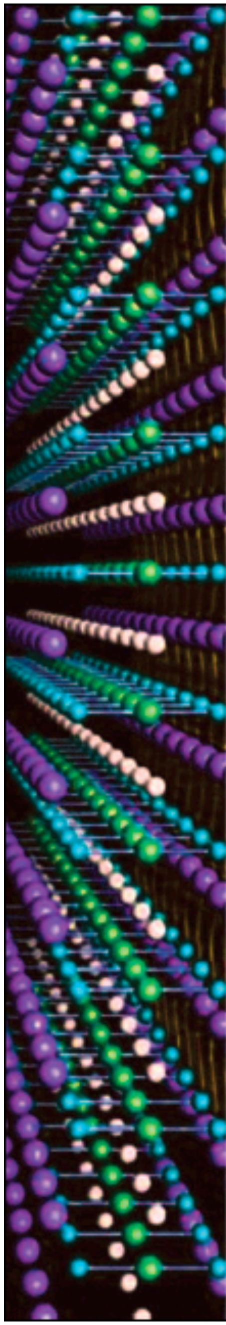
KITP Conference
on
The Physics of Higher Temperature Superconductivity

Will Higher T_c Superconductors Be Useful? Yes, But!

M.R. Beasley

Fundamental issues from the real world

View From The Real World



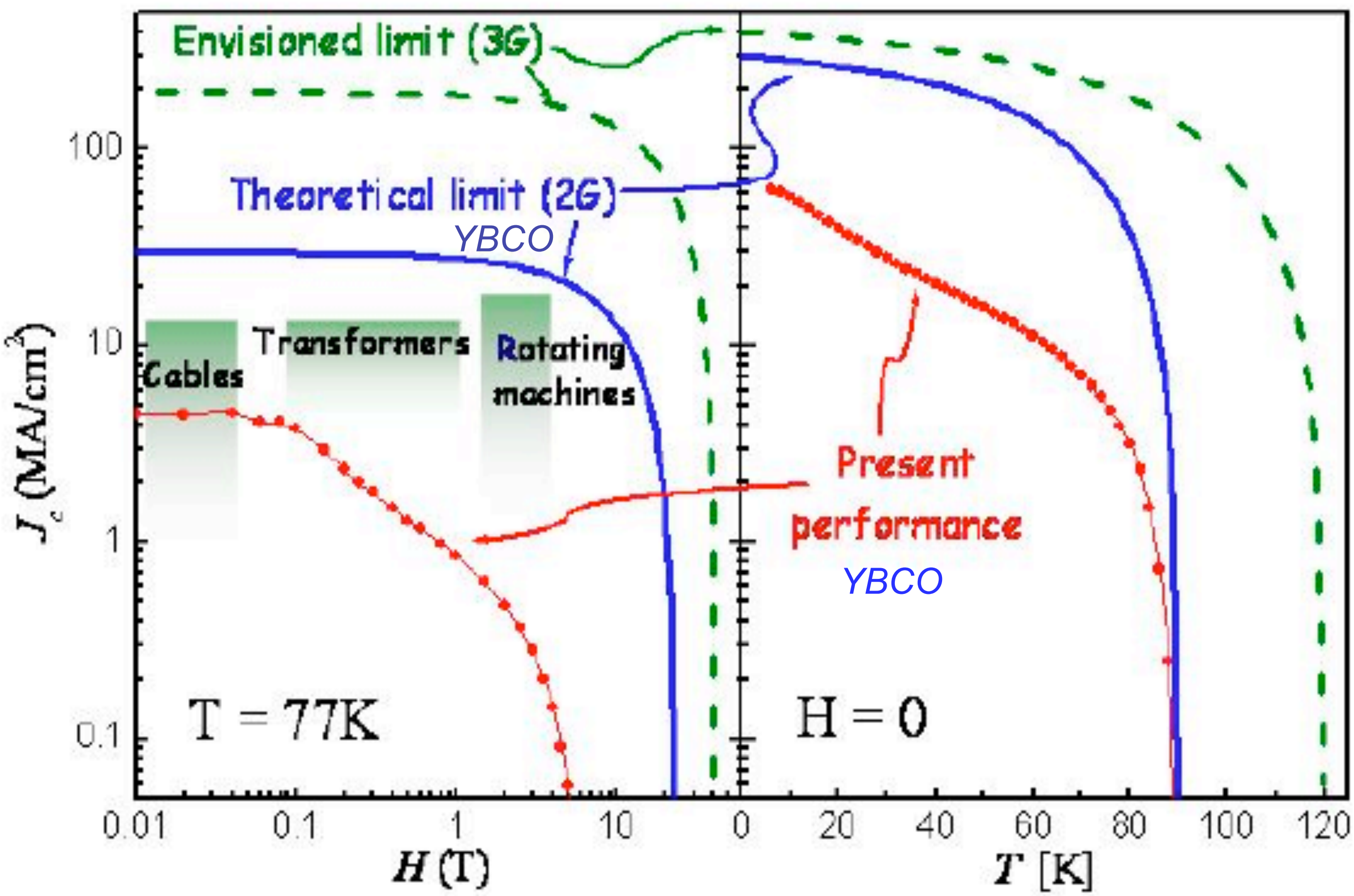
