Zoology of Glasses

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(helicopter overview)

1. Glasses: origin and classification schemes
2. Glasses with built-in disorder:
   - examples from different areas
   - "pure" glasses versus correlated glasses
3. Glasses from frustration only: self-generated disorder
   History-dependence and ageing
   v/s hierarchical organization of states
4. Theory v/s Experiments
   Main unsolved problems

What is a glass in general?

Any system with broken ergodicity without broken symmetry

Example: crystal v/s window glass

	crystal	window glass
symmetry breaking	Yes	No
ergodicity breaking	Yes	Yes

Symmetric state: Liquid

Symmetry operation: Translation

Crystal: a) periodic modulation of density ⇒ Bragg peaks
b) shear modulus

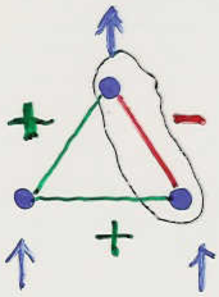
Glass: a) no Bragg peaks b) shear mod.!

What is the origin of glassy state?

Earlier concept (mid-70's):

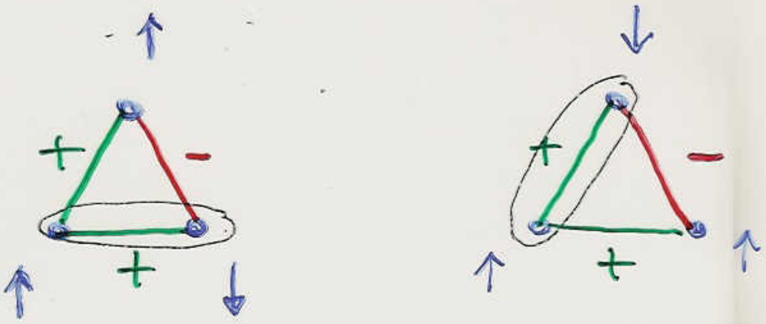
frustration + **disorder**

① Frustration:



+ = Ferromagnet bond

− = ANTIFERRO bond



Degeneracy due to frustration

6 states (out of all 8) are at the same energy $E_{min} = -J$

Without frustration $E_{min} = -3J$

degeneracy = 2 (trivial inversion)

② **Disorder** leads to some (random) choice of low-E states

Applications are numerous:

① **Spin glasses**: magnetic alloys with sign-alternating spin-exchange

$$H = \sum_{ij} J_{ij} \vec{S}_i \vec{S}_j$$

magnetic impurities in metals $\left(\begin{matrix} Cu_{1-x}Mn_x \\ Au_{1-x}Fe_x \end{matrix} \right)$

$$J_{ij} \simeq \frac{J_0}{|\bar{r}_i - \bar{r}_j|^3} \cos\left(2p_F|\bar{r}_i - \bar{r}_j|\right)$$

Low concentration of spins ($x \ll 1$, $\bar{r}_{ij} \gg 1/p_F$)

Random sign of J_{ij}

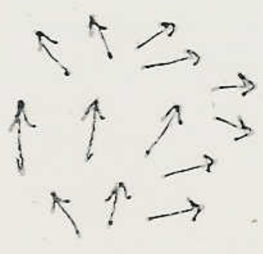
$Y_{1-x}Gd_x$, $x \ll 1$: helical SRO

② **Amorphous random-axis "Ferromagnets"**

a-$Dy_{1-x}Gd_x$ with $x \sim 0.5$

$$H = -\sum_{ij} J_{ij} \vec{S}_i \vec{S}_j + D\sum_i (\vec{S}_i \vec{n}_i)^2$$

$J_{ij} > 0$ (FERRO) **but** $D \gtrsim J$ and $\vec{n}_i$ is <u>random</u>

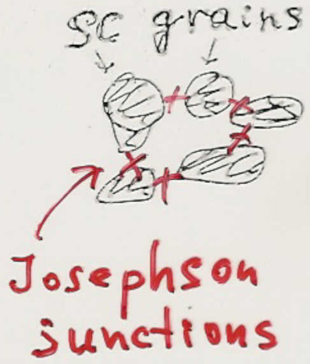


but

FM on short scale

SG on long scale

3. Superconductive ceramics and granular arrays



$$H = -\sum_{ij} E^J_{ij} \cos(\varphi_i - \varphi_j - A_{ij})$$

$$A_{ij} = \int_{\bar r_i}^{\bar r_j} \vec{A}(\bar r)\, d\bar r$$

vector potential

Strong frustration:

