A Route to High-Temperature Superconductivity in Composite Systems

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- Theory:

  PRB **78**, 094509 (2008)

Erez Berg
Steve Kivelson

- Experiment:

  PRL **101**, 057005 (2008)

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The motivating question

How can we design a higher T_c superconductor ?

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What limits T_c in a superconductor ?

The two necessary ingredients for superconductivity

Pairing

Phase Coherence

Complex Order Parameter:

$$\Delta(\mathbf{r}) = |\Delta(\mathbf{r})| e^{i\theta(\mathbf{r})}$$

Amplitude: Pairing Gap

Phase: Condensate Phase

Pairing Temp.

Phase Ordering Temp.

$$T_p \approx \frac{1}{2}\Delta_0$$

$$T_\theta \approx \frac{1}{2}\frac{\hbar^2 n_s}{m^*}\xi^{d-2}$$

$$T_c \leq \min\left[T_p, T_\theta\right]$$

The BCS superconducting transition

$$|\psi\rangle = \prod_k \left(u_k + v_k e^{i\theta} c^\dagger_{k,\uparrow} c^\dagger_{-k,\downarrow} \right) |0\rangle$$

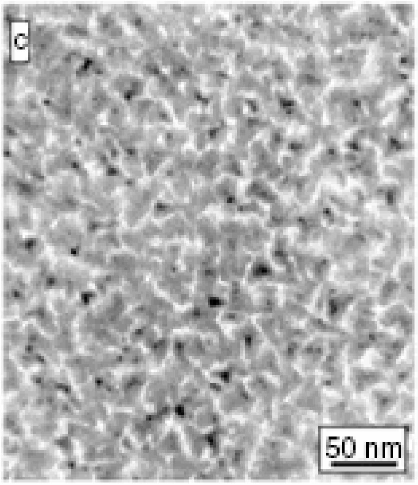
BCS is a mean-field theory in which pairing precipitates order

Indeed, in conventional superconductors:

Material	T_p[K]	T_θ[K]	T_c[K]
Pb	7.9	6×10^5	7.2
Nb_3Sn	18.7	2×10^4	17.8

Pairing and phase coherence may occur separately

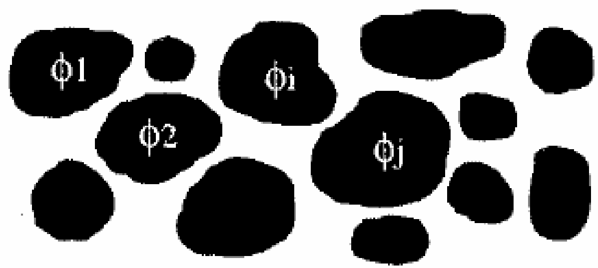
Example: Granular superconductors



Granular niobium film

Pairing

is established on each grain at bulk T_c

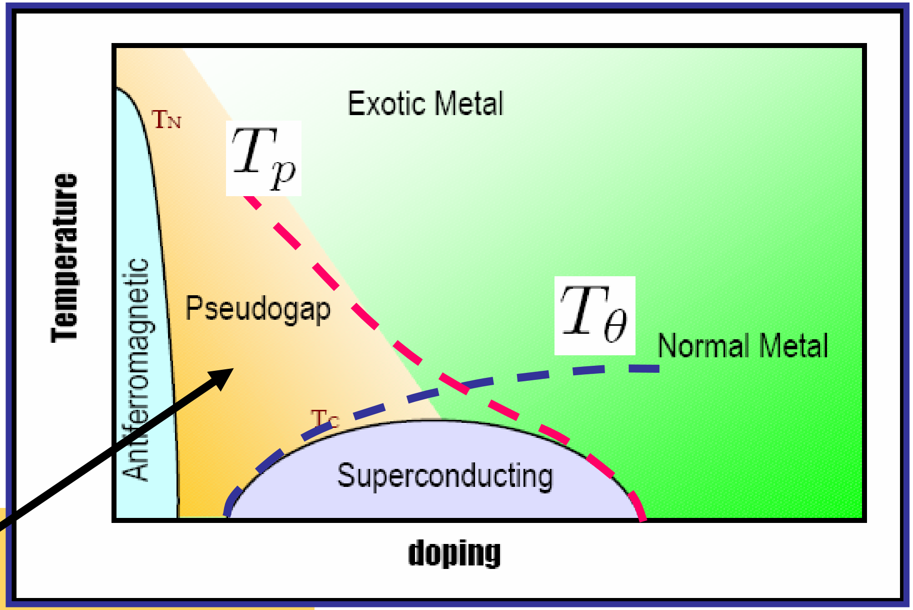


The film's T_c is determined by inter-grain

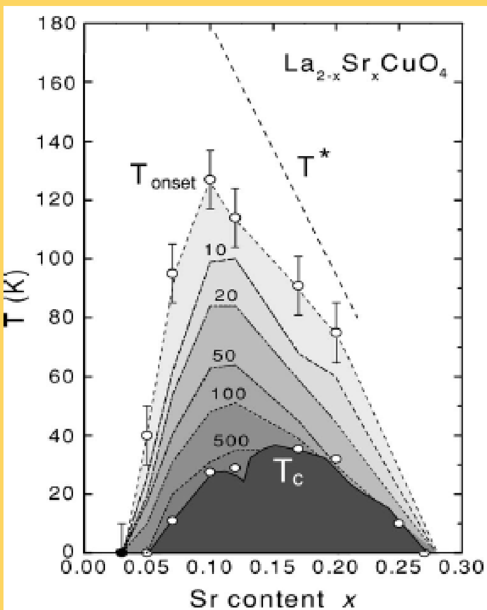
Phase Ordering

Pairing and phase ordering in the HTSC

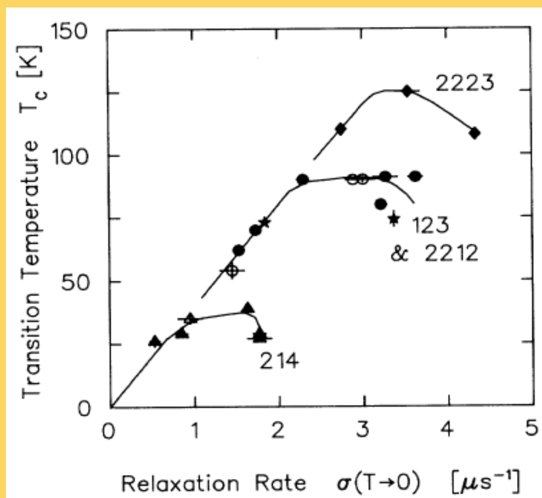
Material	T_p [K]	T_θ [K]	T_c [K]
LSCO (ud)	75	47	30
LSCO (op)	58	54	38
LSCO (od)	30	90	34
YBCO (ud)		42	38
YBCO (op)	116	140	90
YBCO (od)		140	55



Emery Kivelson (Nature 95)



