Electronic transport and many-body localization in disordered bosonic insulators

Markus Müller

Ann. Phys. (Berlin) ***18***, *849 (2009)*

Abdus Salam International Center of Theoretical Physics

Discussions with

M. Feigel'man, M.P.A. Fisher, L. Ioffe, V. Kravtsov

Experiments: B. Sacépé (Grenoble), D. Shahar (Weizmann), T. Baturina (Novosibirsk)

Universität Stuttgart, 1st June, 2010

Outline

- The disordered superconductor-insulator transition (SIT) – dirty bosons

- Review of various puzzling transport experiments in the Bose glass phase

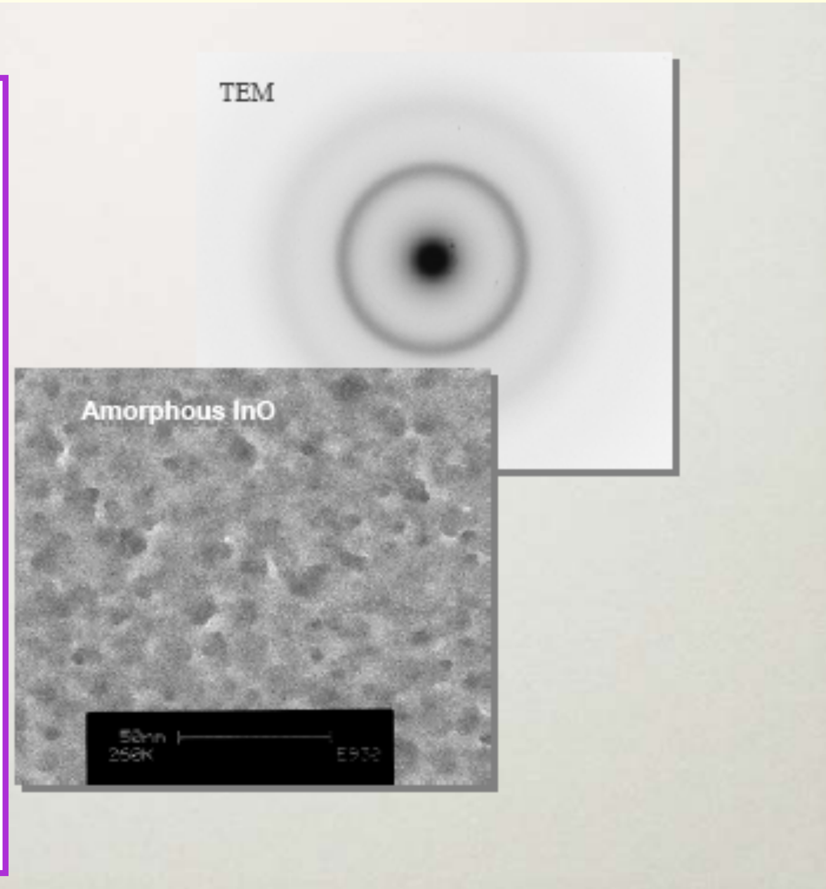
- Proposed resolution based on:
  Characterization of insulators via spectral properties
  - Consequences for transport: *R(T)*
  - ”Many-body localization” and its precursors

Indium-oxide (InO_x)

Indium-oxide: One of the materials used in the experiments discussed here *(Sambandamurthy, Shahar, Sacépé)*

- Strong disorder
- Tunable disorder

Similar experiments in TiN films *(Baturina)*



SI transition in thin films

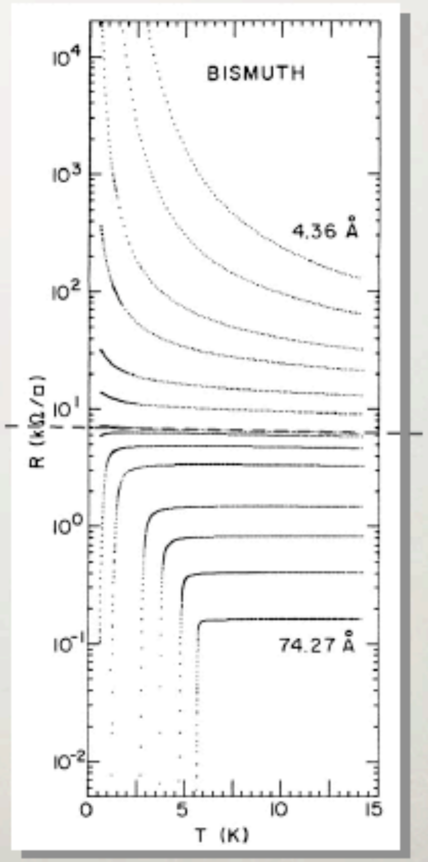
M. Strongin, et. al., Phys. Rev. **B1**, 1078 (1970).

D. B. Haviland, Y. Liu, and A. M. Goldman, Phys. Rev. Lett. 62, 2180 (1989)...

2D

Thickness tuned transition

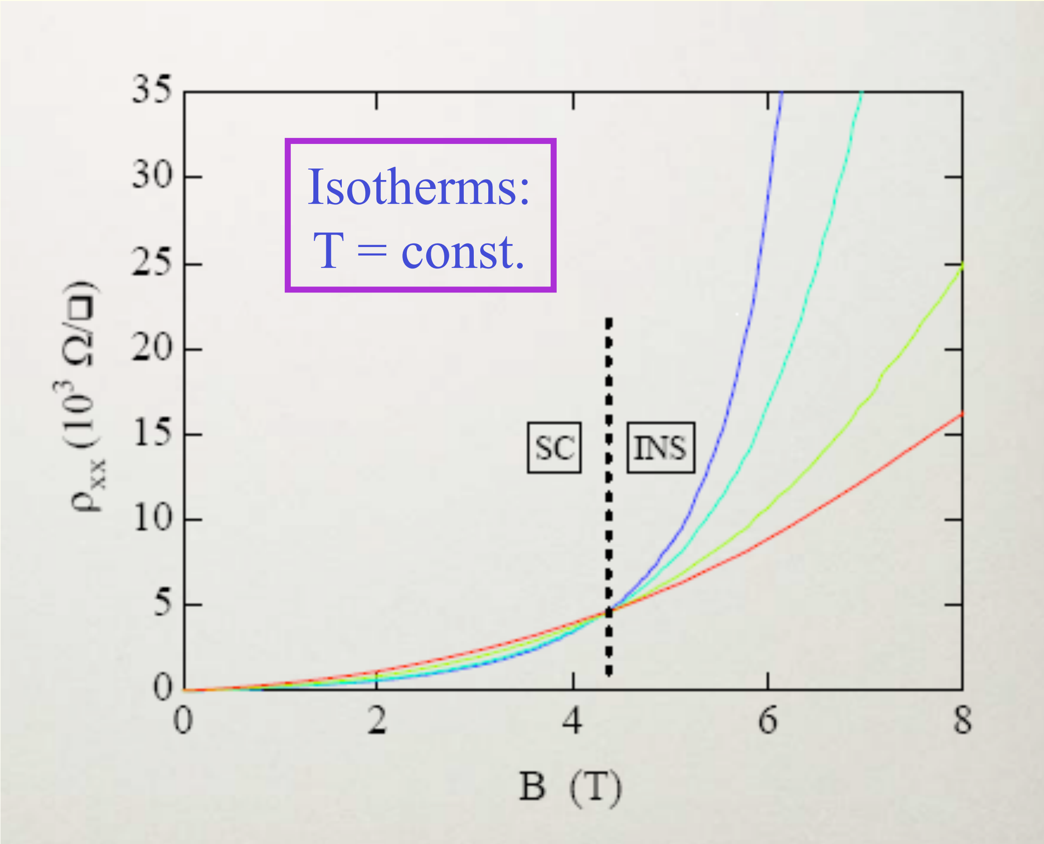
T = 0 transition



Review: Finkl'stein ('94),
Markovic and Goldman ('98).

Field driven transition

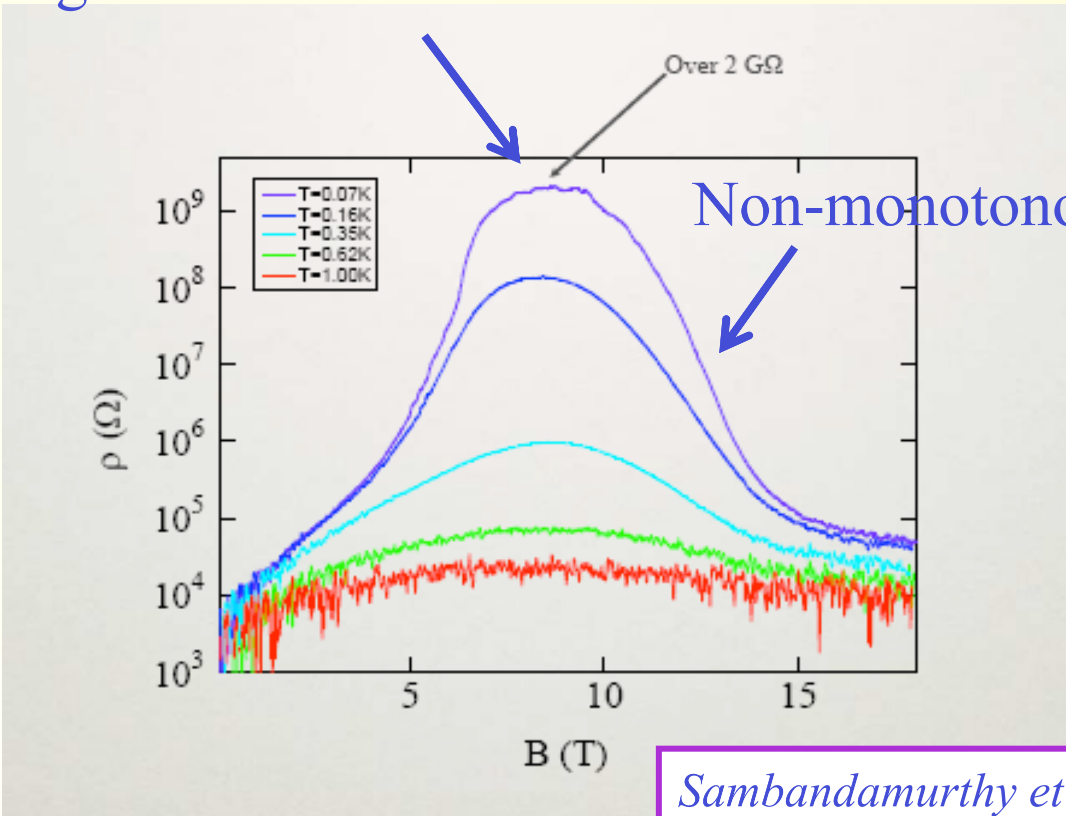
Magnetic field destroys SC!



Gantmakher, Shahar, Kapitulnik, Goldman, Baturina

Insulator: Giant magnetoresistance

Giant magnetoresistance



Non-monotonous R(B)!

Sambandamurthy et al. (PRL 2005)

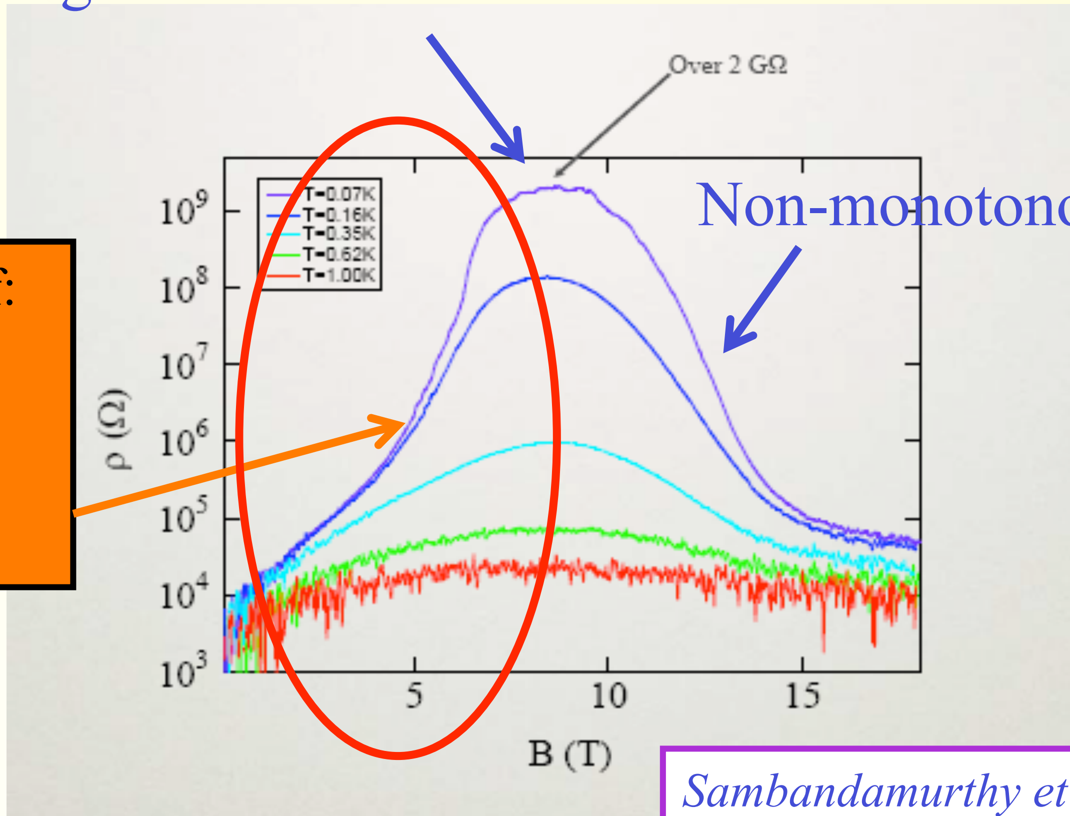
Insulating behavior **enhanced** by local superconductivity!

Insulator: Giant magnetoresistance

Giant magnetoresistance

Non-monotonous R(B)!

Common belief:
Pairs (bosons) survive in the insulator:
Bose glass



Sambandamurthy et al. (PRL 2005)

Insulating behavior **enhanced** by local superconductivity!

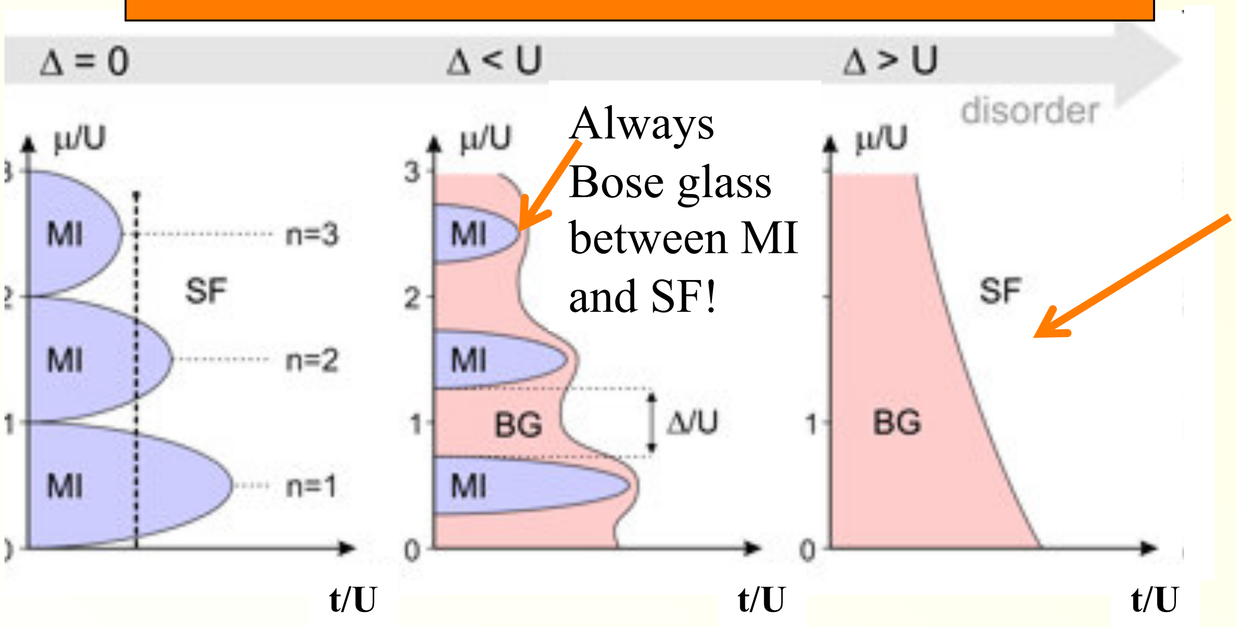
Bose-Hubbard model and Bose glass

Fisher et al., Phys. Rev. B 40, 546 (1989) --- Altland et al, Gurarie et al. (2009)

- Assume "preformed Cooper pairs": bosons without global superconductivity
- Dirty boson model (Bose-Hubbard model with disorder):

$$H = t\sum_{\langle i,j\rangle} b_i^+ b_j + U\sum_i n_i(n_i - 1) + \sum_i (\varepsilon_i - \mu)n_i$$

Disorder: $\varepsilon_i \in [-\Delta, \Delta]$



Most likely scenario for experiments: Strong disorder, no Mott gap!

