Cooper pair transport in an array of Josephson nanojunctions with dice lattice

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Outline

- ✓ Introduction
  - localisation effect in the dice lattice
- ✓ classical superconducing arrays :
  - T_c, I_c suppression, glassy vortex state
- ✓ quantum arrays
  - S-I transition, metallic phase
- ✓ the dice family of JJ arrays
  - exotic superconducting phase

- **Collaborators**
  - E. Serret , F.Balestro, C. Abilio
  - P.Butaud, J. Vidal
  - O. Buisson, K. Hasselbach
  - Th. Fournier

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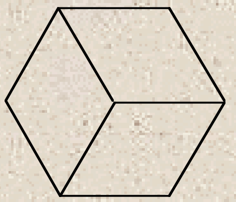
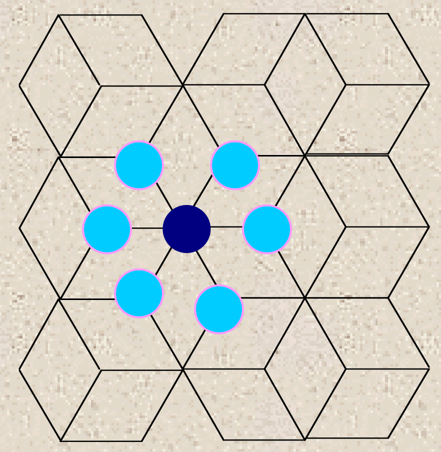
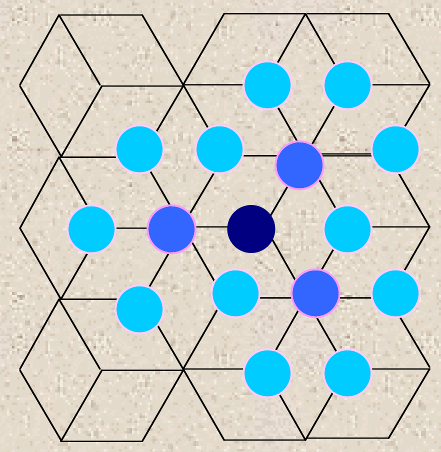
localisation effect in the « dice » lattice



Bravais cell





$f=\phi/\phi_0$

ϕ_0 :flux quantum

- non-interacting tight binding electrons *(Vidal, PRL81, 1998, p5888)*

  f=1/2 ⇒ localisation due to quantum interferences (AB cages)

  cage effect suppressed by : disorder, edge states , <u>interaction</u>.

- GaAs quantum wires (electrons : fermions e) *C. Naud et al. PRL86, 5104 (2001)*

- h/e, h/2e magnetoresistance oscillations → Aharonov Bohm cages

- Superconducting arrays (Cooper pairs : bosons 2e)

- wire networks : Schrödinger equation (1 particle) ≡ linearized GL equations

for the macroscopic superconducting state (fluctuations neglected)

Josephson Junction arrays

- classical dice JJ array

highly frustrated state with thermal fluctuations : $\cos(\phi_i - \phi_j - A_{ij}) \Rightarrow J(f)\, \mathbf{S_i S_J}$

vortices on the Kagomé (dual) lattice

- quantum JJ array

Josephson coupling + Coulomb blockade

$$H = -E_J \sum \cos(\phi_i - \phi_j - A_{ij}) + \frac{(2e)^2}{2} \sum n_i C^{-1}_{ij} n_j$$

$$\frac{1}{2} \sum n_i U_{ij} n_j$$

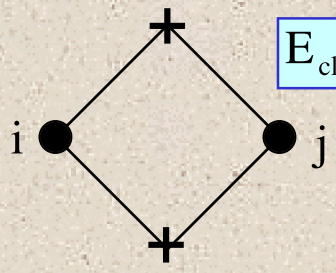
Hubbard

$$-\frac{t}{2} \sum (e^{-iA_{ij}} b_i^{+} b_j + h.c.)$$

hopping of Cooper pairs

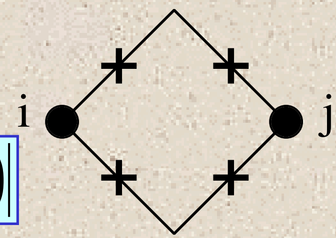
- role of elementary rhombuses ("dimers")

