The Abdus Salam International Centre for Theoretical Physics

2035-12

Conference on Superconductor-Insulator Transitions

18 - 23 May 2009

Compensation driven superconductor-insulator transition

M. Mueller
ICTP
Trieste
Italy

Compensation driven superconductor-insulator transition

Markus Müller

and Boris Shklovskii

The Abdus Salam International Center of Theoretical Physics, Trieste

ICTP, 20th May, 2009

Superconductivity and Coulomb interactions

Clean, granular systems

Josephson junction arrays
(Fazio, Schön, …)

$E_J > E_C \rightarrow$ Superconductivity

$E_J < E_C \rightarrow$ Insulator

Simply exponential pair transport (see K. Efetov's talk)

At lowest T:

$$\boxed{\begin{array}{l} E_J > E_C \rightarrow G = G_0 \exp(T_0 / T) \\ E_J < E_C \rightarrow R = R_0 \exp(T_0 / T) \end{array}}$$

What if there is strong disorder (generic)? $\delta E_C \sim E_C$

Insulator: gap is destroyed $\rightarrow$ a priori no simple activation!

What if there are no pre-structured grains?

Do "effective grains" form due to the disorder configuration?

SIT in strong disorder:

Localization and delocalization of Cooper pairs in Coulomb disorder

Similar analysis for neutral cold atoms in random disorder potentials, see
Falko, Nattermann and Pokrovski (08); Shklovskii (08)

Compensated high Tc materials

*K. Segawa and Y. Ando, PRB **74**, 100508 (2006)*

$YBa_2Cu_3O_y$

Doping n-type carriers by La-substitution for Ba

→ $Y_{1-z}La_z(Ba_{1-x}La_x)_2Cu_3O_y$

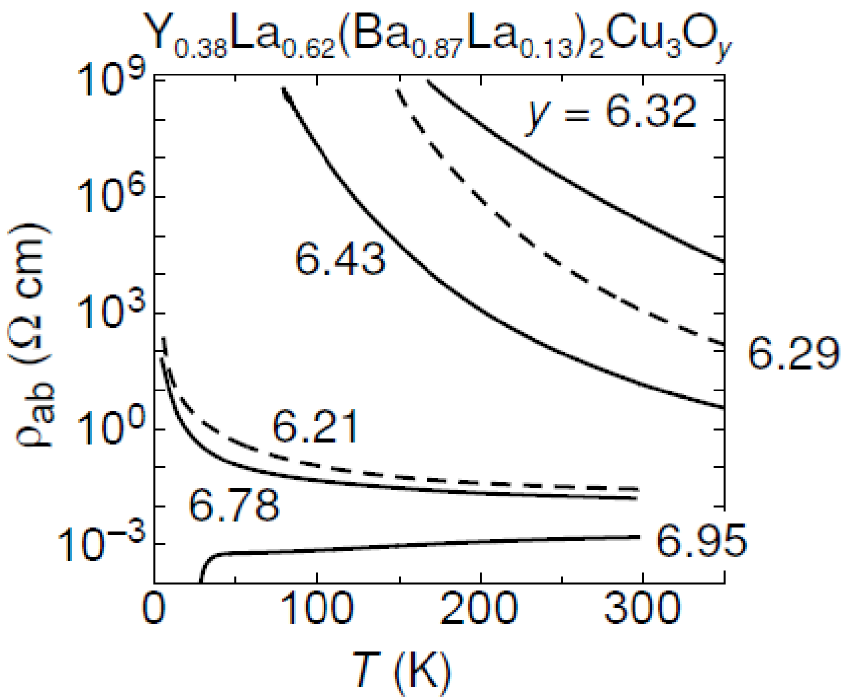
n-type doping controlled by x

$Ba^{2+} \rightarrow La^{3+}$

Vary p-type doping by
annealing oxygen content y

$6.21 < y < 6.95$

$y < 6.32$: n-type doping
$y = 6.32$: fully compensated
$6.32 < y$: p-type doping



