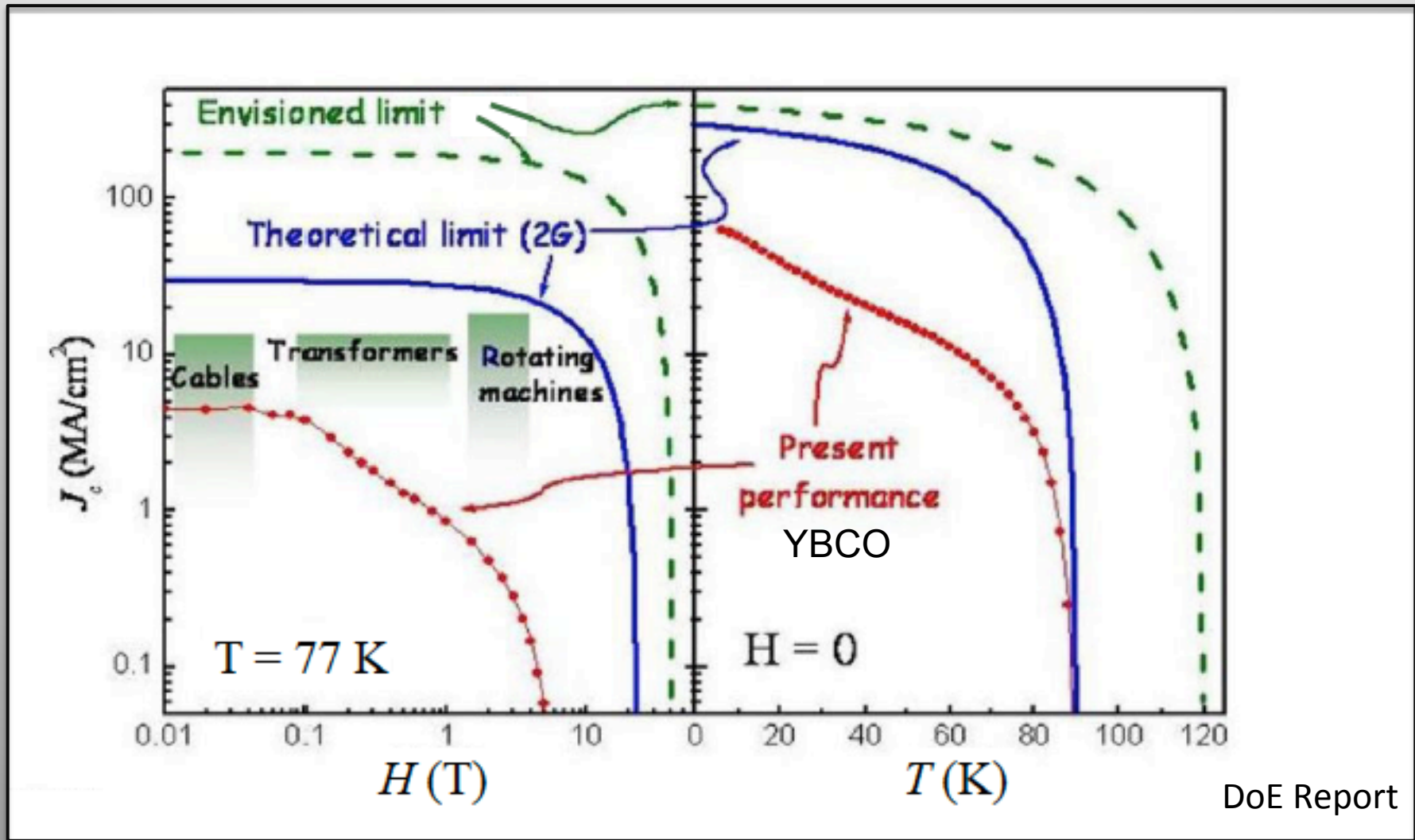
$$J_c = \frac{1}{\sqrt{2}} n_s^* e^* \frac{\hbar}{m^* \xi} \propto \frac{n_s^*}{m^*} T_c$$

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?



The Practical Reality

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

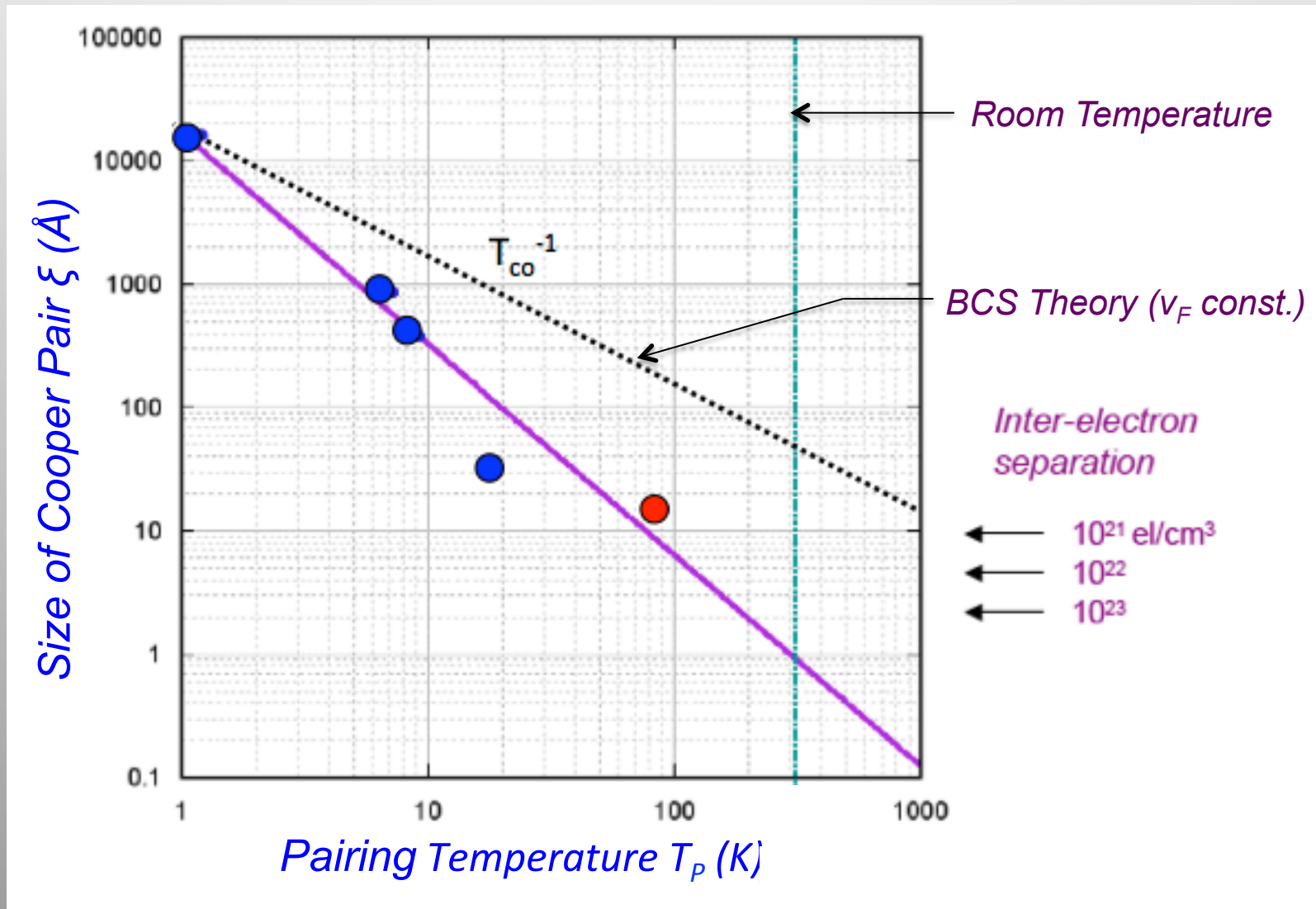
→ If there are to be commercial electric power applications of superconductivity above 77K, an entirely new superconductor will be required

