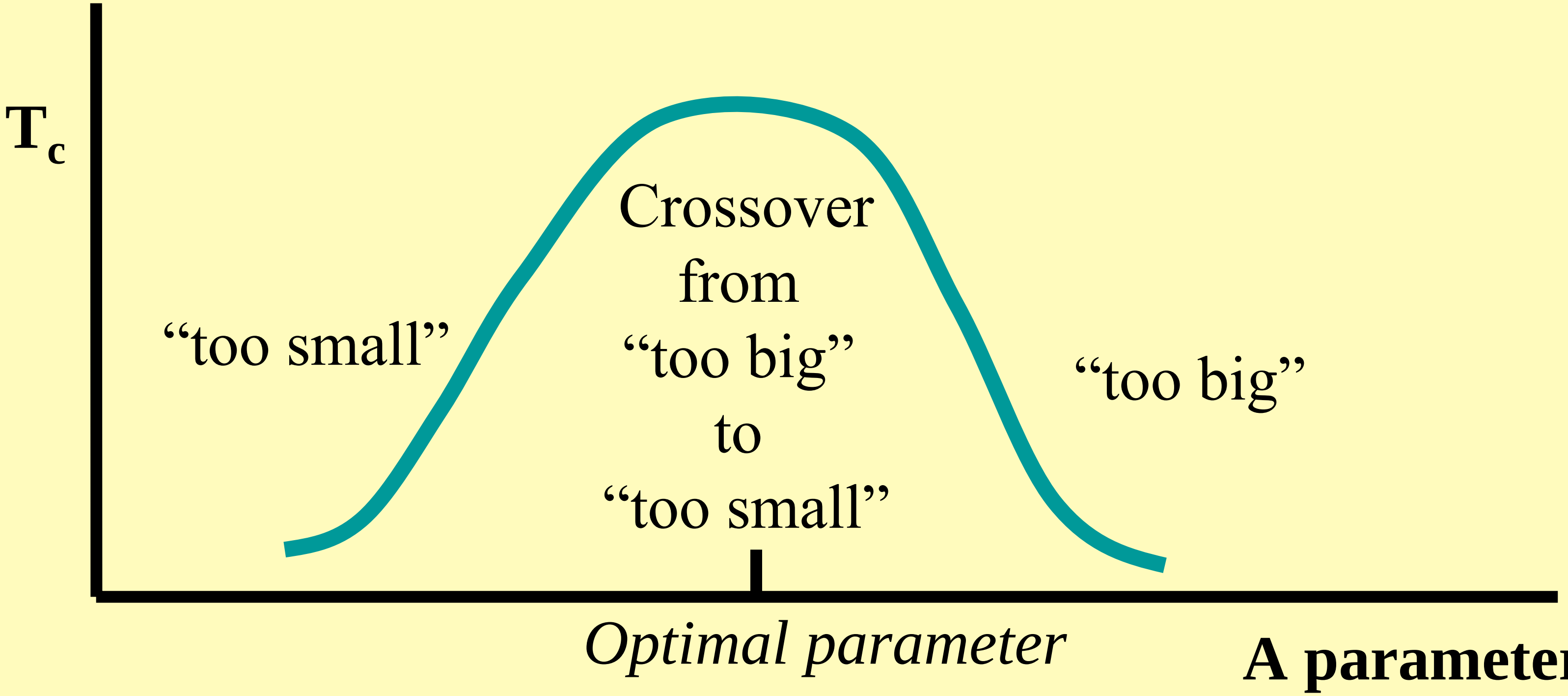
High Temperature Superconductivity is a Crossover Phenomenon

Steven Kivelson, Stanford



KITP Higher Tc Conference, June 22, 2009

“The Goldilocks Principle”

V.J. Emery and E.Fradkin,

H.Yao, W-F. Tsai, E. Berg,

S. White, G. Karakonstantakis

A.Kapitulnik, S. Chakravarty, S.Raghu

J.Tranquada, E-A.Kim, E.Carlson, D.Orgad

D.J.Scalapino, S.White, A.Lauchli

E.Arrigoni, I.Martin, D. Poldolsky, O Zachar

S.A.K. and E.Fradkin, “How optimal inhomogeneity produces high temperature superconductivity,”in "Treatise of High Temperature Superconductivity" edited by J. R. Schrieffer and J. Brooks

KITP, 2009

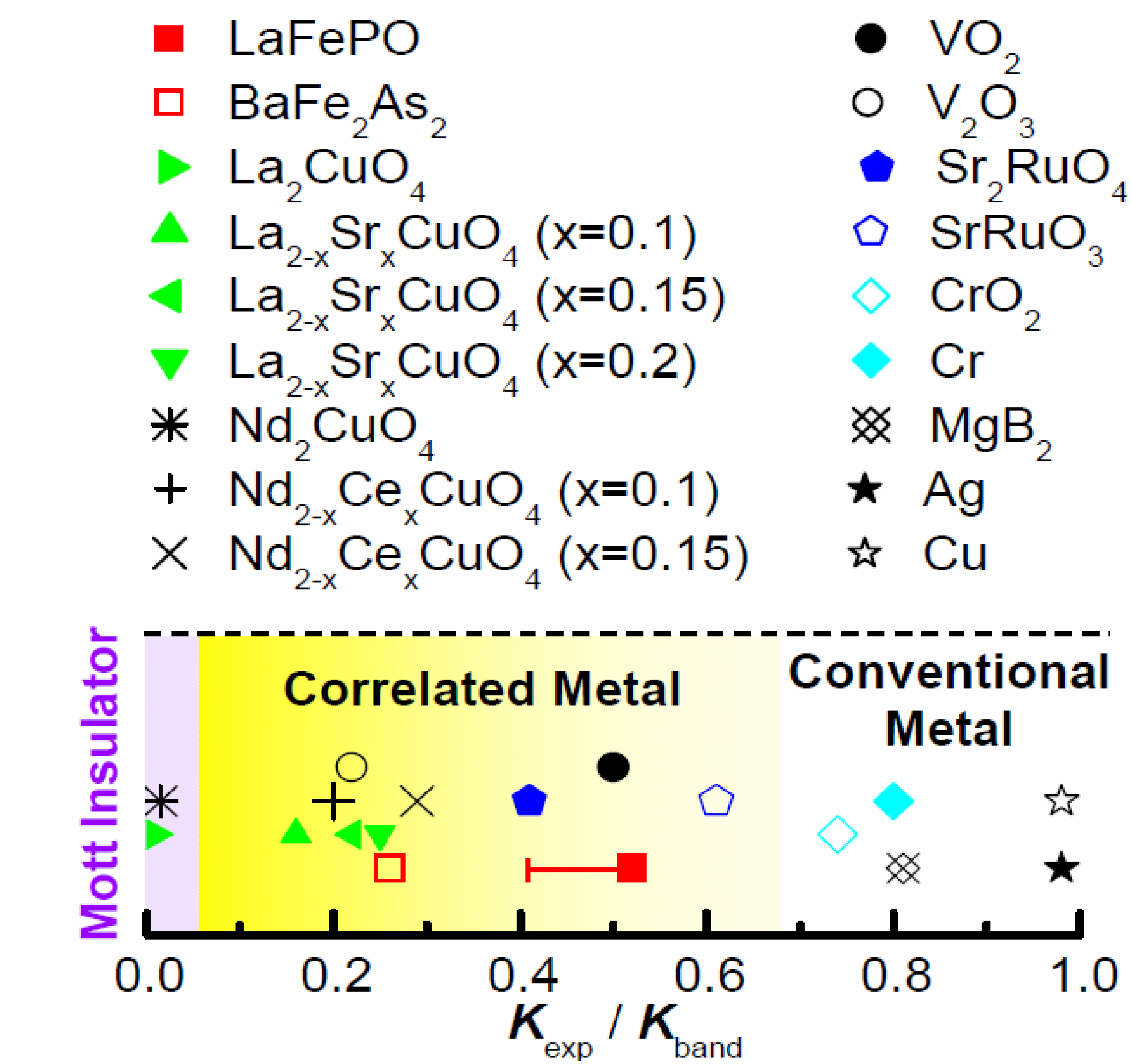
1) Unless the superconducting phase is cut off by a (first order) transition to a competing phase, optimal T_c occurs at a crossover from
a pairing dominated regime - $\mathbf{T_c \sim \Delta_0}$
to a condensation regime - $\mathbf{T_c \sim T_\theta}$

2) High temperature superconductivity occurs at intermediate coupling, where neither weak nor strong coupling approaches are well justified:
U ~ Band-width.

3) Certain forms of nano-scale structuring of materials produce enhanced pairing (enhancement of Δ_0) at the expense of a reduction of T_θ.
There exists an "***optimal inhomogeneity***" for T_c.