Compensated high Tc materials

*K. Segawa and Y. Ando, PRB **74**, 100508 (2006)*

$YBa_2Cu_3O_y$

Doping n-type carriers by La-substitution for Ba

→ $Y_{1-z}La_z(Ba_{1-x}La_x)_2Cu_3O_y$

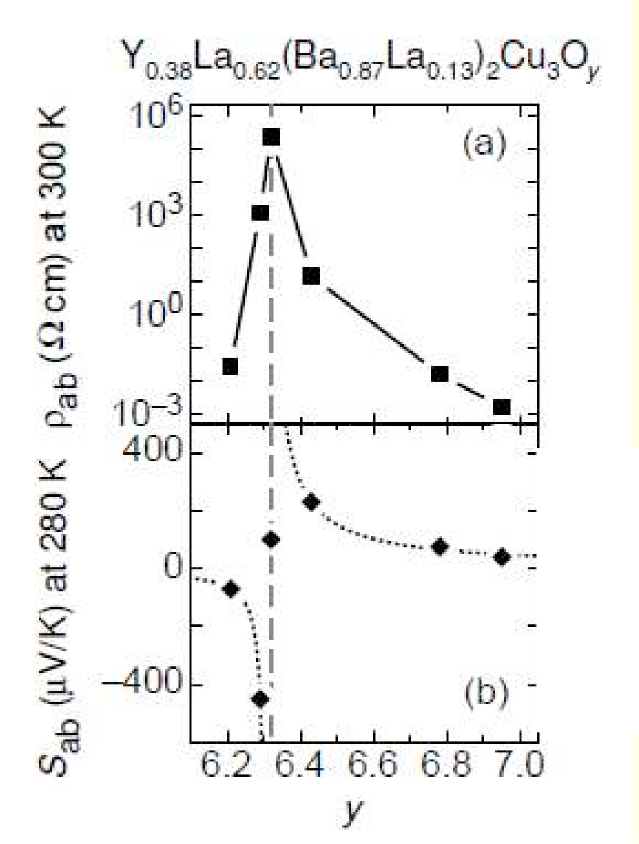
n-type doping controlled by *x*

$Ba^{2+} \rightarrow La^{3+}$

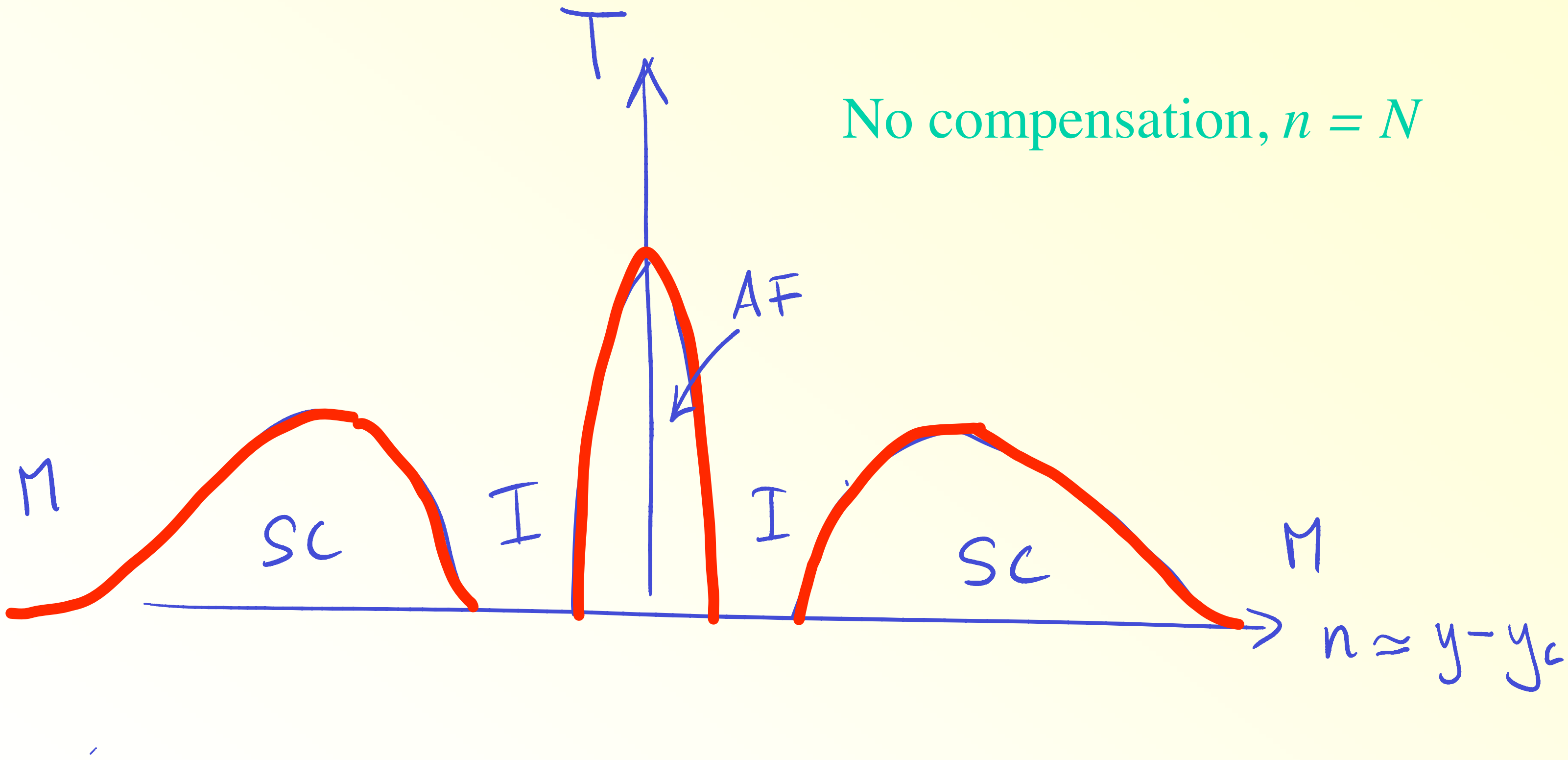
Vary p-type doping by
annealing oxygen content *y*

$6.21 < y < 6.95$

$y < 6.32$: n-type doping
$y = 6.32$: fully compensated
$6.21 < y$: p-type doping