→ 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?*

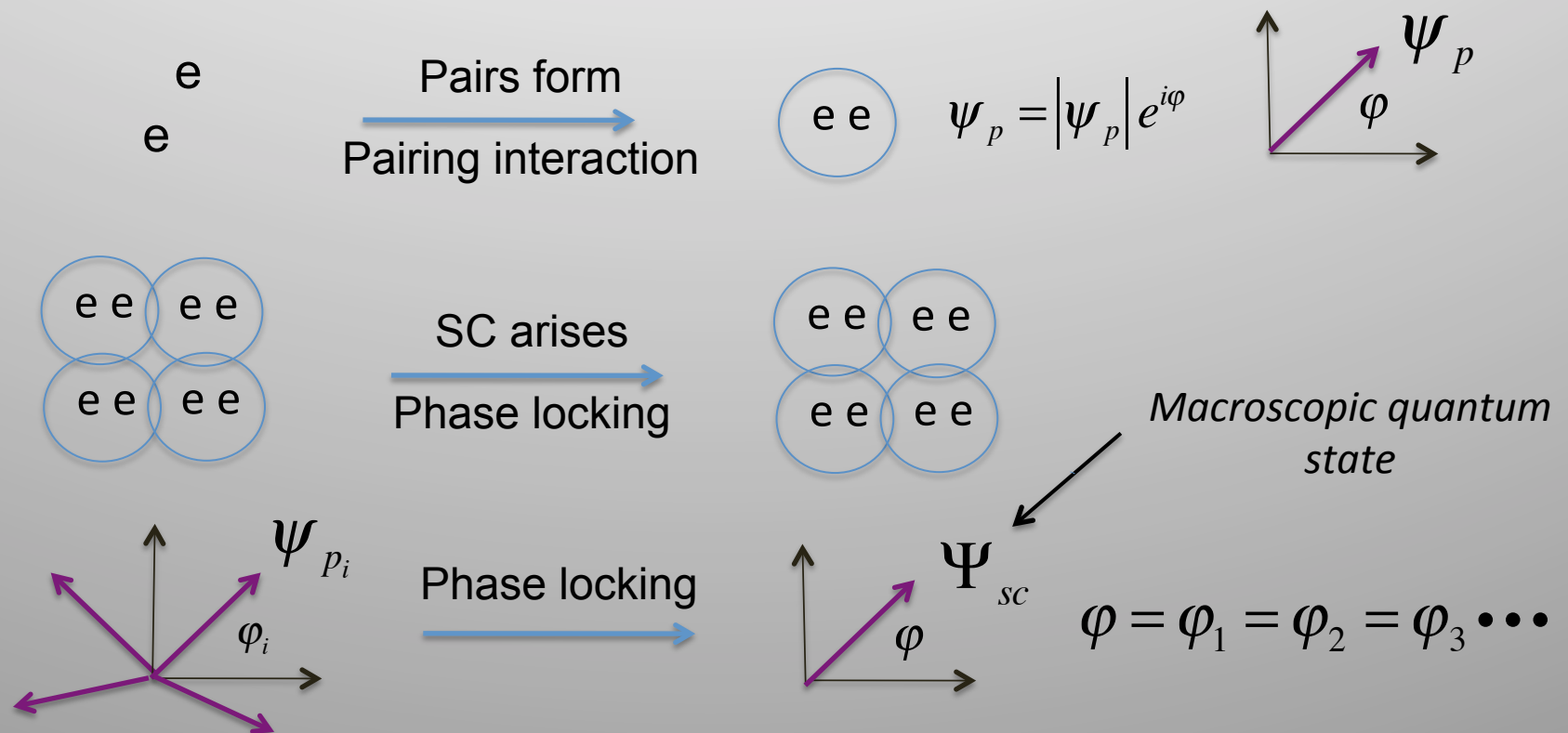
Whatever Else, The Cooper Pairs Will Be Very Small