Electronic correlations in the iron pnictides

Qazibash, Hamlin, Baurnbach Zhang, Singh, Maple, and Basov



Why is it that high temperatures superconductors are in an intermediate coupling regime?

Is it only to make the theorist’s life complicated (and to keep us employed)?

Or is it that when we choose to study materials which are in some sense optimal superconductors, we have implicitly fine tuned the interaction strength to intermediate values?

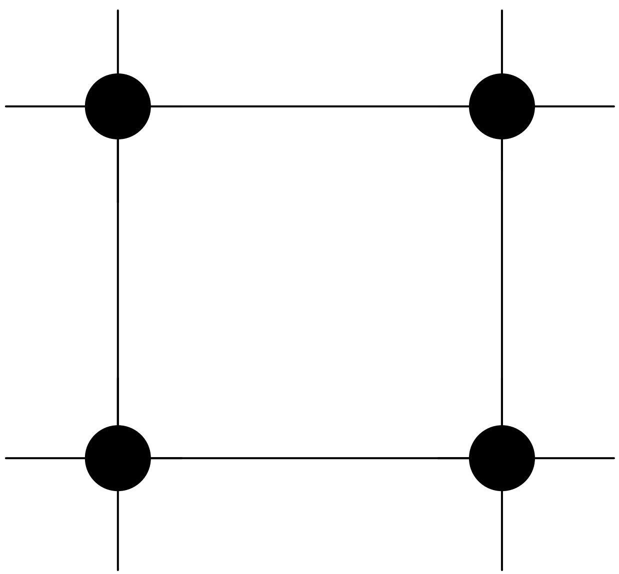
Some solutions of model problems:

1) The negative U Hubbard model

Crossover between pairing and coherence.

The Hubbard model

$$H = -\sum_{ij,\sigma} t_{ij}\ c^\dagger_{i,\sigma} c_{j,\sigma} + U \sum_{j}\ \ c^\dagger_{i,\uparrow} c^\dagger_{j,\downarrow} c_{i,\downarrow} c_{j,\uparrow}$$



U > 0	Repulsive
U < 0	Attractive

$|U| << t$ BCS superconductivity

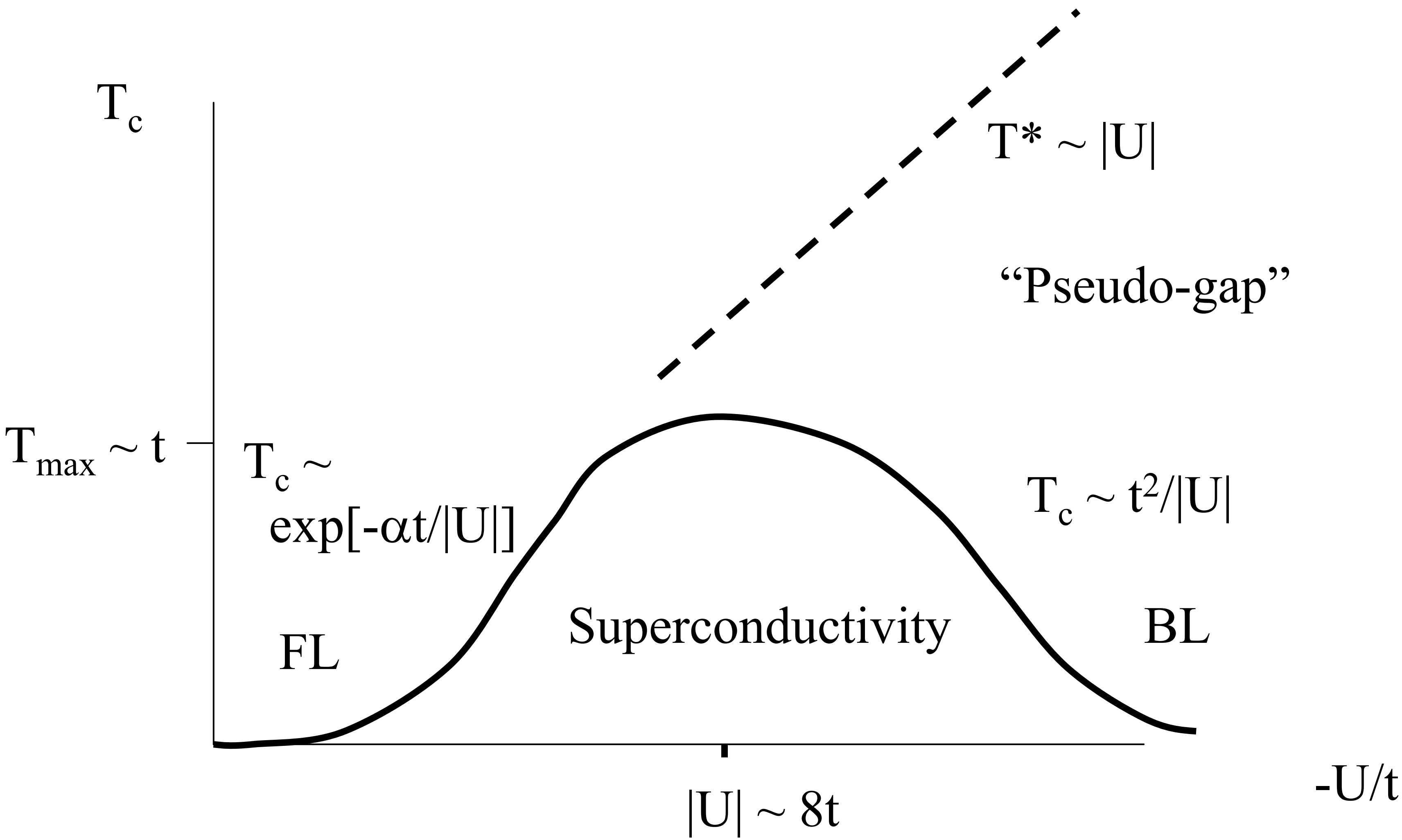
$$T_c \sim t \exp[-\alpha t/|U|]$$

very mean-field like transition.

$|U| >> t$ BEC superconductivity

pairs form at $T \sim |U|$ (pseudo-gap)

$$T_c \sim \rho_s \sim t^2 / |U|$$



Maximal T_c occurs at a point of crossover in the physics:

crossover from pairing to phase ordering transition

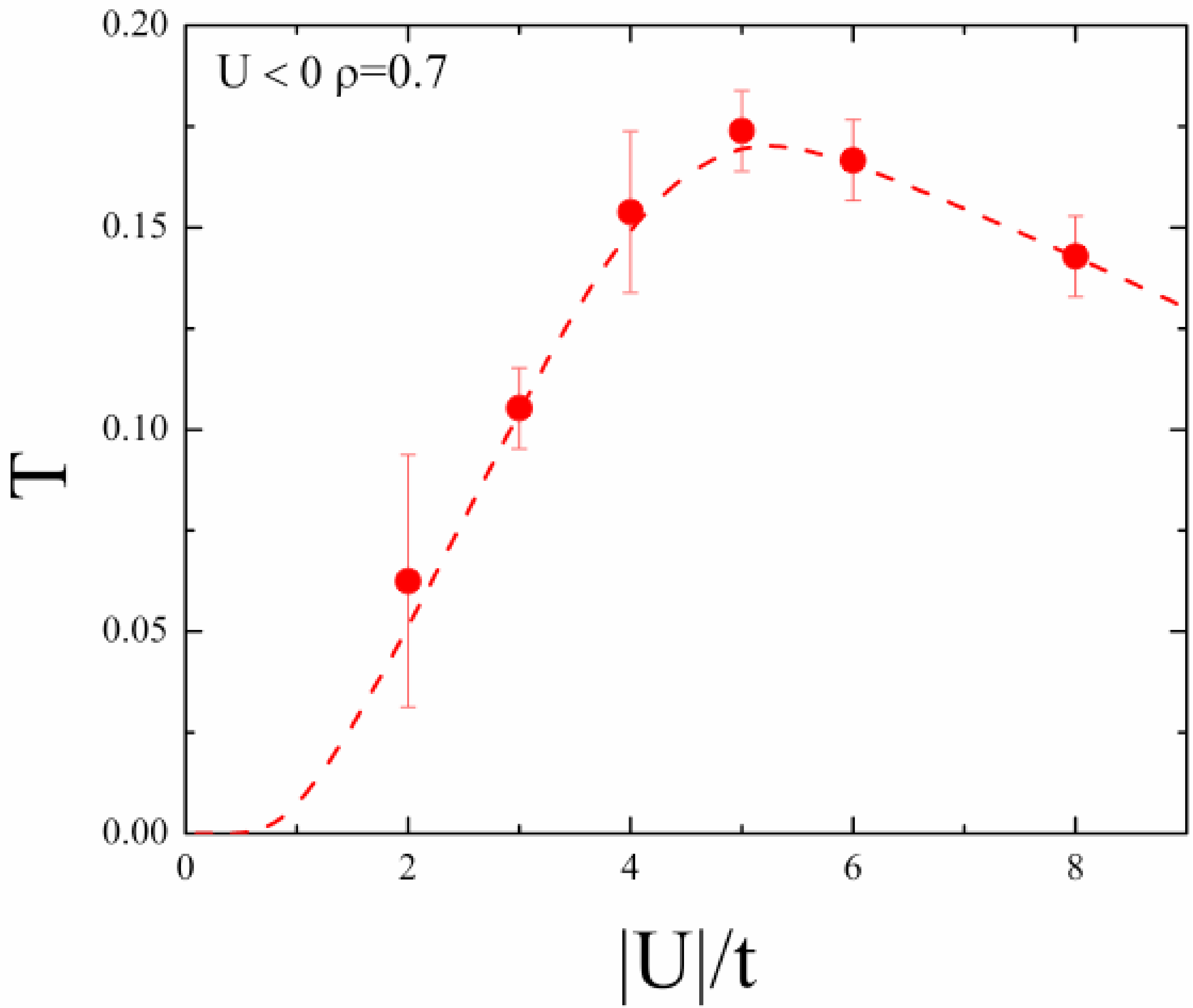
crossover from weak coupling to strong coupling

