Compensation driven superconductor-insulator transition

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Superconductivity and Coulomb interactions

Clean, granular systems

Josephson junction arrays
(Fazio, Schön, …)

$E_J > E_C \to$ Superconductivity

$E_J < E_C \to$ Insulator

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

At lowest T:

$$E_J > E_C \to G = G_0 \exp(T_0 / T)$$
$$E_J < E_C \to R = R_0 \exp(T_0 / T)$$

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

Insulator: gap is destroyed $\to$ 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)

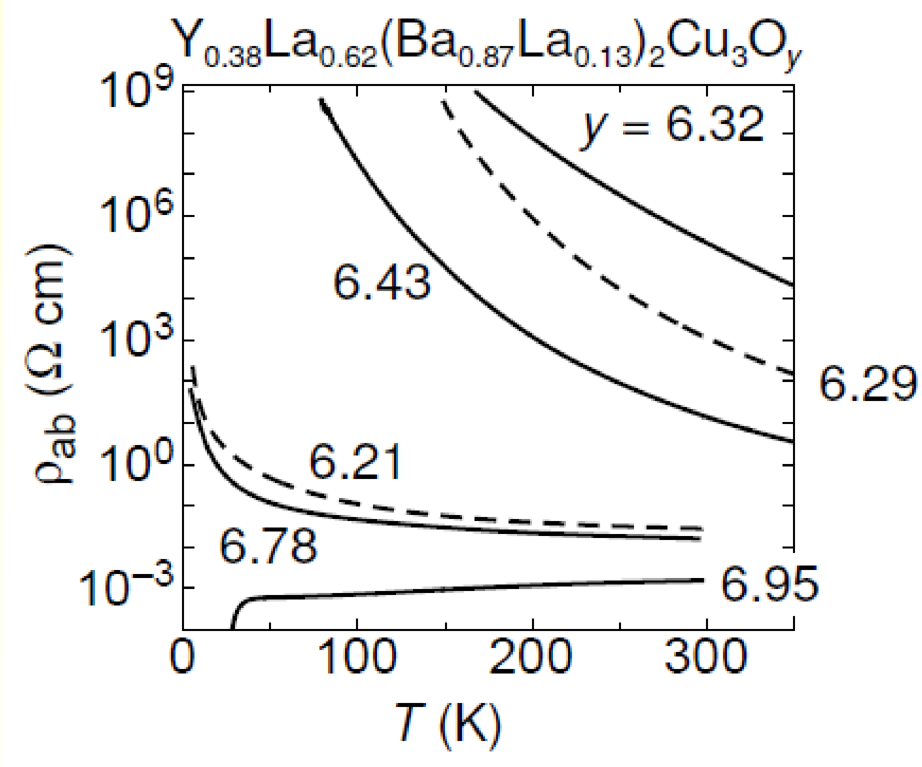
Compensated high Tc materials

*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

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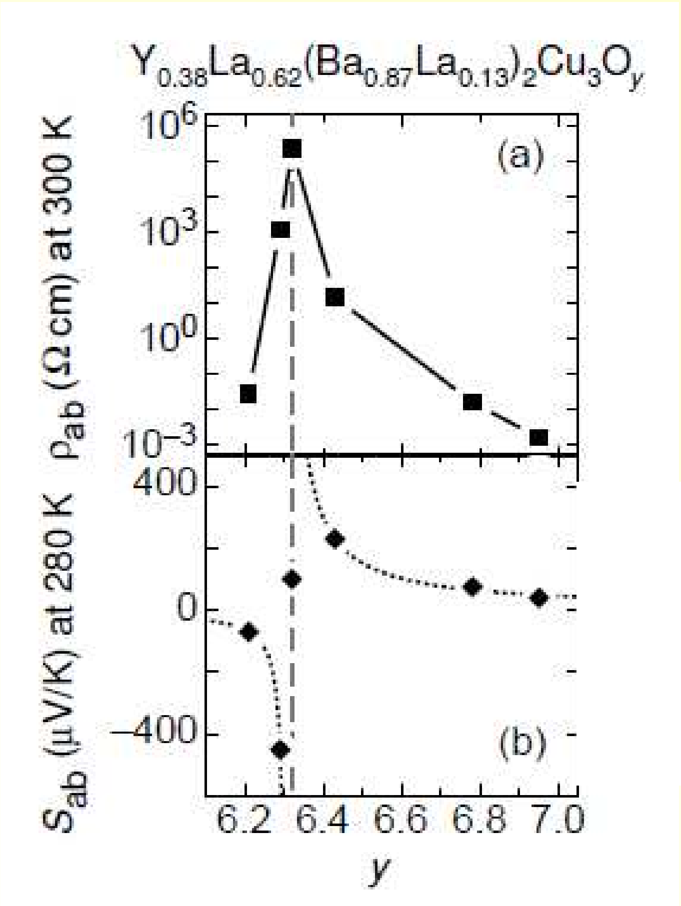