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

To Determine T_c There are Two Characteristic Temperatures to Consider

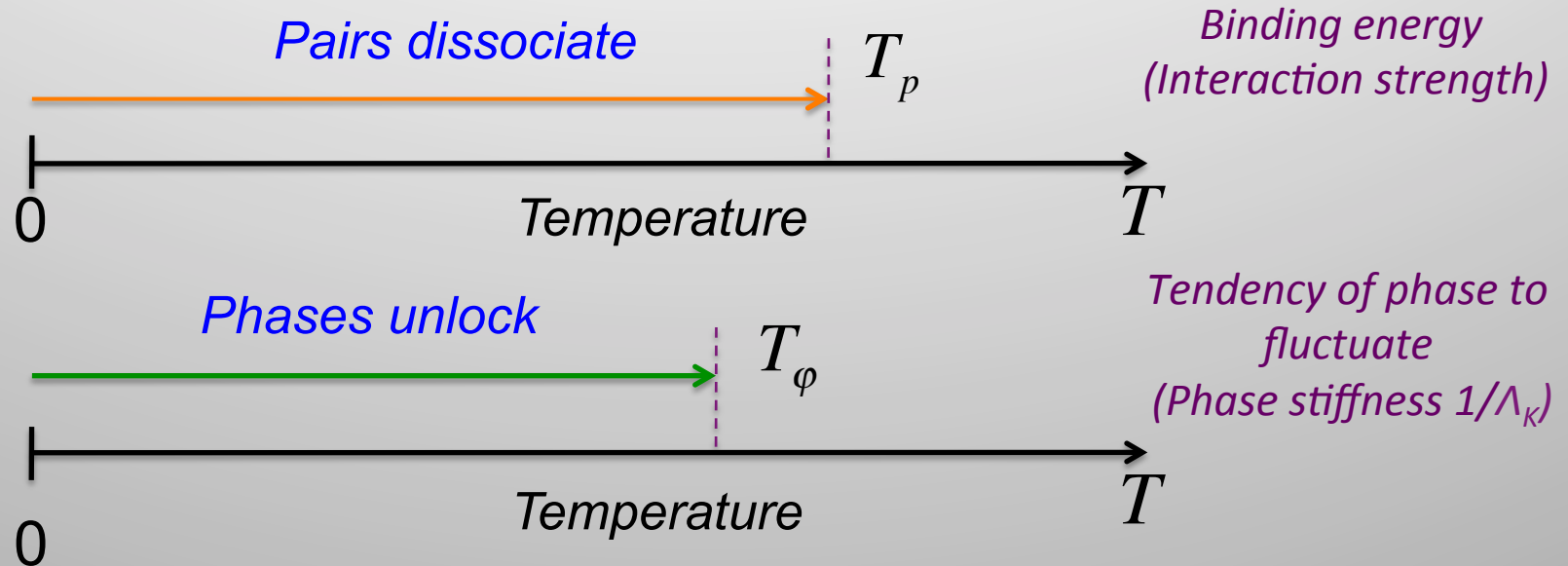
Superconductivity arises when electrons (or holes) form pairs and the quantum phases of these pairs order (lock) to form a coherent macroscopic quantum state with a single phase.



Each process has its own characteristic temperature

The Actual Superconducting Transition Temperature T_c

The Destruction of Superconductivity by Increasing Temperature



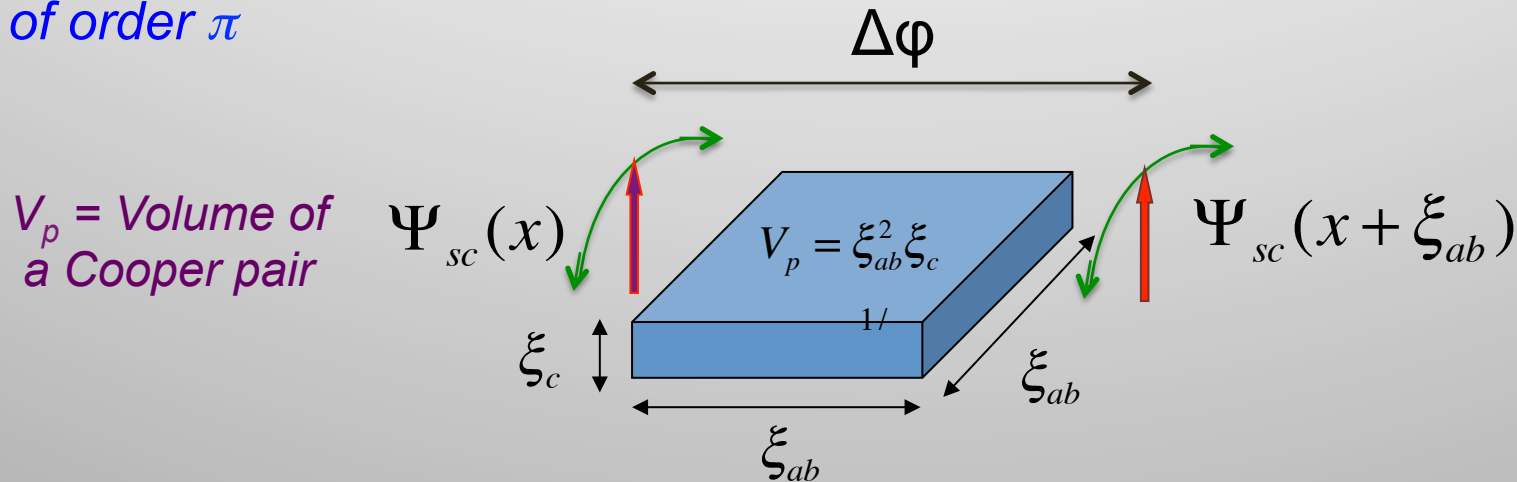
➡ If $T_\phi < T_p \Rightarrow T_c = T_\phi$

➡ If $T_p < T_\phi \Rightarrow T_c = T_p$

(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 $\Delta\phi$ across a Cooper pair due thermal phase fluctuations is of order π



Temperature at which thermal fluctuations produce phase unlocking

Energy to twist phase by π

$$\frac{1}{2} \frac{1}{\Lambda_K} (\nabla \phi)^2 V_p = k_B T_\phi$$

$\frac{\pi}{\xi_{ab}}$

$1/\Lambda_K = \text{Phase stiffness}$

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

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

→

T_p	T_c $\frac{J_c}{J_{YBCO}}$	$\gamma \rightarrow 1$	$n_s^* \times 2$	$n_s^* \times 10$
90 K (YBCO)	90 K 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