BASIC RESEARCH NEEDS FOR SUPERCONDUCTIVITY

Report of the Basic Energy Sciences
Workshop on Superconductivity,
May 8-11, 2006

Office of Science
U.S. DEPARTMENT OF ENERGY

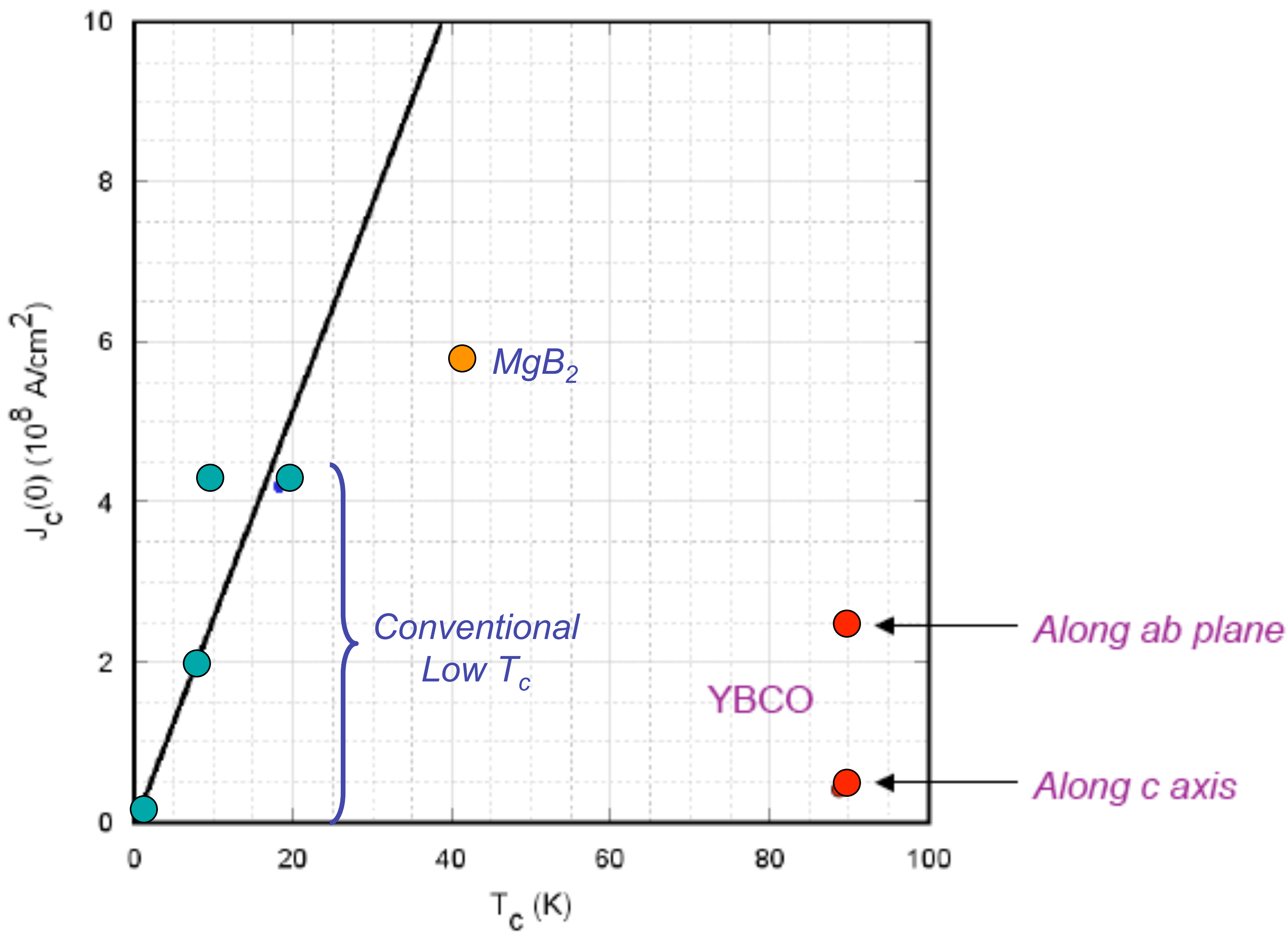
Need for Better High T_c Superconductors*