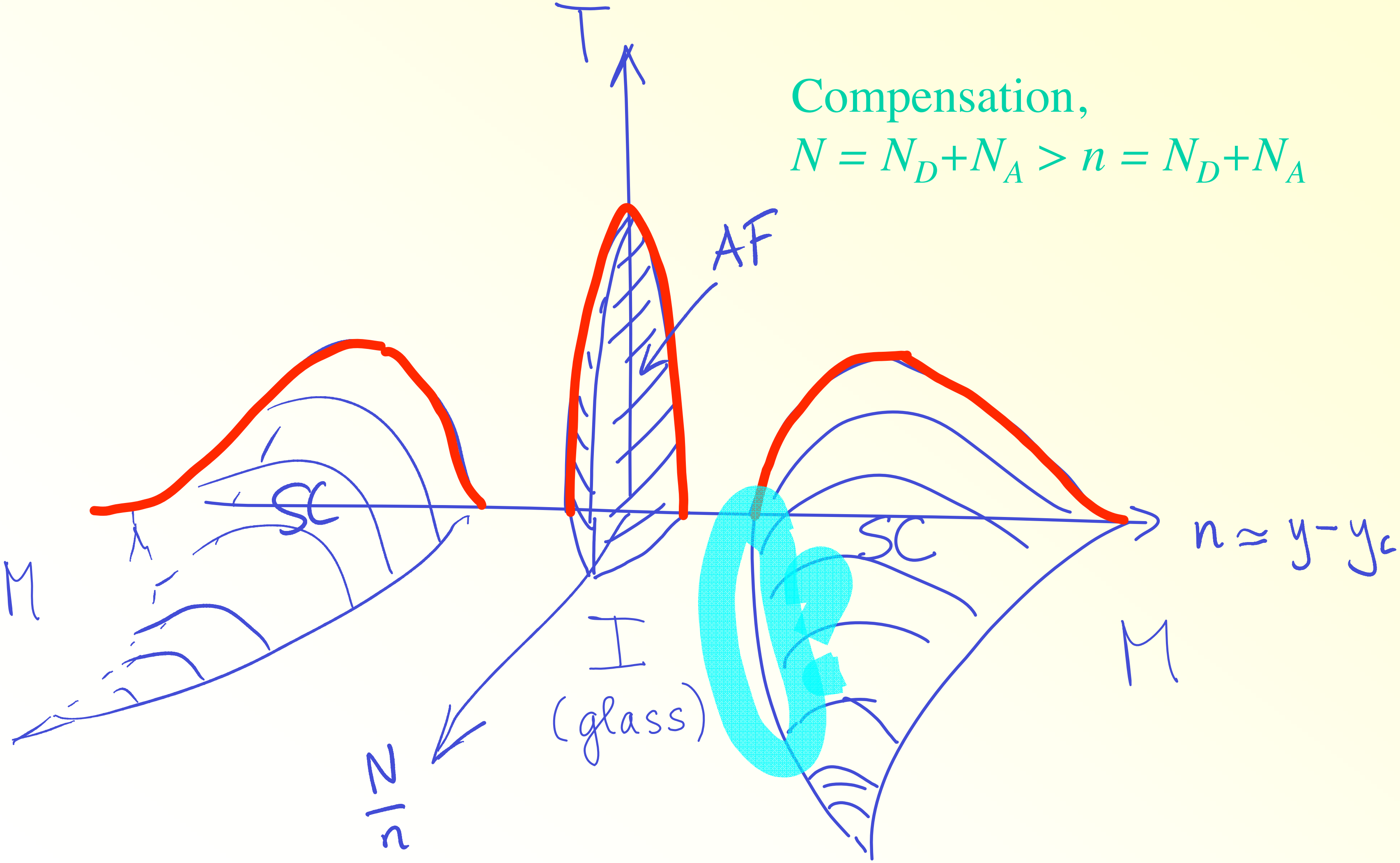
Expected phase diagram



Expected phase diagram

Compensation,

$N = N_D + N_A > n = N_D + N_A$



Analysis of the SIT in terms of a scaling analysis

-

All numerical prefactors will be neglected

The compensation driven metal-insulator transition (fermions)

Uncompensated semiconductors (3d): Mott's criterion

Effective Bohr radius: $a = \dfrac{\hbar^2 \kappa}{m e^2}$

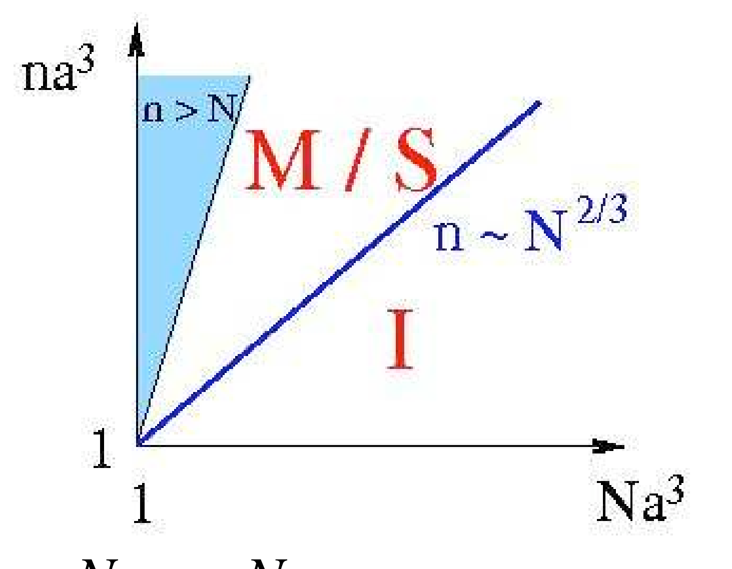
Metal-insulator transition (MIT): $n_{\mathrm{MIT}} a^3 = N_{D,\mathrm{MIT}} a^3 = 0.02 = \mathrm{O}(1)$

$$\boxed{\text{Overlapping hydrogen-like wavefunctions} \longrightarrow \text{delocalization}}$$