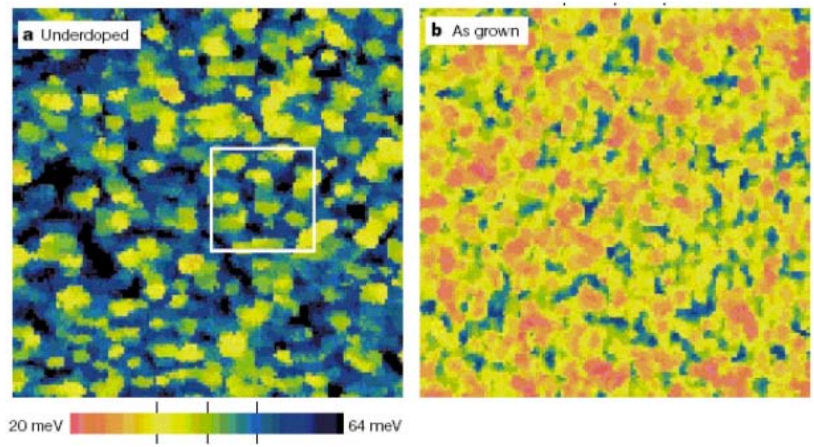
Wang, Li, Ong. (PRB 06)



Uemura *et al*. (PRL 89)

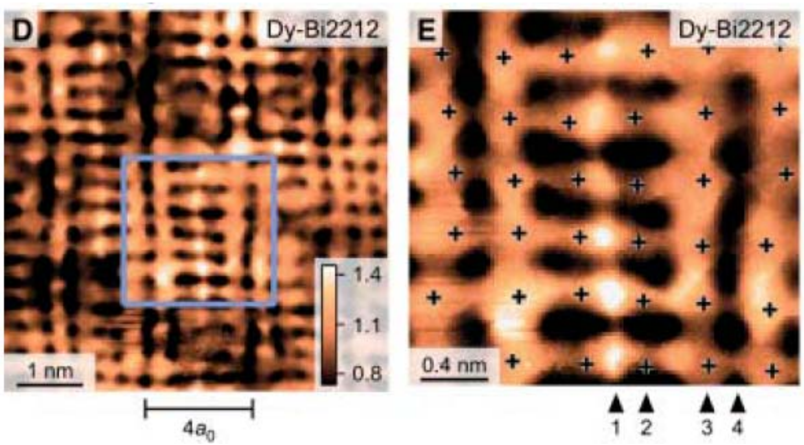
Intrinsic inhomogeneity in the HTSC

Local gap variations



Lang *et al*. (Nature 02)

Local stripe correlations

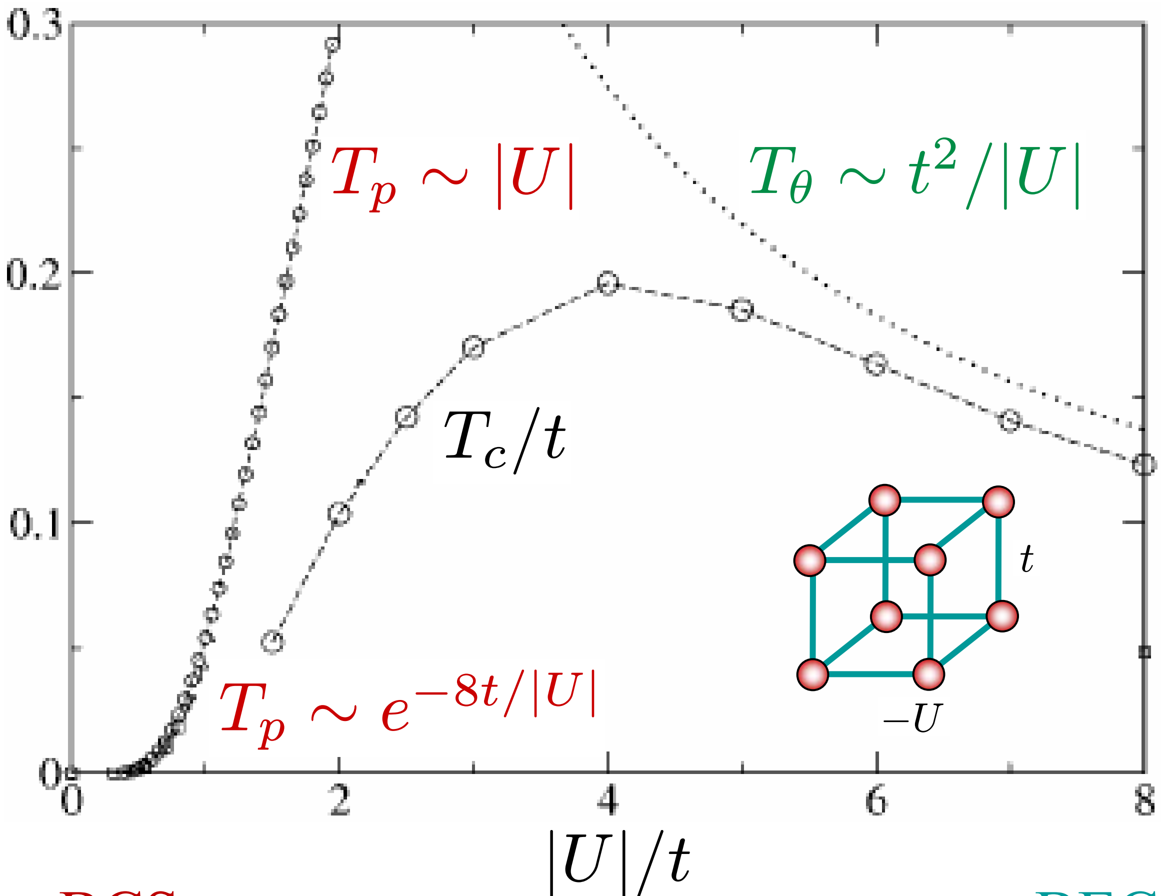


Kohsaka *et al*. (Science 07)

$$R(\vec{r}) \equiv \frac{\int_0^{\Omega_c} N(\vec{r},E)\, \mathrm{d}E}{\int_{-\infty}^{0} N(\vec{r},E)\mathrm{d}E} = \frac{2n(\vec{r})}{1-n(\vec{r})} + O\left(\frac{nt}{U}\right)$$