YBCO is Not Good Enough for Use Above 77K



* DoE Report: *Basic Research Needs in Superconductivity*

Theoretical Upper Limit of the Critical Current Density for Various Superconductors



The Relevant Physics

Theoretical Limit to the Critical Current Density

The Thermodynamic Critical Current Density

(Neglecting depairing)

- *The supercurrent density:*

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

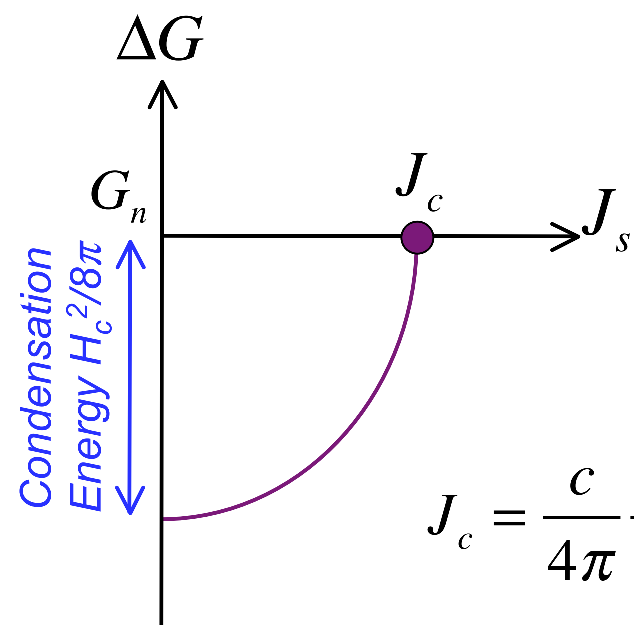
- *The kinetic energy density*

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

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

$$\frac{1}{\Lambda_K} = superfluid\ (i.e.,\ phase)\ stiffness$$

- *Thermodynamic critical current density:*



$$J_c = \frac{c}{4\pi} \frac{H_c}{\lambda}$$

Dependence of J_c on Materials Parameters

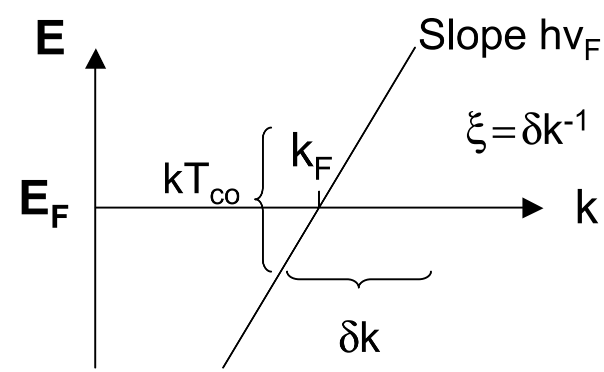
$$J_c = n_s^* e^* v_c = n_s^* e^* \frac{\hbar}{m^* \xi} \longleftrightarrow$$