With BCS instability in the metal $\rightarrow$ SIT: $\boxed{n_{\mathrm{SIT}} a^3 \approx n_{\mathrm{MIT}} a^3 \sim 1}$

The compensation driven metal-insulator transition (fermions)

Metal-Insulator transition in strongly compensated semiconductors



Non-trivial regime: $Na^3 >> 1$

Heavy doping $N = N_D + N_A$

Most carriers are captured by doping ions $\rightarrow$
Excess carriers in the conduction band: $n = N_A - N_D << N$

Experimentally confirmed in compensated Ge

$\rightarrow$ Strong disorder from N random charged impurities!

Delocalization transition upon tuning n:

$$n_{\mathrm{MIT}}(N) = \frac{N}{\left(Na^3\right)^{1/3}} = \frac{N^{2/3}}{a}$$

$$\rightarrow n_{\mathrm{MIT}}\, a^3 = (Na^3)^{2/3} >> 1$$

$$\rightarrow n_{\mathrm{MIT}} << N$$

MIT: Derivation

Efros and Shklovskii (1971)

1. Non-linear screening of the disorder

Random charge density in volume R^d : $n_{\text{net imp}}(R) \sim \dfrac{(NR^3)^{1/2}}{R^3}$

Non-linear screening scale R_s: $n_{\text{net imp}}(R) \sim n \quad \rightarrow \quad R_s(n) \sim \dfrac{N^{1/3}}{n^{2/3}}$

Roughness of the disorder potential: $eV_{\text{dis,Cb}}(R_s) \sim \dfrac{e^2}{\kappa R_s}(NR_s^3)^{1/2} \sim \dfrac{e^2 N^{2/3}}{\kappa\, n^{1/3}}$

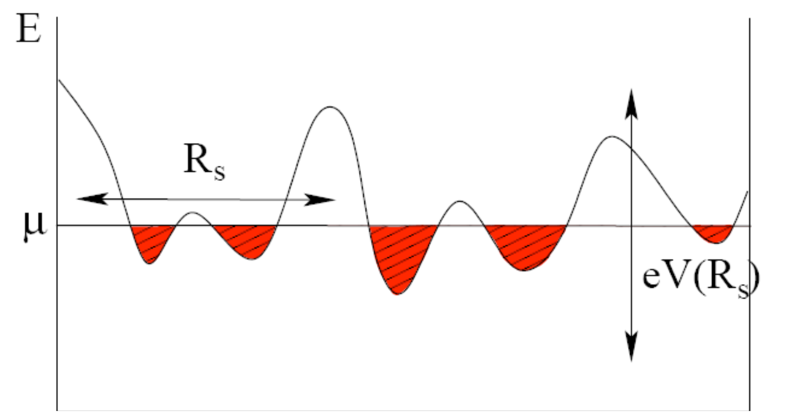
2. Delocalization condition

Fermi energy of excess carriers:

$$E_F \sim \hbar^2 n^{2/3} / m$$

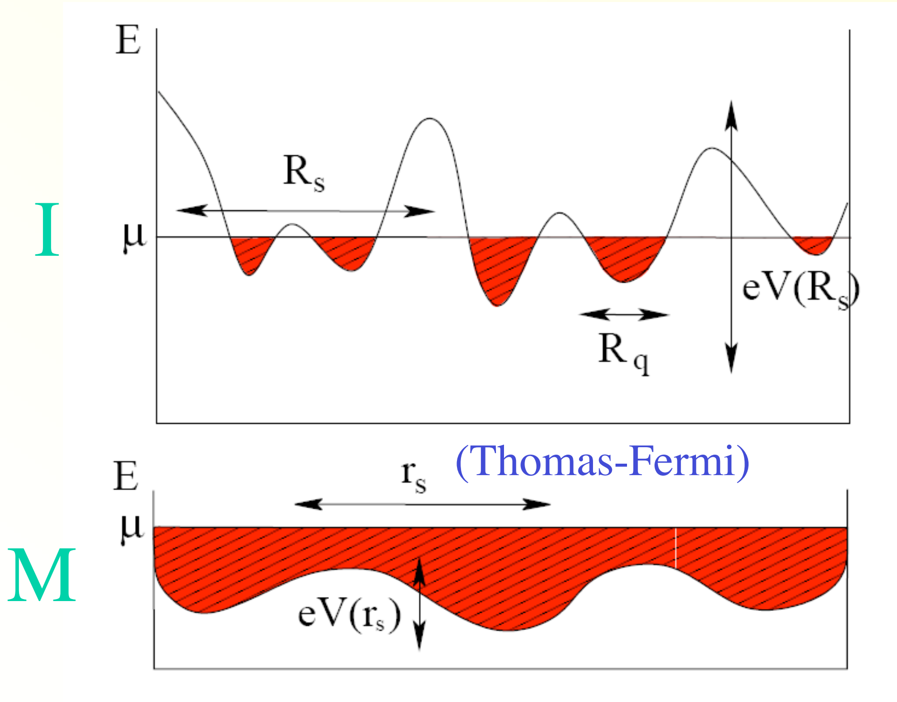
Delocalization if disorder is weak enough:

$$E_F \geq V(R_s) \leftrightarrow \boxed{n_{\text{MIT}} \sim \frac{N}{(Na^3)^{1/3}}}$$



Consistency condition for scaling analysis: $NR_s^3 >> 1 \leftrightarrow Na^3 >> 1$

Droplets in the insulator



In the insulator: $n < n_{\mathrm{MIT}}$

Small droplets (Fermi lakes in the deepest wells) of size $R_q < R_s$!