The negative-U Hubbard model

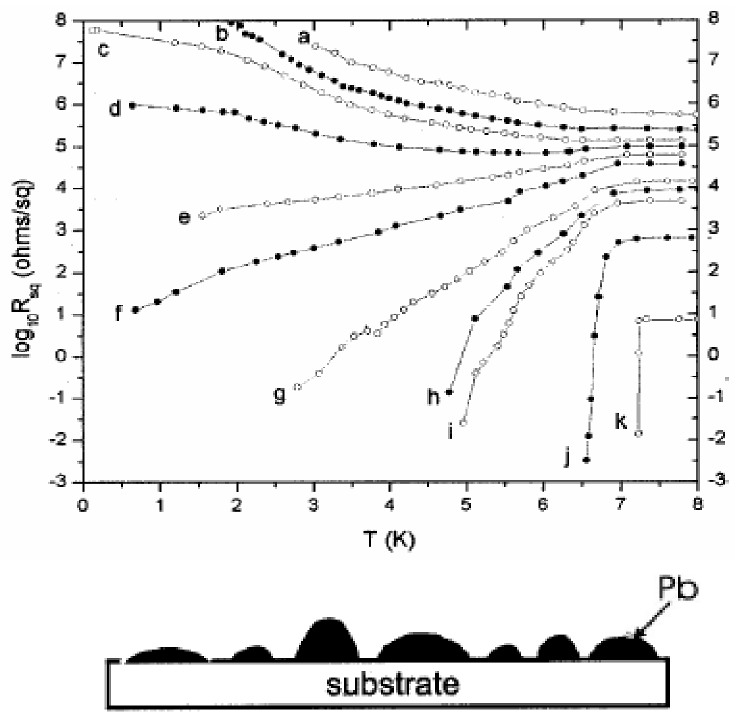
Keller *et al.* (PRL 01)

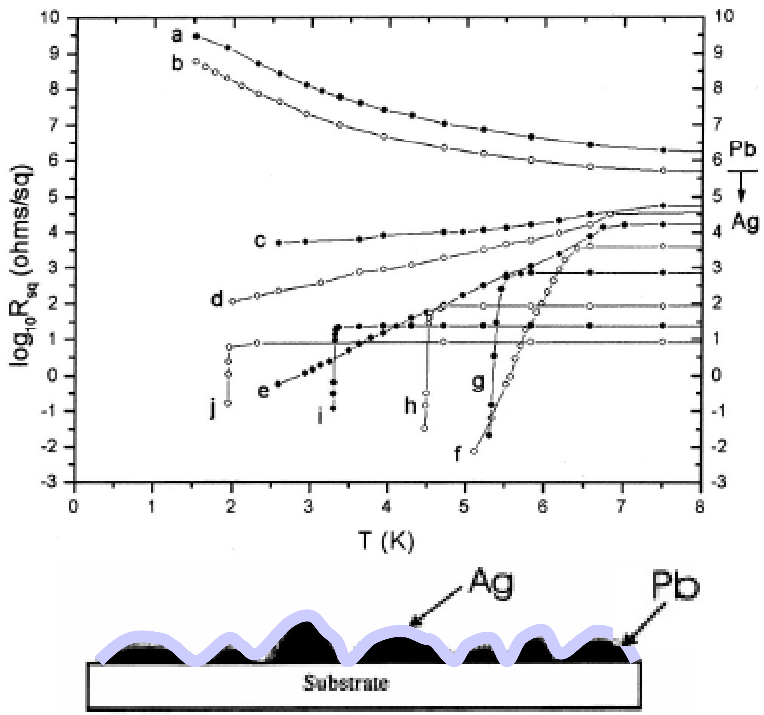


BCS
Pairing limited

BEC
Phase-stiffness limited

How to increase T_c in a granular superconductor ?



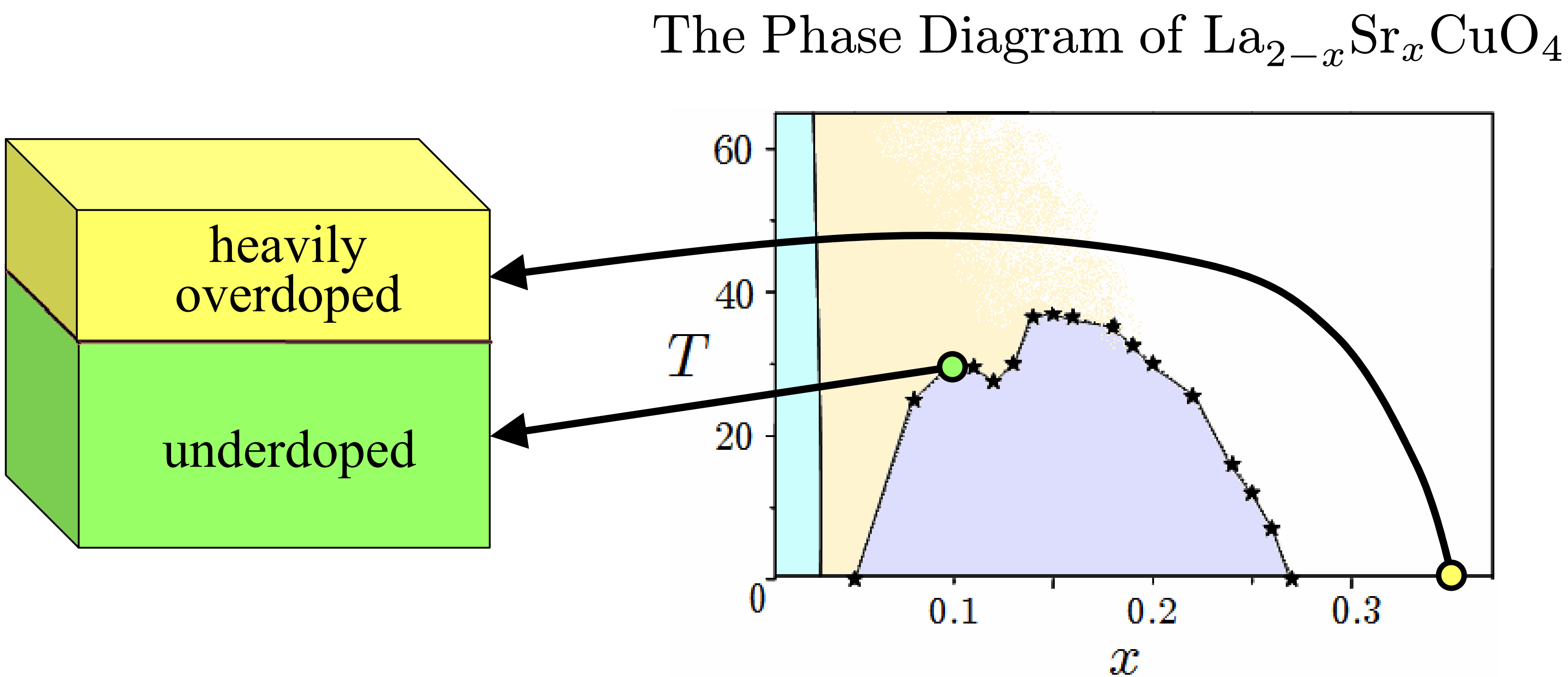


Merchant *et al*. (PRB 01)

Better metallic coverage:

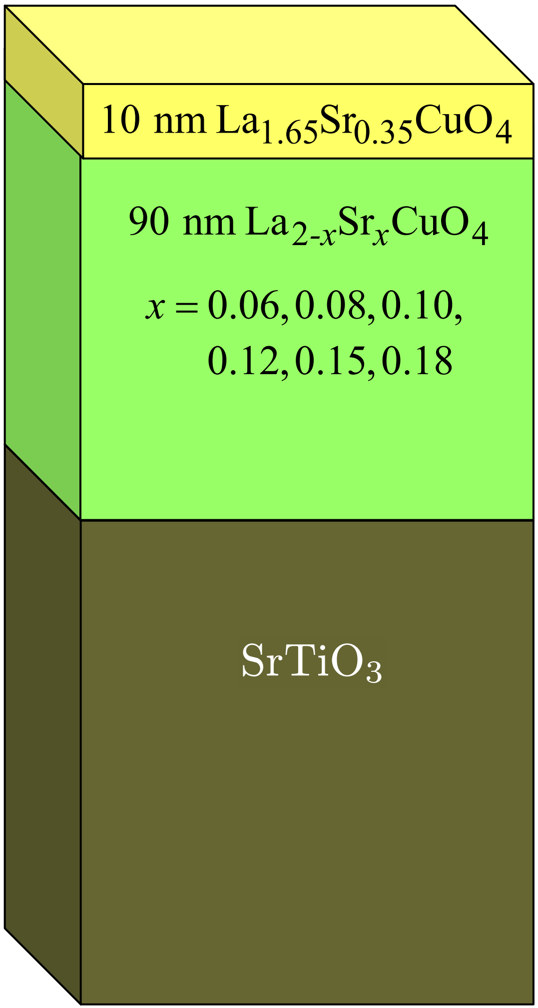
- Larger phase stiffness
- Weaker pairing (proximity effect)

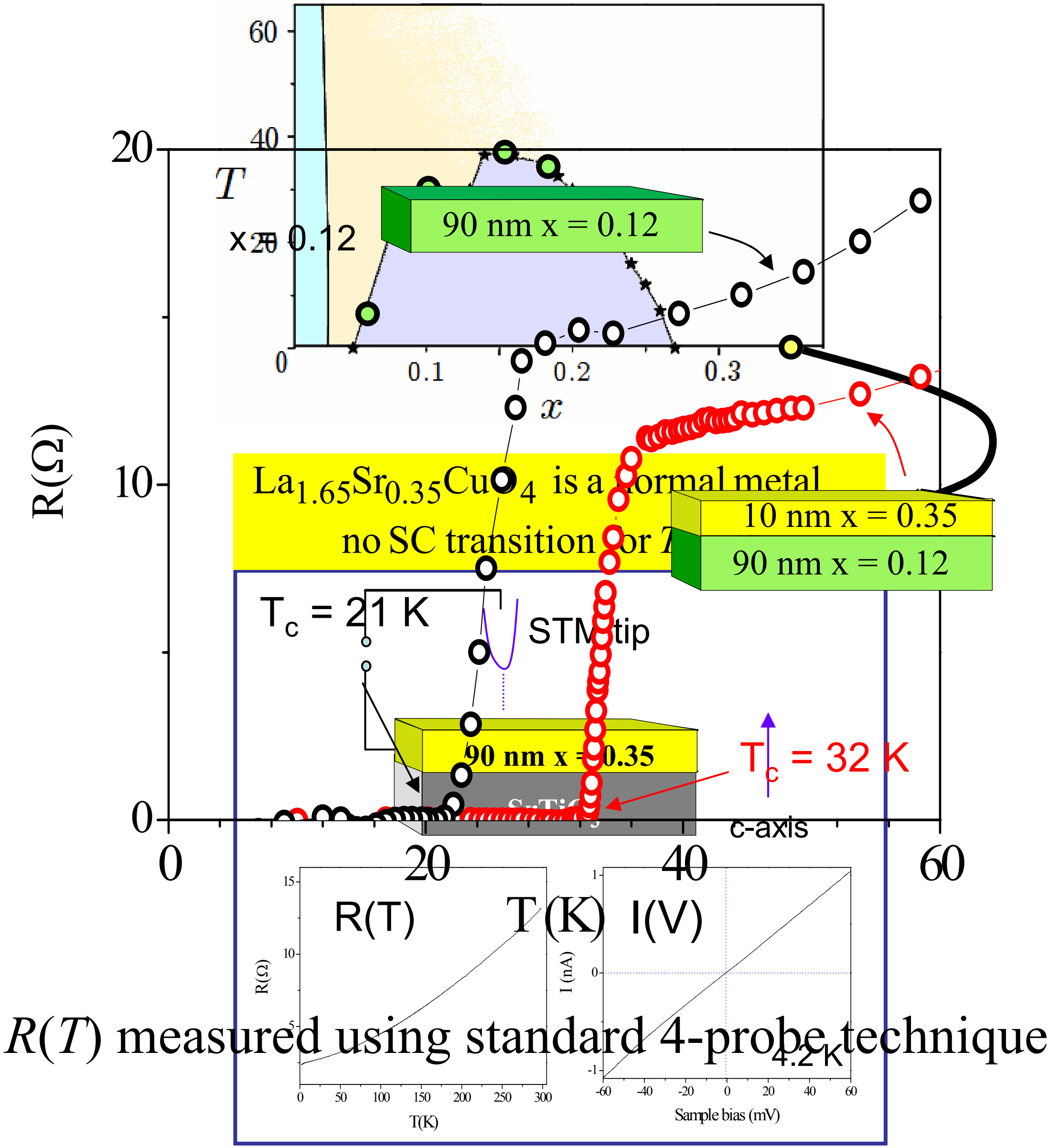
Using the same strategy in a HTSC bi-layer



The best or the worst of both worlds ?