Two puzzling features in transport in strongly disordered samples

1. Simple activation in R(T)

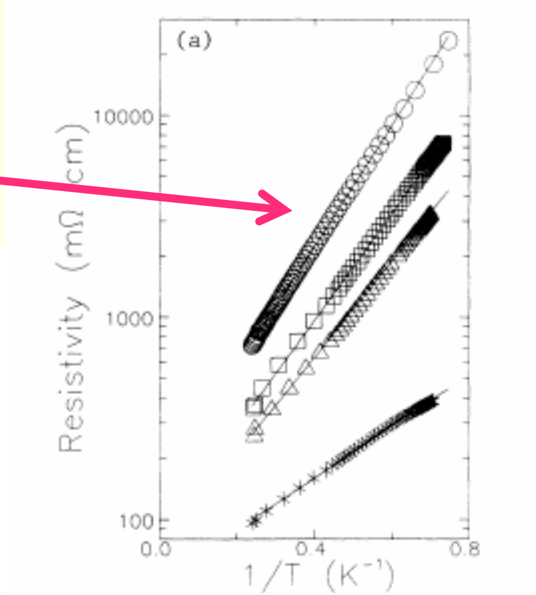
2. Evidence for purely electronic mechanism

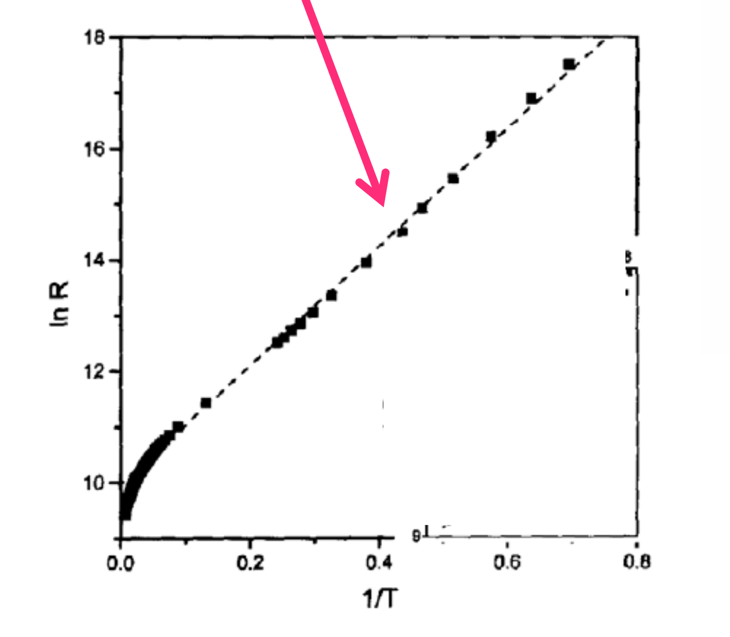
Activated transport near the SIT

*D. Shahar, Z. Ovadyahu, PRB **46**, 10971 (1992).*

Insulating InO_x

Simple activation!?





$$R(T) = R_0 \exp\left[\frac{\Delta}{T}\right]$$

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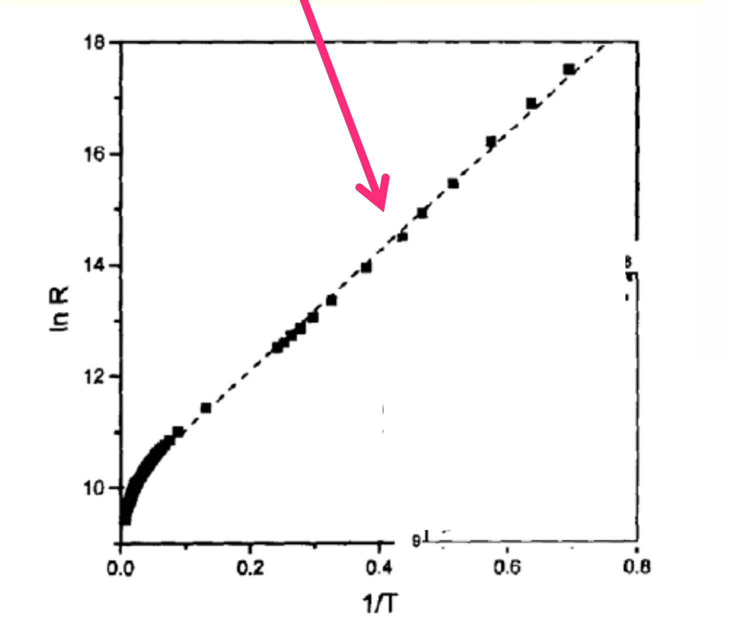

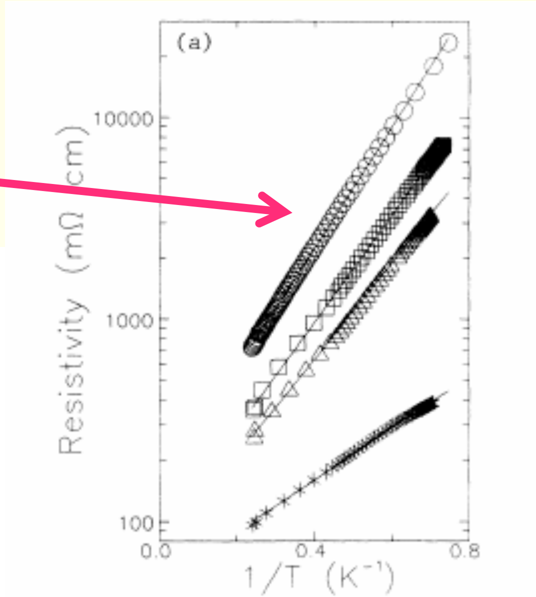

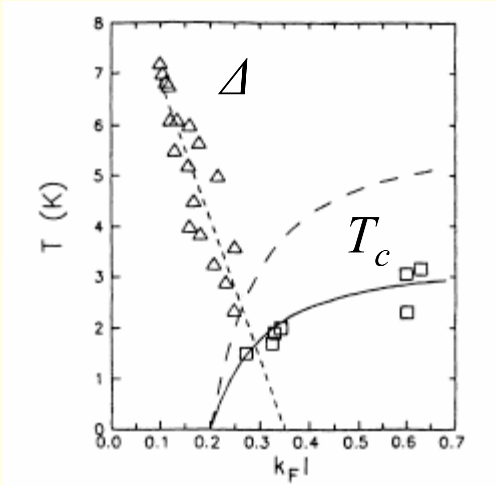

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Natural aspect:
Activation energy increases with distance to SIT

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Activated transport near the SIT

*V. F. Gantmakher, M. V. Golubkov, J. Lok, A. K. Geim, Sov. Phys. JETP, **82**, 951 (1996).*

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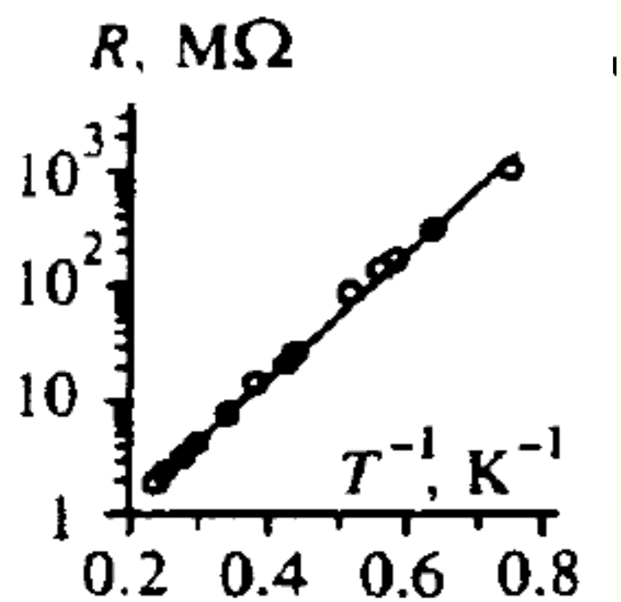

$$R(T) = R_0 \exp\left[\frac{\Delta}{T}\right]$$

Origin of simple activation?

- Gap in the density of states?

A: NO! Too disordered systems!
There is no (Mott) gap!

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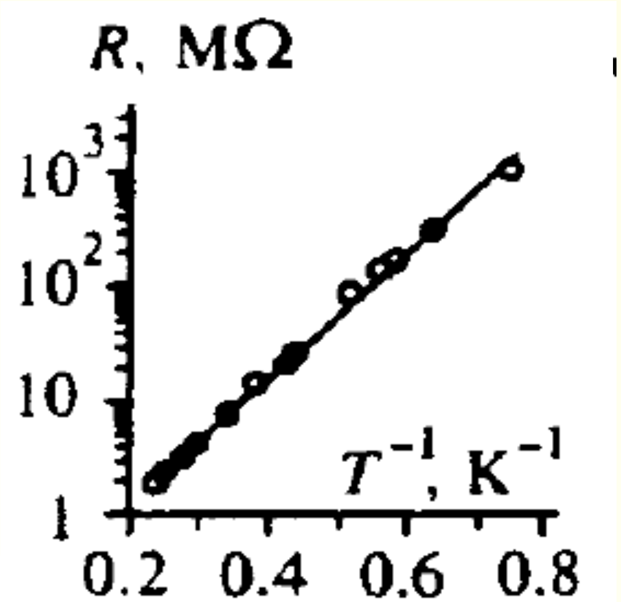

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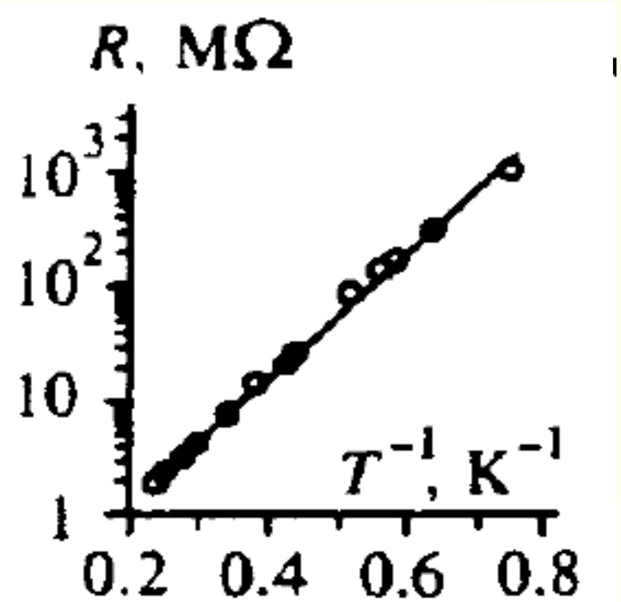

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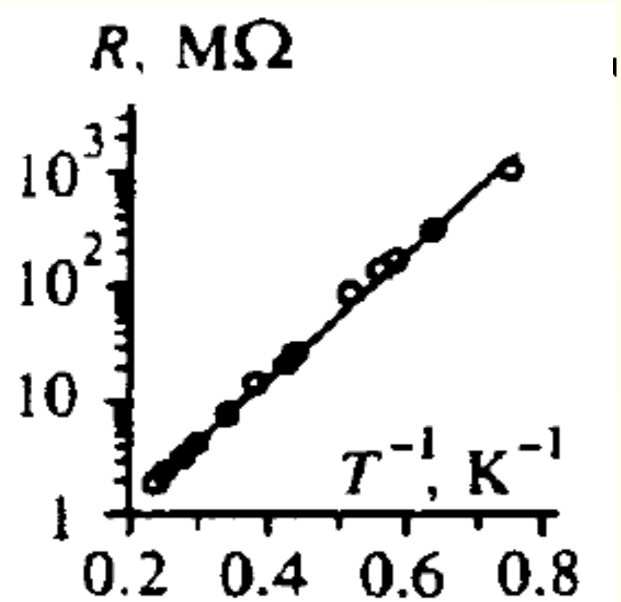

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• No depairing of bosons (positive MR!)
[Feigel'man et al.]

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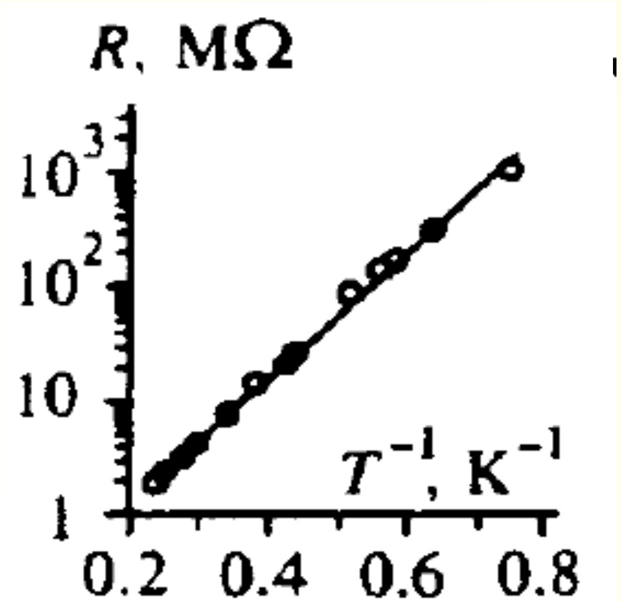

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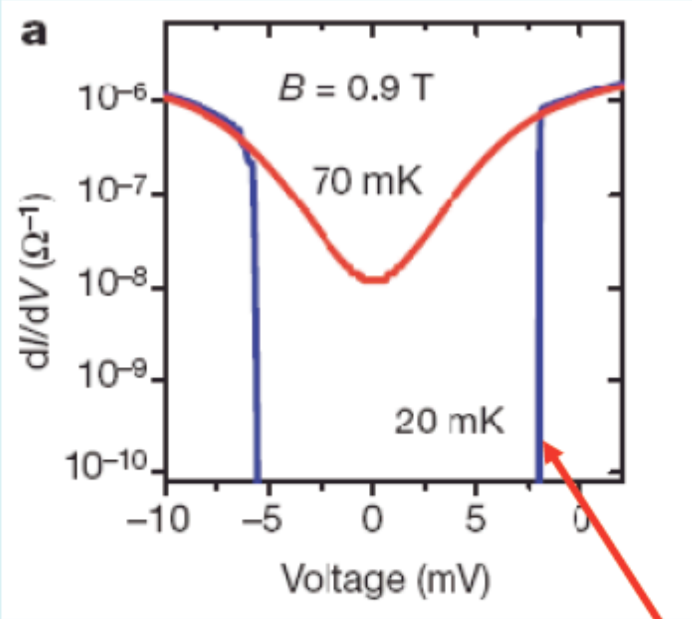
• No depairing of bosons (positive MR!)

→ • Instead propose: Boson mobility edge!
(Similar to Anderson localization)

Purely electronic transport mechanism!