Typical size of the droplets:

$$\mu\left(n = (N / R_q^3)^{1/2}\right) = eV_{\mathrm{Cb}}(R_q)$$

$$\rightarrow R_q = \frac{a}{(Na^3)^{1/9}} = R_s(n) \cdot \left(n / n_{\mathrm{MIT}}\right)^{2/3}$$

Transport: Variable range hopping between the droplets!

Compensated superconductors with preformed pairs

Assume strong coupling mechanism ("glue")

→ preformed Cooper pairs of size ξ
(finite pairing energy E_{pair} - no nodal quasiparticles)

Possible systems with preformed pairs:
- Underdoped high Tc materials
- Bipolarons
- [Anderson pseudospins (doubly occupied localized wavefunctions)]

- How do bosons modify non-linear screening and delocalization?
- How does the BEC-BCS crossover manifest itself?

$$\boxed{n\xi^3 = 1}$$

- What is the transport on the insulating side?

BEC – BCS crossover

BEC – BCS crossover : $\boxed{n\xi^3 \sim 1}$

- For $n_{\mathrm{SIT}}\xi^3 > 1$ the transition remains the same as with fermions
- Distinctly "bosonic" behavior occurs at the SIT when

$$n_{\mathrm{SIT}}\xi^3 < 1 \quad \leftrightarrow \quad \xi < \mathrm{a}$$

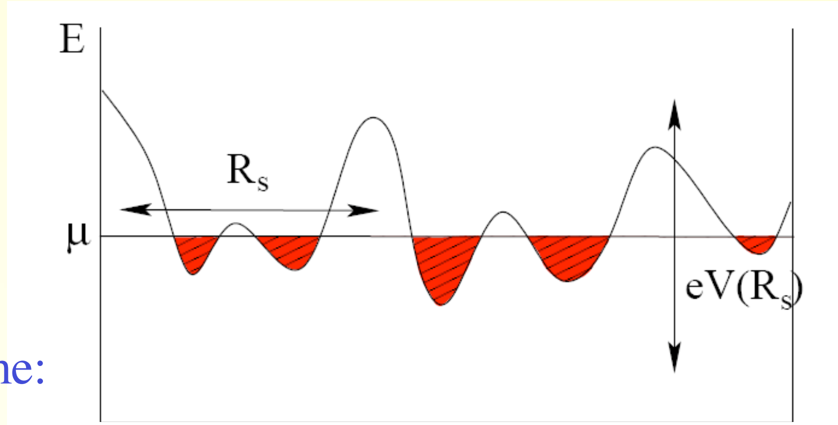
$\longrightarrow$ Needed: small pairs, large Bohr radii

$$\longrightarrow \quad \boxed{n_{\mathrm{SIT}}(N) = ?}$$

BEC regime – 3d SC

1. Nonlinear screening with (2e)'s instead of e's, but otherwise no difference

$$eV_{\mathrm{Cb}}(n) = eV_{\mathrm{Cb}}(R_s) \sim e^2\, N^{2/3} / n^{1/3}$$



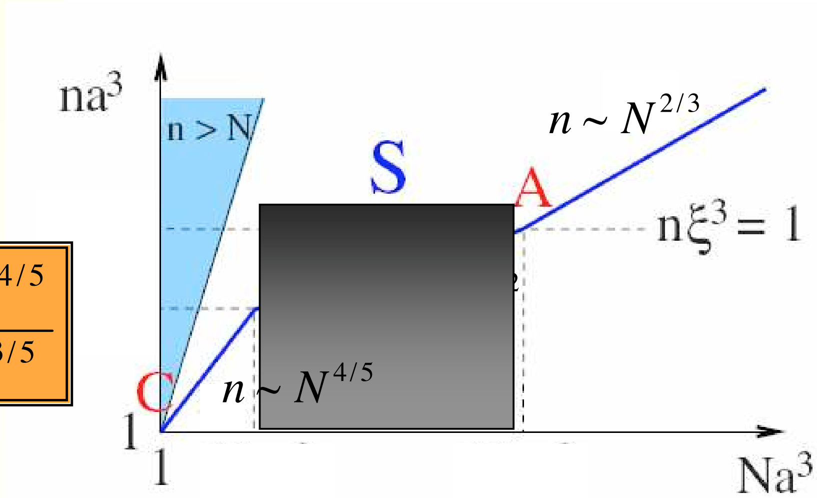
2. Very low density

Energy of confinement to screening volume:

$$\mu(n,R) = \frac{\hbar^2}{mR^2}$$

Delocalization of the BEC condensate:

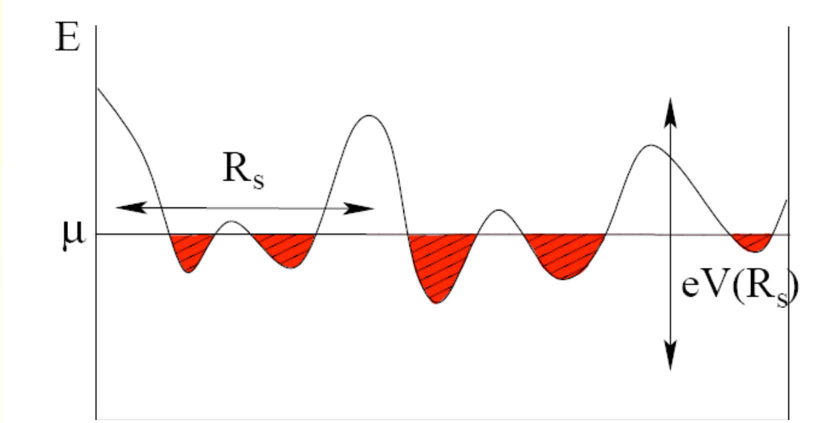
$$\mu(n,R_s) \sim eV_{\mathrm{Cb}}(n) \quad \boxed{\rightarrow\ n_{\mathrm{SIT}}(N) = \frac{N^{4/5}}{a^{3/5}}}$$



BEC regime – 3d SC

1. Nonlinear screening with (2e)'s instead of 1e's, but otherwise no difference

$$eV_{\mathrm{Cb}}(n) = eV_{\mathrm{Cb}}(R_s) \sim e^2\, N^{2/3} / n^{1/3}$$



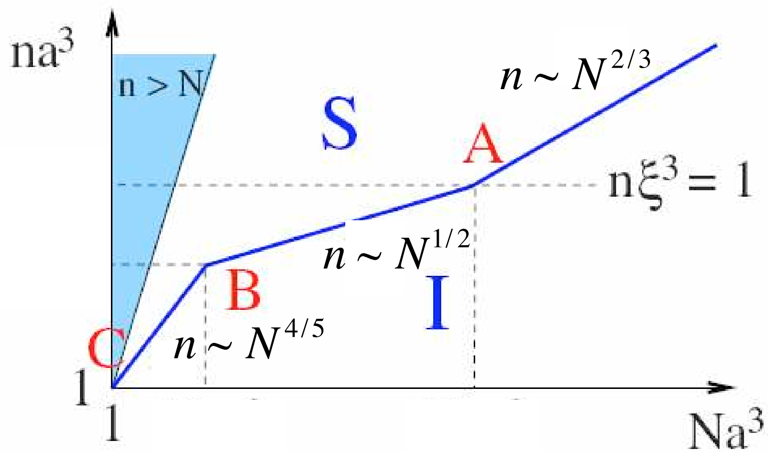
3. Chemical potential for bosons:
Bose gas with scattering length ξ

$$\mu(n) = \frac{\hbar^2}{2m} n\xi \quad < E_F(n)!$$

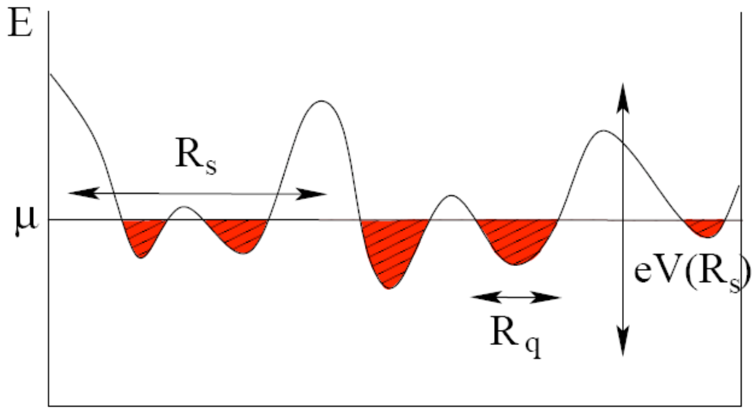
4. Bose delocalization criterion:

$$\mu(n) \sim eV_{\mathrm{Cb}}(n)$$

$$\boxed{\rightarrow \; n_{\mathrm{SIT}}(N) = \frac{N^{1/2}}{(a\xi)^{3/4}}}$$



The Bose insulator



In the insulator: $n < n_{\mathrm{SIT}}$

Small droplets (boson lakes in the deepest wells) of size $R_q < R_s$!

Typical size of the droplets:

$$\mu\left(n = (N / R_q^3)^{1/2}\right) = eV_{\mathrm{Cb}}(R_q)$$

BEC regime: $\rightarrow R_q = (a\xi)^{1/2} < R_s(n)$

Nature of the ground state

Level spacing in a droplet (±1e): $\delta \sim (d\mu / dn\, R_q^3) \overset{!}{=} e^2 / R_q$

BEC: $\xi < a$

Pair-breaking energy: $E_{\mathrm{pair}} \sim \hbar^2 / m\xi^2$

$\boxed{\rightarrow E_{\mathrm{pair}} > \delta}$

→ Breaking pairs is unfavorable, all electrons are paired!
Single electron excitations are gapped!