T_c for 2D negative U Hubbard model with x=0.3

“Real” Monte Carlo version from Paiva, Scalettar, Randeria, Trivedi

$(U/t)_{opt} = 5$

$T_{opt} \approx t / 6$



Some solutions of model problems:

1) The negative U Hubbard model

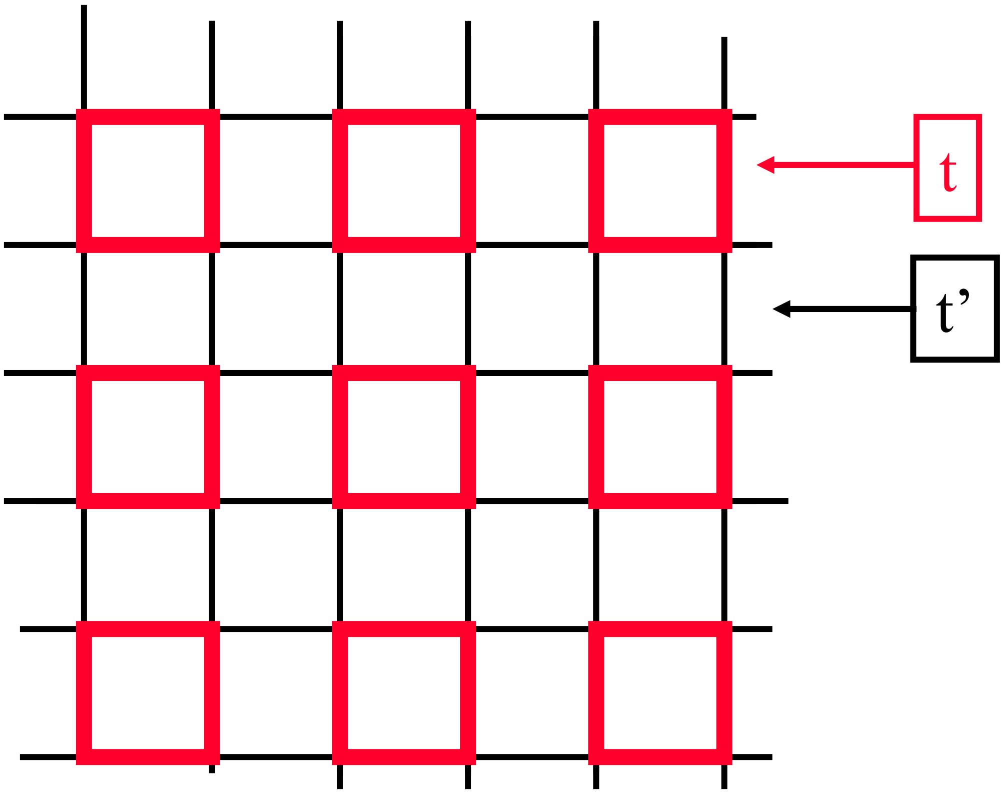
2) The "Checkerboard Hubbard model."

Crossover between too homogeneous and too inhomogeneous

Crossover between strong and weak coupling

Phase diagram of checkerboard Hubbard model

"Homogeneous" (t'/t=1) to "highly inhomogeneous" (t'/t << 1)

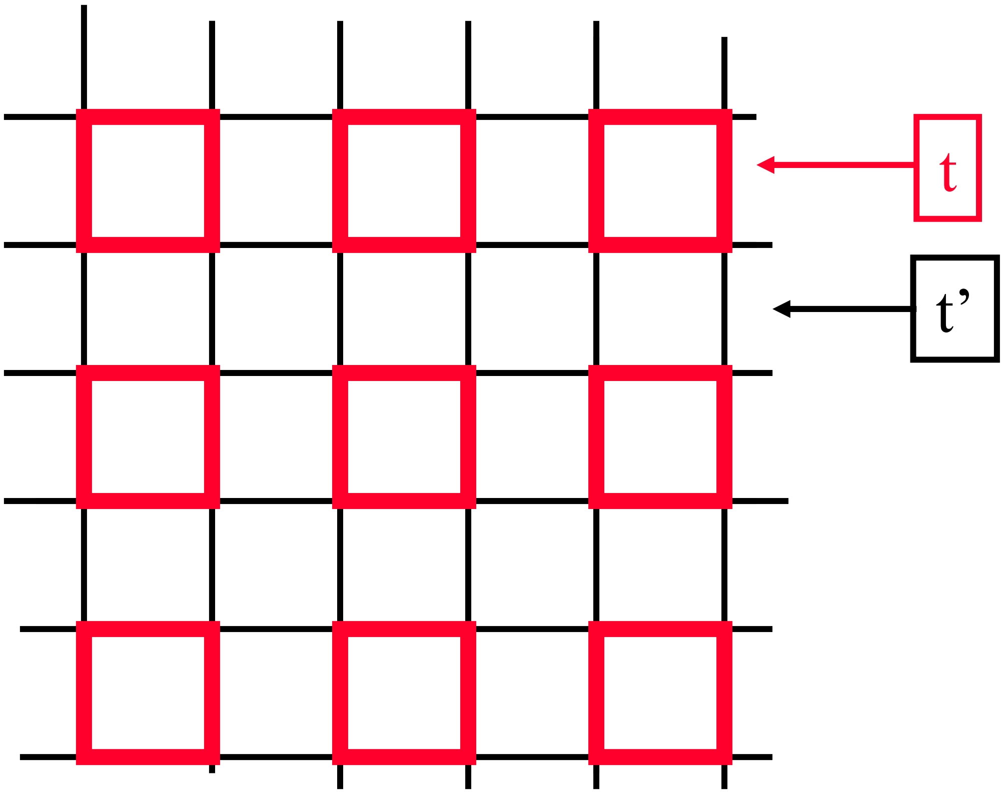


The Hubbard model for t = t'

The Checkerboard Hubbard model for t > t'

Phase diagram of checkerboard Hubbard model

“Homogeneous” (t’/t=1) to “highly inhomogeneous” (t’/t << 1)



As a function of U/t and t’/t, what are the conditions for the maximal T_c?

Can “solve” the checkerboard Hubbard model if:

1) U/t << 1 (weak coupling physics).
   (unpublished results)

2) N < 20 by exact diagonalization.
   (W.F.Tsai et al, PRB 2008)

3) Limit of large inhomogeneity, t’/t << 1.
   (W.F.Tsai and SAK, PRB 2006;
   H.Yao et al, PRB 2007
   Kocharian et al, 2005, 2006,2008)

4) 1d (“checkerboard ladder”) using DMRG.
   (E.Berg, G.Karakonstantakis, S.White, SAK)

5) Variational and mean-field (DMFT) approaches,
   CORE, …
   (Altman and Auerbach, PRB (2002)
   Jarrell, Maier et al,PRB (2008)

Numerical studies of the 16 site Checkerboard Hubbard model:

Pair-binding energy: $E_{pair} = 2\,E(2n+1) - E(2n) - E(2n+2)$

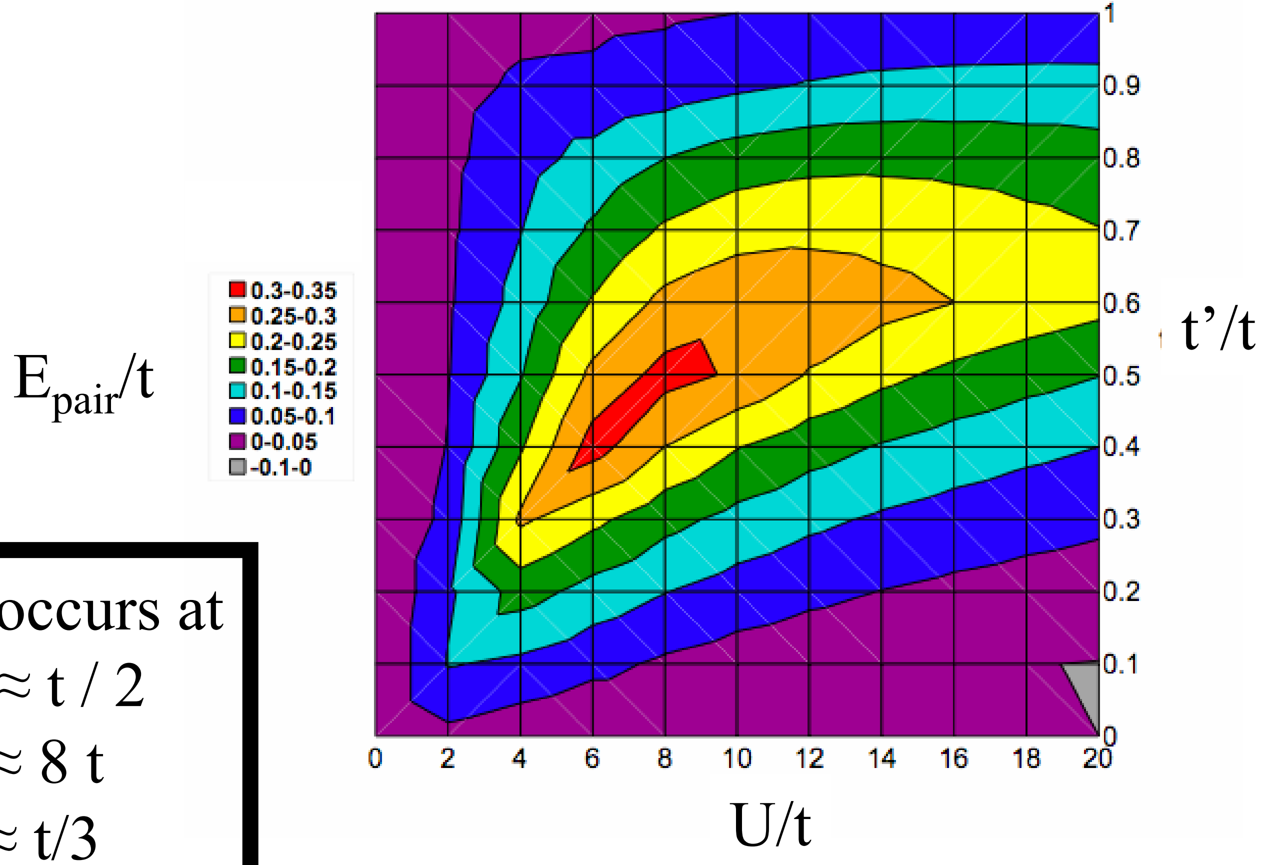
$E_{pair} \longrightarrow 2\Delta_{min}$ as $N \longrightarrow \infty$ in gapped SC
$E_{pair} \sim 2\Delta_0 N^{-1}$ as $N \longrightarrow \infty$ in nodal SC

Spin-gap: $E_{SG} = E(S=1) - E(S=0)$

Finite size scaling is not possible, but sensitivity to boundary conditions is: Periodic vs Twisted Periodic B.C.

W-F. Tsai, H. Yao, A. Lauchli, S. A. Kivelson

Pair-binding energy 16 site checkerboard model with PBC



Max occurs at

$t' \approx t / 2$

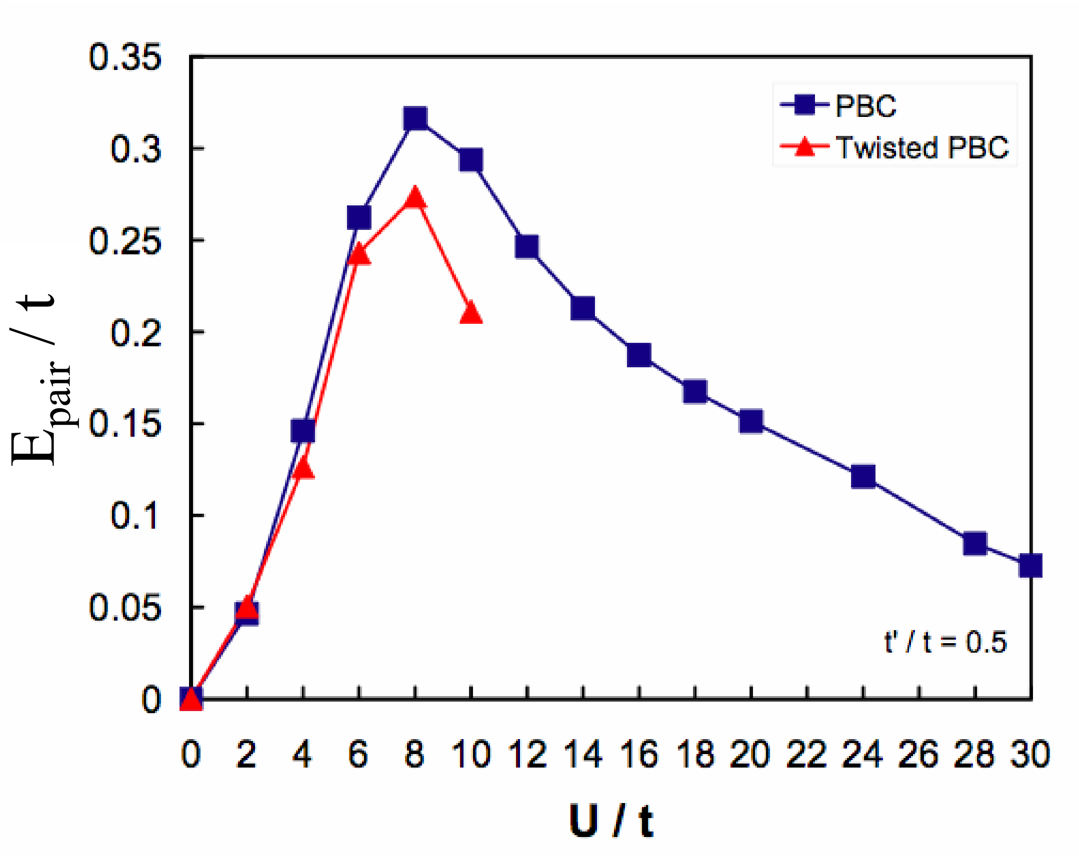
$U \approx 8\ t$

$E_{pair} \approx t/3$

$(T_{MF} \sim t / 12)$

$E_{pair}(x=1/16) = 2\ E(15) - E(16) - E(14)$

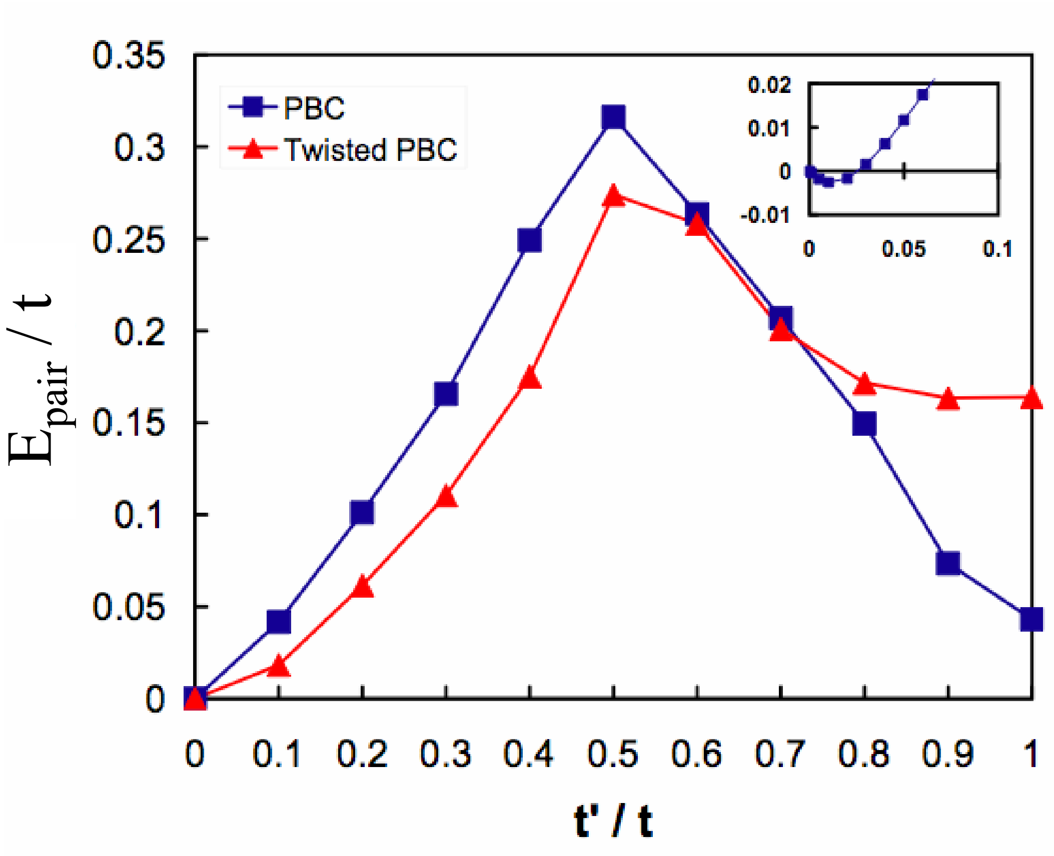
Pair-binding energy 16 site checkerboard model with t'=t/2



$E_{pair} = 2\ E(15) - E(14) - E(16)$

High temperature superconductivity occurs
at a crossover between weak and strong coupling regime.