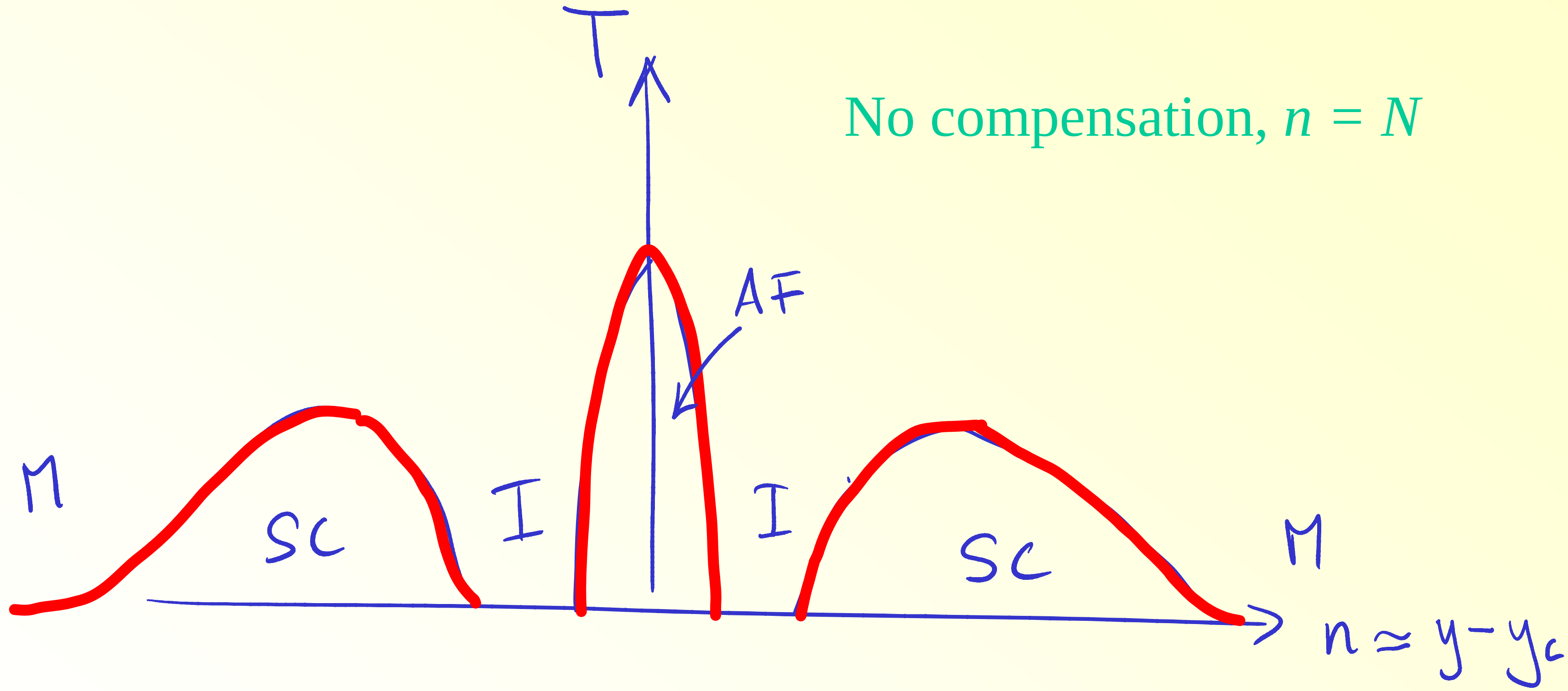
$y < 6.32$: n-type doping

$y = 6.32$: fully compensated

$6.21 < y$: p-type doping

Expected phase diagram

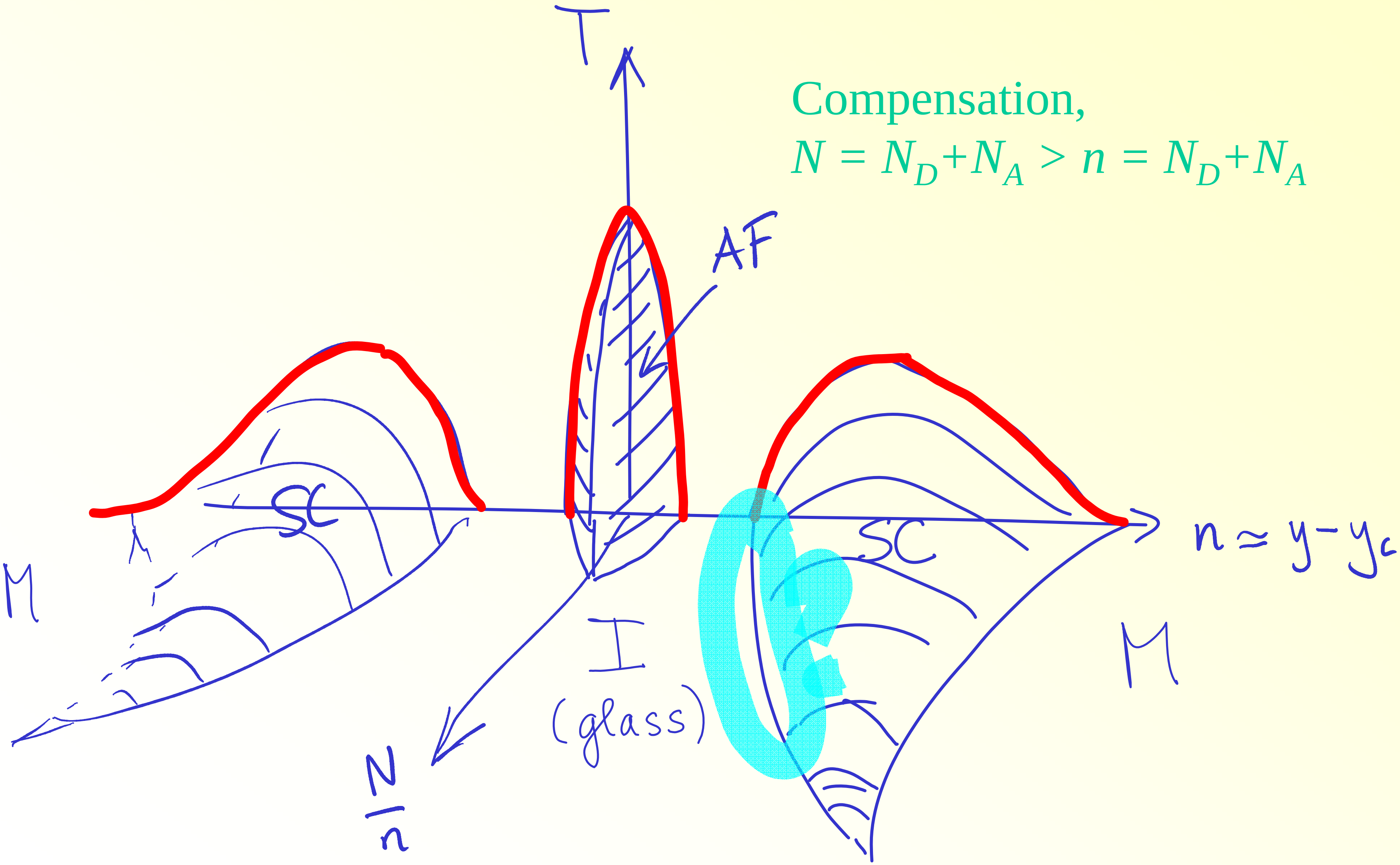
No compensation, $n = N$



Expected phase diagram

Compensation,

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



Analysis of the SIT in terms of a scaling analysis