$$|\mathrm{rot}\, \vec{A}| = |\vec{B}| \gtrsim \Phi_0/d^2$$

grain size

φ_i is the phase of SC order parameter of i-th grain

At $T \lesssim Z E^J_{ij}$ and $B = 0$:

<u>MACRO-SC state</u>: $\Psi = \overline{\langle e^{i\varphi_i} \rangle} \neq 0$

At $T \lesssim \sqrt{Z}\, E^J_{ij}$ and $B \gtrsim \Phi_0/d^2$?

$\Psi = \frac{1}{N}\sum_i \langle e^{i\varphi_i} \rangle = 0$ but <u>$R(T \to 0) = 0$</u>

Superconductive (Josephson, gauge) Glass

④ Type-II Superconductors with disorder + B

a) Abrikosov lattice of vortex-lines is formed at $H_{c1} < B < H_{c2}$

Crystal with triangular lattice – translational symmetry breaking

b) Take into account positional disorder in superconductor:

$$H = \int dz \left\{ \sum_{ij} V(\bar{r}_i(z) - \bar{r}_j(z)) + \sum_i U[\bar{r}_i(z)] \right\}$$

vortex-vortex repulsion

random potential for vortex

The result (A. Larkin 1970):

1) LR crystalline order is destroyed
Vortex lattice is transformed into <u>VORTEX GLASS</u> and <u>PINNED</u>

2) Superconductivity is recovered !

5 Electron glass:

low-temperature transport in doped semiconductors and granular metals.

$$H = \sum_{ij} n_i \frac{e^2}{|\vec{r}_i - \vec{r}_j|} n_j + \sum_i \mu_i n_i$$

$n_i = 0$ or 1 $\qquad$ μ_i is random as well as $\vec{r}_i$

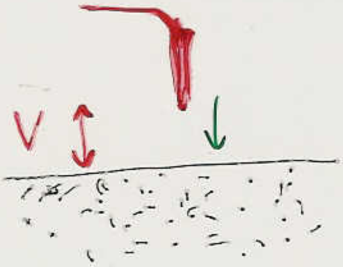
Define $\sigma_i = 2n_i - 1 \Rightarrow \sigma_i = \pm 1$

and get **strongly frustrated Ising random ANTIFERRO**

Signatures: 1) Efros-Shklovsky dc resistivity

$$\rho(T) \propto \frac{h}{e^2} \exp\left(\sqrt{T_0/T}\right)$$

2) Soft „Coulomb gap" in the tunnelling density of states:



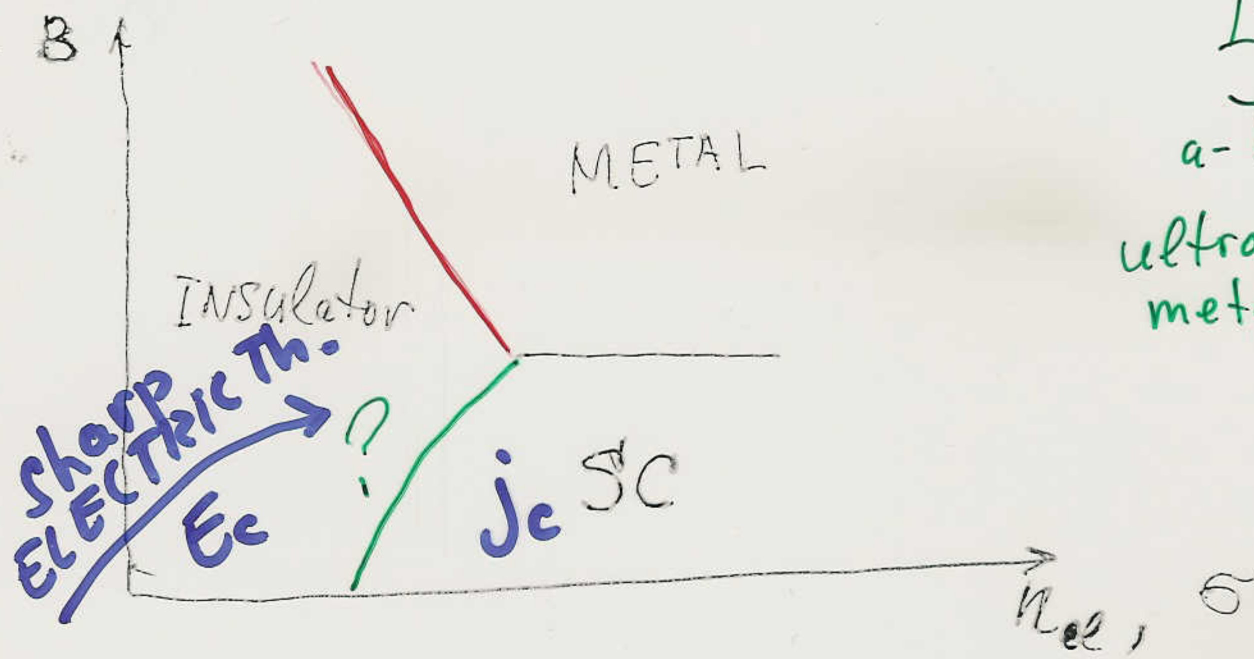
$$dI/dV \propto N(eV)$$

$$N(E) \sim |E| \quad \text{in 2D}$$

$$\sim E^2 \quad \text{in 3D}$$

1st "glassy theory" of EG: M. Müller, L. Ioffe MAY 2004

⑥ Superconductor – Insulator Transition



In_2O_{3-x}

a-TiN

ultrathin metal films

1. Local superconductivity (grains)
2. Josephson coupling induces superconductive correlations
3. Coulomb repulsion tends to localize charges
4. Magnetic field induces frustration in Josephson coupling, thus makes it weaker

SC = Josephson glass

I = Cooper-pair glass (or Coulomb glass)

Compare:

Spin glass v/s Random-axis FM

Josephson glass v/s Vortex glass

Completely RANDOM glassy states

Glassy states with short-range order of „usual" kind

Remote example:
Statistical models of associative memory

The idea: to arrange interaction between „bits" ($m_i = 0, 1$) in such a way that some specific patterns are the most stable attractors

Number of patterns $K \lesssim N$ $(i = 1 \dots N)$

At larger K transition to glass occurs

Do we really need both frustration and disorder to obtain glassy state?

No!

Some highly frustrated systems without built-in disorder produce at low T glassy states (stationary or quasistationary)

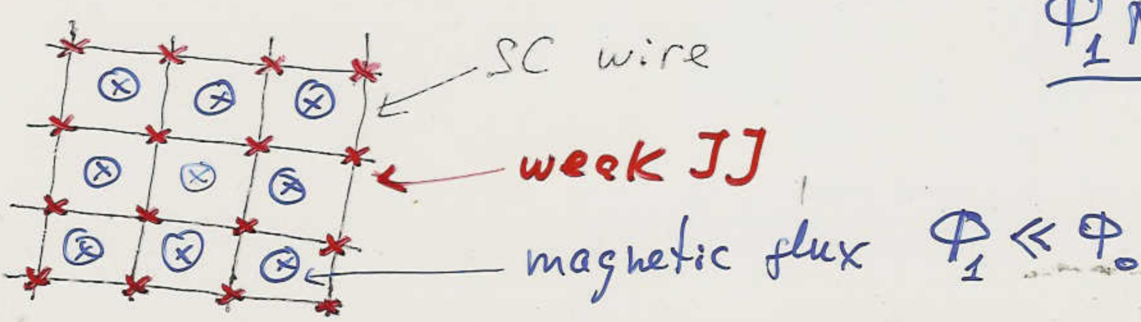
Examples:

Structural glasses: SiO_2 glass
metal glasses

glassy states: result of sufficiently fast cooling

Periodic Long-range Josephson array
(Chandra, Feigelman, Ioffe '96)

$$\Phi_1 N^2 \gg \Phi_0$$



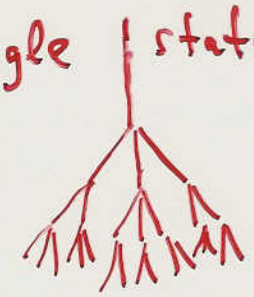
Glasses:

Built-in v/s self-generated

What is the difference?

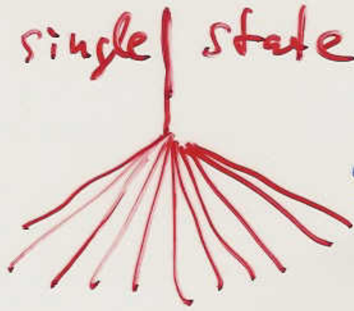
Hierarchy of metastable states

single state



T down ↓

single state



$\mathcal{M} \sim e^{\alpha N}$

continous branching during cooling below T_g (both dynamic and thermodynamic transition)

continuous RSB

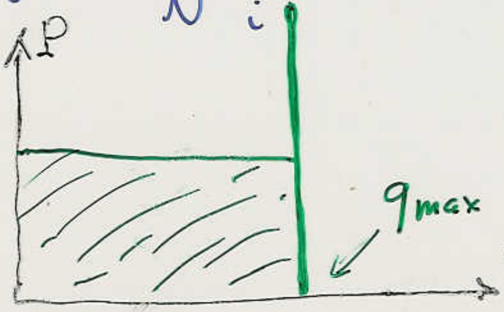
Instanteneous branching at $T = T_g$ (purely dynamic transition)

1-step RSB

Distribution of overlaps: $P(q)$

$m_i^\alpha = \langle S_i \rangle_\alpha$ $\quad$ $m_i^\beta = \langle S_i \rangle_\beta$

$q^{\alpha\beta} = \frac{1}{N} \sum_i m_i^\alpha m_i^\beta$ $\quad$ $P(q) = \frac{1}{\mathcal{M}^2} \sum_{\alpha\beta} \delta(q - q^{\alpha\beta})$

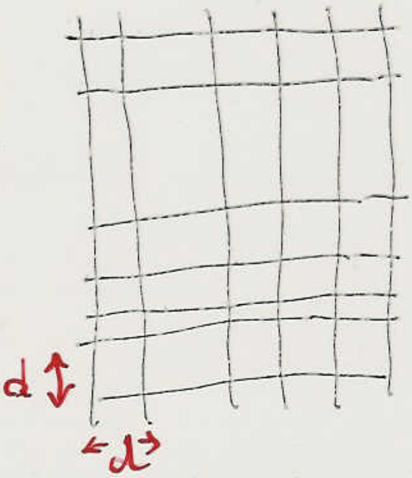


How to detect difference between 2 types of glasses (built-in v/s self-generated) experimentally?

Compare two versions of the Josephson Glass with long-range coupling: Random (Ioffe, Larkin, Feigelman, Vinokur 1987)

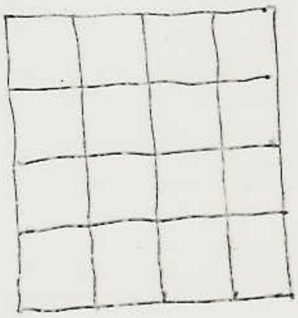
regular (Chandra, Ioffe, Feigelman 1996)

SK-like SG



1)

$\otimes$ B



2)