TiN films



Baturina, Mironov, Vinokur, Baklanov, Strunk,'07

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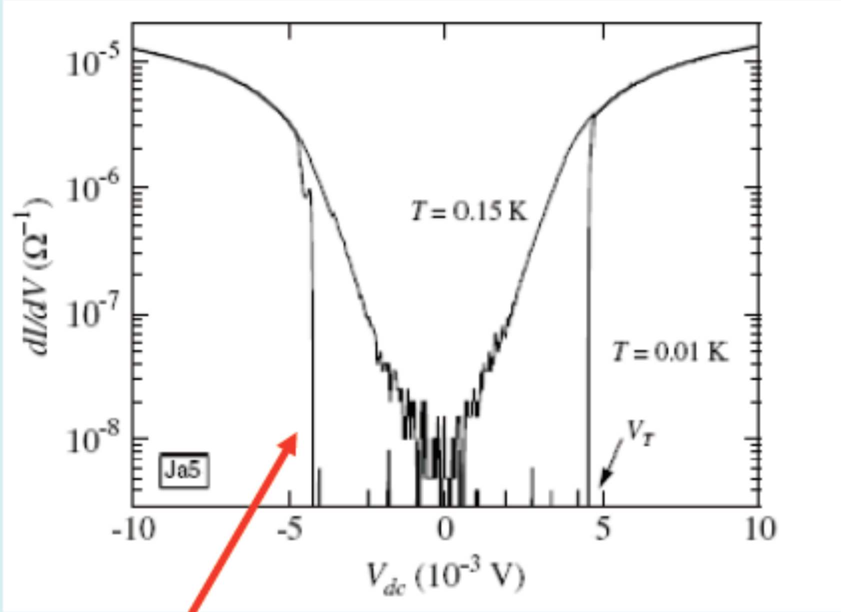

Sambandamurthy, Engel, Johansson, Peled, Shahar, '05

Giant jumps in resistance from kΩ to GΩ regime

Non-Ohmic resistance in the insulator!

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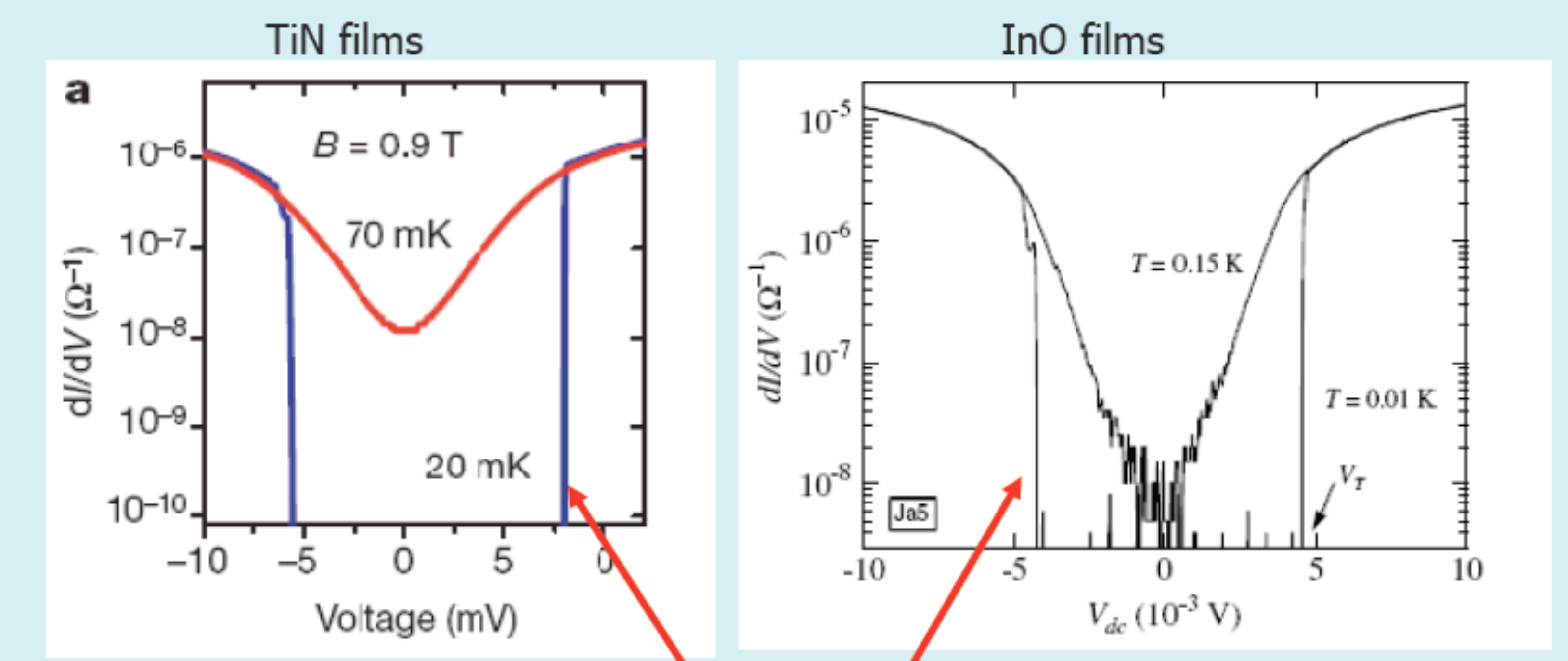

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Simple explanation: instability from low T/high R state to overheated state.

Altshuler, Kravtsov, Lerner, Aleiner (09)

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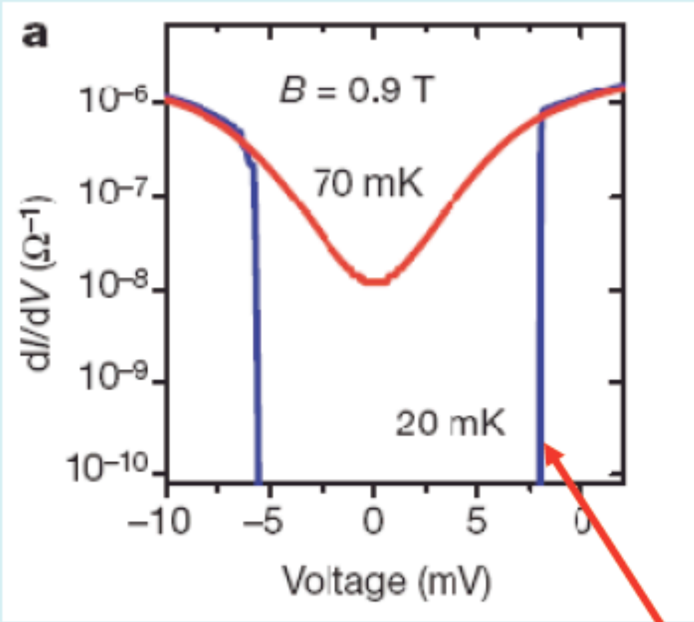

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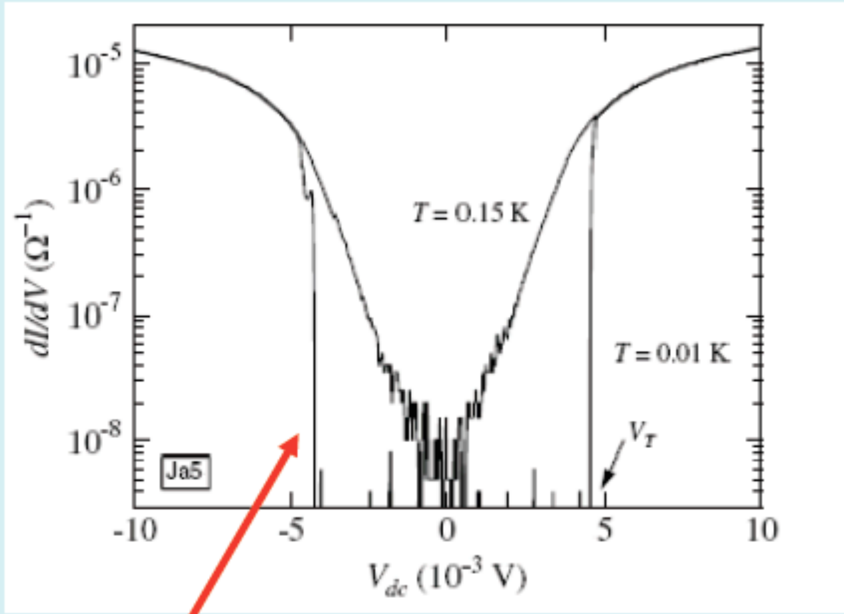

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But: Crucial ingredient: transport is not phonon- but electron-activated! – Mechanism?

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Transport is not phonon- but electron-activated in the insulators! - Mechanism???

Not a new phenomenon in itself! Close to the MI-transition:

Electronic mechanism experimentally inferred from non-linear transport:

$R = R(T_{el}(V))$ -- not $R = R(T_{ph})$ *(West, Pfeifer; Gershenson; Pepper)*

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But: Mechanism ??? Long standing, not resolved question!

Proposal for the MIT: *(Müller & Ioffe (2007))*

Quantum (Coulomb) glassiness of the electrons leads to low energy collective modes.

✓ Can activate hopping of charges

✓ Efficient thermal transport!

✓ Efficient electron-phonon coupling!

Summary of puzzles at the SIT

1. **Close to the SI transition the transport is essentially simply activated (Arrhenius):**

   How come?

2. **Evidence for purely electronic transport from heating instability in non-Ohmic regime. Direct evidence of electronic transport mechanism in insulators**

   What is its origin?

From dirty superconductor to Bose glass

Models

$$H = -t\sum_{\langle i,j\rangle} b_i^+ b_j + U\sum_i n_i\left(n_i - 1\right) + \sum_i\left(\varepsilon_i - \mu\right)n_i$$

Disorder: $\varepsilon_i \in \left[-\Delta, \Delta\right]$

Easier to think about: U = ∞ limit, i.e., hard core bosons
→ equivalent to Anderson pseudospins (s=1/2)

Interactions (e.g. Coulomb)

(Anderson, Ma+Lee, Kapitulnik+Kotliar)

$$H = -t\sum_{\langle i,j\rangle} s_i^+ s_j^- + \sum_i\left(\varepsilon_i - \mu\right)s_i^z + \sum_{\langle i,j\rangle} J_{ij} s_i^z s_j^z$$

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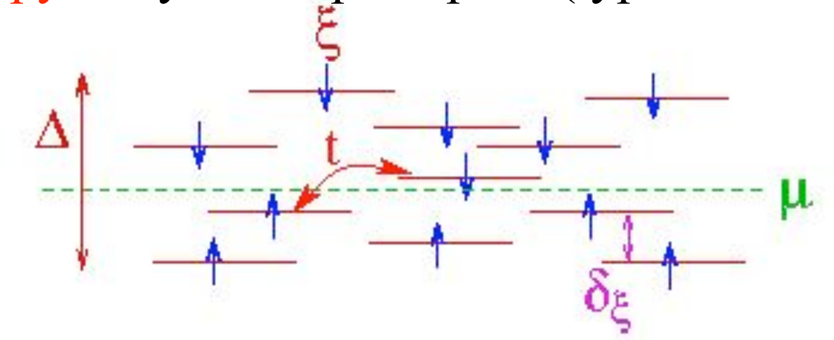
- "Sites" i: localized states for a pair to occupy. May overlap in space (typical size: ξ)

- Relevant scale characterizing disorder:

Level spacing δ_ξ between close levels
Disorder strength: $g \equiv \delta_\xi / t$



From dirty superconductor to Bose glass: the phases

• Superconducting phase: Bose condensation into delocalized mode in the presence of self-consistently screened disorder
→ finite phase stiffness
→ infinite conductivity for $T < T_c$

• Bose glass: No delocalized bosonic mode anymore (otherwise condensation would occur)
- role of disorder: no homogeneous gap, still compressible phase

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- **Note:** "Bose glass" : = disordered Bose insulator without spectral gap
- It is an **insulator**, i.e. $\sigma(T \rightarrow 0) = 0$ [no Bose metal!]

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Nature of transport in the Bose glass?

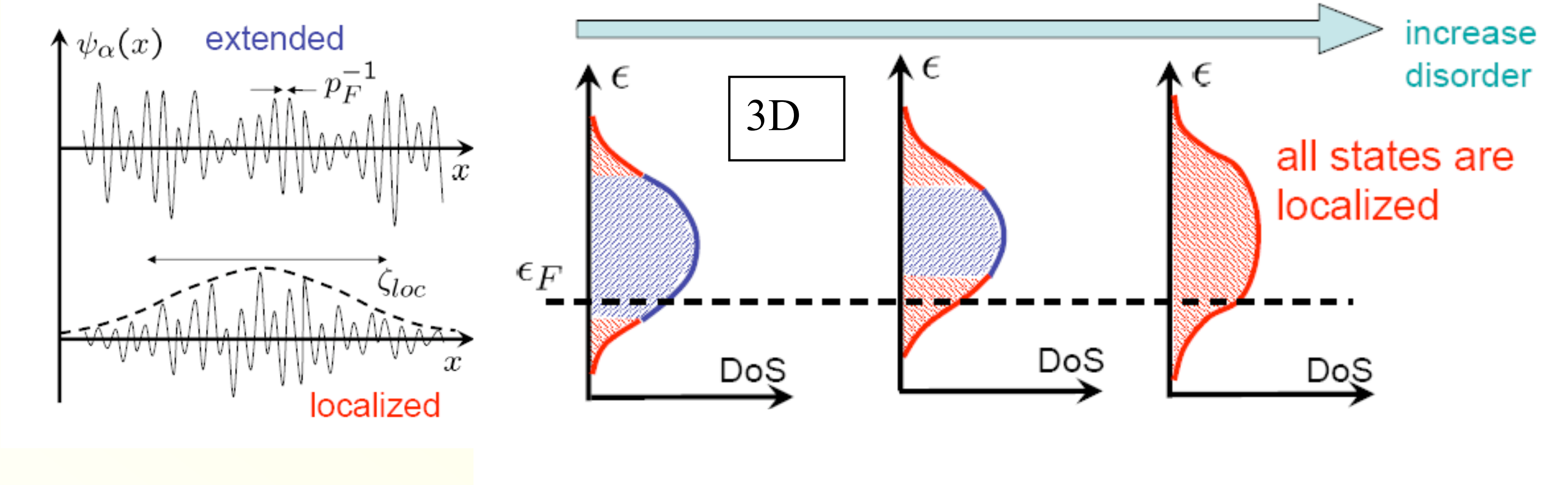
From dirty superconductor to Bose glass

SIT = "Localization of the bosons"!

Think about the evolution of the manybody spectrum!

Berkovits and Shklovskii
Basko, Aleiner, Altshuler
Huse, Oganesyan

Reminder: Anderson localization



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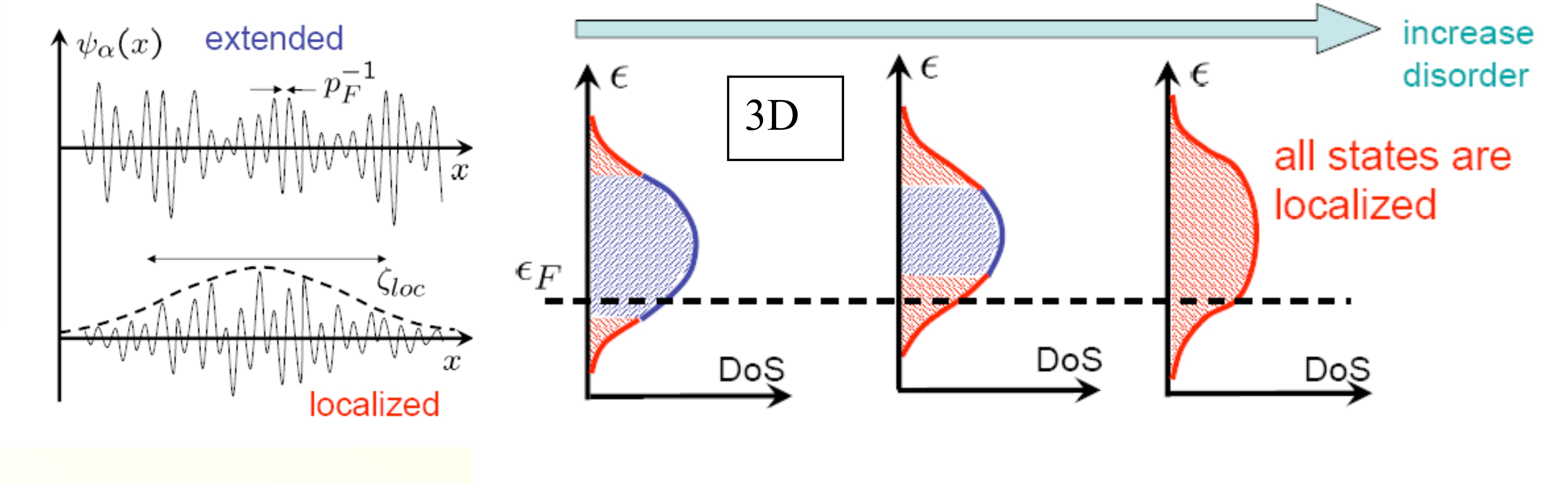

Old but very difficult question (Anderson, Fleishman; Larkin)

What happens in presence of interactions??