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All numerical prefactors will be neglected

The compensation driven metal-insulator transition (fermions)

Uncompensated semiconductors (3d): Mott's criterion

Effective Bohr radius: $$a = \frac{\hbar^2 \kappa}{me^2}$$

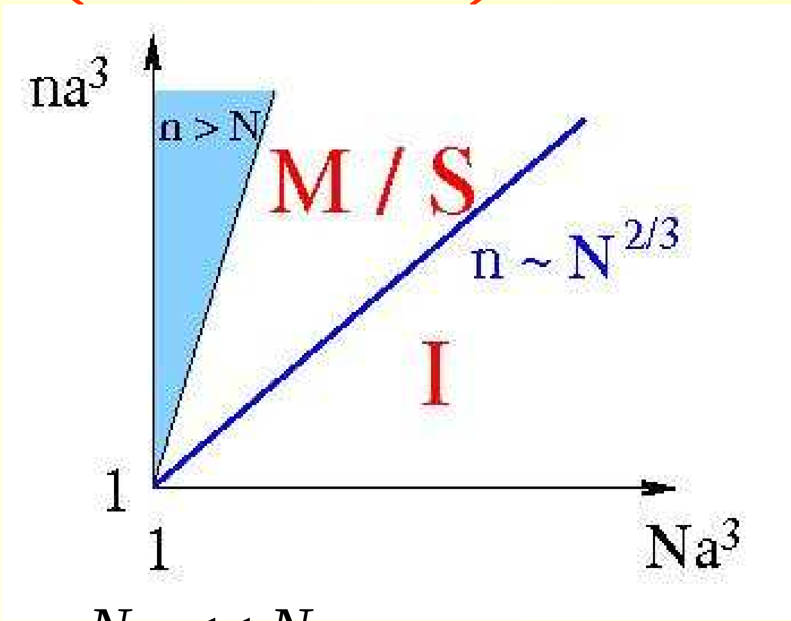
Metal-insulator transition (MIT): $$n_{\mathrm{MIT}} a^3 = N_{D,\mathrm{MIT}} a^3 = 0.02 = \mathrm{O}(1)$$