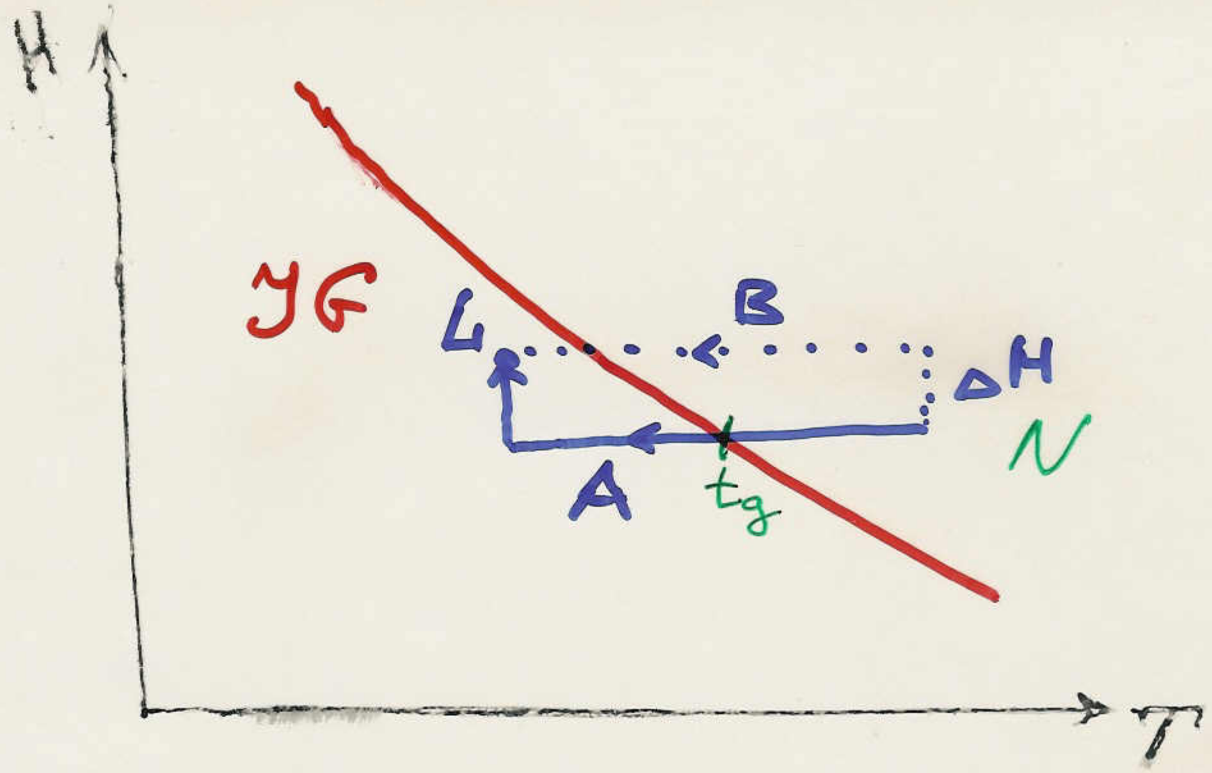
mode-coupling dynamics

p-spin spherical SG

Frustration comes via random areas in case 1) or via equal areas in 2)

Glassy phase is formed at $B \gg \frac{\Phi_0}{d^2 N^2}$ in both cases.

Observable: diamagnetic response NON ERGODIC!



$M(H,T)$ is path (history) - dependent :

$$M\left[(H,T)=L,\ B\right]=0$$

$$M\left[(H,T)=L,\ A\right]=-\mu\int q(t,t')\,\Delta(t,t')\times(H(t)-H(t'))\,dt'$$

Anomalous response function $\Delta(t,t')\neq 0$ at $T<T_G(H)$ [i.e. in glassy phase]

RANDOM ARRAY $\quad M[A]=-\mathrm{const}\,(T_g-T_f)^3\,\Delta H$

does not decay with time of observation

Regular array $\quad M[A]=-\mathrm{const}\left(\dfrac{t_H-t_g}{t-t_g}\right)^{2\gamma}\Delta H$

Strong ageing

Theory v/s Experiment

Spin glass (the most studied one!)