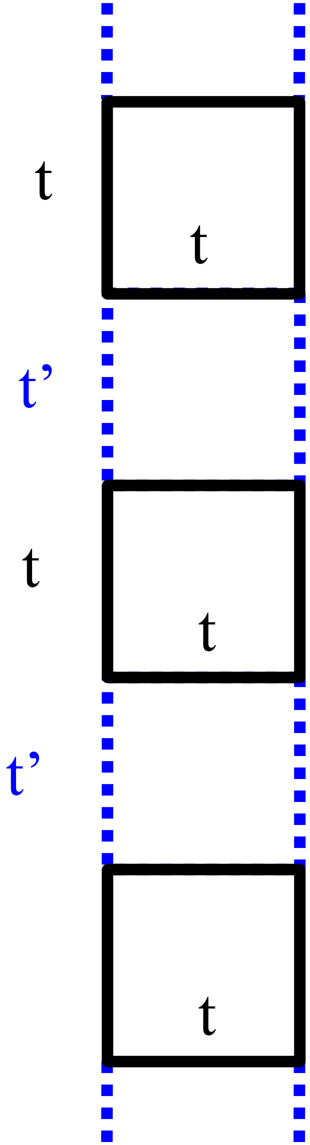
Pair-binding energy 16 site checkerboard model with U=8t



$E_{pair} = 2\ E(15) - E(14) - E(16)$

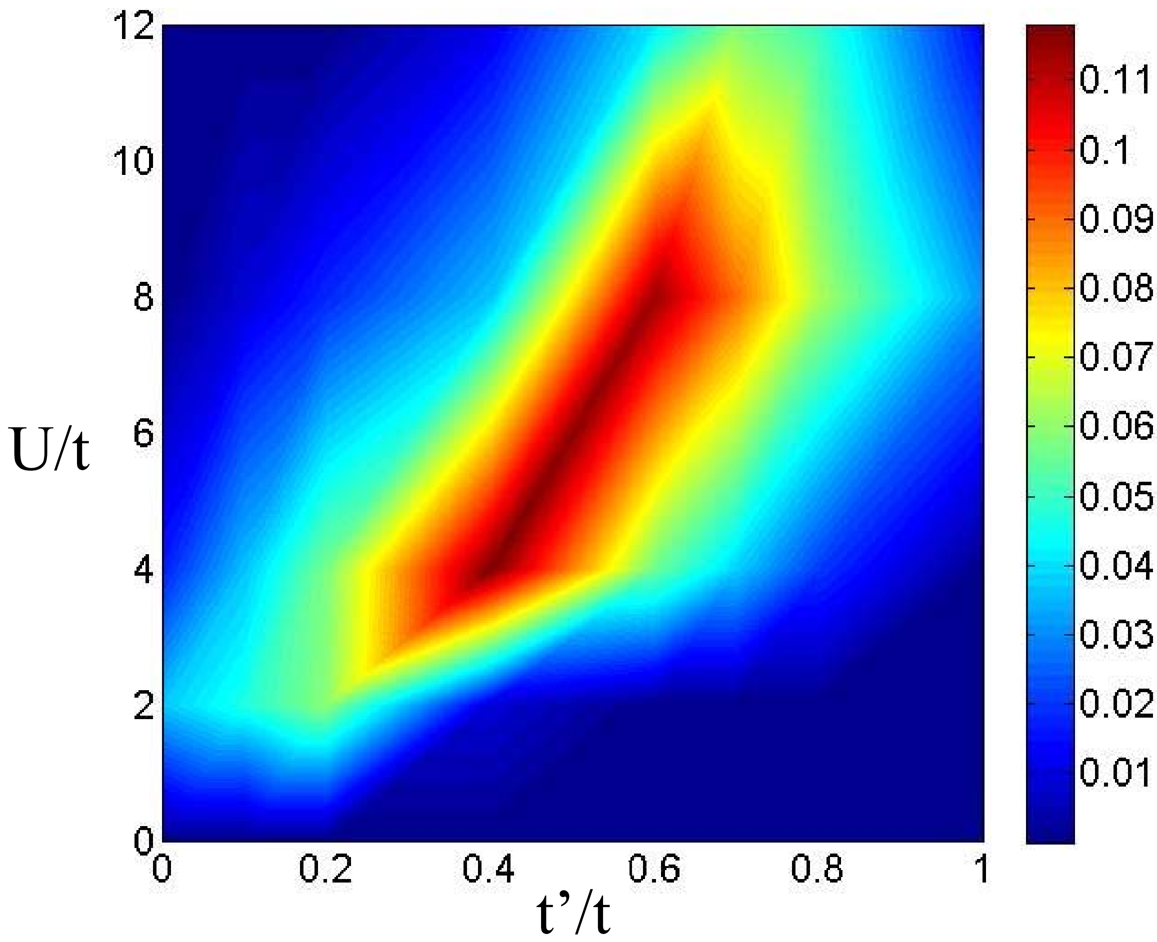
High temperature superconductivity occurs
at a crossover between too inhomgoeneous
and insufficiently structured.

Checkerboard Hubbard ladder
(DMRG results extrapolated N to ∞)

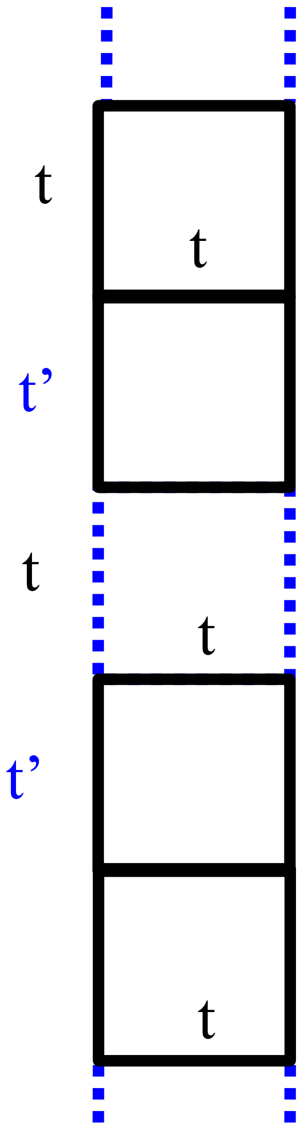


(Results for up to 2 x 64)

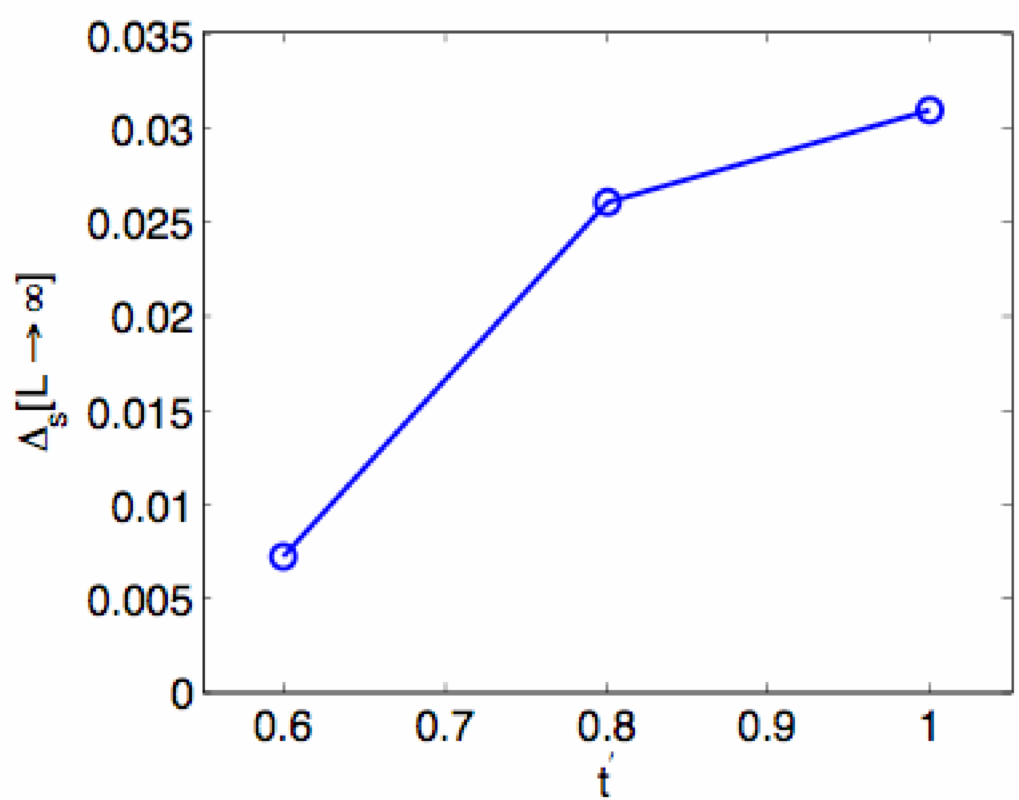
Spin gap for n = 0.875



Other patterned Hubbard ladder
(DMRG results extrapolated N to ∞)