Overlapping hydrogen-like wavefunctions $\rightarrow$ delocalization

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

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 →
Excess carriers in the conduction band: $n = N_A - N_D << N$

Experimentally confirmed in compensated Ge

→ Strong disorder from *N* random charged impurities!

Delocalization transition upon tuning *n*:

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

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

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

MIT: Derivation

Efros and Shklovskii (1971)

1. Non-linear screening of the disorder

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

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

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

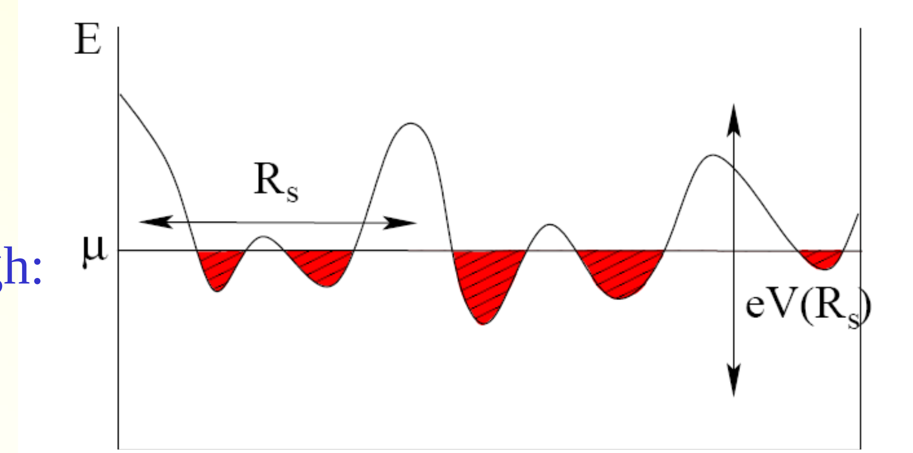
2. Delocalization condition

Fermi energy of excess carriers:

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

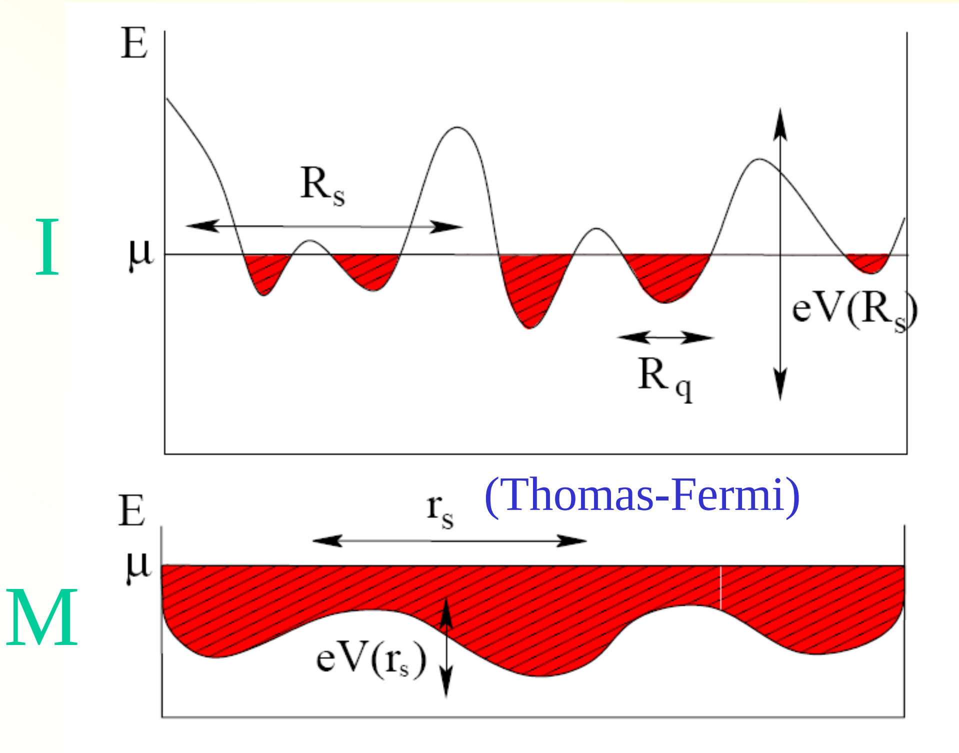
Delocalization if disorder is weak enough:

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



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

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?

$$n\xi^3 = 1$$

- What is the transport on the insulating side?