Critical velocity corresponds to a phase difference of π across a distance ξ

$$where\ \xi = size\ of\ Cooper\ pair$$

$$\xi = h v_F / k T_{c0} \propto \frac{v_F}{T_{c0}}$$

$$n_s \leq n = total\ carrier\ density$$



$$\Longrightarrow \quad J_c \propto \frac{n T_{c0}}{v_F}$$

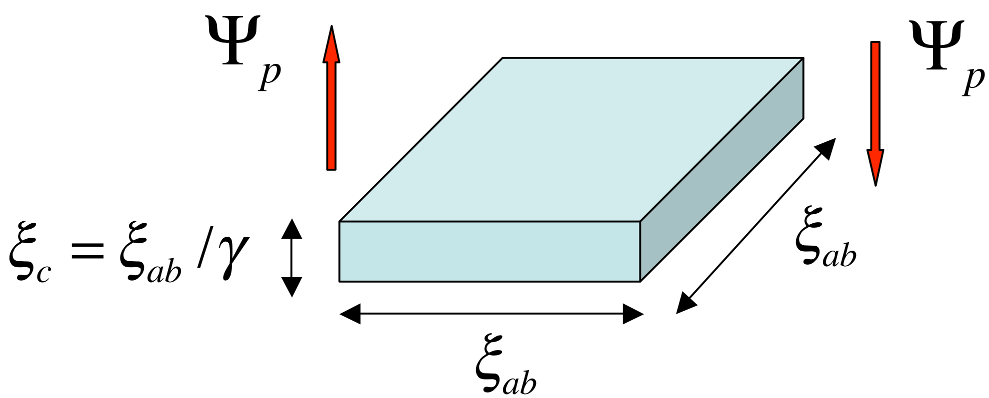
More Consequences of Low Superfluid Density

Thermal Phase Fluctuations

- *Destruction of Superconductivity with Increasing Temperature**

Superconducting Pair Wave Function

$$\Psi_p = |\Psi_p| e^{i\phi}$$



π/ξ_{ab}

$$\frac{1}{2}\frac{1}{\Lambda_K}(\nabla\phi)^2 V = k_B T$$

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

Temperature at which thermal fluctuations destroy superconducting quantum phase coherence

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

*See, for example, Carlson, Emery, Kivelson and Orgard

Searching for Higher T_c Superconductors

Historical paradigm:

- *Strong interactions → Large pairing energy T_p and everything else follows*

New paradigm:

- *Strong interactions → Large pairing energy T_p*

and

- *Low anisotropy*
- *High carrier density*

} → *Large J_c and $T_\phi / T_p > 1$*

Is a room temperature superconductor possible from this point of view?

Notional Better and Higher Temperature Superconductors Relative to YBCO (v_F constant)

Cumulative Improvement in γ and n →

Increasing Pairing Strength ↓

T_P	Performance Parameters	Affect of T_P Alone	$\gamma = 1$	n x 2	n x 10
90K	Jc/Jc^{YBCO} T_ϕ/T_P	1 1.6	1 8	2 16	10 80
180K	Jc/Jc^{YBCO} T_ϕ/T_P	2 0.4	2 2	4 4	20 20
270K	Jc/Jc^{YBCO} T_ϕ/T_P	3 0.2	3 1	6 2	30 10
360K	Jc/Jc^{YBCO} T_ϕ/T_P	4 0.1	4 0.5	8 1	40 5