The actual experiment

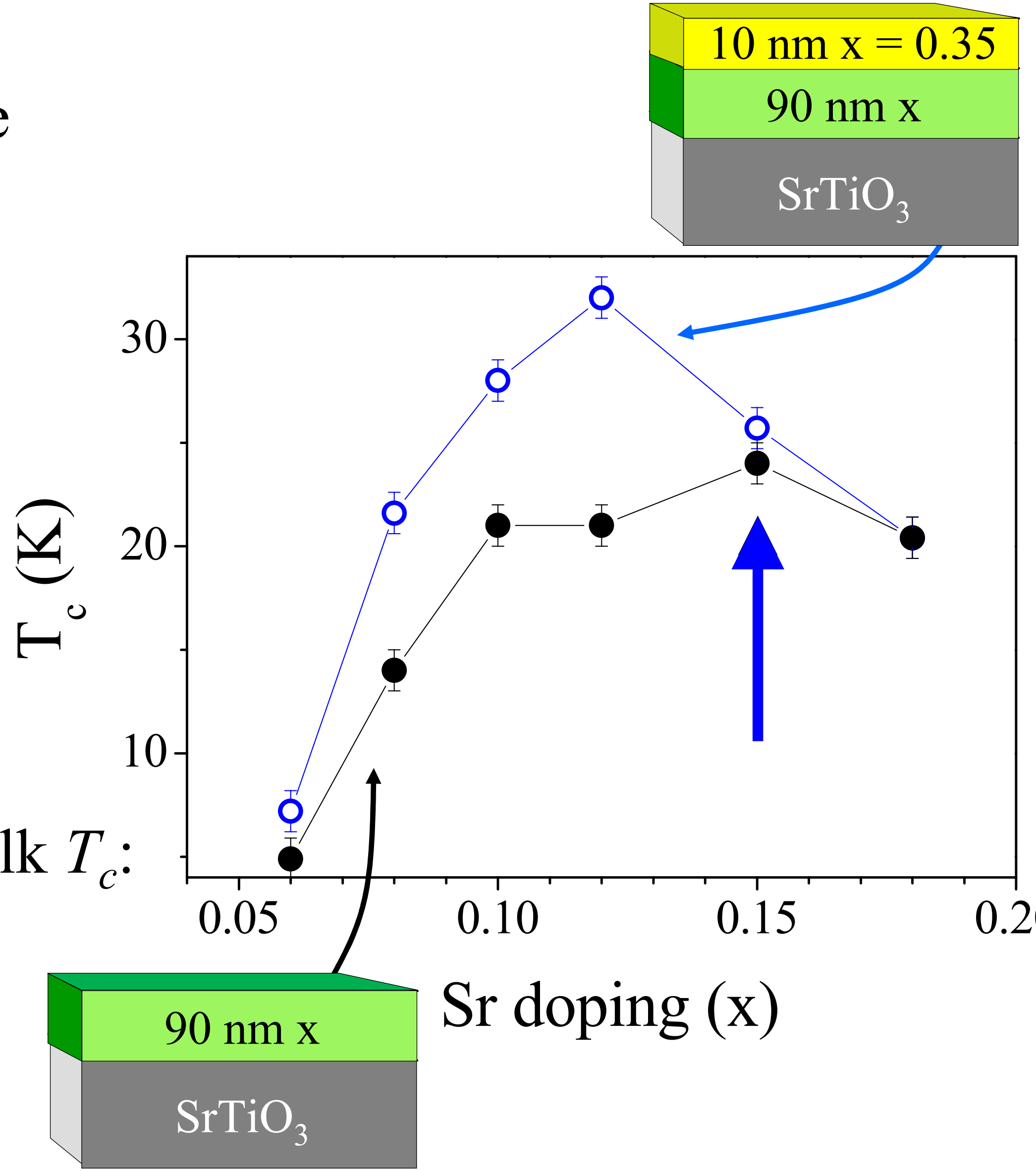




R(*T*) measured using standard 4-probe technique

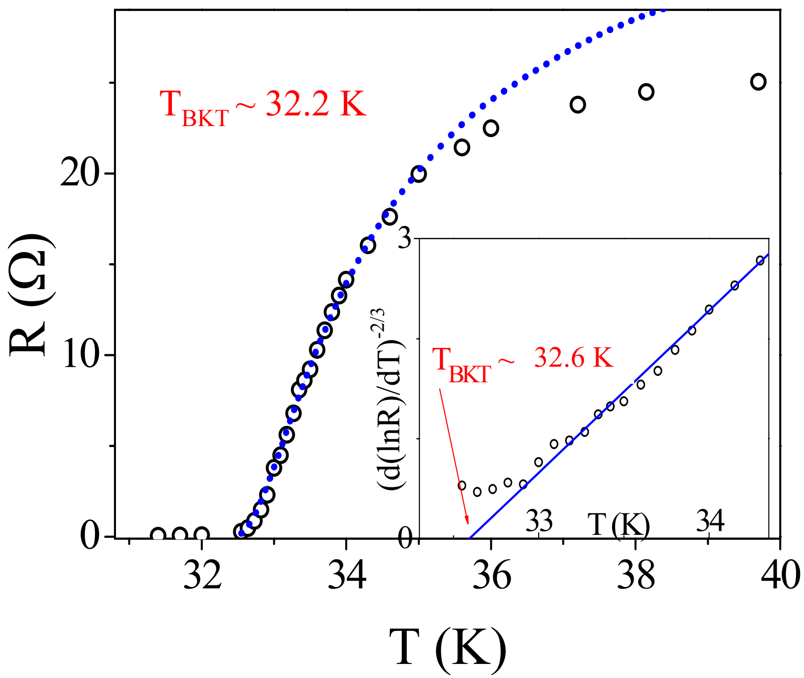
The doping dependence of the enhancement

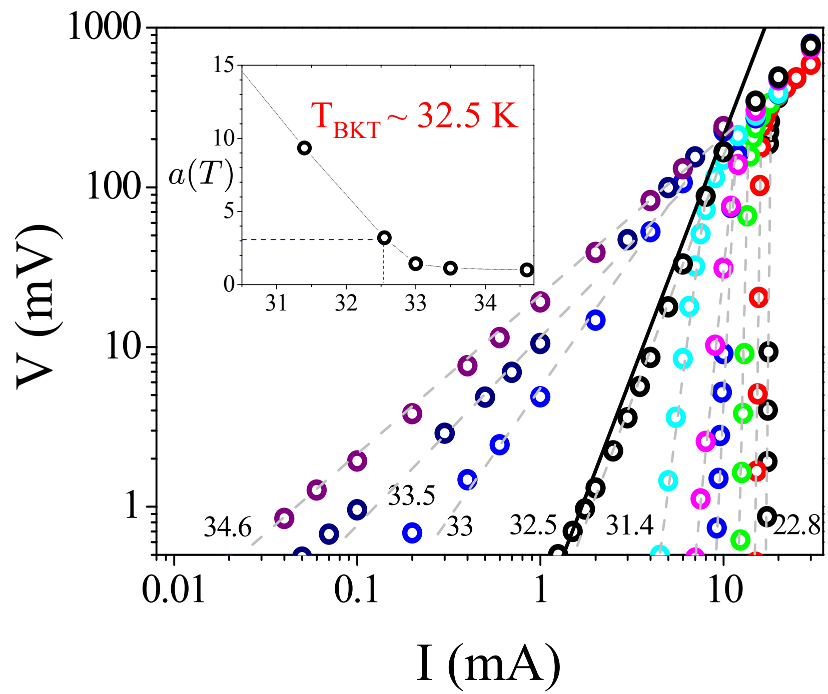
- The enhancement takes place in the underdoped regime.
- Tensile strain exerted by the STO lowers T_c relative to the bulk.
- The peak has shifted $x = 0.15 \rightarrow x = 0.12$
- No Meissner effect above bulk T_c: Surface superconductivity