Detailed theory for INFINITE-RANGE models (both built-in and self-generated)

in two versions: Replica theory (Parisi) and Dynamic „slow cooling" theory (L. Ioffe et al; L. Cugliandolo and J. Kurchan)

Experiment for 3D spin glass:

most detailed study by

M. Ocio and D. Herisson

could not discern between <u>1-step RSB</u> (simultaneous branching) and <u>continuous RSB</u> (hierarchical branching)

but excludes „simple domain growth" <u>(no RSB)</u>

other glasses: much less is known

Electron glass:

Experimentally aging was observed (Z. Ovadyahu et al) but with quite different protocol compared to spin glass (M. Ocio et al)

Theory: analitic approach just started now (L. Ioffe, M. Muller

Vortex glass:

Theory: S. Korshunov (1993)
T. Giamachi and P. le Doussal (1994)

PINNED LATTICE without Disloc.

How does it transform into Phase (Josephson) Glass ??

Theory: eigenfunction expansion

$$E\{\vec{S}_i\} = -\sum_{ij} J_{ij}\, \vec{S}_i \vec{S}_j \qquad \text{(energy)}$$

$$F\{\vec{m}_i\} = -\sum_{ij} \vec{m}_i \vec{m}_j J_{ij} - T\, S\{\vec{m}_i\}$$

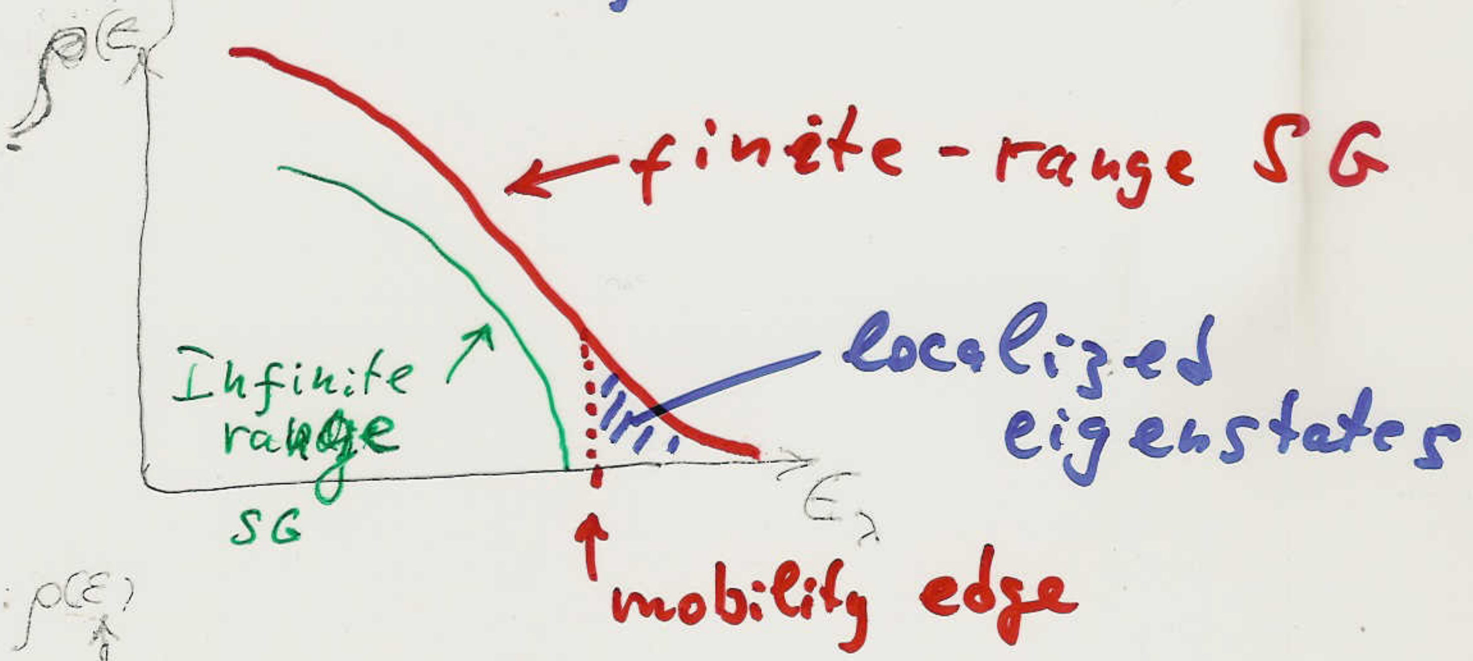
free energy entropy

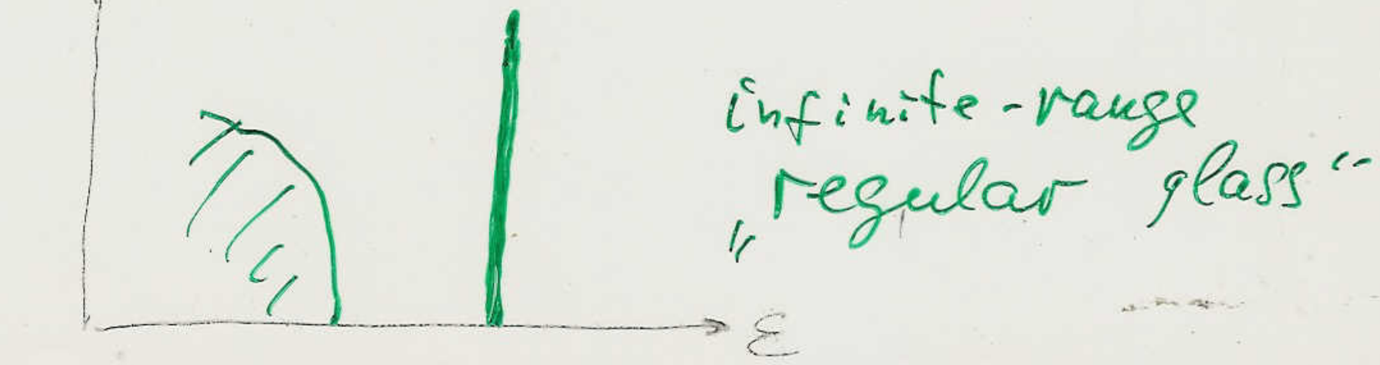
(Landau-Ginzburg expansion)

For SG: Thouless-Anderson-Palmer (1977)

Expand $S\{m_i\}$ up to 2^{nd} order

$$F_2\{\vec{m}_i\} = -\sum_{ij} \vec{m}_i \vec{m}_j \left(J_{ij} - T\delta_{ij}\right)$$





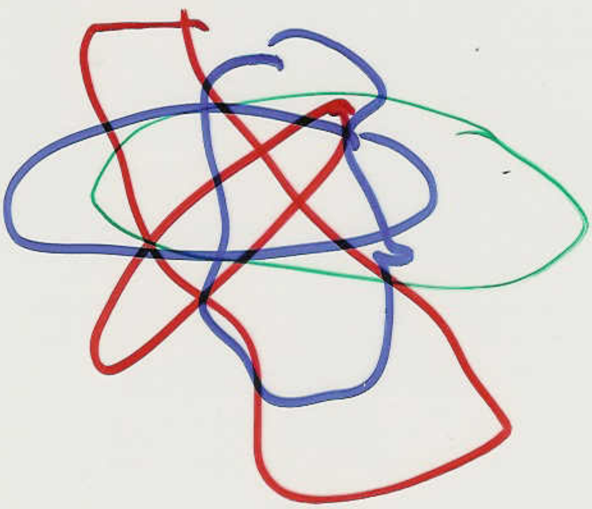
Finite range SG:

condensation of localized modes

$$\vec{m}_i = \sum_\lambda \vec{a}_\lambda \psi_i^{(\lambda)}$$

eigenfunction

amplitude
(new dynamic variable)



„overlapping
fractal
clusters"

$$\tilde{F}\{\vec{a}_\lambda\} = -\sum_{\lambda\mu} \vec{a}_\lambda \vec{a}_\mu \tilde{J}_{\lambda\mu}$$

Dicrete RG near 3D
Ising SG transition