↑

Increase Pairing Interaction - T_p

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

$$T_c = \min\{T_\phi, T_p\}$$

$$J_c \propto n_s^* T_p$$

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

$$\xi \propto 1/T_p$$

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*

Increase interactions

Low carrier density

Two dimensional

General Physical Considerations

Increase interactions

High carrier density

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

Fundamental Questions

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

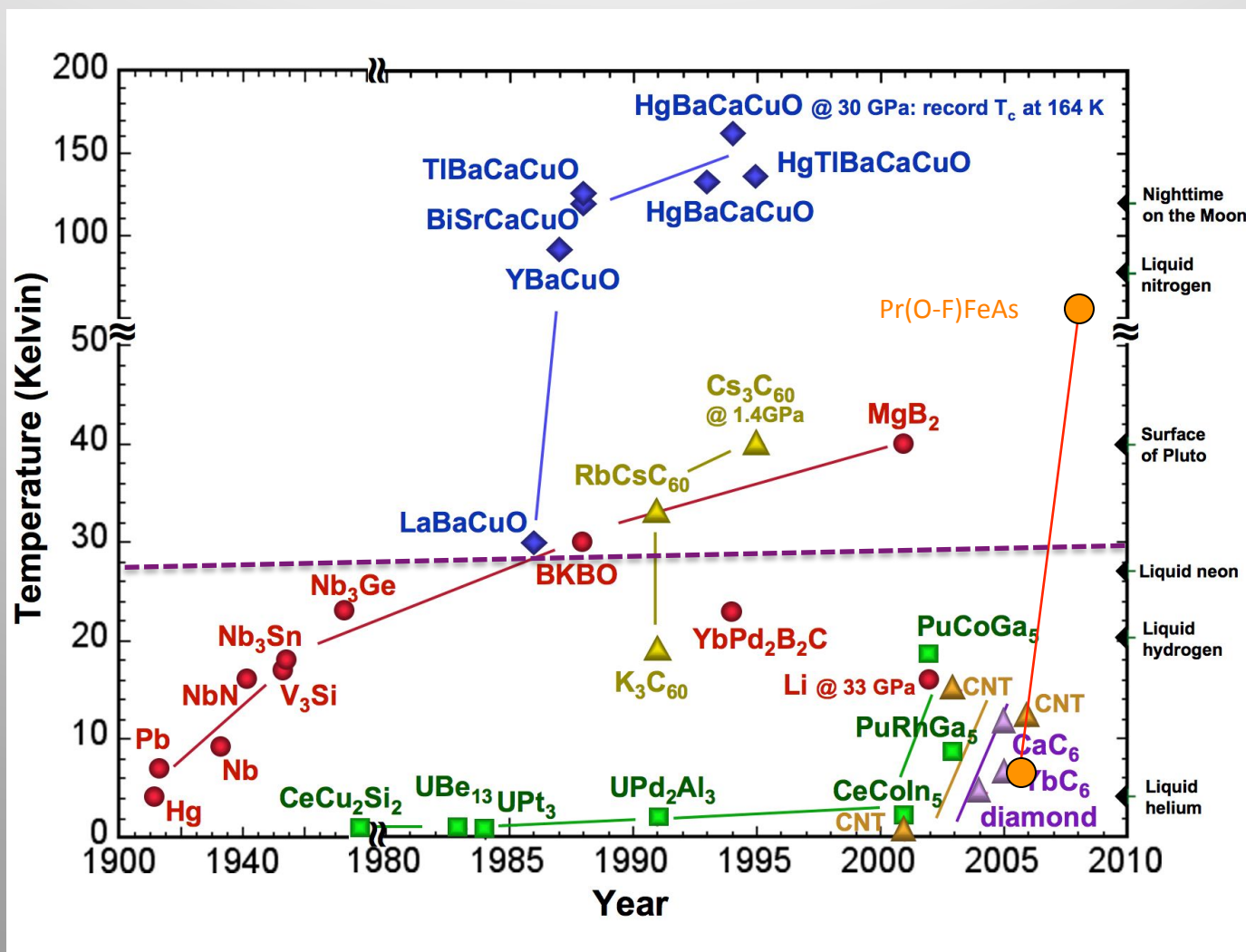
This clearly raises some very fundamental questions:

- Can strong interactions and high pair density be achieved under the same conditions? 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 a competing ordered phase (e.g., 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

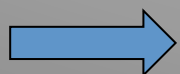
- *What do we know empirically?*
- *What can we say theoretically?*
- *What guidance do theory and experiment provide us?*