Properties of the insulator

Tunneling

- Single particle gap
- SC spectrum of small droplets (and corresponding coherence peaks)

Transport

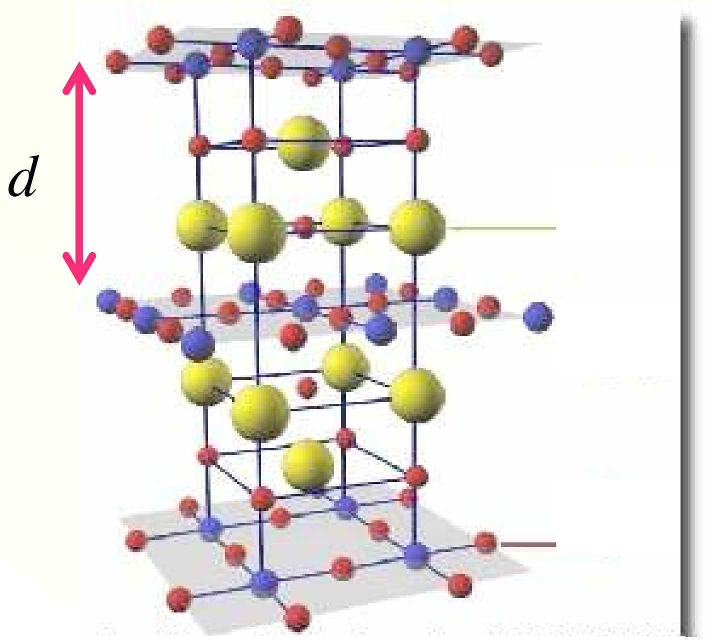
- At low T: Variable range hopping of pairs between droplets!
- In the BEC regime (strong coupling, small pairs) : always 2e-transport
- In the BCS regime (weak coupling): 1e-transport when $\Delta < \delta$.

$$\sigma = \sigma_0 \exp[-(T_{ES}/T)^{1/2}]$$

$$T_{ES} = 2.7 \cdot (2e)^2 / \kappa\xi_{2e}$$

Layered superconductors

Examples: Cuprates (CuO compounds), pnictides (FeAs compounds)



d : Distance between layers hosting the carriers

Differences 2d vs. 3d:

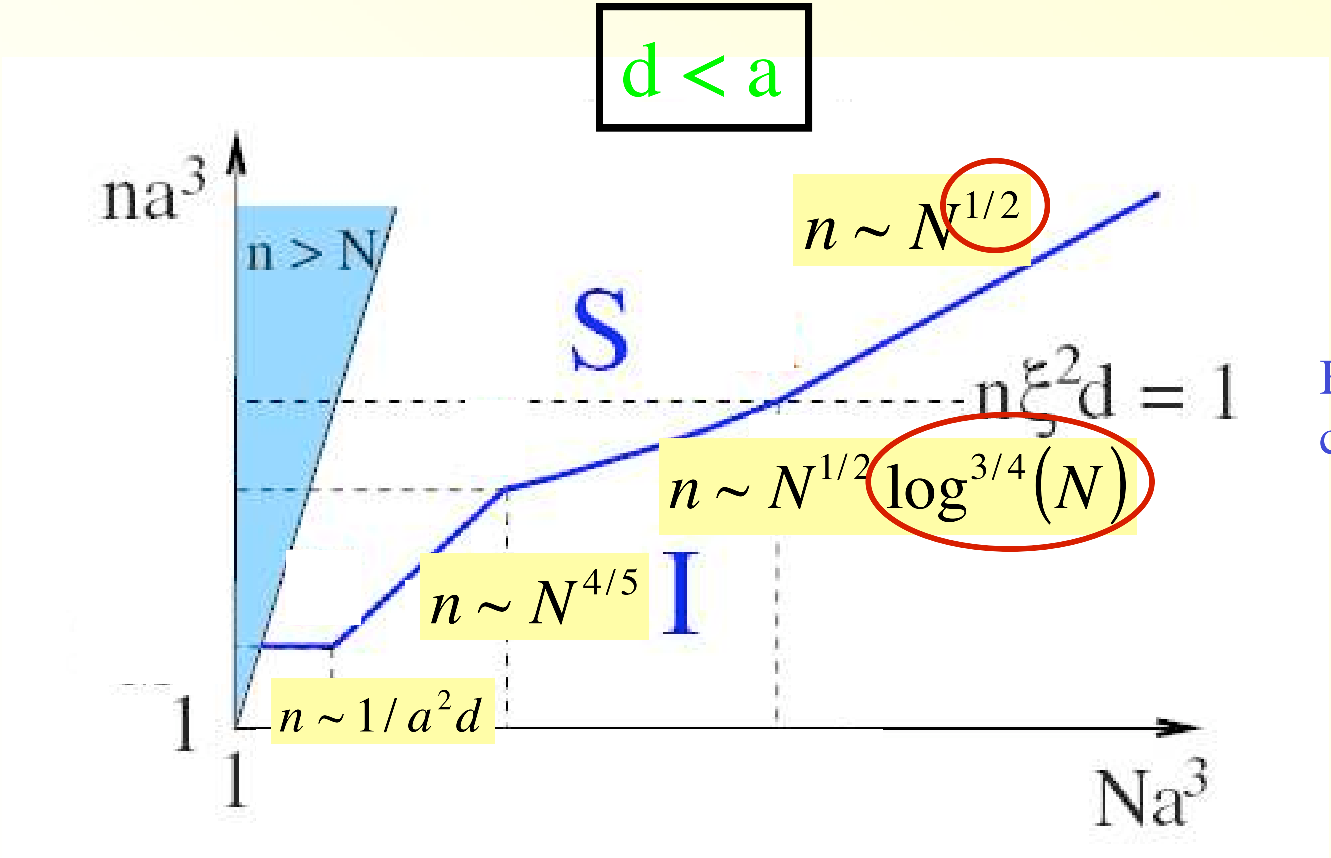
1. Nonlinear screening is modified when d > R_s ; need to account for anisotropic dielectric constant