Example: the Bose glass!

The spectrum:
Warm up - the clean case

- Superconductor: gapless excitations (phonons)

- Mott insulator of bosons: finite gap
  Spectrum:
  No discrete spectrum!
  All excitations are delocalized and
  disperse with well-defined momenta **k**

↔ With disorder: much more complex!

From dirty superconductor to Bose glass

Local spectrum of operator O at T = 0

$$\rho_{\mathrm{O}}(\omega) = \int_0^\infty \langle \mathrm{O}(x,t)\mathrm{O}(x,0)\rangle_{GS}\, e^{i\omega t}\, dt$$

2 possibilities:

- Continuous spectrum (↔ delocalized excitations)
- Point spectrum: "locally discrete" (bunch of delta functions in local correlation functions ↔ localized excitations)

From dirty superconductor to Bose glass

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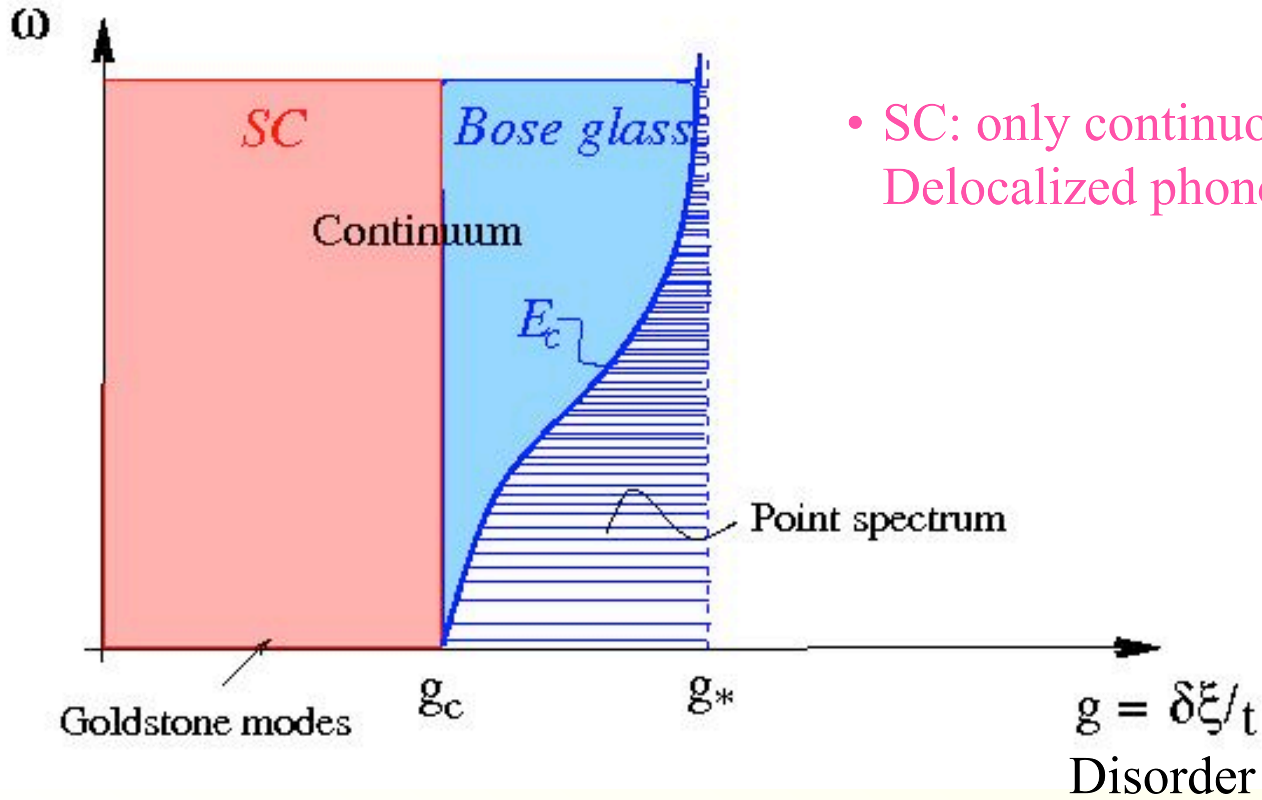

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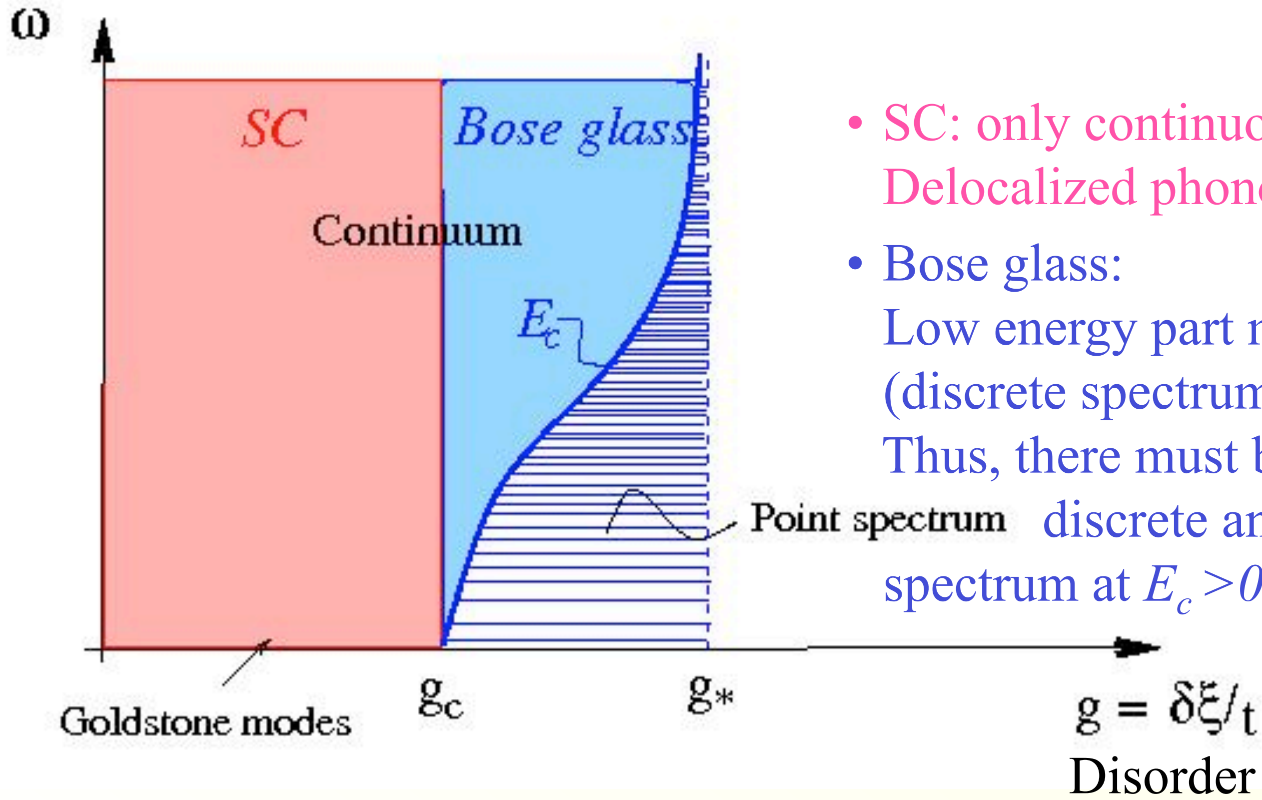
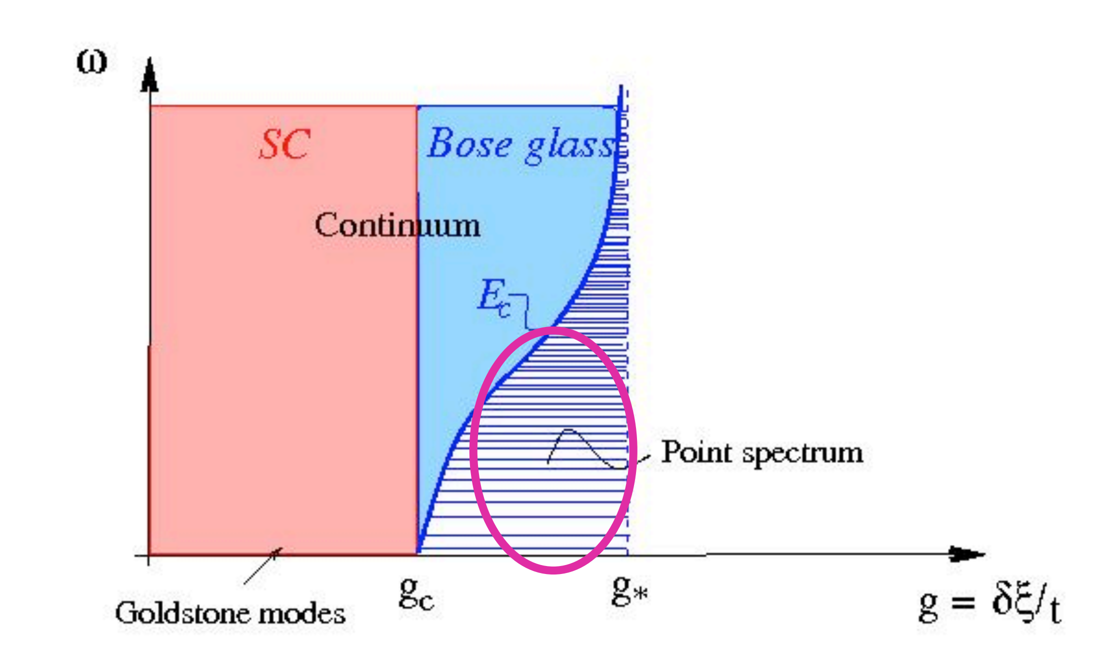


- SC: only continuous spectrum! Delocalized phonons down to ω=0
- Bose glass: Low energy part must be localized (discrete spectrum). Thus, there must be a border between discrete and continuous spectrum at $E_c > 0$

Spectrum at T = 0

The point spectrum at low energies



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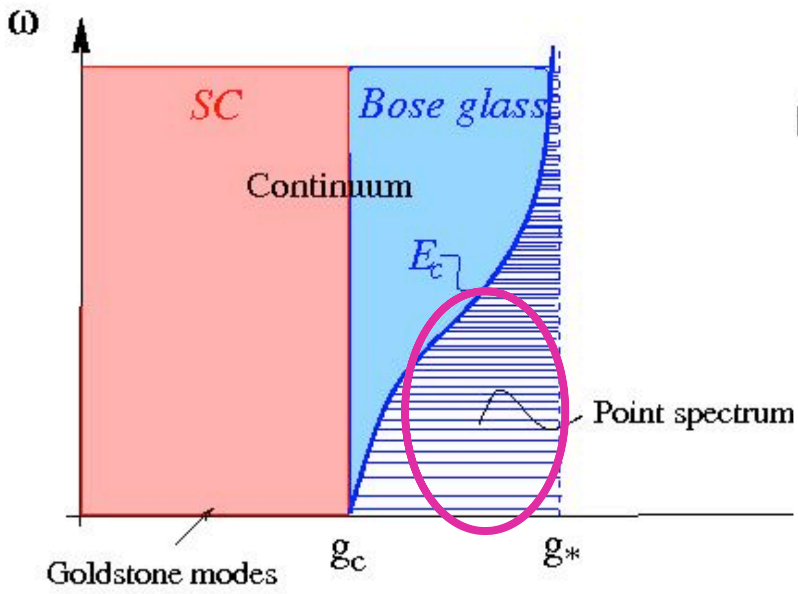

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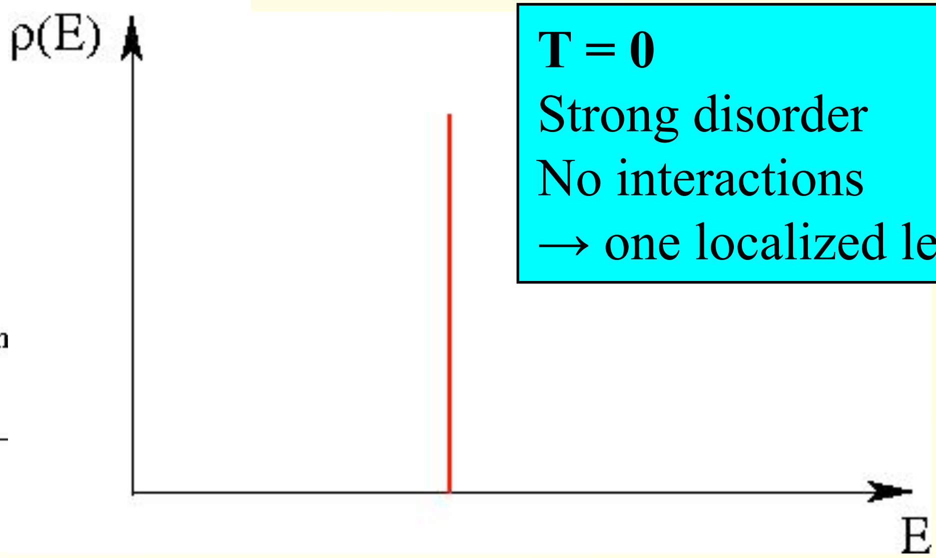
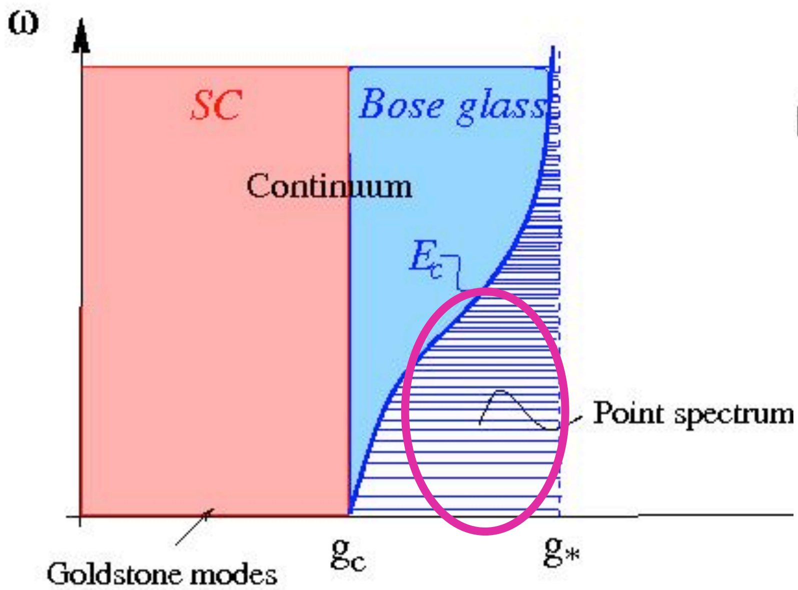