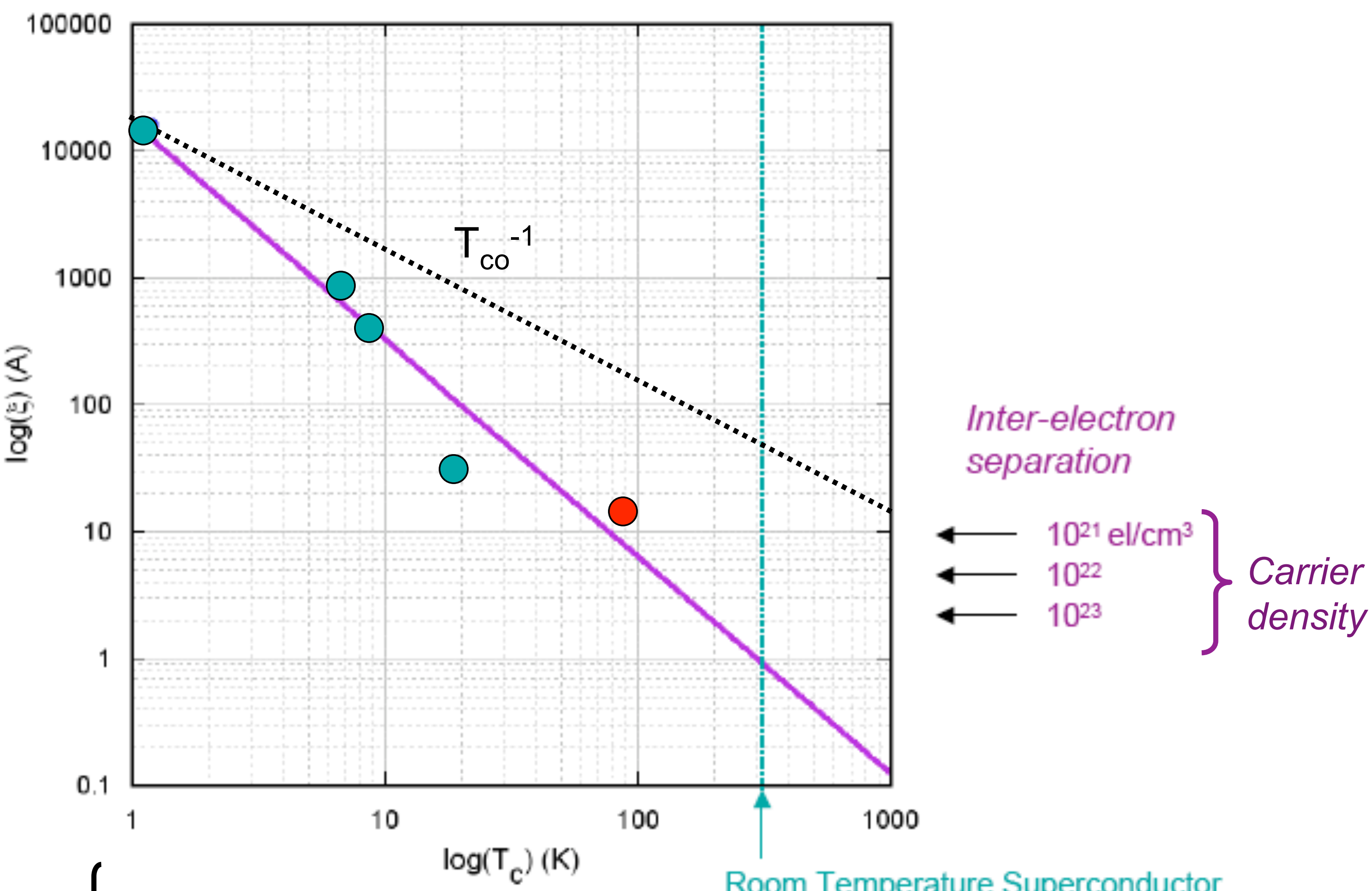
$$J_c \propto \frac{nT_P}{v_F} \qquad \frac{T_\varphi}{T_P} \propto \frac{nv_F}{\gamma T_P^2} \qquad \gamma = \sqrt{\frac{M}{m}}$$

Some Questions – Fundamental and Practical

- *Does high Tc require reduced dimensionality, low carrier density?*
- *What mechanisms are effective for making such small pairs?*
- *What are the physical properties of a superconductor in the very small Cooper pair limit? Opposite of BCS.*
- *How good can a "bad" superconductor be? (i.e., quantitative understanding of resistivity in the presence of strong thermal and quantum fluctuations)*
- *How good is good enough? (i.e., how much lower than that of copper does the resistivity of a superconductor have to be?)*