2. Delocalization criterion:

$$\mu_{2D}(n) = eV_{Cb}(n,N)$$

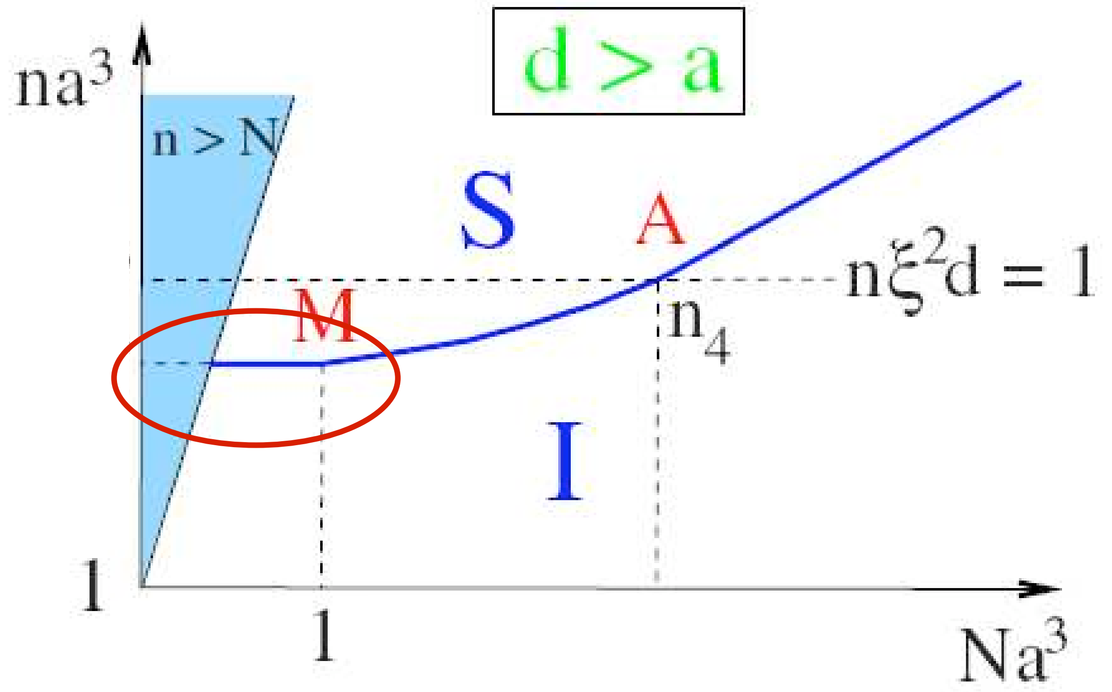
Only extra log at the BCS-BEC crossover! $$\mu_{2D,\,BEC}(n) = \frac{\hbar^2 nd}{m\log\left(1/\xi^2 nd\right)} = \frac{E_F(n)}{\log\left(1/\xi^2 nd\right)}$$

SIT Phase diagram – 2D



BEC-BCS crossover

SIT Phase diagram – 2D



Applicability to high Tc ?

Candidate systems:

$Y_{1-z}La_z(Ba_{1-x}La_x)_2Cu_3O_y$ *Segawa & Ando*

BaFeCoKAs (Co donor, K acceptor) *D. Canfield*

Condition for the SI transition to occur in the BEC regime:

$$\boxed{n_{\mathrm{SIT}}\xi^3 < 1 \quad \leftrightarrow \quad \xi < \mathrm{a}}$$

Parameters for typical underdoped high Tc's:

$$a = \frac{\hbar^2\kappa}{m_{\mathrm{pair}}(2e)^2}$$

$$\mathrm{BSCCO:}\quad \mathrm{a} \sim 4-5\mathrm{A}$$

$$\xi_{typ} \approx 1-2\mathrm{nm}$$

→ At the border of BEC-BCS crossover

BEC-regime in bipolarons

Condition for the SI transition to occur in the BEC regime:

$$\boxed{n_{\mathrm{SIT}}\xi^3 < 1 \quad \leftrightarrow \quad \xi < \mathrm{a}}$$

Two independent parameters:

- Electron-phonon coupling: $\alpha > \alpha_c = 2.9$ (in 2d)

- Ratio between electronic and static dielectric constant:
  $\eta = \kappa_{el}/\kappa$ needs to be $\eta >> 1$:

$$\boxed{\frac{\xi}{a} \sim \alpha^2\eta \overset{!}{<} 1}$$

Summary

- SIT in the presence of strong Coulomb disorder: Delocalization of preformed pairs in a self-consistently screened disorder potential

- Non-linear screening is less efficient with bosons (exclusion principle less effective in BEC regime)

$$\boxed{n_{SIT}^{(bosons)} > n_{SIT}^{(fermions)}}$$

- Low T transport in the insulator in the BEC regime is always dominated by pairs