Spin gap, optimal for t' = t.



Checkerboard Hubbard model proves many points of principle.

Can get superconductivity directly from strong repulsion between electrons

Highly non-BCS **mechanism** of SC - no well defined phonon (or any other well defined boson) exchanged, and (typically) no FL “normal” state.

D-wave superconductivity emerges naturally from lattice geometry and strong repulsion.

(Whether RVB or SFE)

If there is an “optimal inhomogeneity” for HTC.

Then “stripes” may be essential - a form of self-organized inhomogeneity.

Mesoscale structure of another kind is demonstrably important T_c rises for n=1 to 2 to 3, then drops for n=4 to 5 … (n=number of layers)

Search for ways of making inhomogeneous systems with high pairing regions and highly coherent (itinerant) regions.

How to make High T_c higher - a theoretical proposal

Physica **B 318**, 61-67 (2002).

Suppose it is true that in underdoped cuprates, $T_{pair} >> T_c$.

Then, to enhance T_c, we need to enhance T_θ.

$x_2 \geq x_{opt}$ — T_θ large

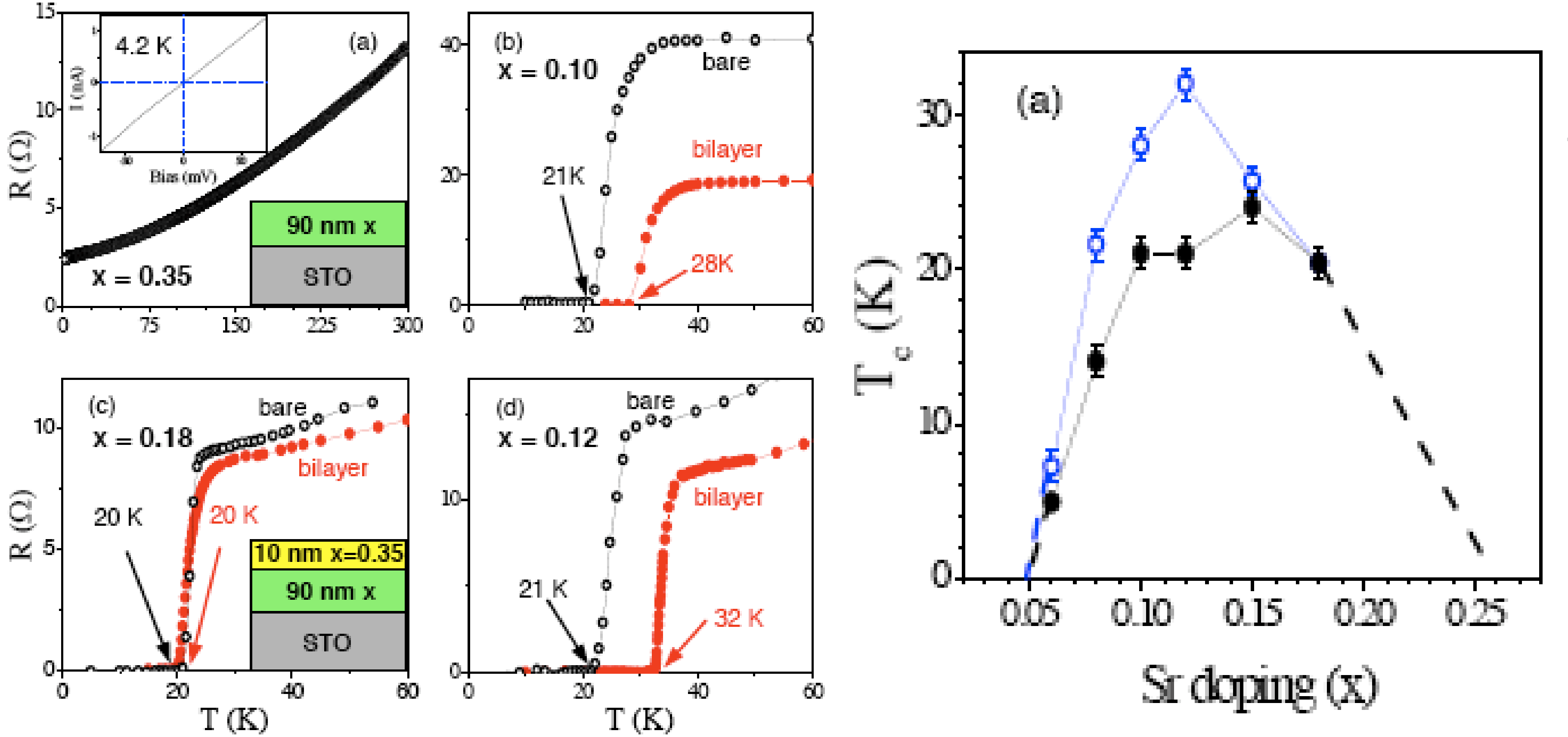
$x_1 < x_{opt}$ — Δ_0 large

$x_2 \geq x_{opt}$ — T_θ large

$T_{pair} \sim T_{BCS} \sim \Delta_0/2$

$T_\theta \sim \rho_s/m^*$

Enhancement of the superconducting transition temperature in $La_{2-x}Sr_xCuO_4$ bilayers



Ofer Yuli, Itay Asulin, Leonid Iomin, Gad Koren, Oded Millo, Dror Orgad arXiv:0805.0405

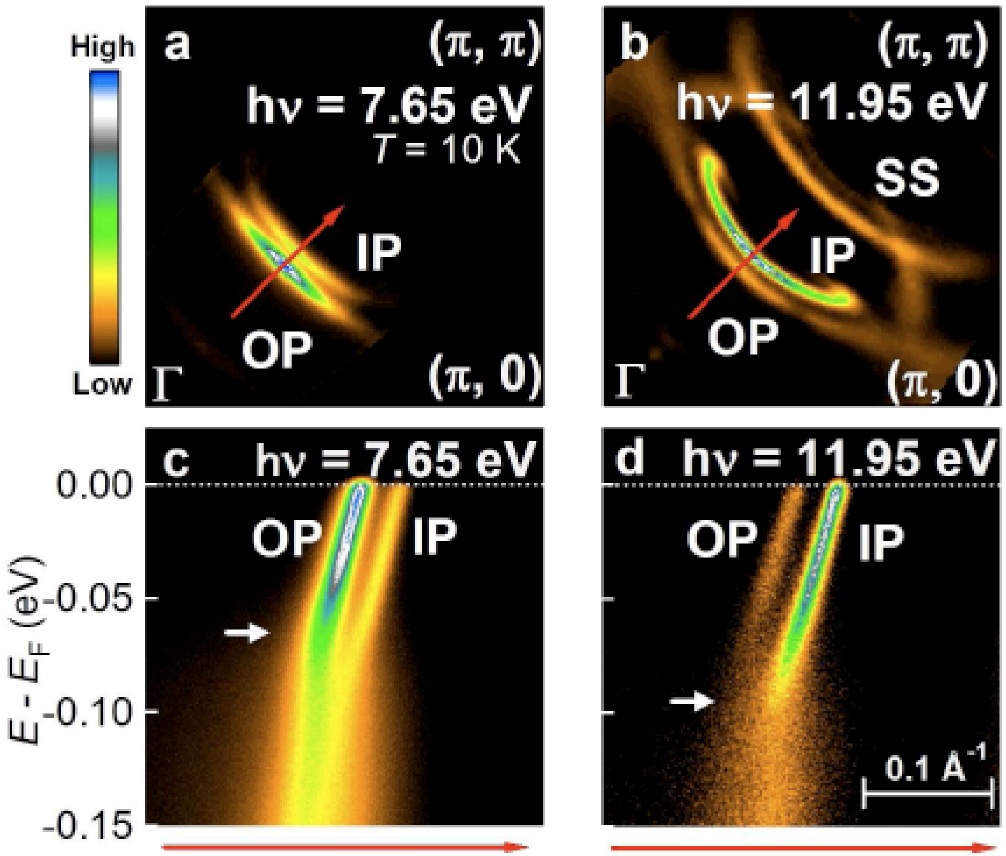
Similar results by Gozar, Logvenov, Kourkoutis, Bollinger, Giannuzzi, Muller, and Bozovic, arXiv:0810.1890
However, role of strain complicates the interpretation of both of these results.