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



Empirical Guidance on Specific Interactions

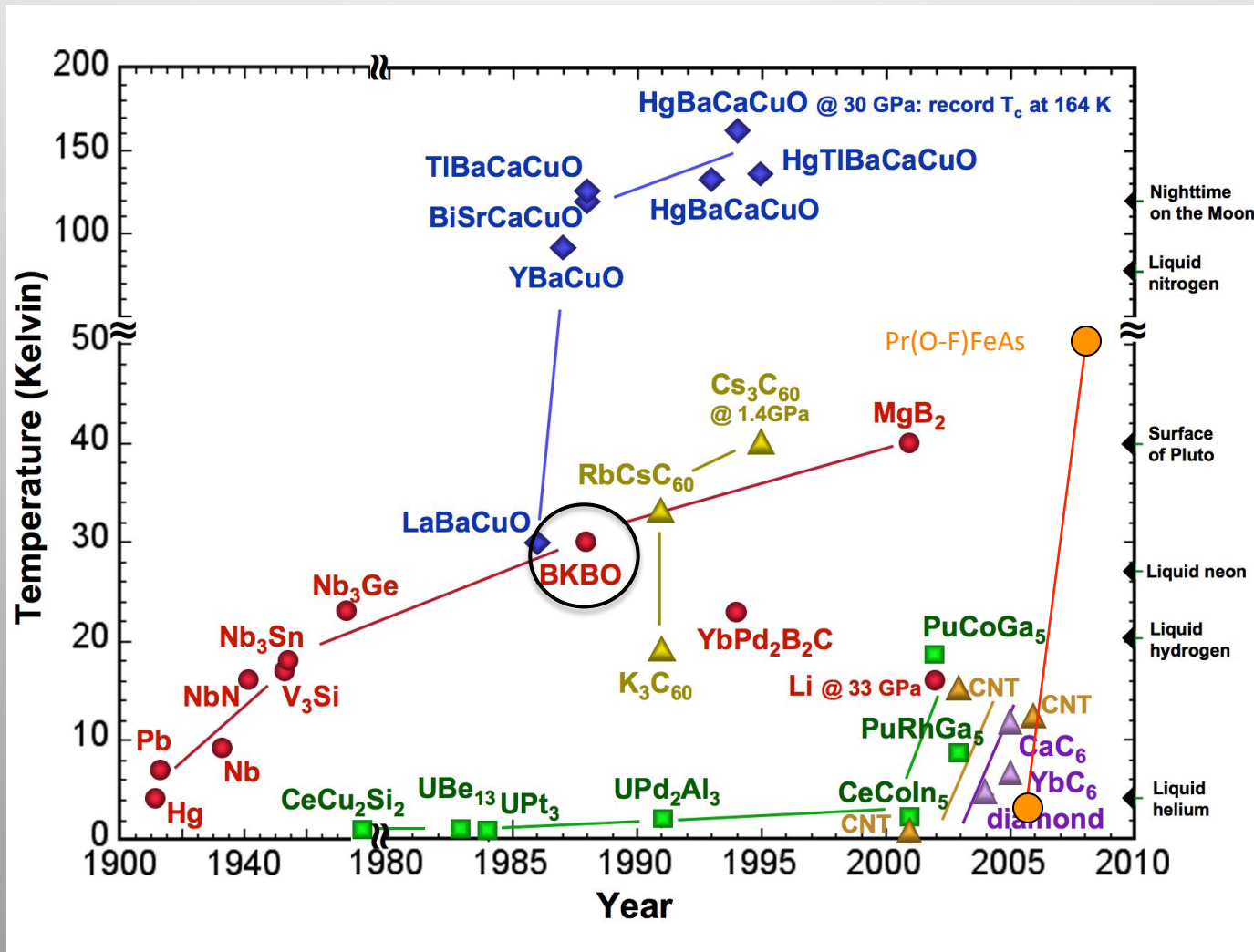
<i>Material Archetype</i>	T_c	<i>Interaction</i>	Guidance
Bismuthates (i.e., doped BaBiO ₃)	30K	Charge + Lattice	<i>Doped Negative U Insulator</i>
Cs ₃ C ₆₀	40K	Lattice + Correlation (charge)	<i>El-Ph Covalent Bonds</i>
MgB ₂	40K	Lattice	<i>El-Ph Covalent Bonds Prediction</i>
Fe-Based	50K	Spin	<i>Antiferromagnetism Multiple orbitals</i>
Cuprates	130K	Spin	<i>Doped Antiferromagnetic Positive U Mott Insulator</i>
Trace High T_c Anomalies	> Room Temperature	?	<i>Shouldn't Ignore</i>