T = 0
Strong disorder
No interactions
→ one localized level

Spectrum at T = 0

The point spectrum at low energies



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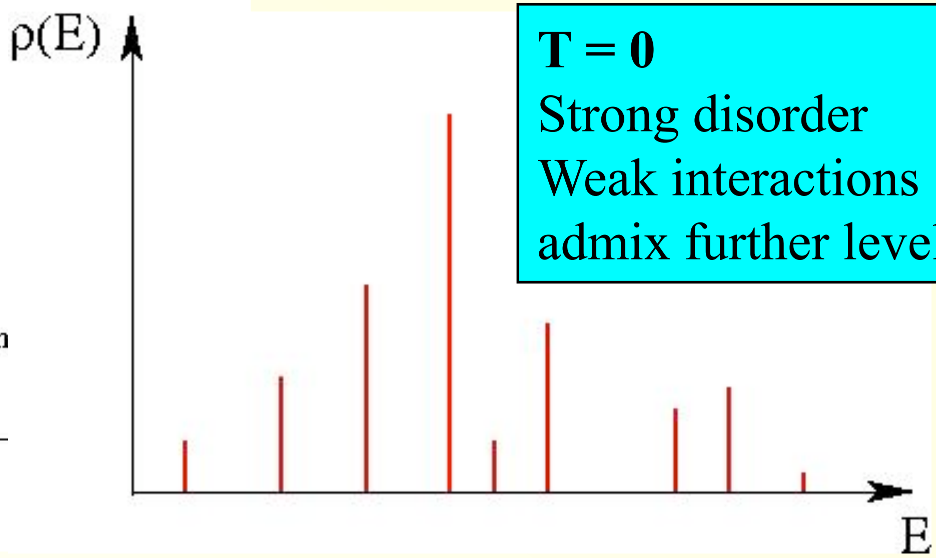
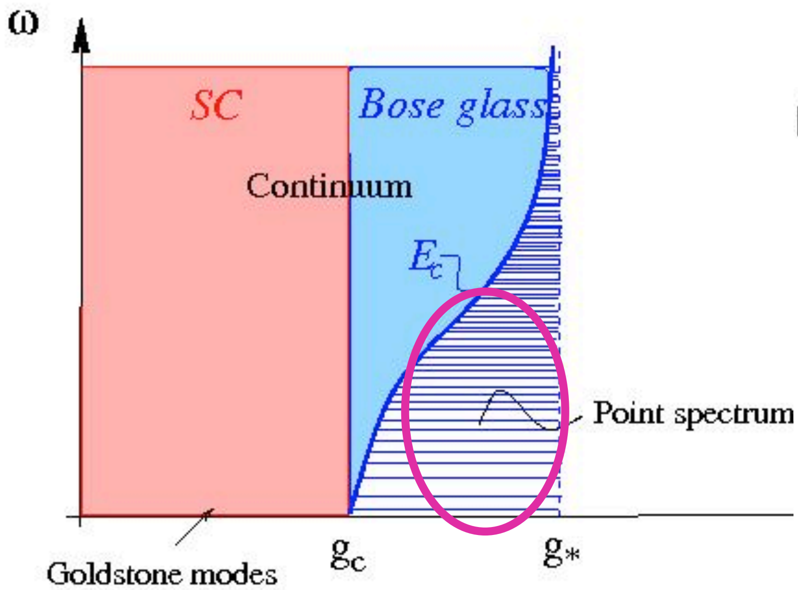


T = 0
Strong disorder
Weak interactions
admix further levels

Spectrum at T = 0

The point spectrum at low energies



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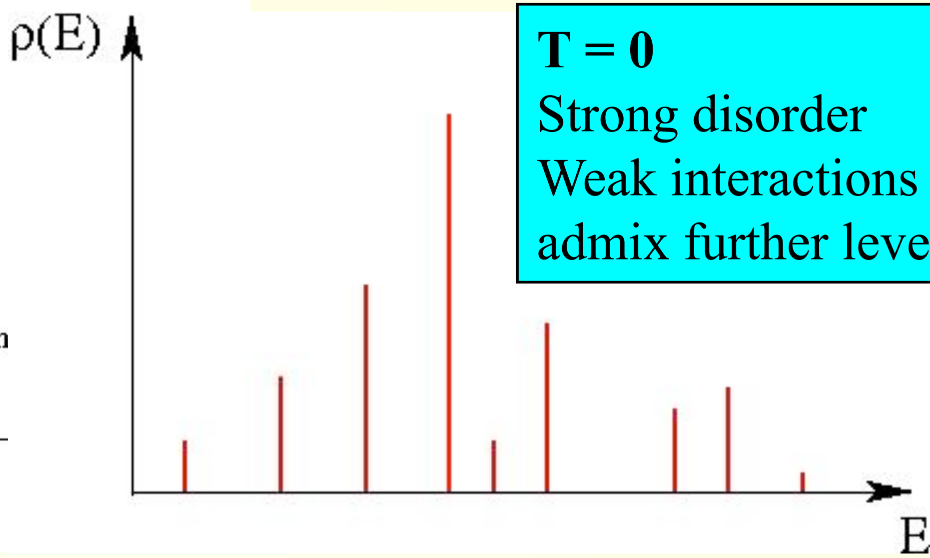


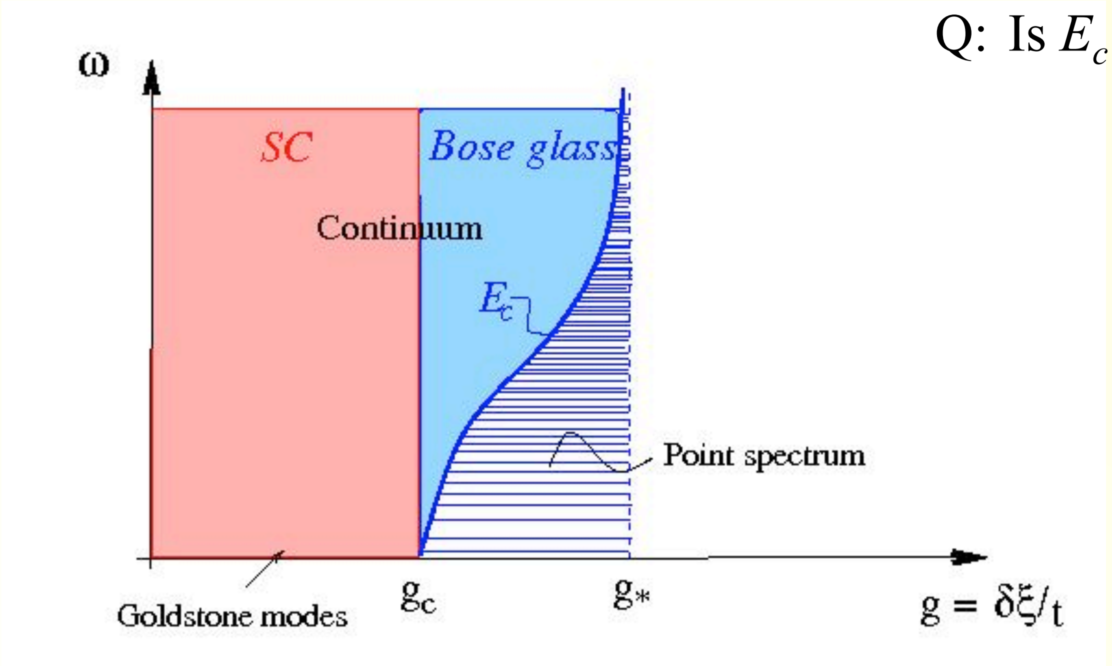
T = 0
Strong disorder
Weak interactions
admix further levels

- Discrete levels: no transport, no current!
  $\sigma(T=0) = 0$
- Genuine glass at T=0: perturbations don't relax

Reason: Transition probabilities are zero because energy conservation can never be satisfied!

Mobility edge

Many-body "mobility edge" in the Bose glass



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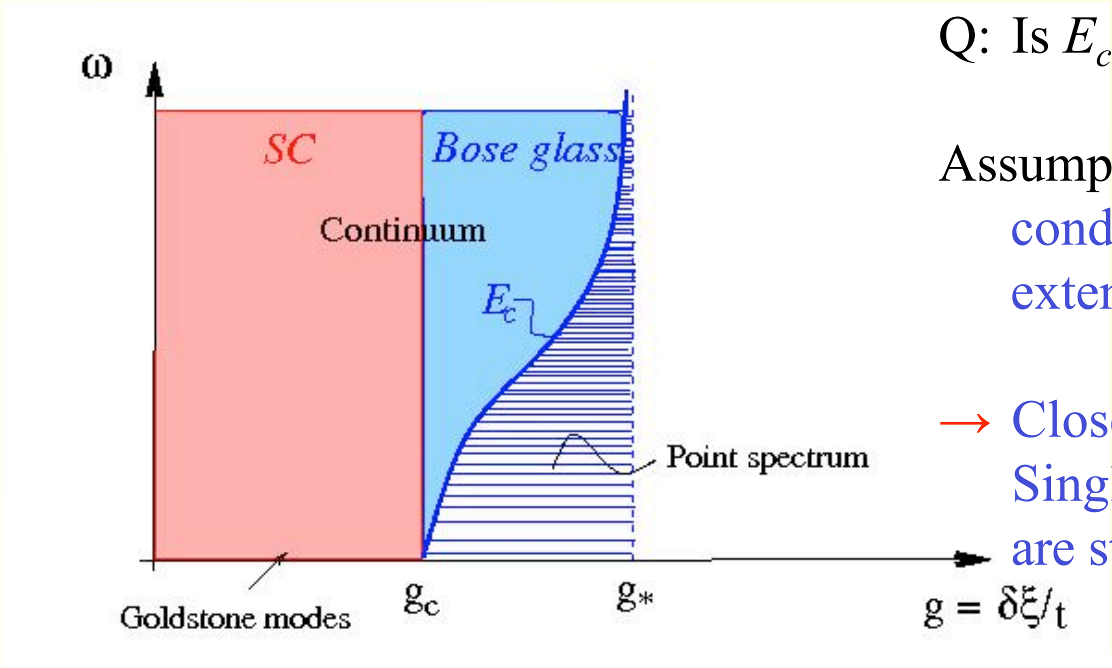

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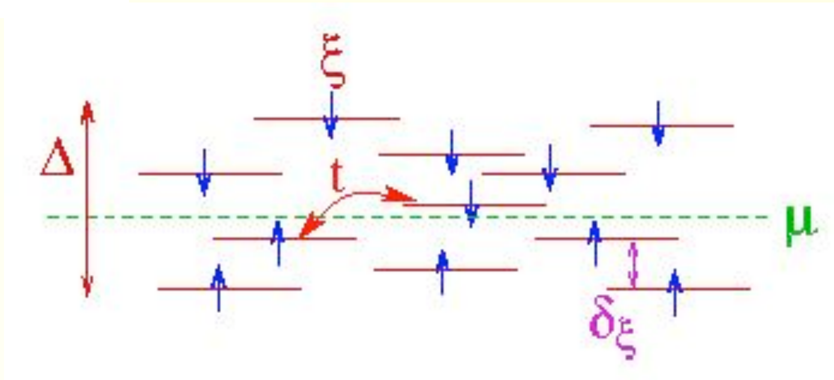
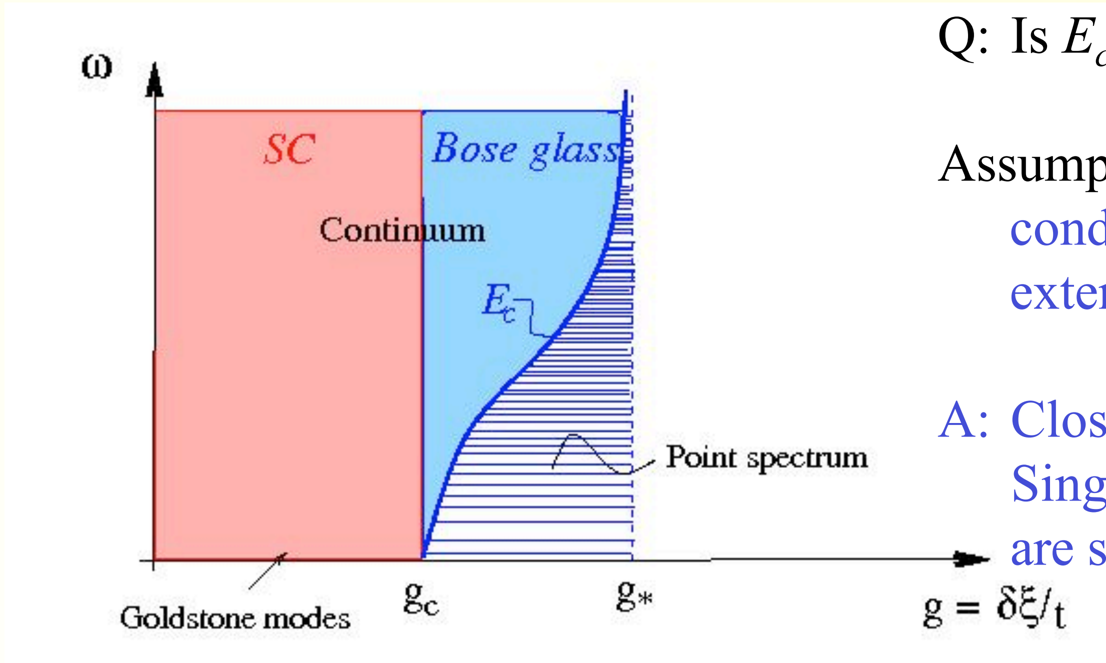
Assumption: The SIT is essentially a condensation of a self-consistent, extended single boson mode.

→ Close to the SIT ($g = g_c$) E_c is bounded: Single boson excitations at $E\text{-}\mu >> t$ are still delocalized (for d > 2) → $E_c < \infty$



Mobility edge

Many-body “mobility edge” in the Bose glass

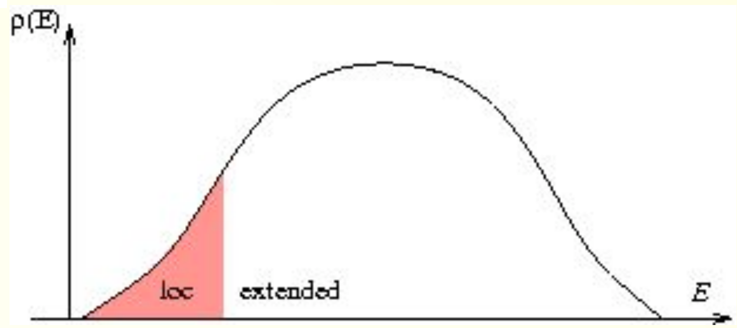


Q: Is E_c finite or extensive? (~Volume)

Assumption: The SIT is essentially a condensation of a self-consistent, extended single boson mode.

A: Close to the SIT ($g = g_c$) E_c is bounded: Single boson excitations at $E\text{-}\mu >> t$ are still delocalized (for d > 2) → $E_c < \infty$

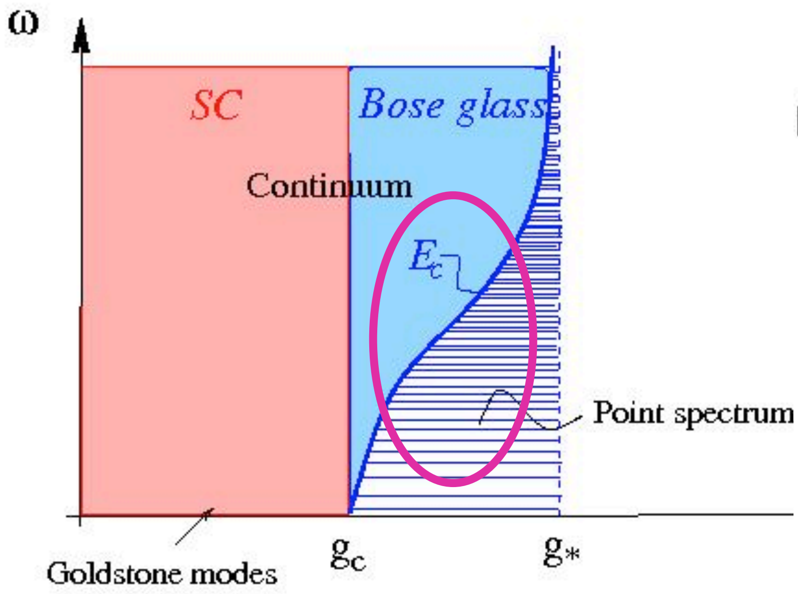
Non-interacting analogon:
Localization at band edge (Anderson model)