Do these considerations have any relation to reality?

Enhanced superconducting gaps in the tri-layer high-T_c cuprate $Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$

Ideta, Takashima, Hashimoto, Yoshida, Fujimori, Anzai, Fujita, Nakashima, Ino, Arita, Namatame, Taniguchi, Ono, Kubota, Lu, Shen, Kojima, Uchida

ArXiv - 0905.1223



From the area enclosed by the Fermi surface -

x_{IP} = 6%

x_{OP} = 26%

$T_c = T_{opt}$ = 110K

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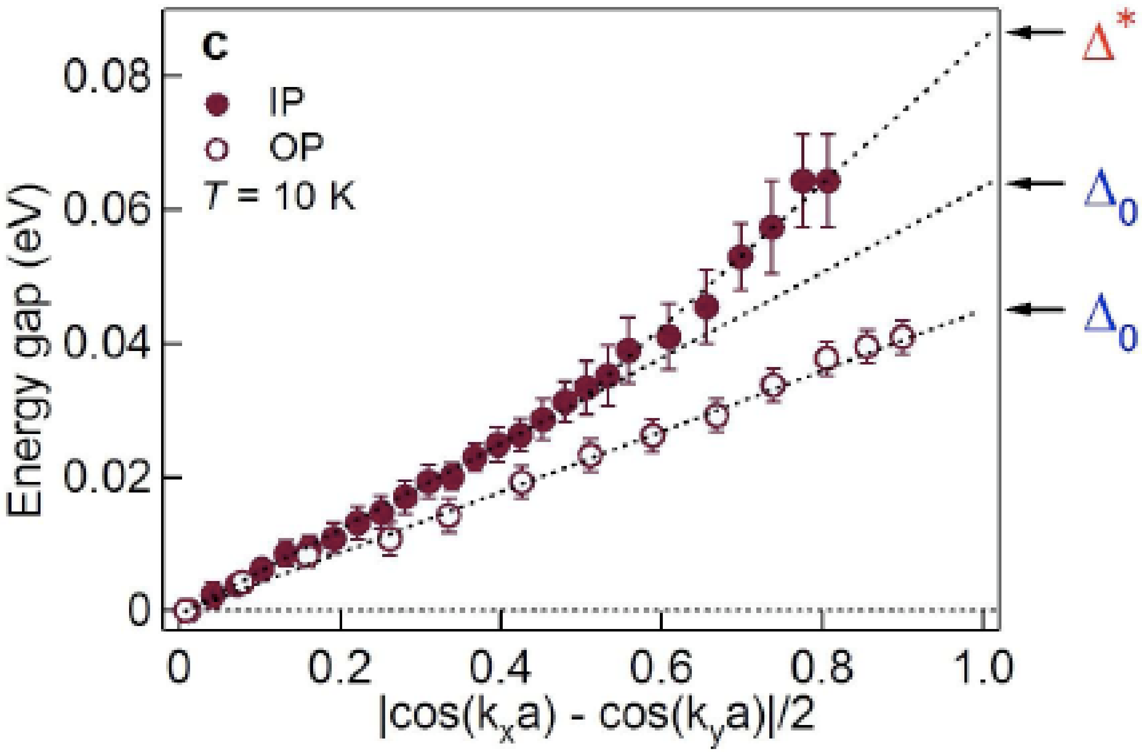

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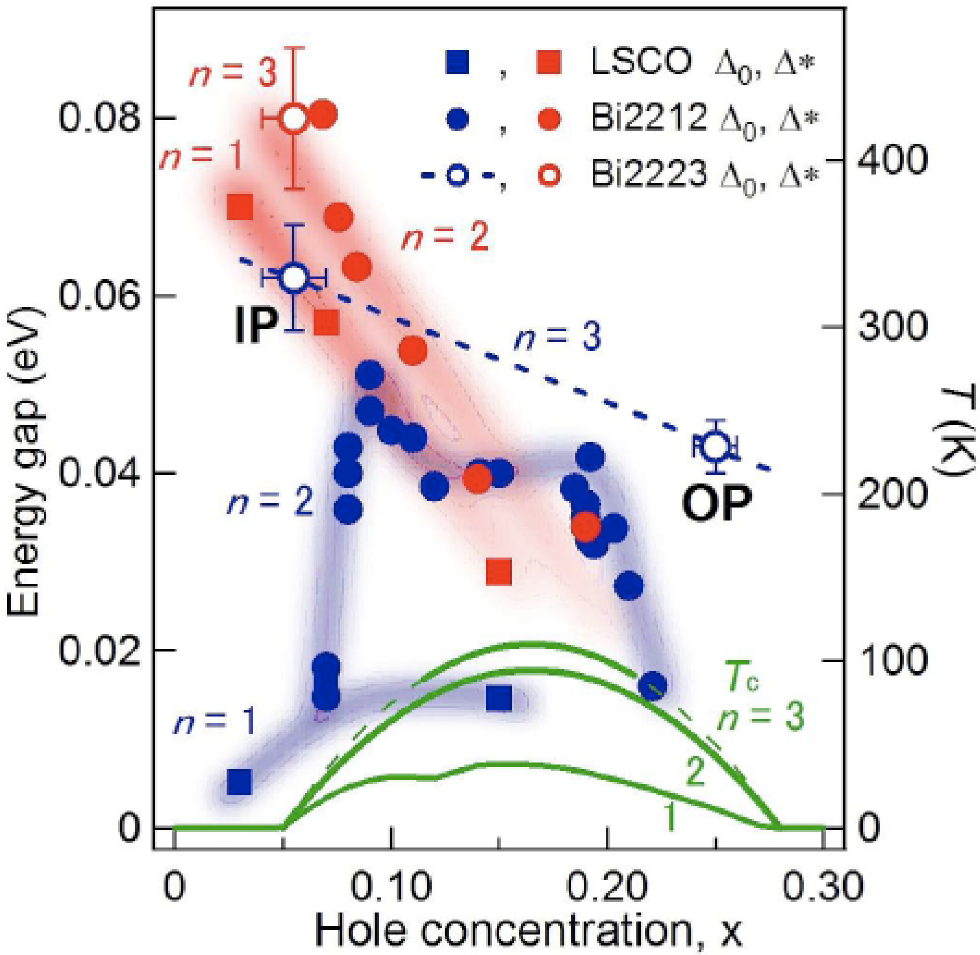

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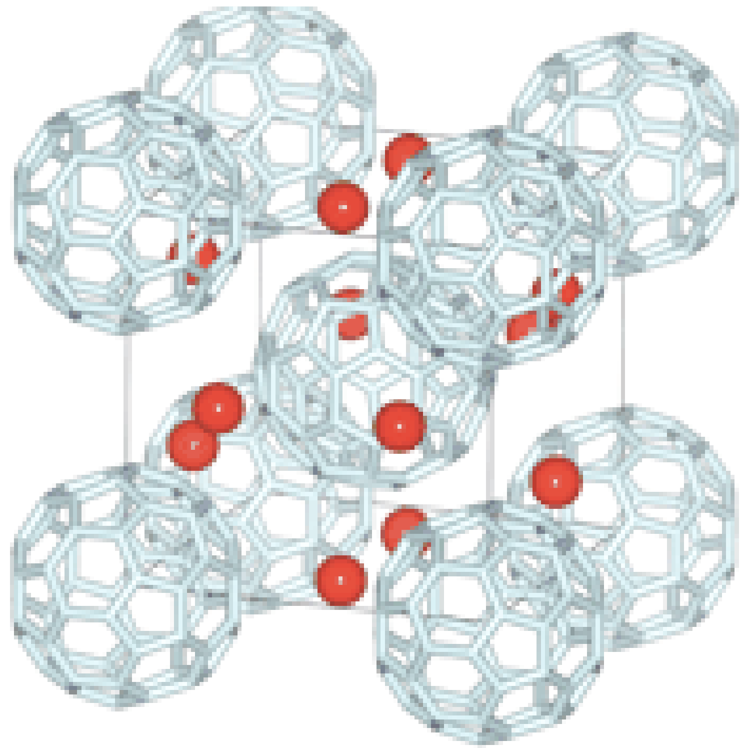
The Disorder-Free Non-BCS Superconductor Cs_3C_{60} Emerges From An Antiferromagnetic Insulator Parent State

Takabayashi, Ganin, Jeglic, Arcon, Takano, Iwasa, Ohishi, Takata, Prassides, Rosseinsky, Science 323, 1585 (2009)



C_{60} molecule is a mesoscale structure which generates effective pairing correlations.