Evidence for 2d superconductivity: a BKT transition

x = 0.12





For $T \approx T_{BKT}$: $R(T) = R_0 e^{-b\sqrt{\frac{T_{BKT}}{T-T_{BKT}}}}$

$V \propto I^{a(T)}$

$a(T_{BKT}) = 3$

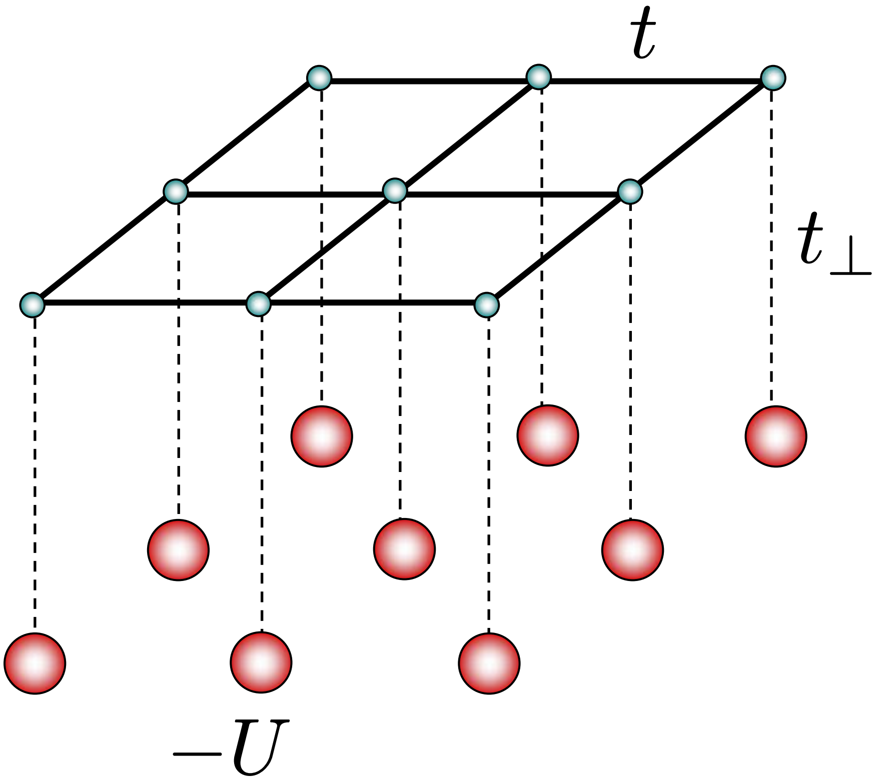
A BKT transition was not observed for unenhanced bilayers (x=0.18) nor for bare films

Reformulating the question

Given a system with a high pairing scale Δ_0 *but with* T_c *reduced by phase fluctuations, can one design a composite system in which* T_c *approaches its mean field value*

$$T_c \to T_{MF} \approx \Delta_0/2\ ?$$

The model



metallic layer =
tight-binding free electrons

pairing layer =
disconnected negative-U
Hubbard sites

What is the optimal $t_\perp$?

What is the optimal T_c ?

Calculation strategy

- Mean-field approximation:

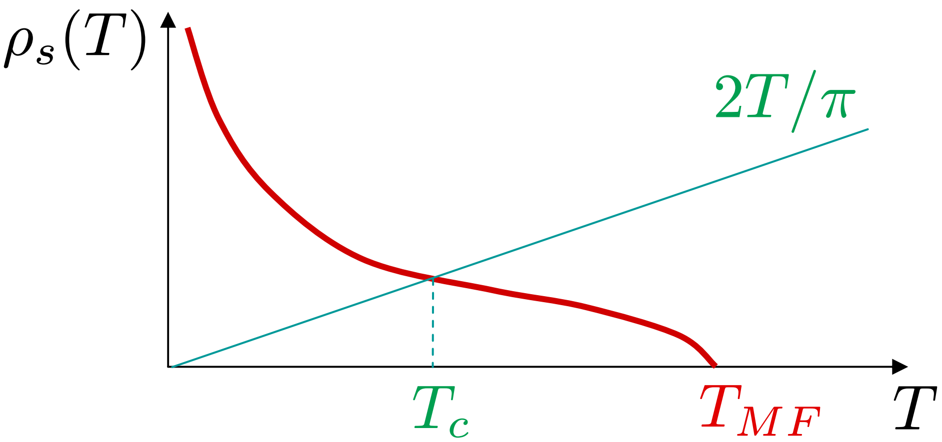
$$-Uf^{\dagger}_{\mathbf{r}\downarrow}f^{\dagger}_{\mathbf{r}\uparrow}f_{\mathbf{r}\uparrow}f_{\mathbf{r}\downarrow} \rightarrow -\Delta^* f_{\mathbf{r}\uparrow}f_{\mathbf{r}\downarrow} - \Delta f^{\dagger}_{\mathbf{r}\downarrow}f^{\dagger}_{\mathbf{r}\uparrow} + \delta\varepsilon n_{f,\mathbf{r}}$$

$$\Delta = U\langle f_{\mathbf{r}\uparrow}f_{\mathbf{r}\downarrow}\rangle$$

$$\delta\varepsilon = -\frac{U}{2}\langle n_{f,\mathbf{r}}\rangle$$

- Calculate T_{MF} at which $\Delta \rightarrow 0$
- Calculate $T_c = T_{BKT}$ from $T_c = \frac{\pi}{2}\rho_s(T_c)$, $\rho_s(T) = \frac{1}{\Omega}\frac{\partial^2 F}{\partial q_x^2}$

phase twist



Takes account of both pairing and classical phase fluctuations

Analytical results

- Perturbatively in $t_\perp/U$ find: $T_c \sim t\left(\frac{t_\perp}{\sqrt{Ut}}\right)^{4/3}$

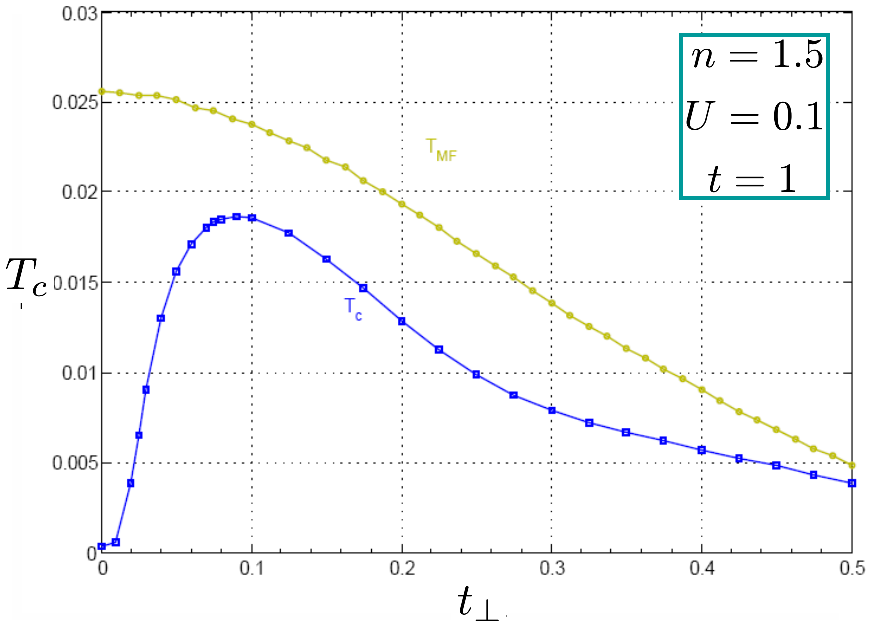
  Result breaks at $t_{\perp,1} \sim t\left(\frac{U}{t}\right)^{5/4}$ where $T_c\left(t_{\perp,1}\right) \approx U \approx \Delta_0$