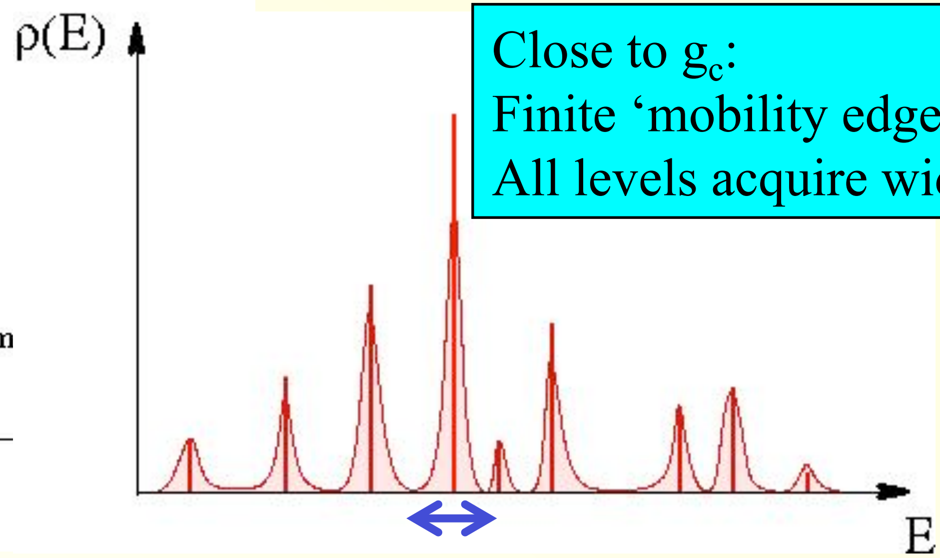


Finite T

The point spectrum at low energies

Local spectrum at T > 0





Close to g_c:
Finite 'mobility edge' →
All levels acquire width

$\Gamma \sim \exp[-E_c/T]$

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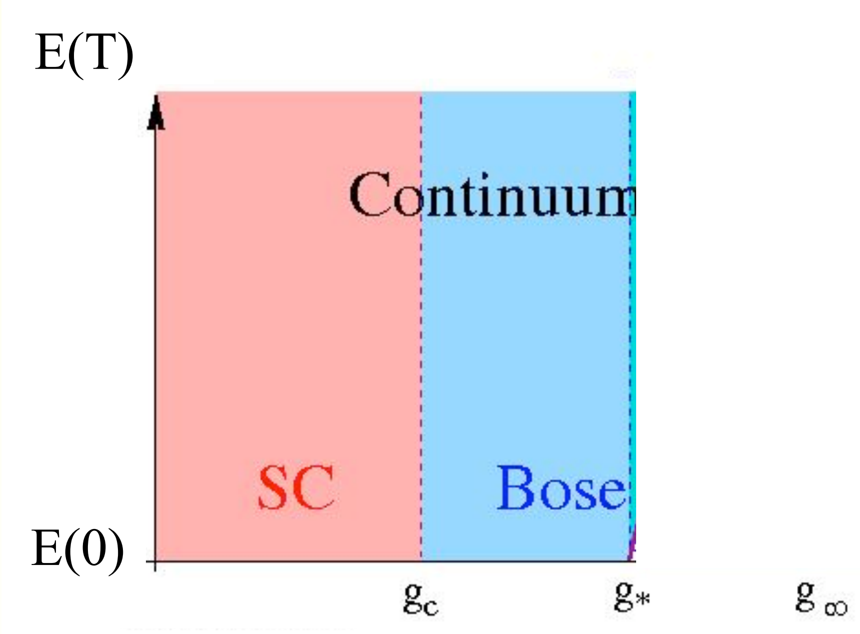

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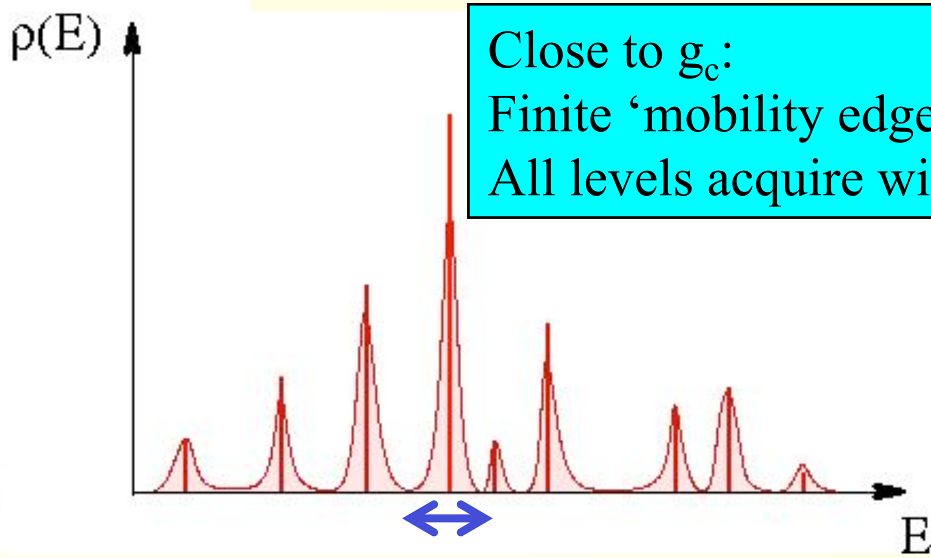


$\Gamma \sim \exp[-E_c/T]$

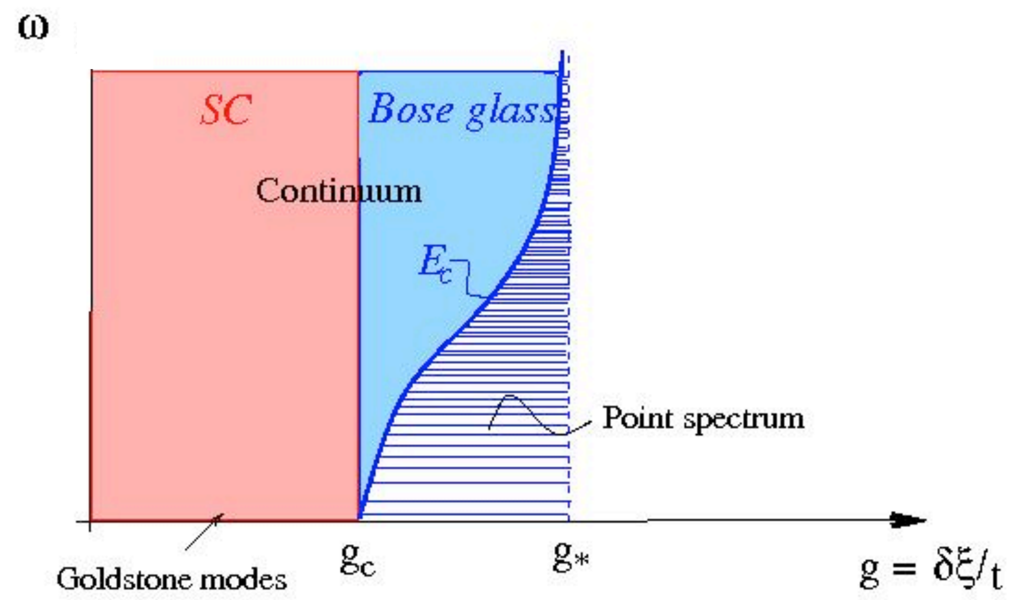
→

- Continuum everywhere! $\sigma(T > 0) \neq 0$ for $g < g_*$ where $E_c(g) < \infty$

Electronic activated conduction

$g < g_* \ : \ E_c(g) < \infty$

- Continuum at finite T! $\longrightarrow$ $\sigma(T>0) \neq 0$



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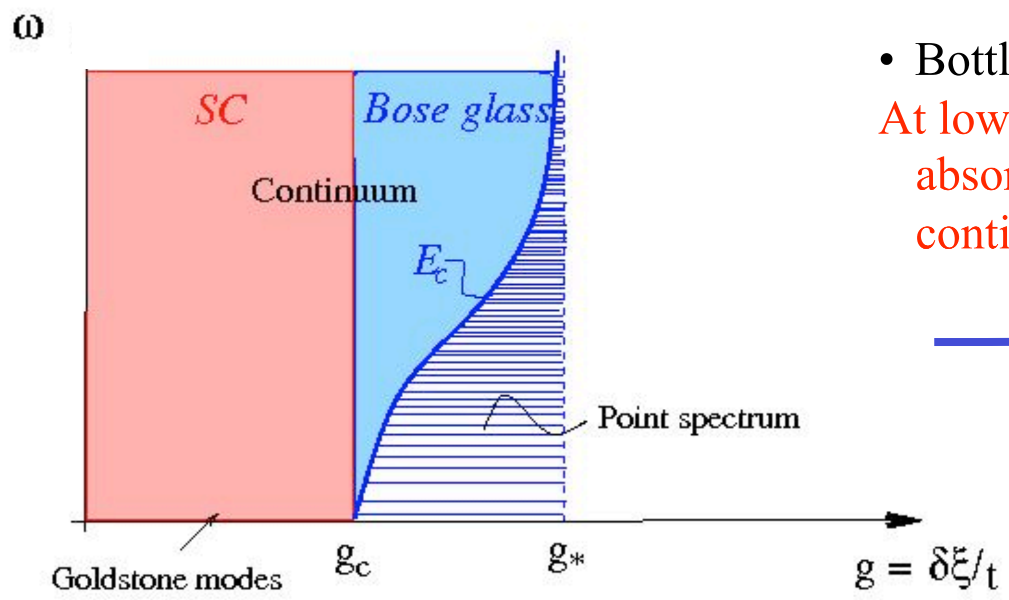

- Continuum at finite T! → $\sigma(T>0) \neq 0$
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At low T: Transitions allowed only due to the absorption of modes from the (T=0) continuum or diffusion above E_c

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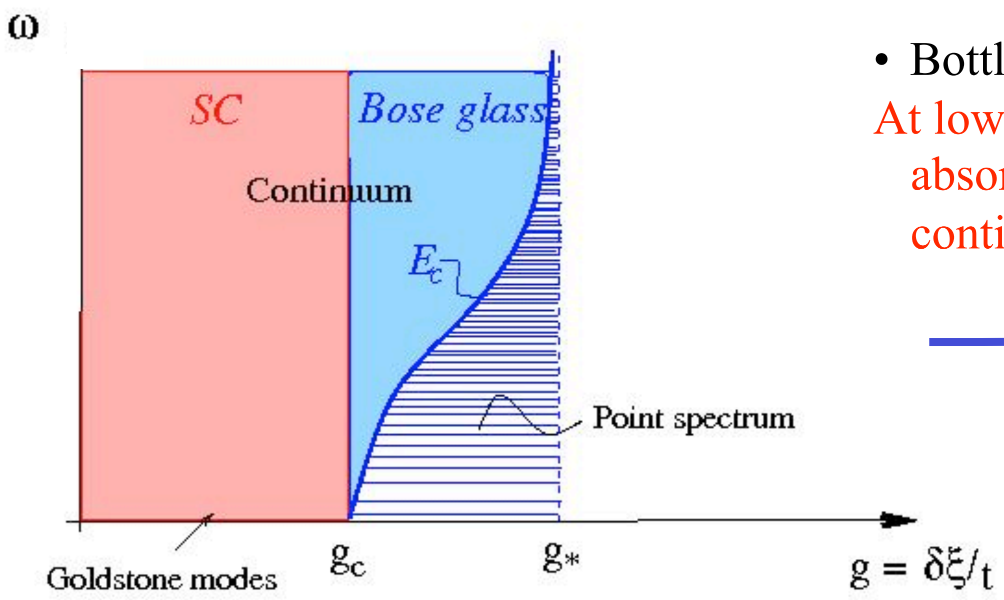

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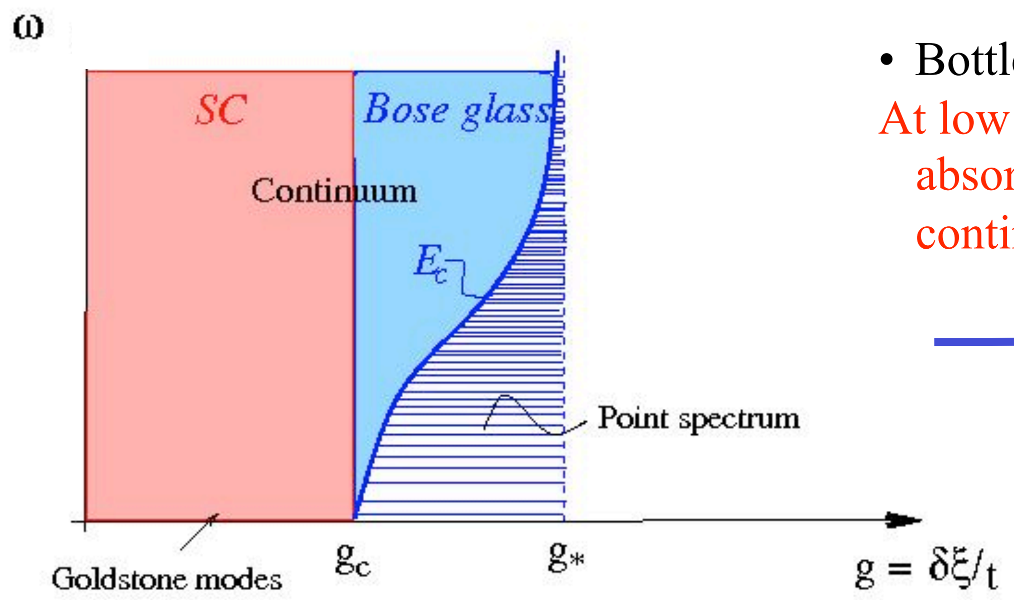

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!

- No phonons needed! (they are anyway very inefficient at low T)
- Purely electronic transport mechanism
  → crucial ingredient to explain the overheating in the non-Ohmic regime
- Prefactor: $\sigma_0 \sim e^2/h\xi^{d-2}$ nearly universal in quasi 2d, similar to experiment!

!

But: Why no standard
variable range
hopping transport?

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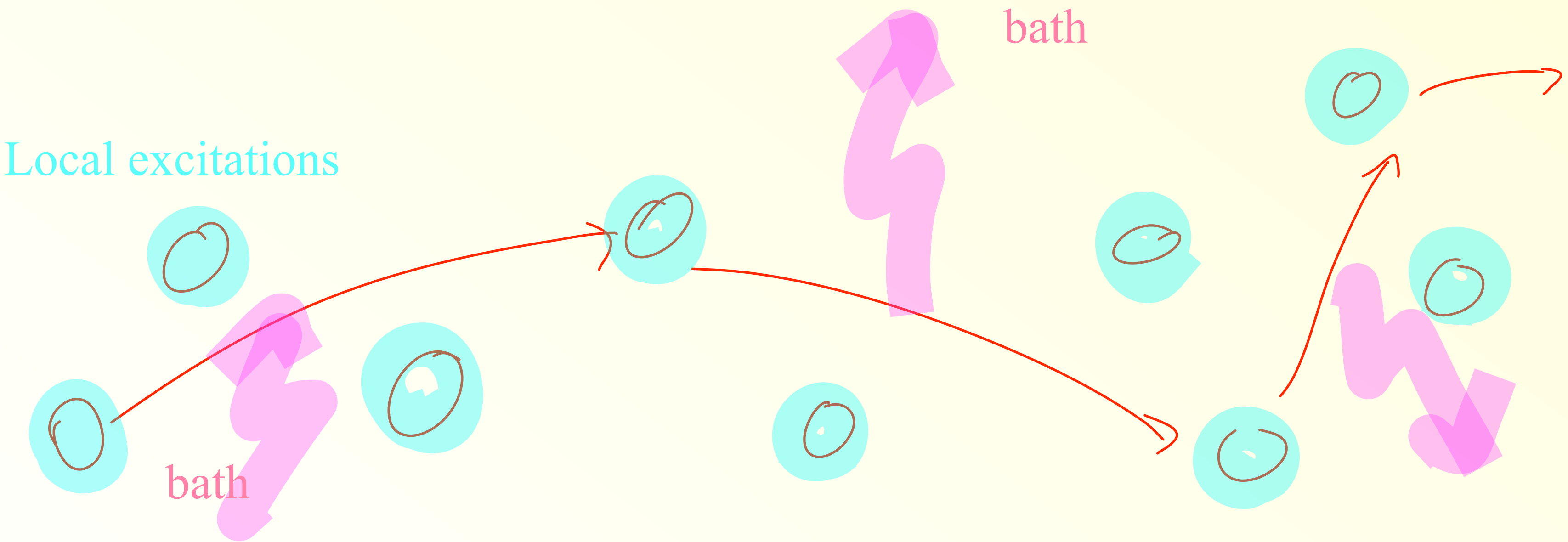
Many body
localization??

? Transport and thermalization in insulators ?

Essential ingredient into variable range hopping:
Continuous bath which activates the hops!