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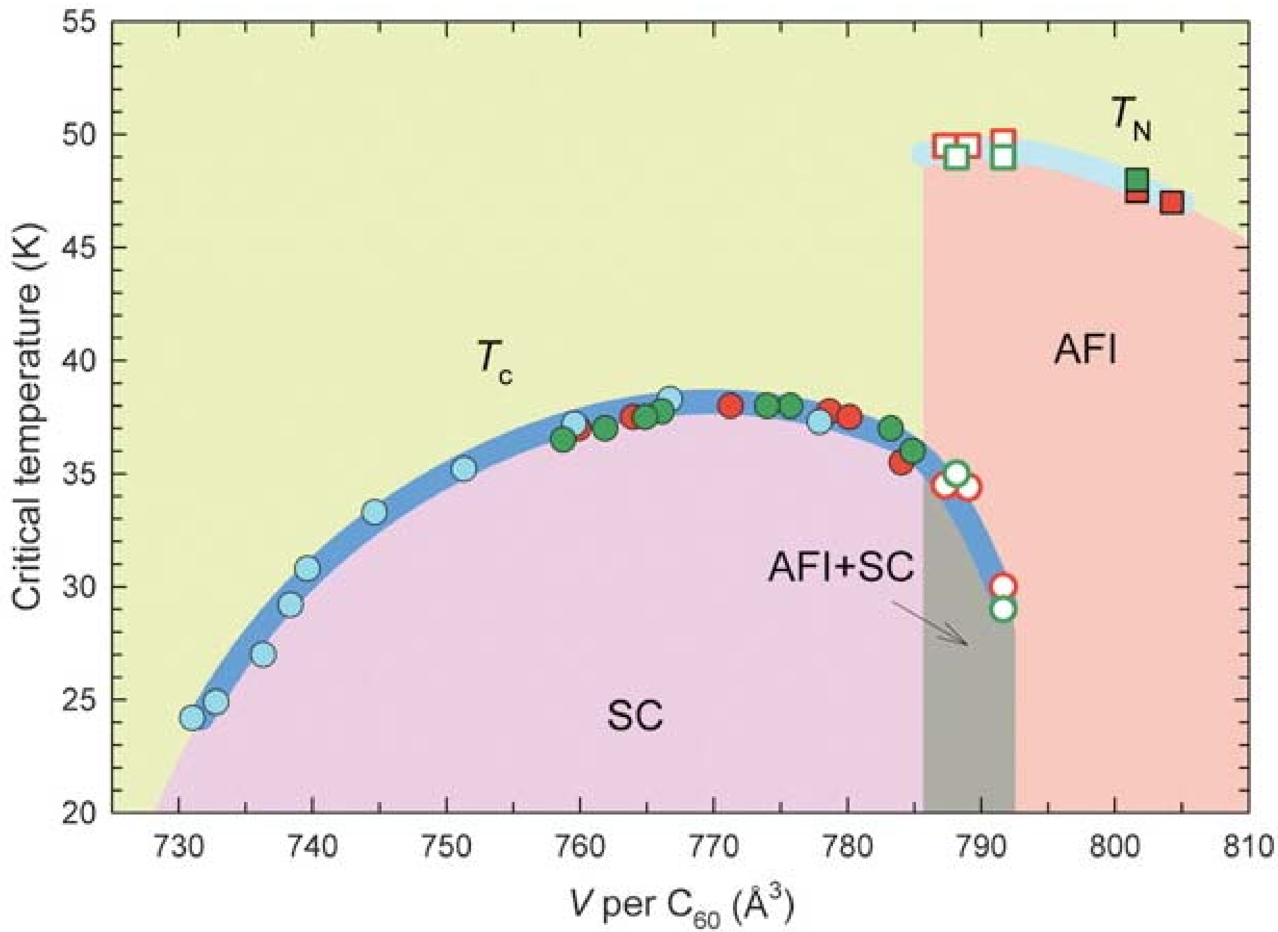


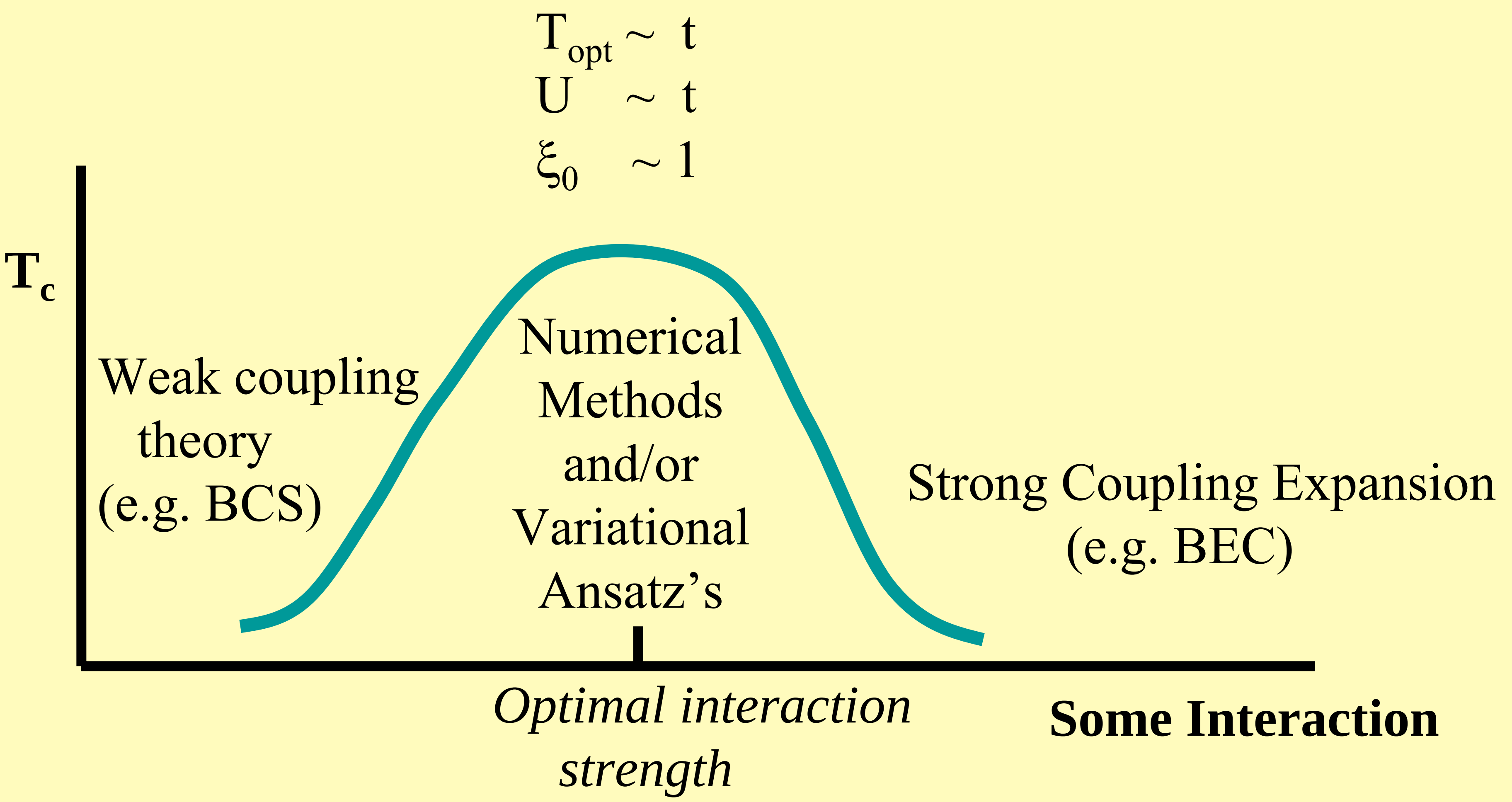
1) Optimal T_c occurs at a crossover from
a pairing dominated regime - $\mathbf{T_c \sim \Delta_0}$
to a condensation regime - $\mathbf{T_c \sim T_\theta}$

2) High temperature superconductors occur at
a crossover from strong to weak coupling
regimes.

3) Special forms of mesoscale structure (“optimal
inhomogeneity”) is favorable for high temperature
superconductivity.

4) Composite systems consisting of coupled regions of
strong pairing and large Drude weight
can produce an optimal combination of large Δ_0 and T_θ.

HTS is a Crossover Phenomenon: Implications for theory



The end