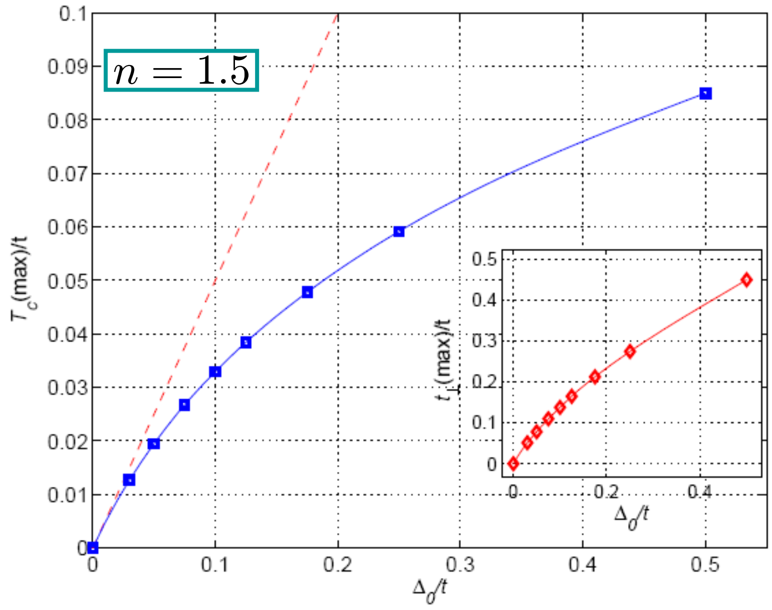
- $T_{MF} = \frac{U}{4}\left[1 - \frac{At_\perp^2}{Ut} + O\left(t_\perp^4\right)\right]$

  T_{MF} not significantly suppressed until $t_{\perp,2} \sim t\left(\frac{U}{t}\right)^{1/2}$

For large t/U there is a parametrically wide region $t_{\perp,1} \lesssim t_\perp \lesssim t_{\perp,2}$ with large pairing and plenty of phase stiffness

Numerical results

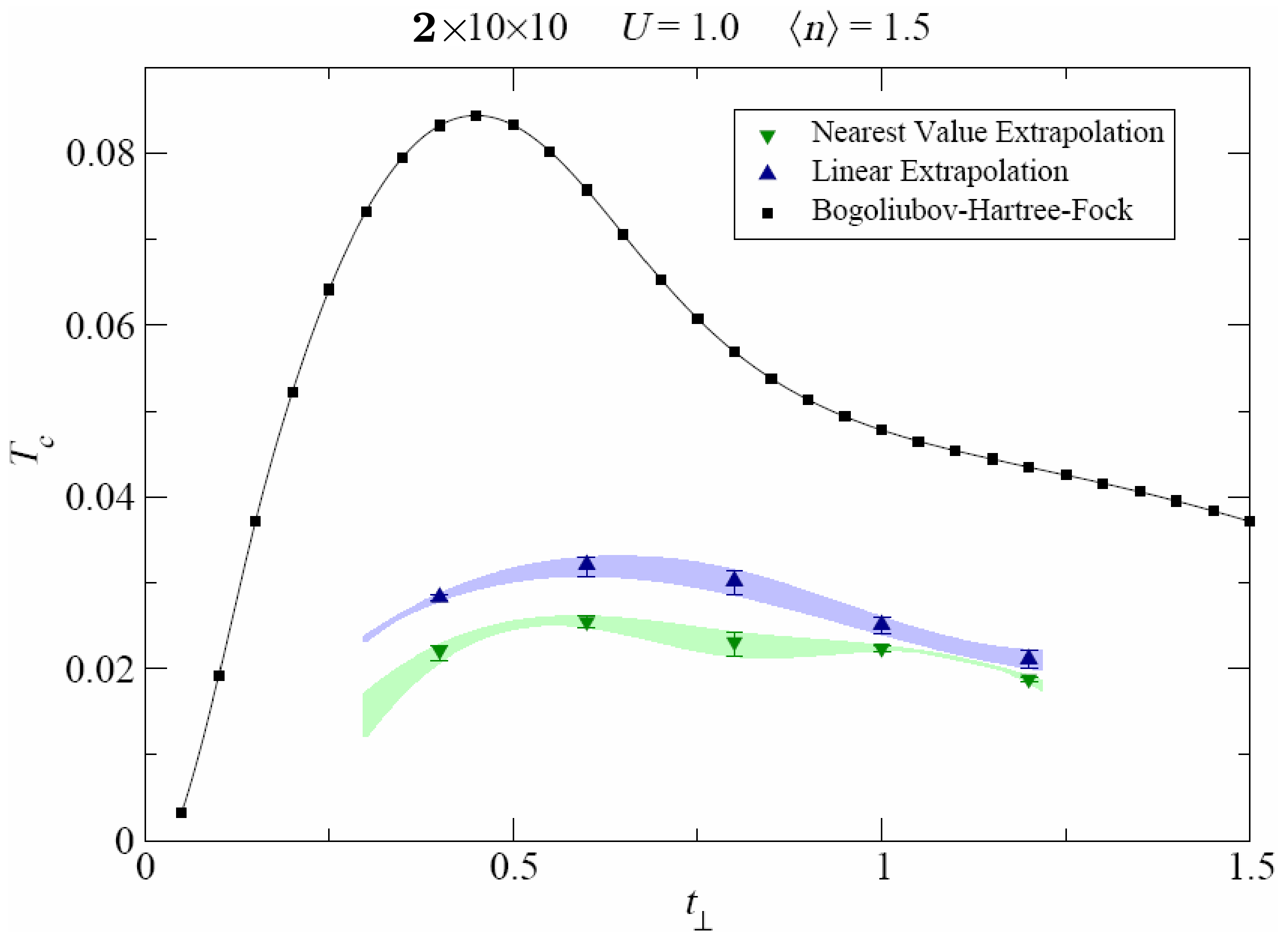




- Competition between phase stiffness and the proximity effect
- T_c reaches a maximum for $t_\perp^{\max} \approx \Delta_0$
- As $t/\Delta_0 \to \infty$, the maximal T_c approaches the full pairing scale:

$$T_c^{\max} \to \frac{\Delta_0}{2}$$

Preliminary QMC results



Gideon Wachtel

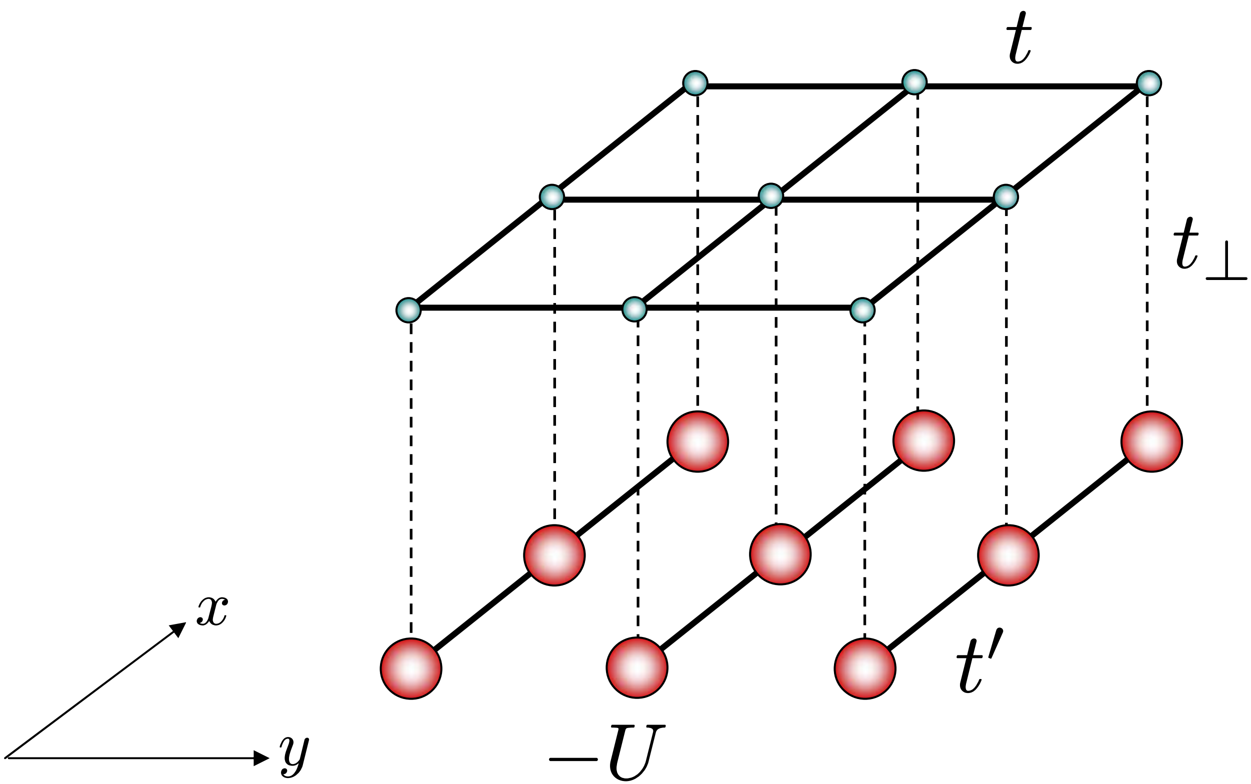
$$\rho_s = \frac{1}{4}[\Lambda^L - \Lambda^T]$$

$$\Lambda^L \equiv \lim_{q_x\to 0} \Lambda_{xx}(q_x, q_y=0, \omega_n=0)$$

$$\Lambda^T \equiv \lim_{q_y\to 0} \Lambda_{xx}(q_x=0, q_y, \omega_n=0)$$

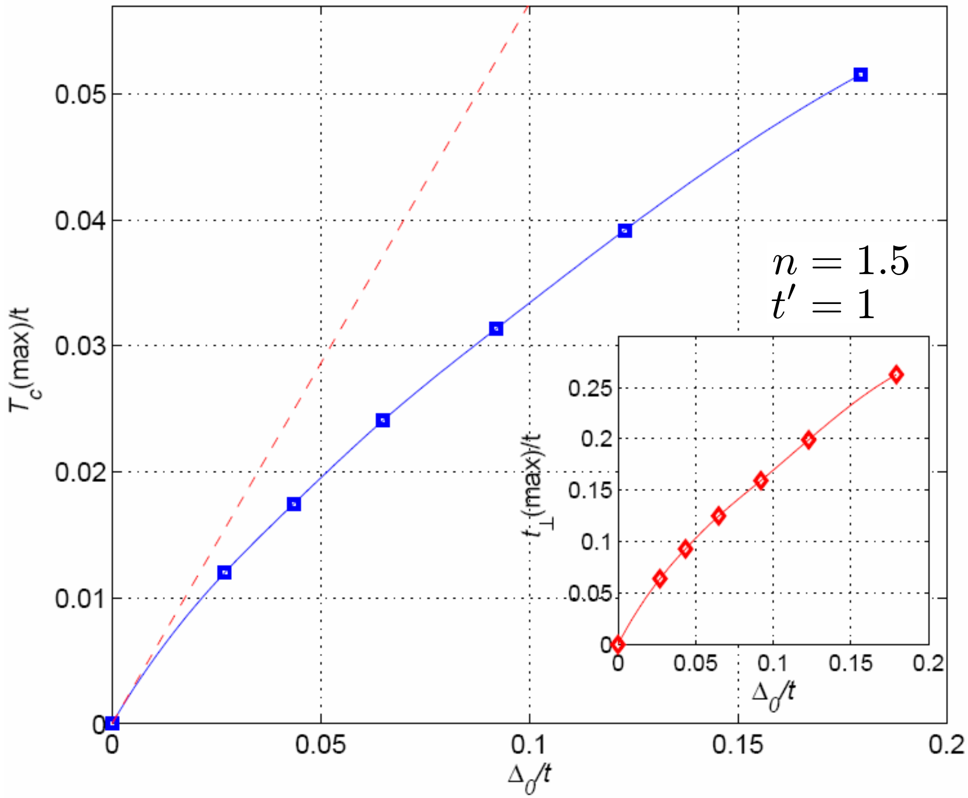
Scalapino, White, Zhang
(PRB 93)

Superconducting wires



$$\rho_s = \sqrt{\rho_{s,x}\rho_{s,y}}$$

Superconducting wires - Results



As $t/\Delta_0 \to \infty$, the region of simultaneous pairing and phase stiffness is parametrically wide: $t_{\perp,2}/t_{\perp,1} \sim (t/\Delta_0)^{3/4}$ and

$$T_c^{\max} \to T_{MF,0}$$

Conclusions

A route to high-temperature superconductivity

Couple a system with a high pairing scale Δ_0 but low T_c due to low phase stiffness, to a metal with large stiffness, to form a superconductor with $T_c^{\max} \to T_{MF} \approx \Delta_0/2$

Provided that: 1. The coupling is optimal: $t_\perp^{\max} \approx \Delta_0$
2. Large metallic bandwidth: $W \gg \Delta_0$

Extensions:
Effects of disorder in the metal and in the pairing layer, *d*-wave symmetry, Strong correlations (positive U).