Candidates for the bath:

• Phonons: at low T for pair hopping are very inefficient!

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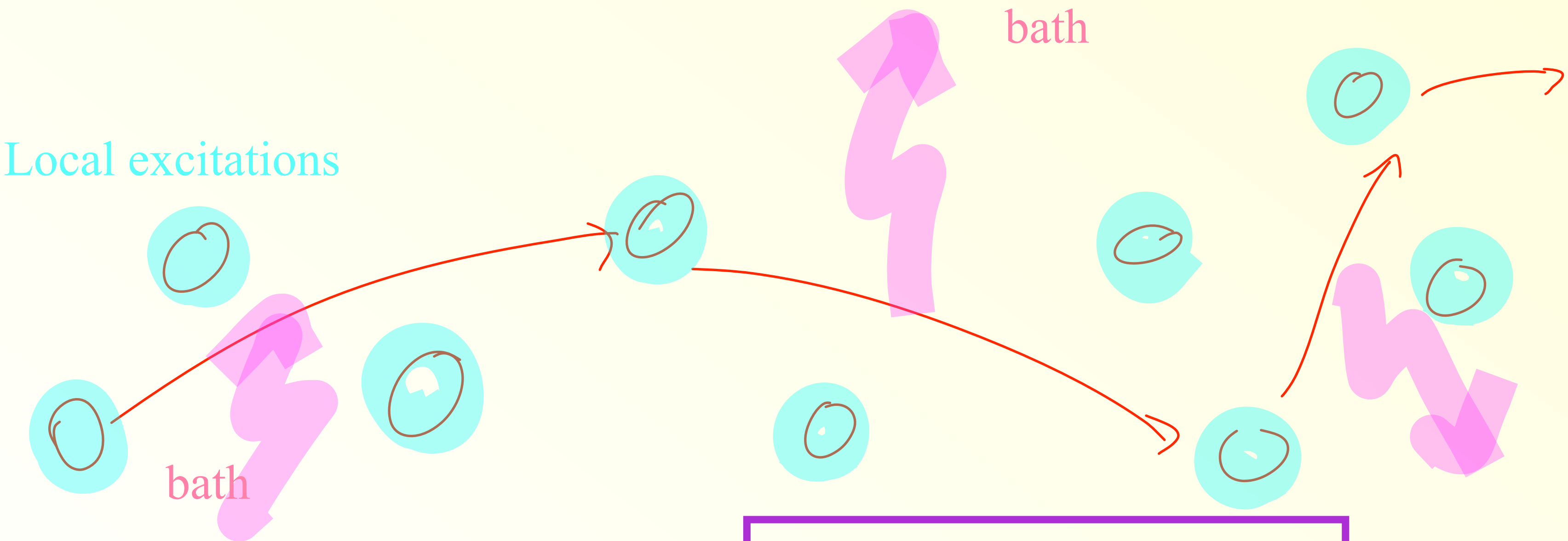

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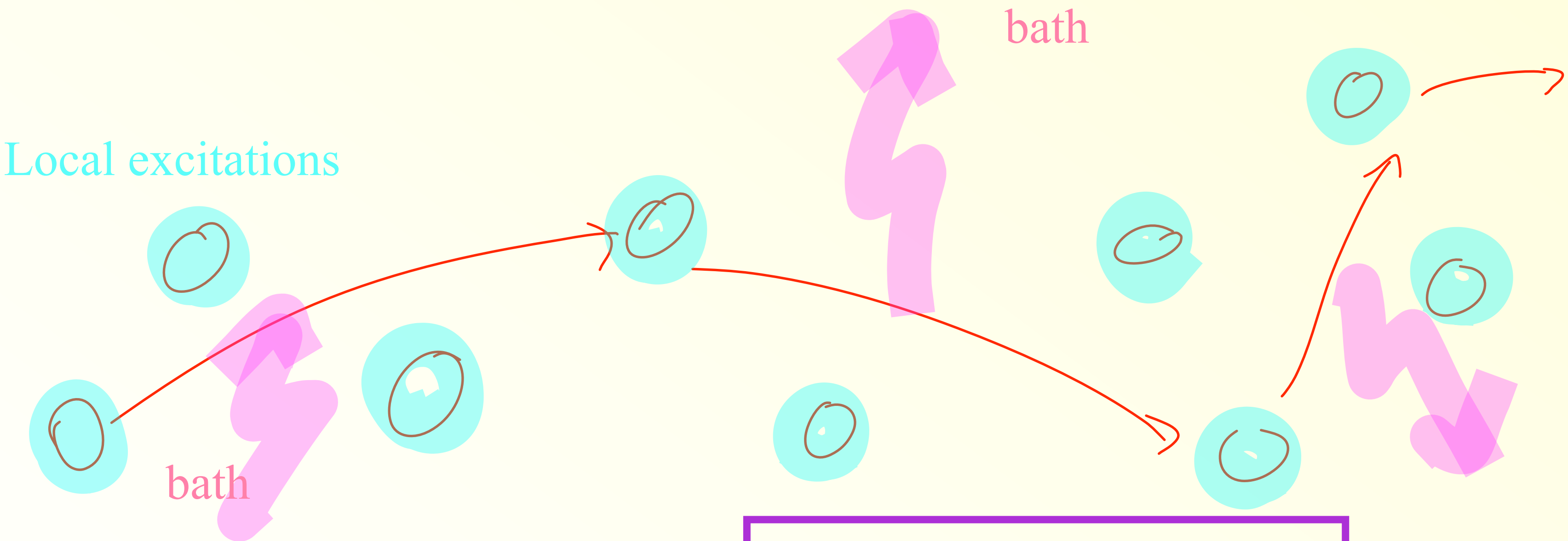

Candidates for the bath:

Too weak → not considered

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- bosonic excitations above the many body(!) mobility edge

What if there is no bath whatsoever?

Strong disorder

$g > g_* \ : \ E_c(g) = \infty \ \ (\sim \text{Volume})$

- If disorder is strong ($g = \delta_\xi/t > g_*$) *all* single boson excitations above the GS (at $T = 0$) are localized: $E_c \to \infty$

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  delocalization in Fock space at $T=T_{loc}$ *(Gornyi et al.; Basko et al.)*
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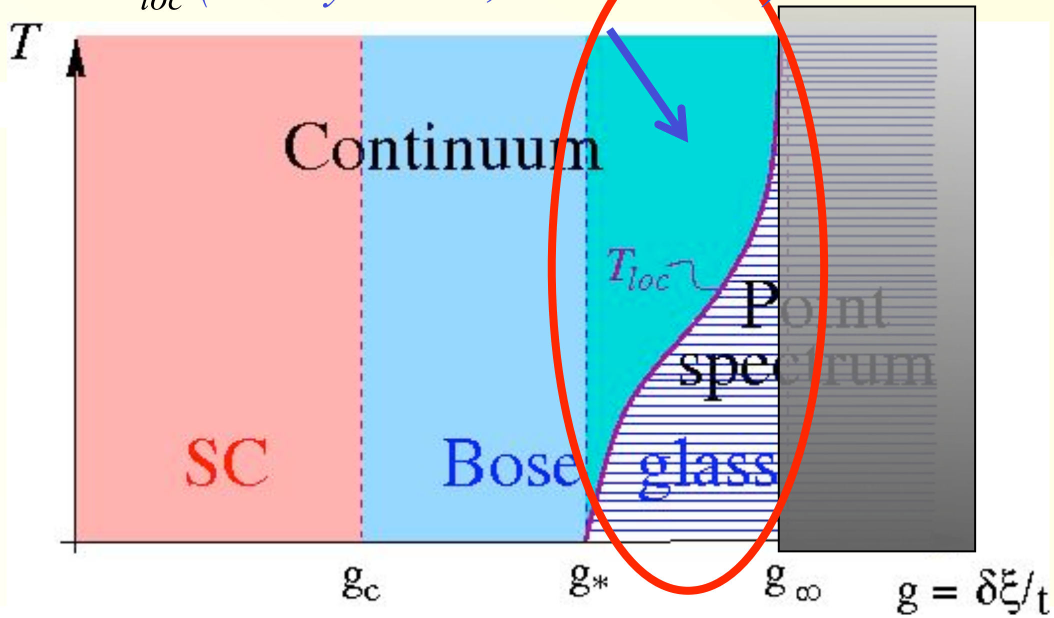

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  complete localization in very
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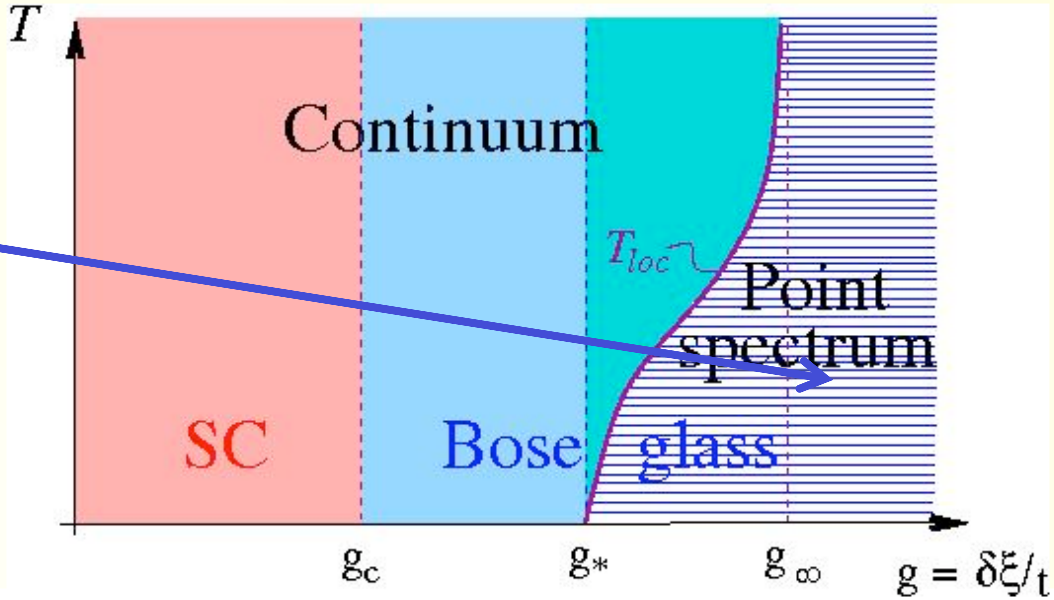

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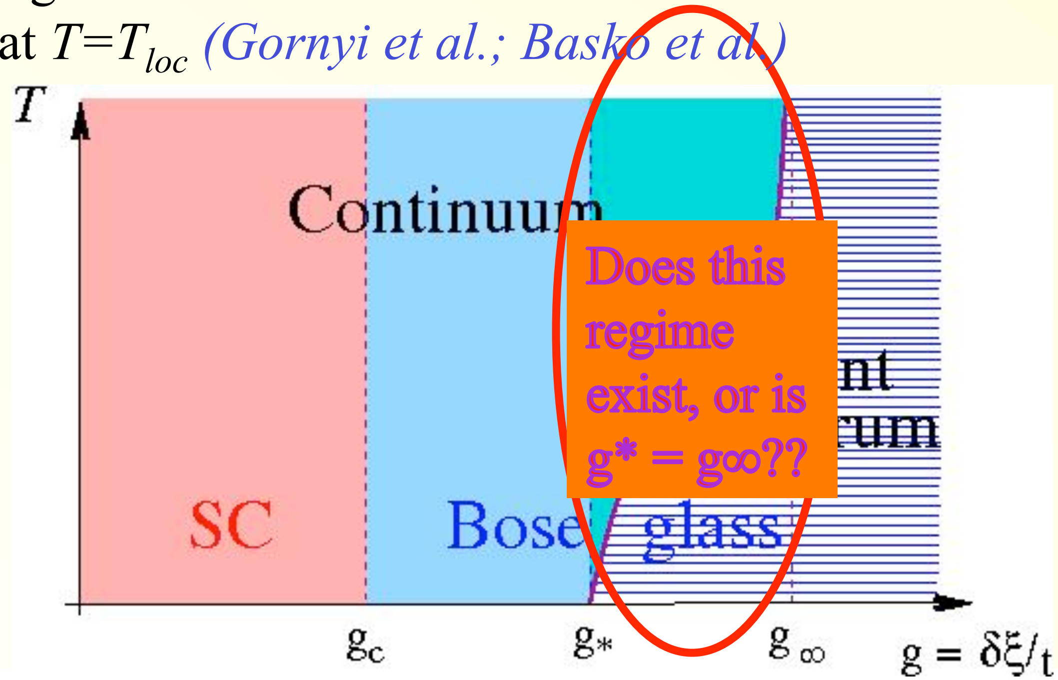
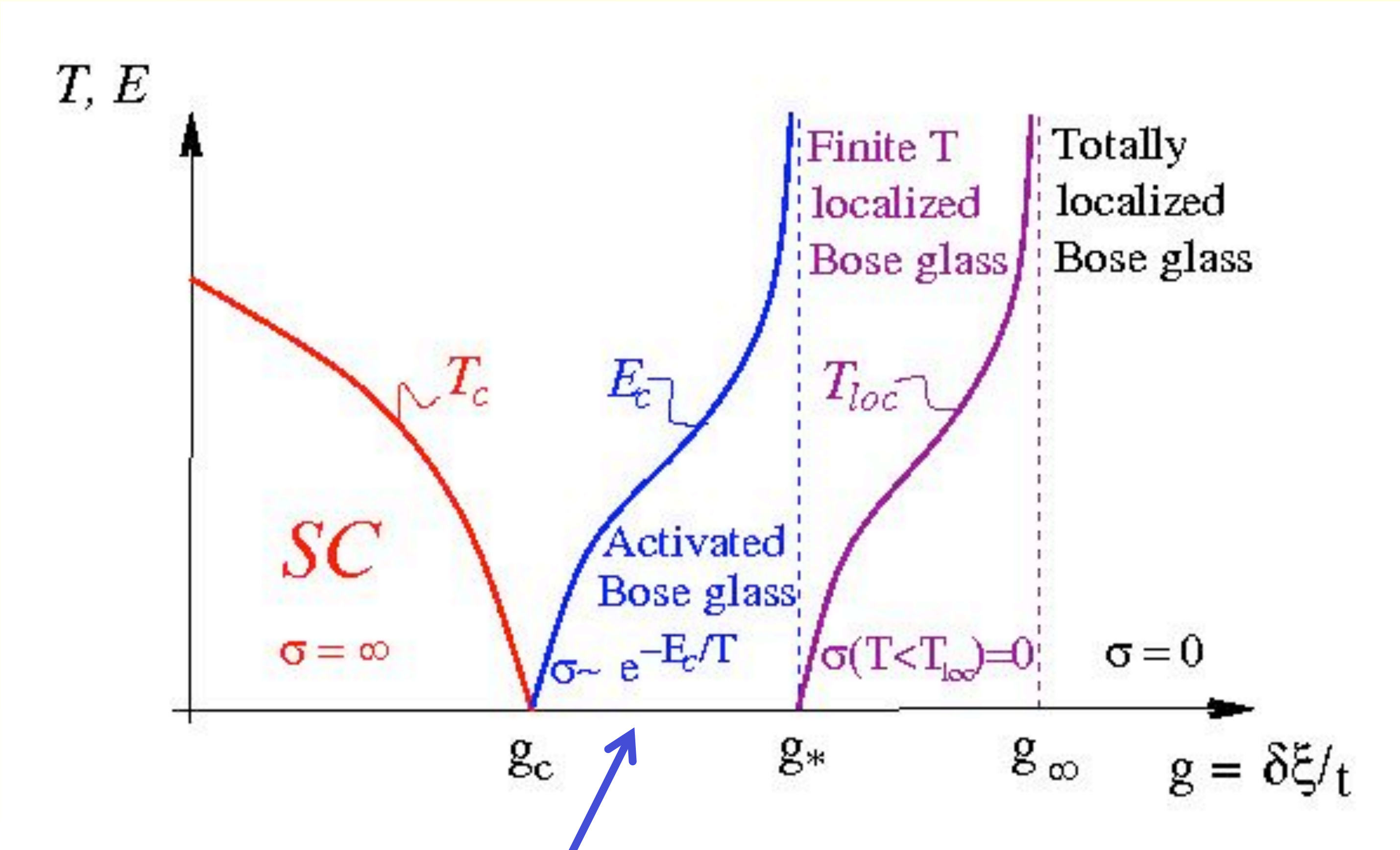
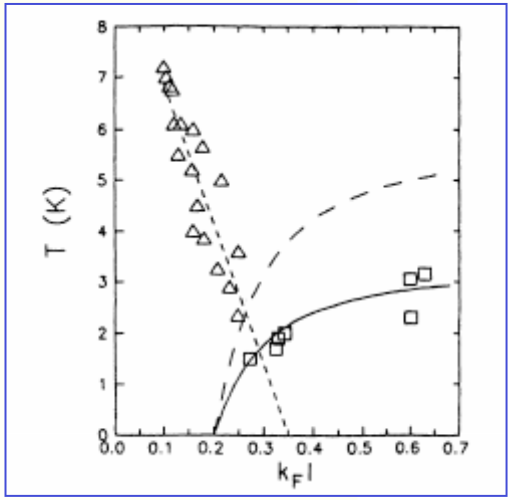