BEC – BCS crossover

BEC – BCS crossover : $n\xi^3 \sim 1$

- For $n_{\text{SIT}}\xi^3 > 1$ the transition remains the same as with fermions

- Distinctly "bosonic" behavior occurs at the SIT when

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

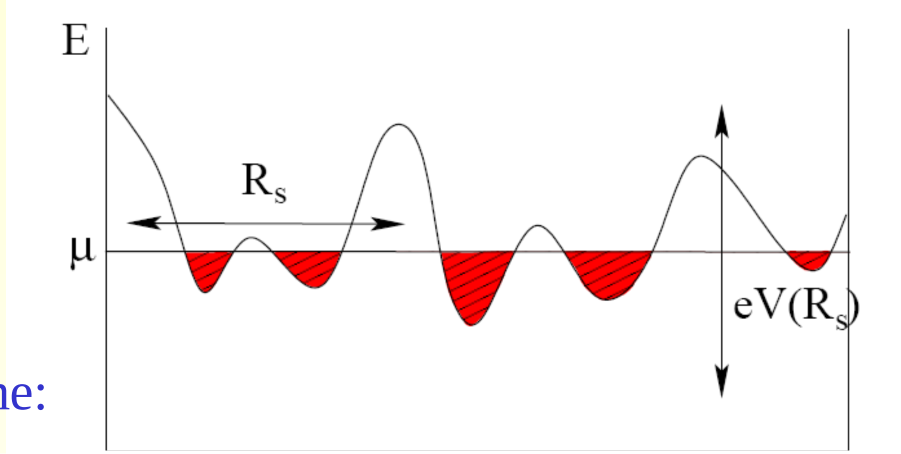
$\rightarrow$ Needed: small pairs, large Bohr radii

$\longrightarrow$ $n_{\text{SIT}}(N) = ?$

BEC regime – 3d SC

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

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



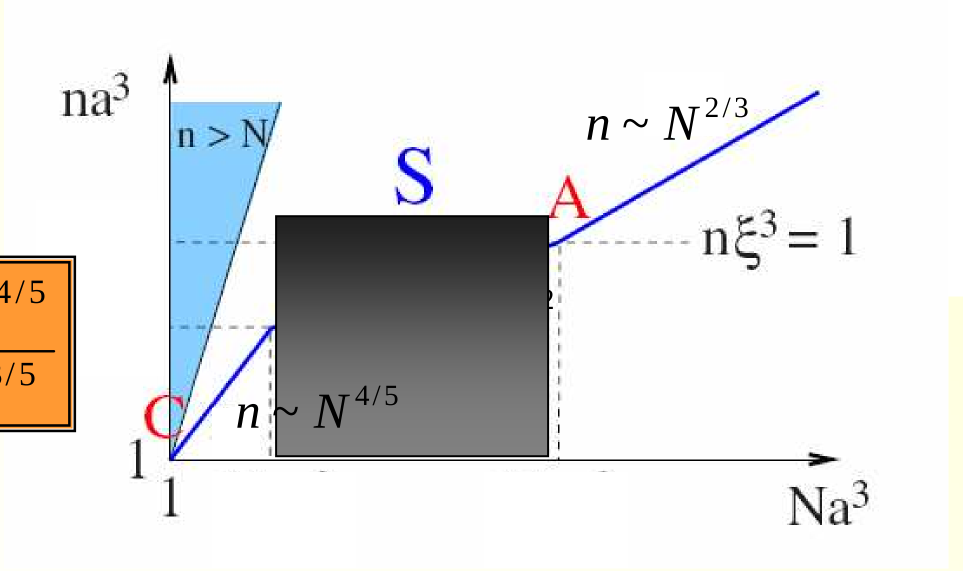
2. Very low density

Energy of confinement to screening volume:

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

Delocalization of the BEC condensate:

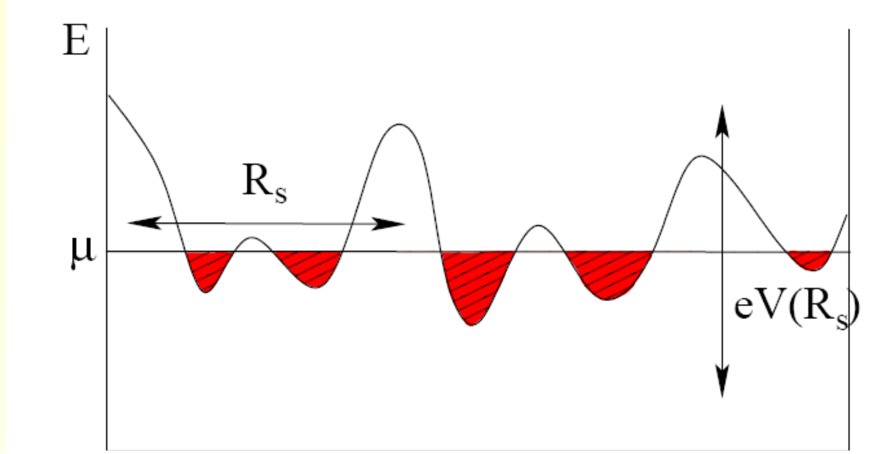
$$\mu(n,R_s) \sim eV_{\text{Cb}}(n) \quad \boxed{\rightarrow\ n_{\text{SIT}}(N) = \frac{N^{4/5}}{a^{3/5}}}$$



BEC regime – 3d SC

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

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



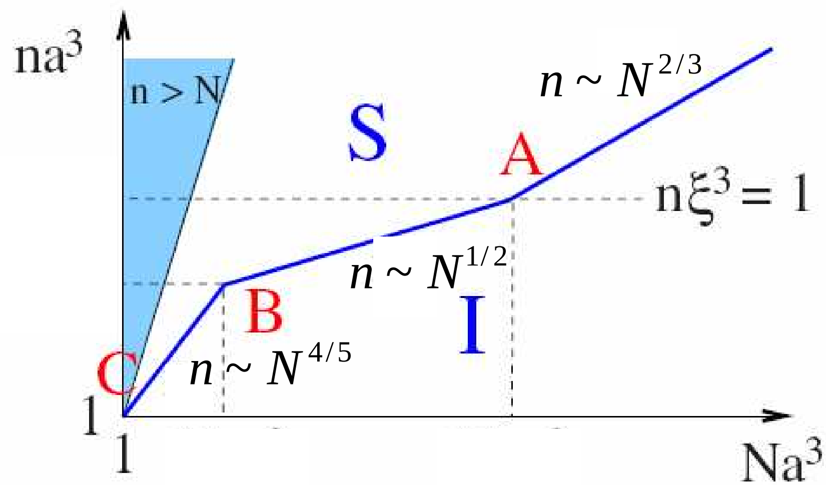
3. Chemical potential for bosons:
Bose gas with scattering length ξ

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

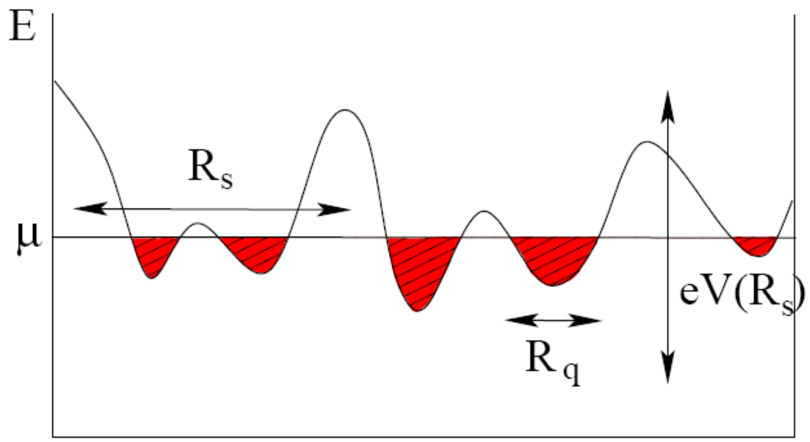
4. Bose delocalization criterion:

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

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



The Bose insulator



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

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

Typical size of the droplets:

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

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: $E_{\text{pair}} \sim \hbar^2 / m\xi^2$ $\rightarrow E_{\text{pair}} > \delta$