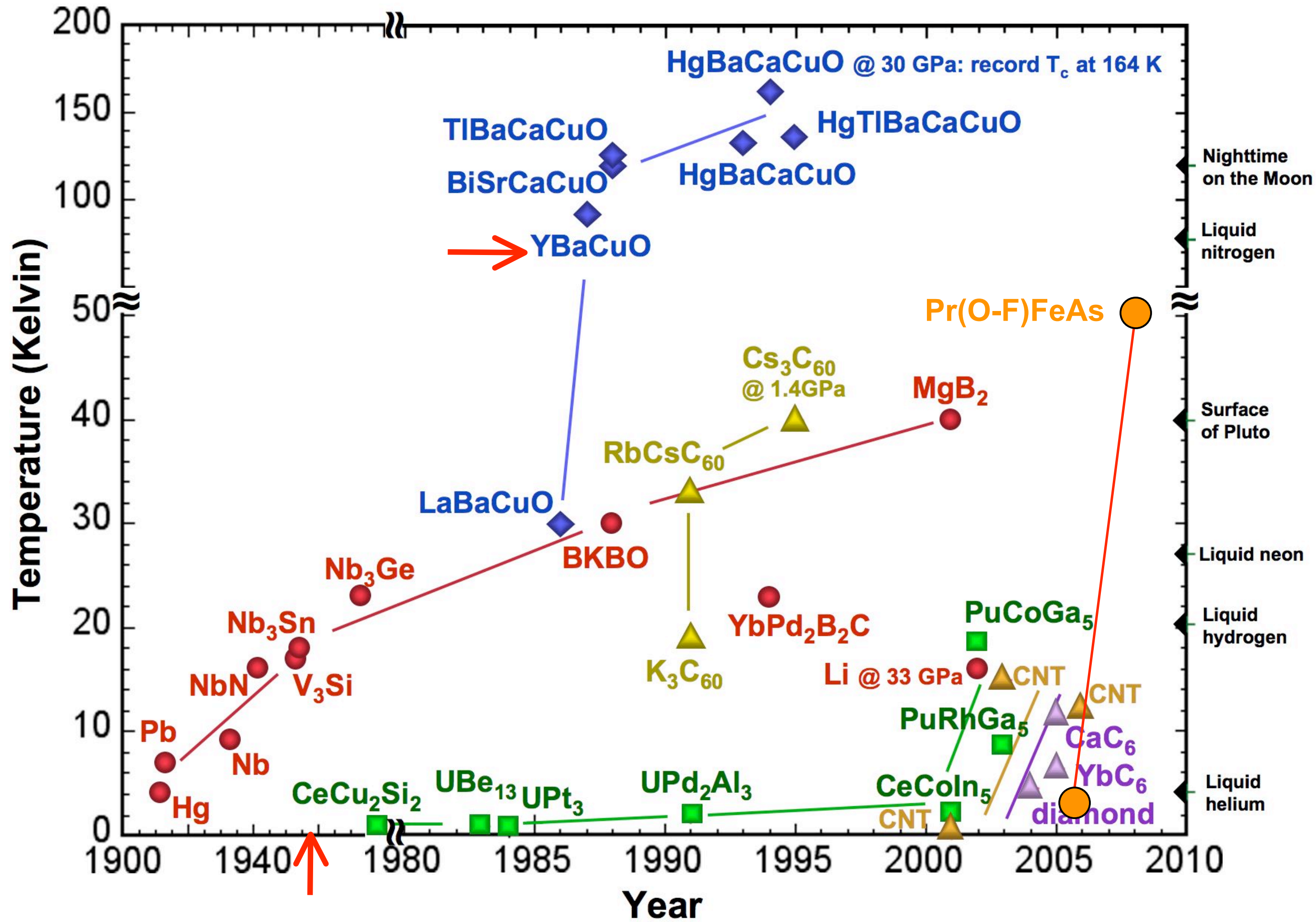
Guidance For Very High Temperature Superconductors

Size of Cooper Pair -- *vs* T_{co}



Pairing interaction must operate on the scale of a unit cell
Can we now shake hands with the solid state chemists?

The Archetypical High T_c Superconductors
Can They Guide Us?