Comparison to experiment

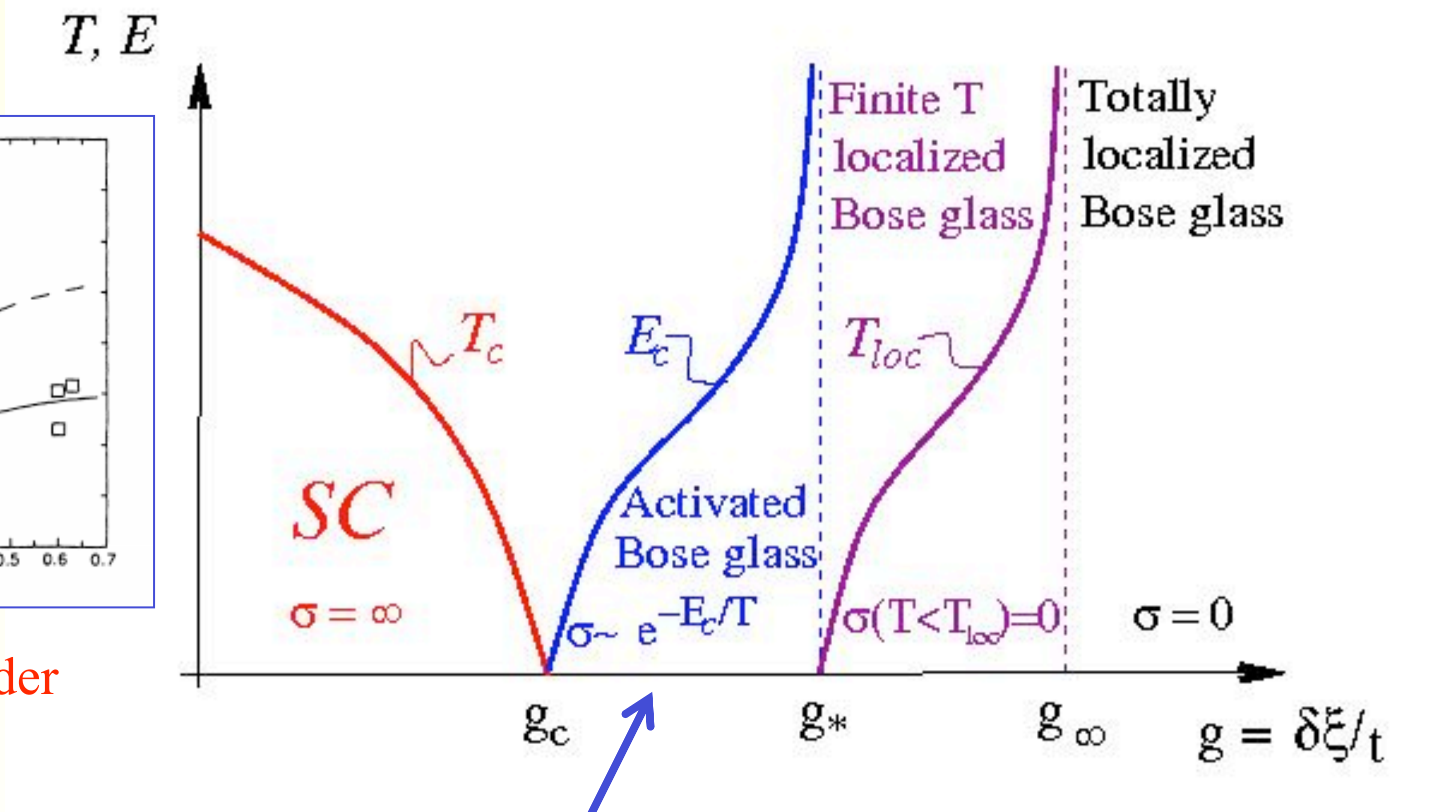


Purely electronic transport at low T: **Asymptotically** Arrhenius law!

Comparison to experiment



1/Disorder



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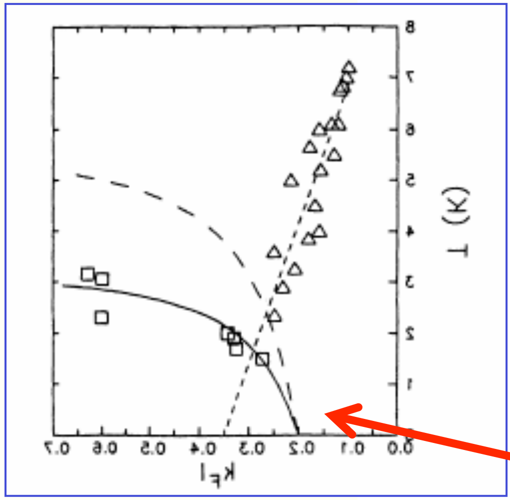

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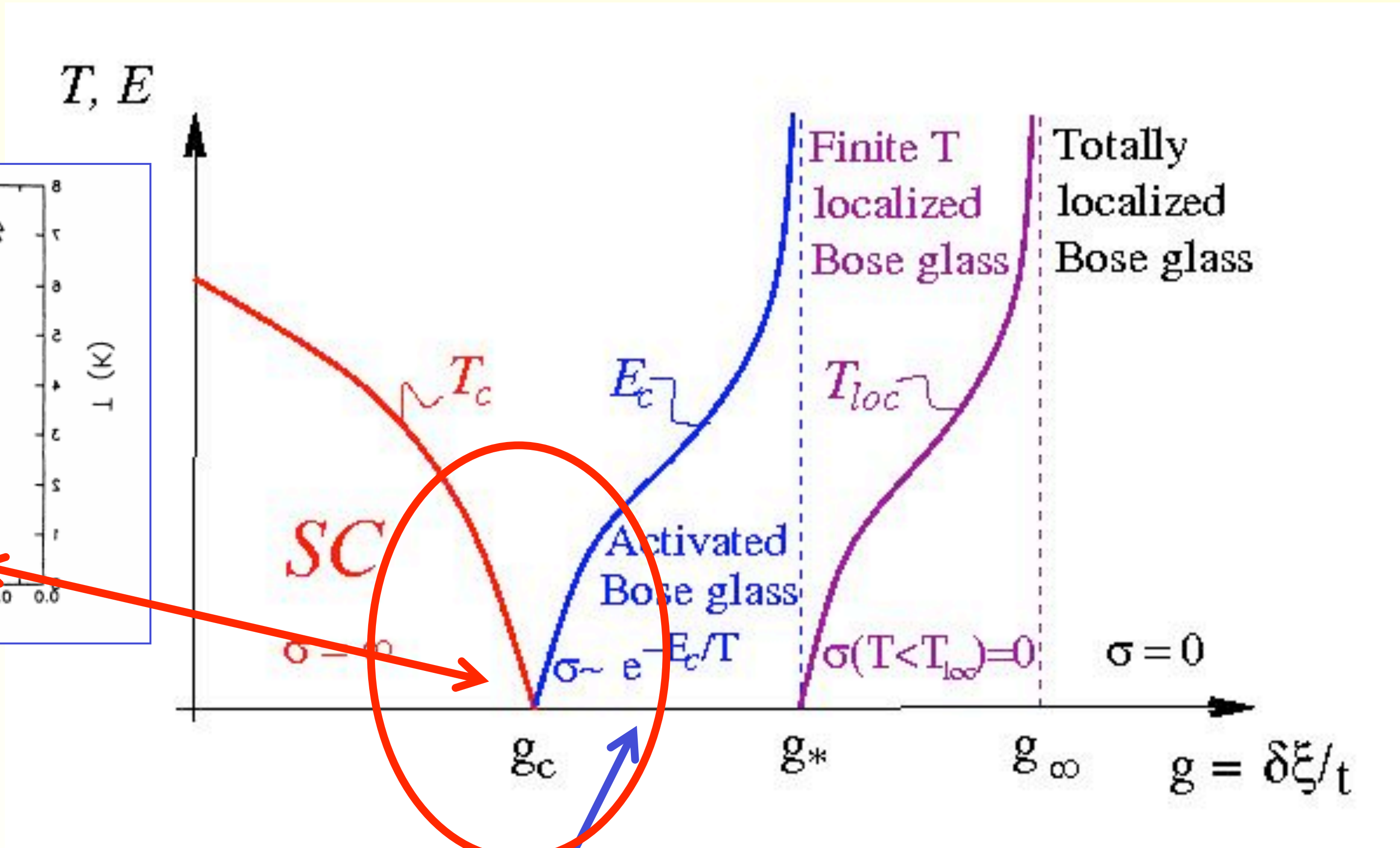

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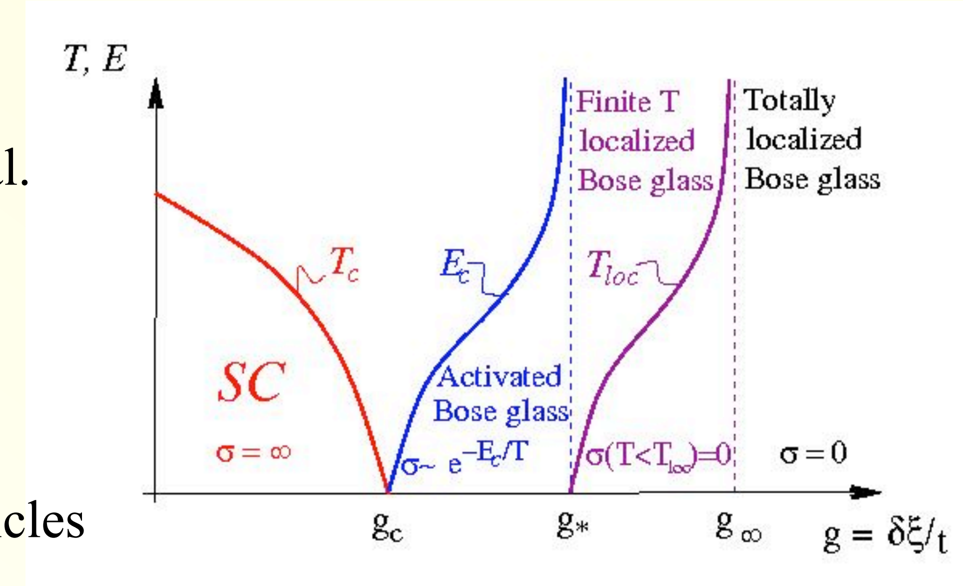
Summary: Bose-Hubbard model and Bose glass

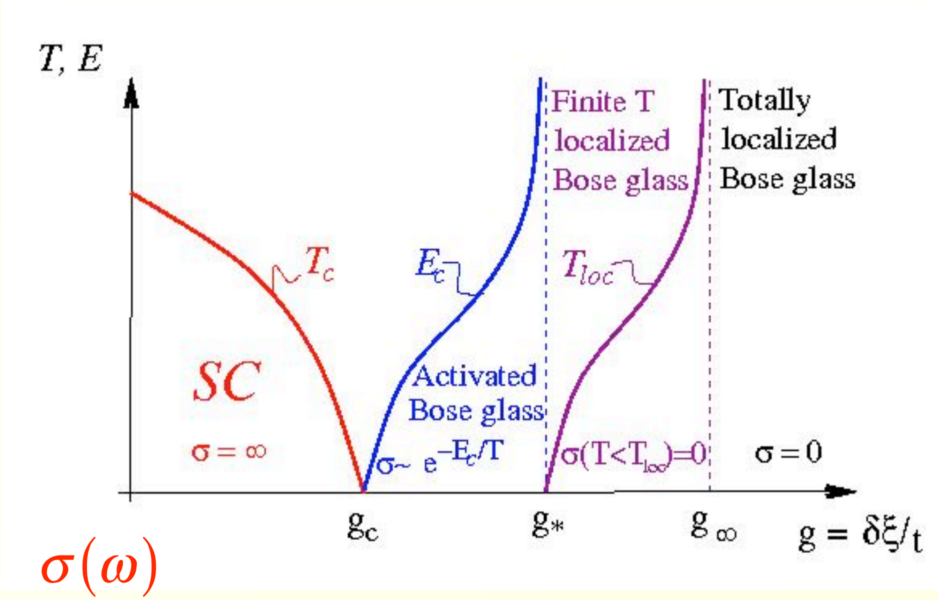
Can this scenario be proved?



- Total localization: similar to Mirlin et al. and Basko et al. (*Aleiner et al., '09*);
- Finite mobility edge: Controlled approximation on Bethe lattice (*Ioffe & Mézard '09*): mobility edge very similar to single particles
- Is the scenario true in d =1 and 2?
  - Aleiner, Altshuler & Shlyapnikov conjecture: direct transition from SC to manybody localization
  - More likely: intermediate phase also in d<3, or at most a weakly volume-dependent Ec

How to test the activated Bose glass scenario?

• Prediction: hard gap for single electrons (→ as observed in tunneling)



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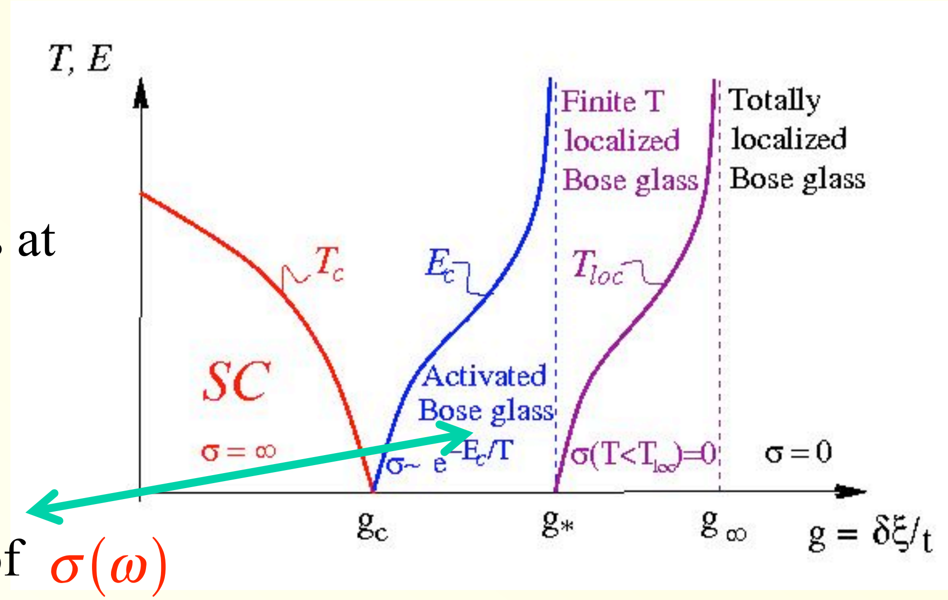
• Prediction: hard gap for single electrons (→ as observed in tunneling)

• Absence of delocalized electronic modes at low energy! Experimental consequences:

→ discrete low energy spectrum
→ very low microwave absorption
→ only imaginary (non-dissipative) part of $\sigma(\omega)$
→ very inefficient electron-phonon coupling (as observed in InOx → strong heating)
→ energy/charge diffusion may set in after a minimal, finite energy injection!



Conclusion

• Transport in the Bose glass is a rich problem due to manybody localization (quantum interference) phenomena

• SI transition: promising system to observe these phenomena and their precursors experimentally

• Similar ideas may apply to the metal-insulator and other disordered quantum phase transitions