$\rightarrow$ 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

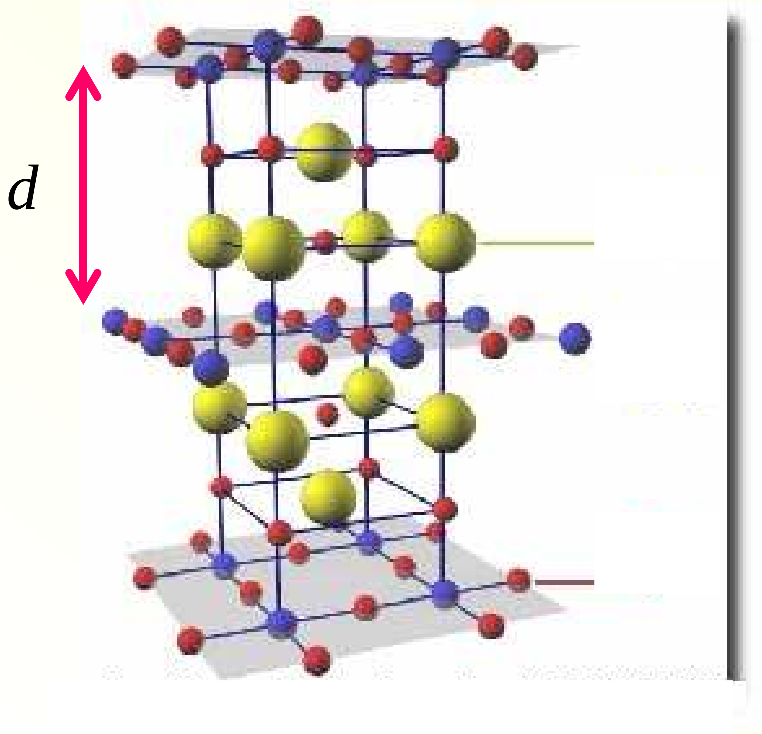
- At low T: Variable range hopping of pairs between droplets!
- In the BEC regime (strong coupling, small pairs) : always 2e-transport
- In the BCS regime (weak coupling): 1e-transport when $\Delta < \delta$.

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

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

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:

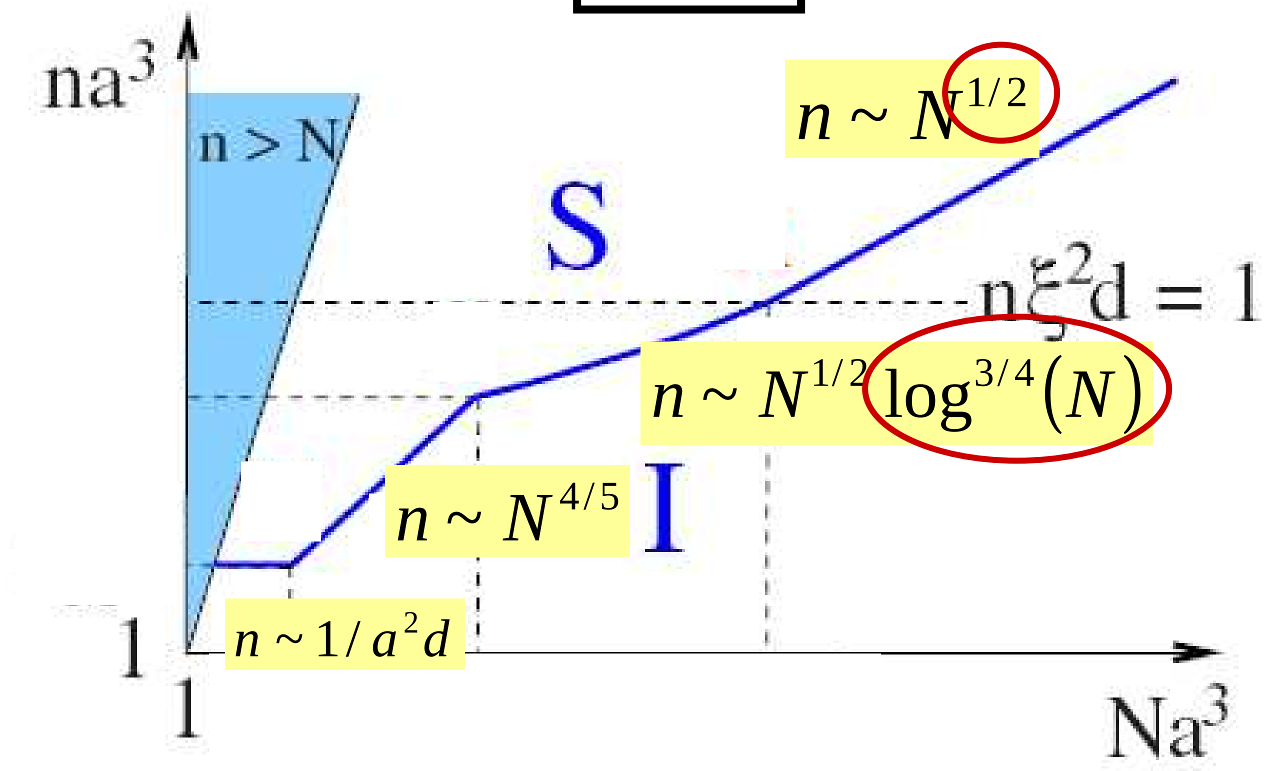
$$\mu_{2D}(n) = eV_{Cb}(n, N)$$

Only extra log at the BCS-BEC crossover!