* Adapted from DoE Report: *Basic Research Needs in Superconductivity*

Guidance from History

(My input to the Materials Panel)

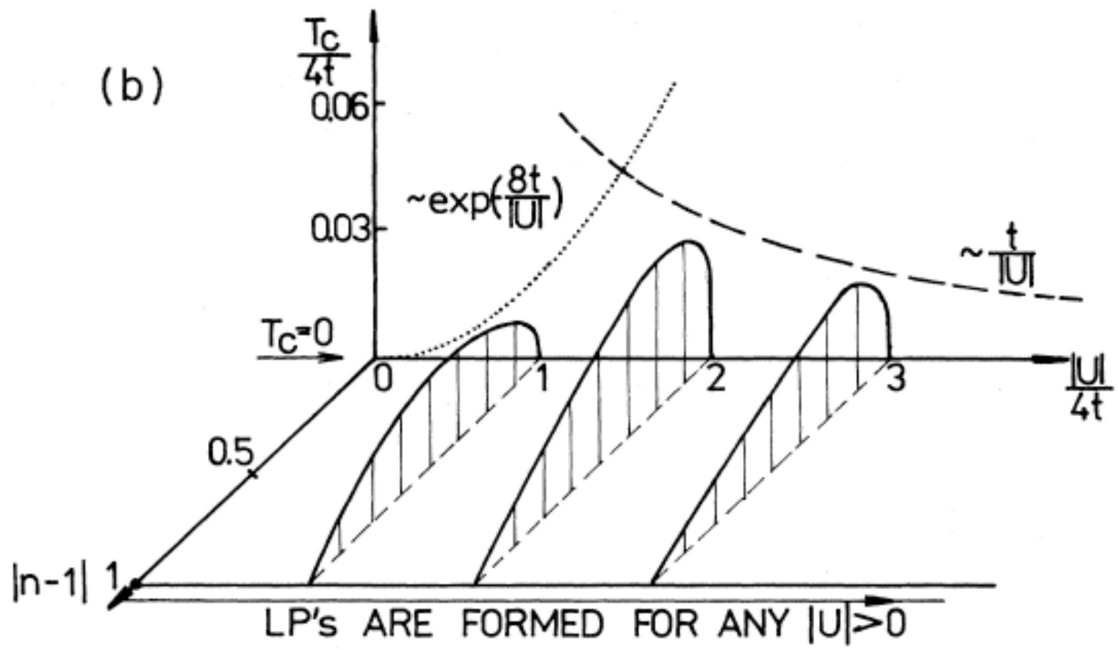
Material Archetype	*T_c*	*Interaction*	*Guidance?*
Doped $BaBiO_3$	30K	Lattice Charge?	Negative U/ Valence Skipping
Cs_3C_{60}	40K	Lattice Correlation?	El-Ph/ Covalent Bonds
MgB_2	40K	Lattice	El-Ph/ Covalent Bonds
Cuprates	130K	Spin	Doped Mott Ins/ Antiferromagnetism
Pnictides	50K	Spin (Charge?)	Antiferromagnetism (Bi-excitons?)
Trace High T_c Anomalies	> Room Temperature	?	Confirm/ Diagnose (scan)

Electronic interactions (charge and spin) are effective!

Illustrative Phase Diagram

(2D Negative-U Hubbard Model)

Seeking the Maximum T_c



- *T_c maximal at crossover from localized (e.g., AF, CDW) to itinerant carriers; U and bandwidth of same order; optimal carrier density*

How Can Theory Help?

Prediction is not necessary; Guidance is enough

Could we have:

- *Real space formulation of model microscopic theories including relevant dynamics?*
- *Associated electronic structure studies to provide guidance on parameters of low energy Hamiltonians in terms of high energy (chemical, structural) inputs?*
- *Reduced dimensionality in a 3D structure?*
- *Find mutually understandable language between physicists and solid-state chemists?*

And finally, wish the searchers good luck

Questions for the Session
"The Landscape of Superconductivity"

✓ What have we learned on what makes high T_c high from the cuprates and other materials?

✓ What makes a material be "high T_c"? Chemistry? Dimensionality? Luck?

More is different?

✓ What can theory reasonably (and honestly) say about T_c and how to raise it (or lower it?) ?

✓ Do we need a new conceptual framework to deal with this problem?