Electronic (charge and spin) interactions look good

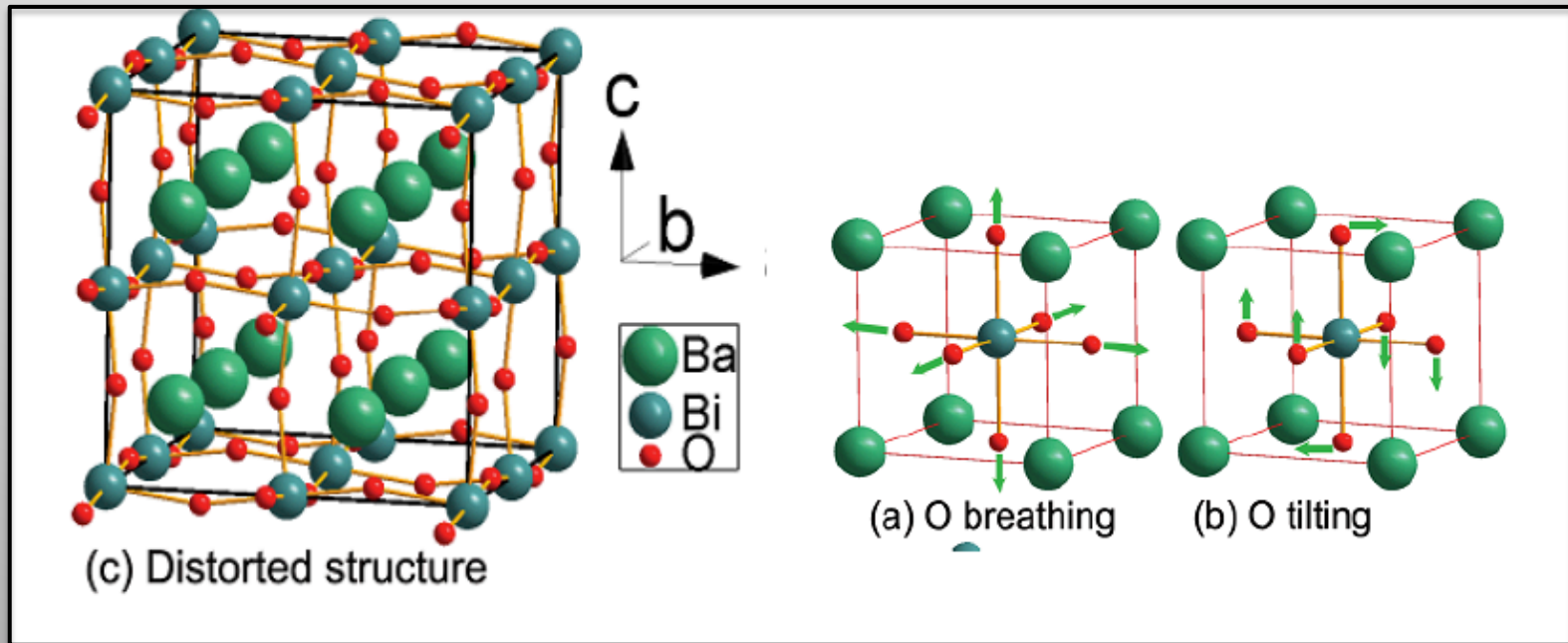
A Case Study – The Bismuthates

Superconductivity in a doped charge-ordered oxide insulator



Crystal Structure of BaBiO_3

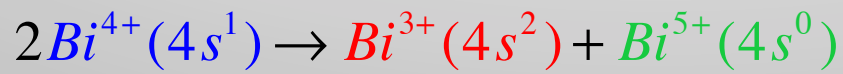
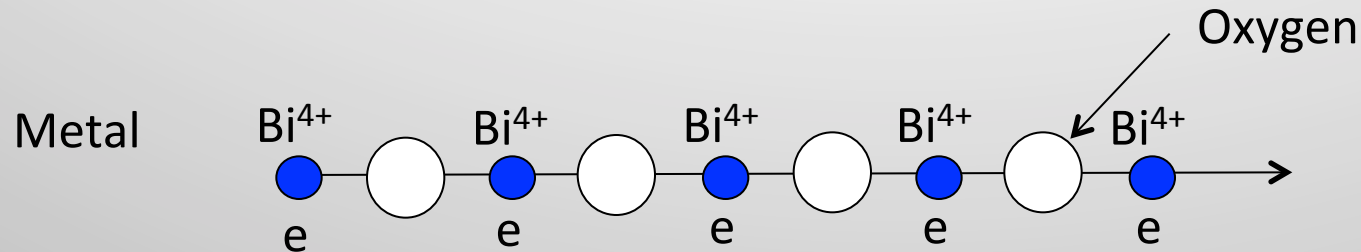
Distorted Perovskite



Note three dimensional structure

Charge-Disproportionated (Negative U) Superconductors (e.g., BaBiO₃)

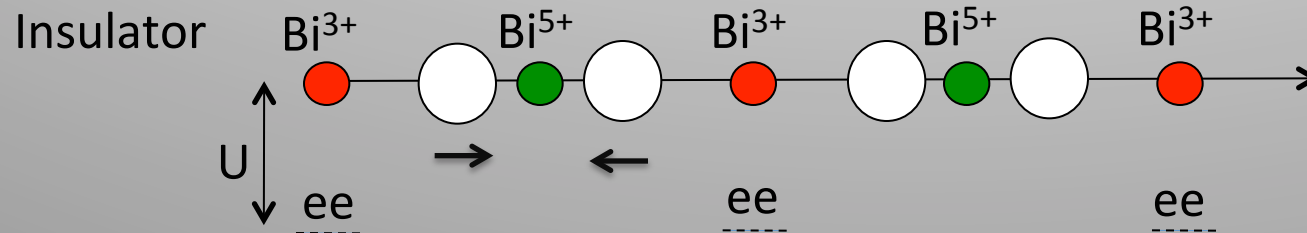
A Failure of LDA Theory → A new class of correlated insulator



and

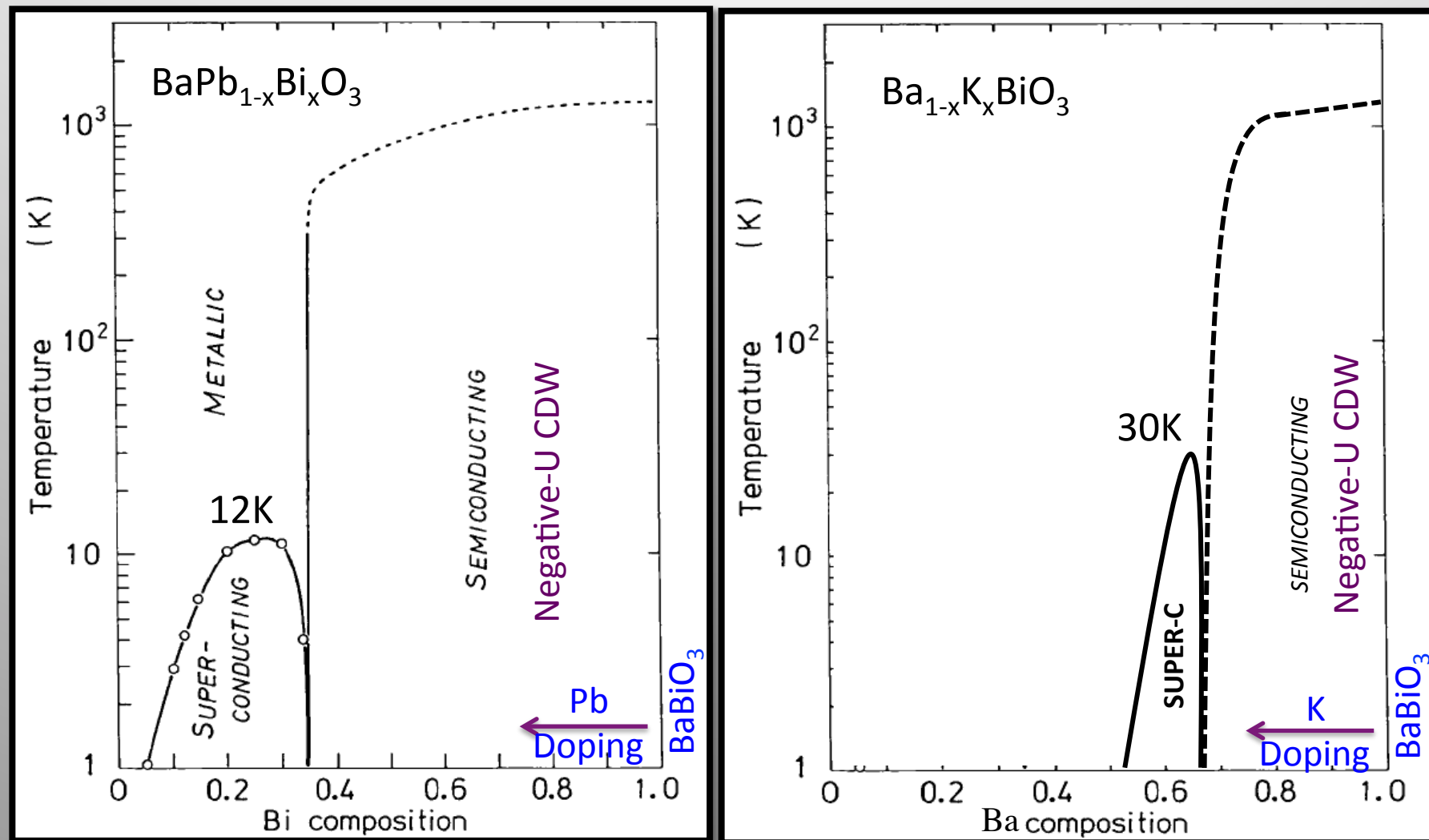
Oxygen atoms move to screen charge (Breathing mode)