$$\mu_{2D,\,BEC}(n) = \frac{\hbar^2 nd}{m \log(1/\xi^2 nd)} = \frac{E_F(n)}{\log(1/\xi^2 nd)}$$

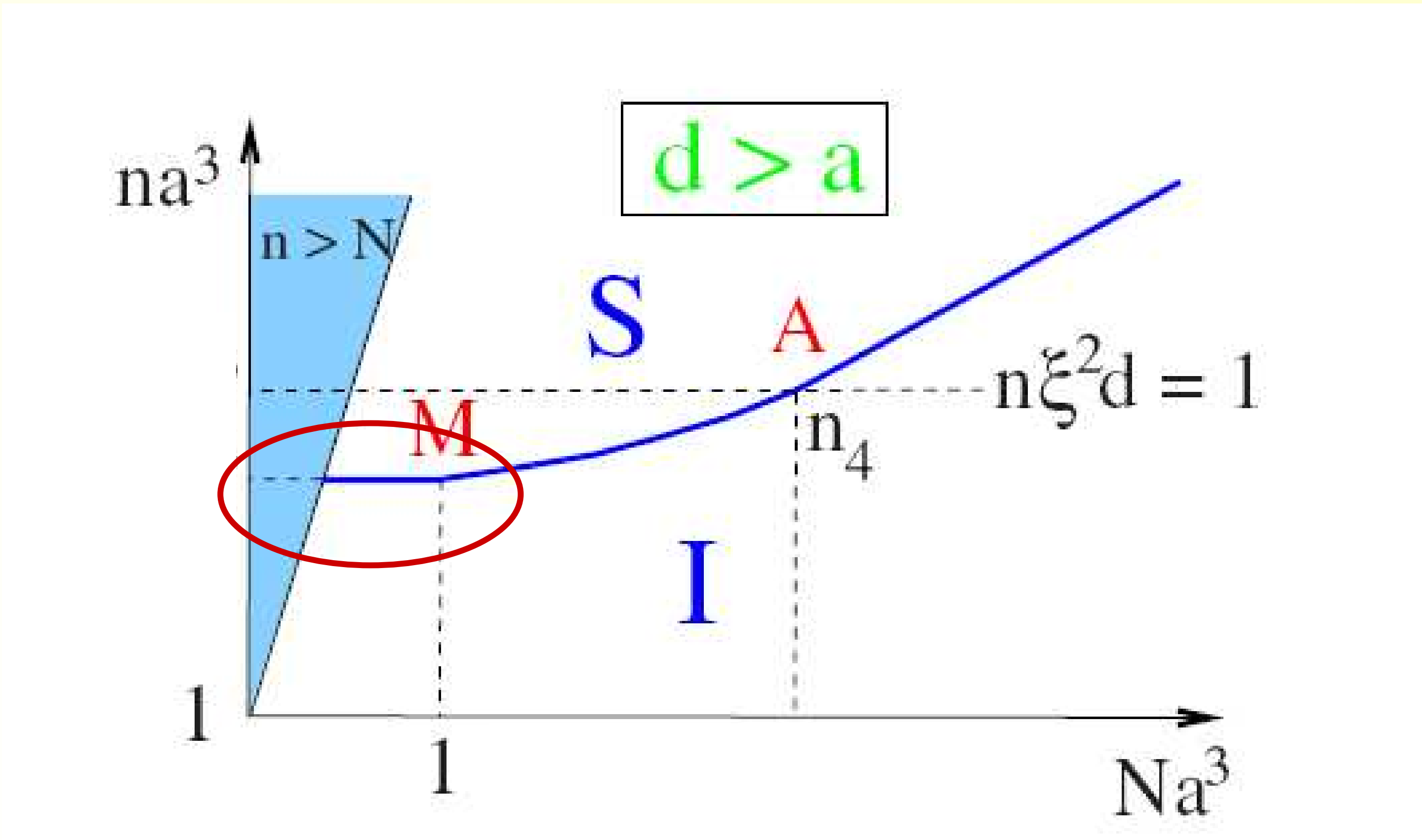
SIT Phase diagram – 2D

d < a



BEC-BCS crossover

SIT Phase diagram – 2D



Applicability to high Tc ?

Candidate systems:

$Y_{1-z} La_z (Ba_{1-x}La_x)_2 Cu_3 O_y$ *Segawa & Ando*

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

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

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

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:

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

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 $\eta >> 1$:

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

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)

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

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