Negative U --
Involves both
charge and
lattice



Superconductivity arises upon doping (Ba_{1-x}K_xBO₃ and BaPb_{1-x}Bi_xO₃)

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

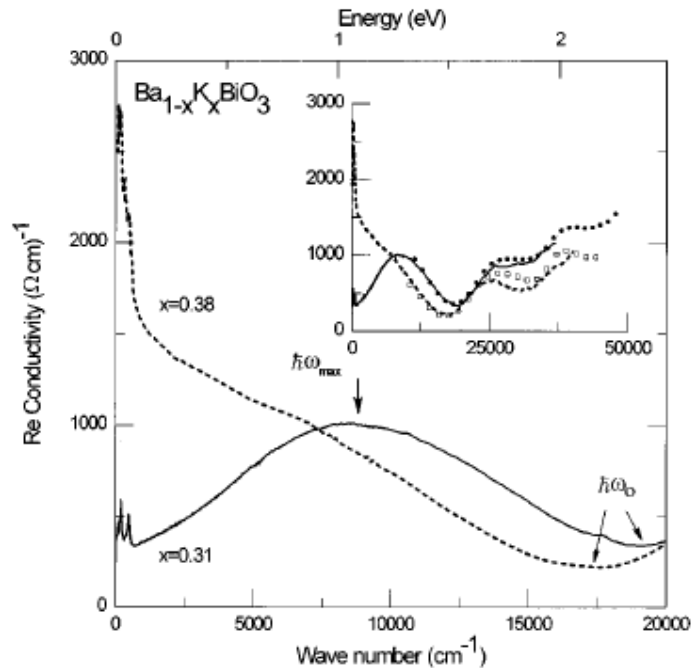


FIG. 1. The optical conductivity of $\text{Ba}_{1-x}\text{K}_x\text{BiO}_3$ just below and just above the insulator-metal transition. The characteristic energies $\hbar\omega_{\text{max}}$ and $\hbar\omega_0$, used in the text, are shown. The inset: the lines represent the real part of the optical conductivity obtained from the KK analysis of reflectivity spectra. The symbols show results of ellipsometric measurements.

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

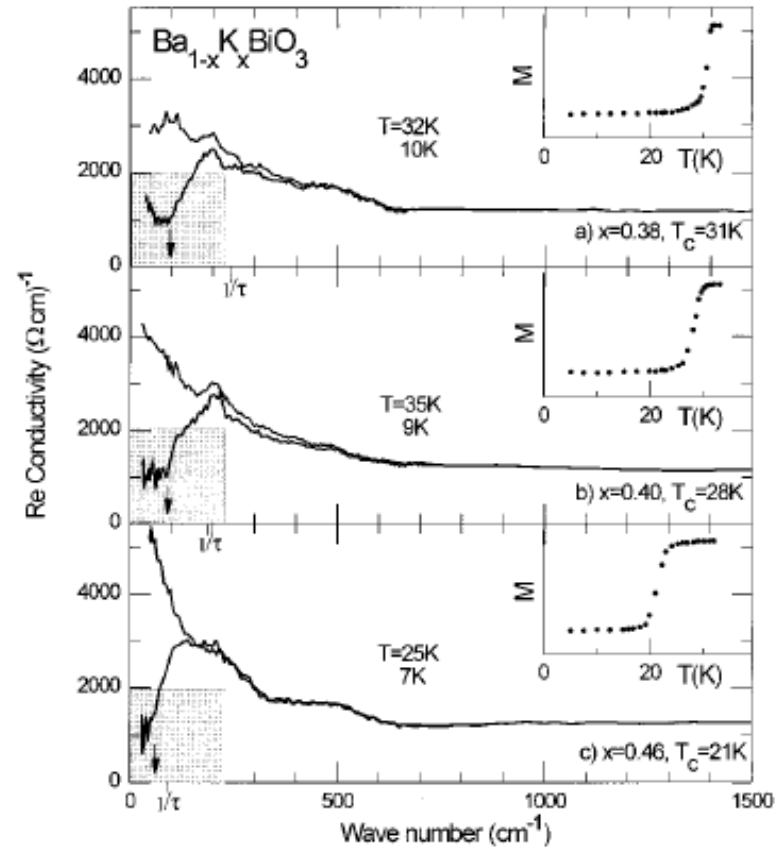
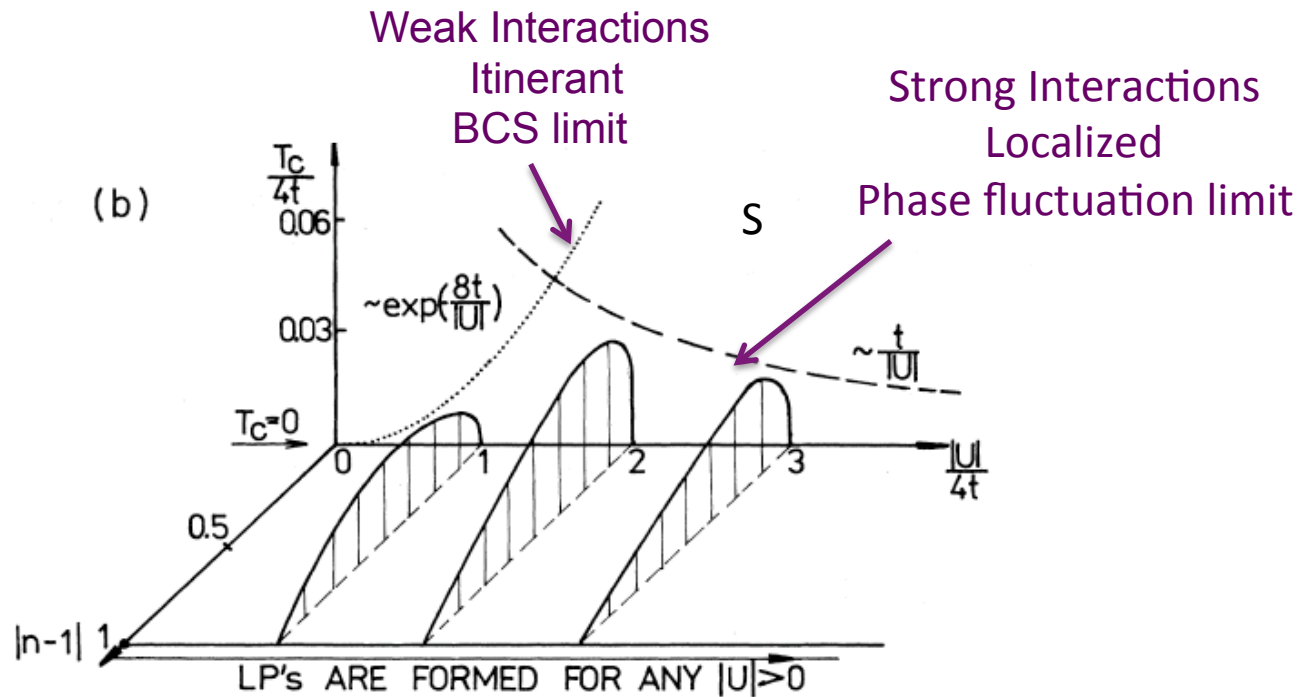


FIG. 4. The optical conductivity of the three metallic samples BKBO in the superconducting and the normal states. The results of magnetization measurements are shown on the insets. The scattering rate values $1/\tau$ in the normal state are shown on the frequency axis for all three samples. The shaded 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.

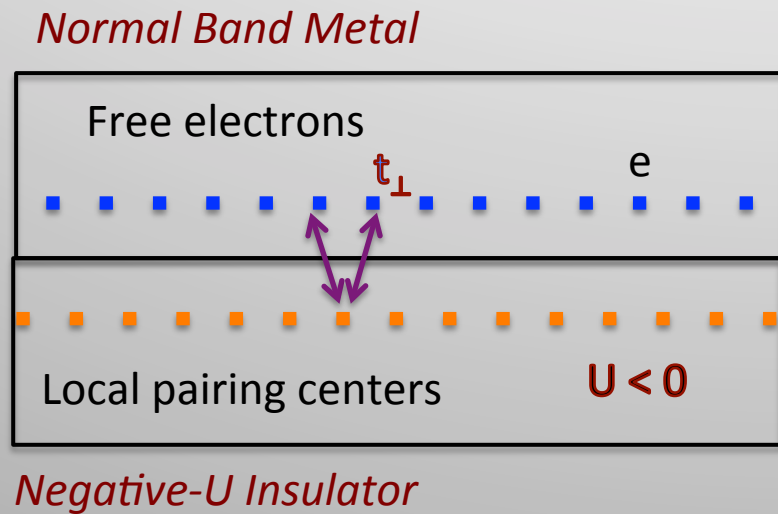
Illustrative Theoretical Phase Diagram (Numerical Solution to the Negative-U Hubbard Model)



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)

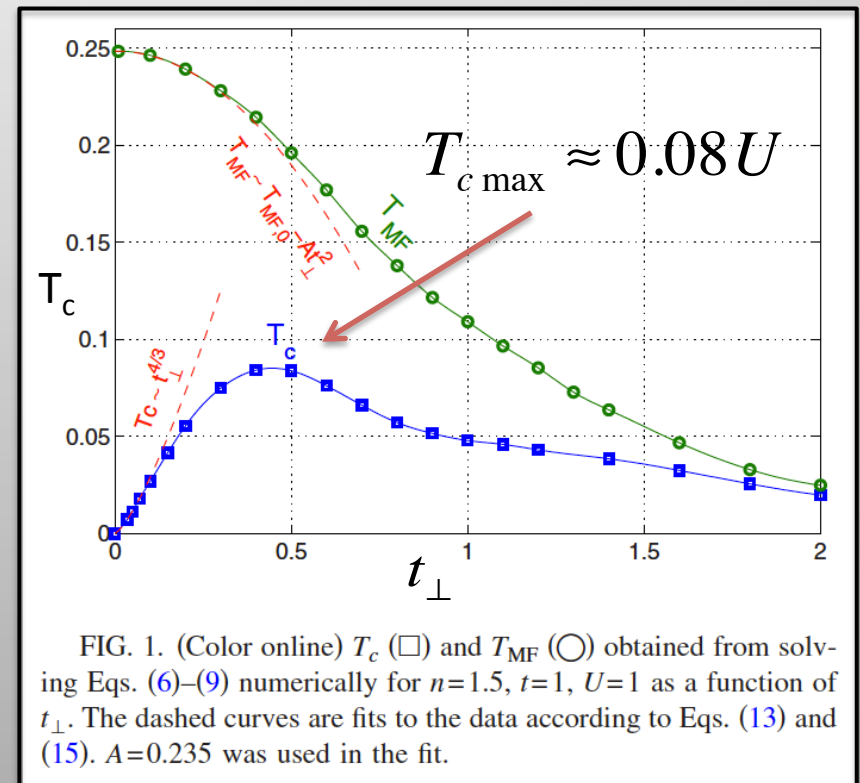
A New Theoretical Concept

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



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



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*

We offer three specific guidelines that seem essential:

- The interaction must be local (i.e., a real space phenomenon) because the size of the Cooper pairs will necessarily be small – enlist the solid state chemists
- The structural units out of which the superconductor is built (e.g., the unit cell, or some molecular cluster) must be small in order to produce the necessary high pair density
- Three dimensional structures are advantageous and maybe necessary depending on the magnitude of the pair density.

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