SQUID : E_J suppressed at f=1/2



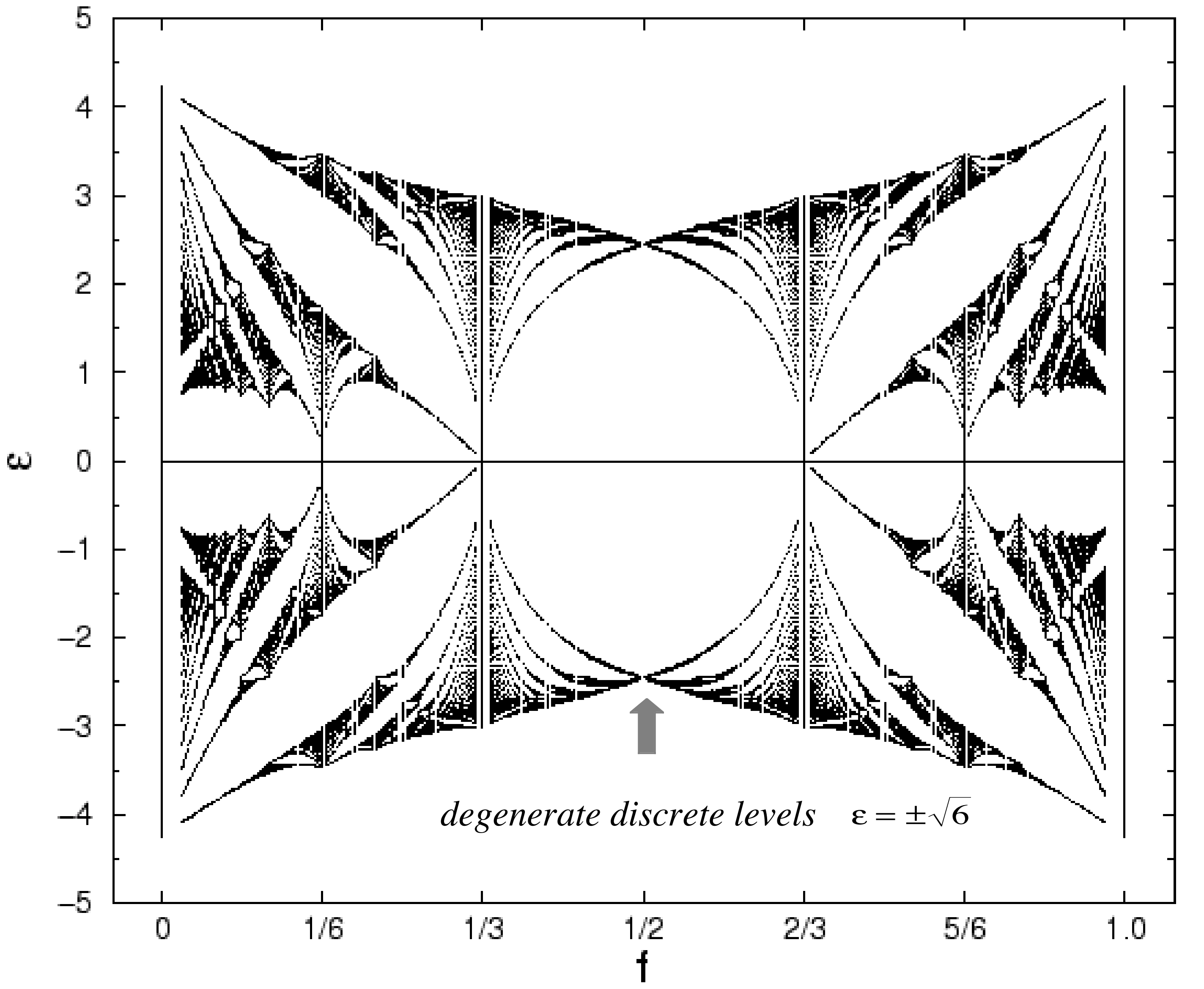
$$E_{class} = -2\cos\theta_{ij} \left|\cos \pi f\right|$$

Rhombus : additionnal degree of freedom : phase of intermediate island



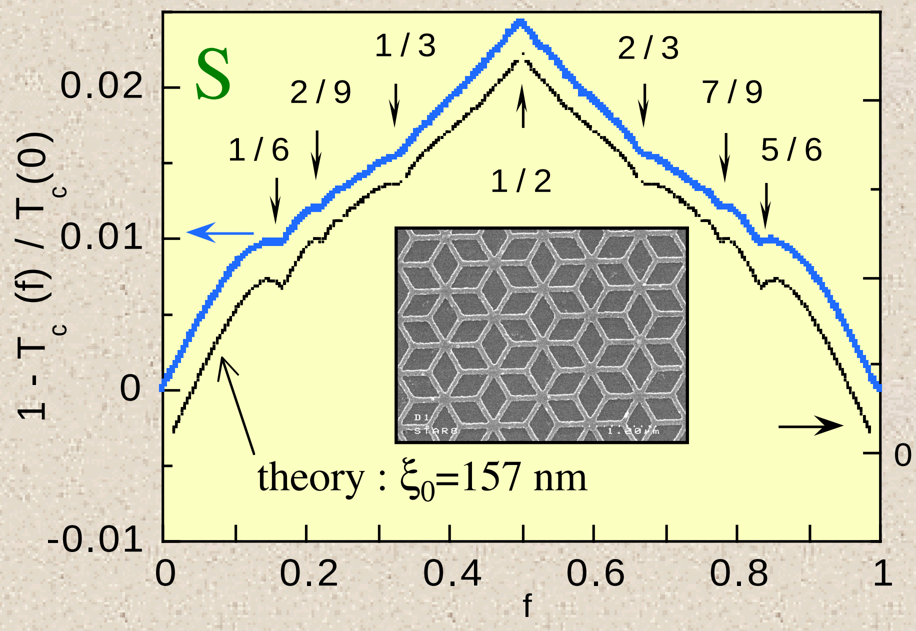
$$E_{class} = -2\left|\cos\left(\tfrac{\theta}{2} - \tfrac{\pi f}{2}\right)\right| - 2\left|\cos\left(\tfrac{\theta}{2} + \tfrac{\pi f}{2}\right)\right|$$

Landau levels of the ‘dice’ array



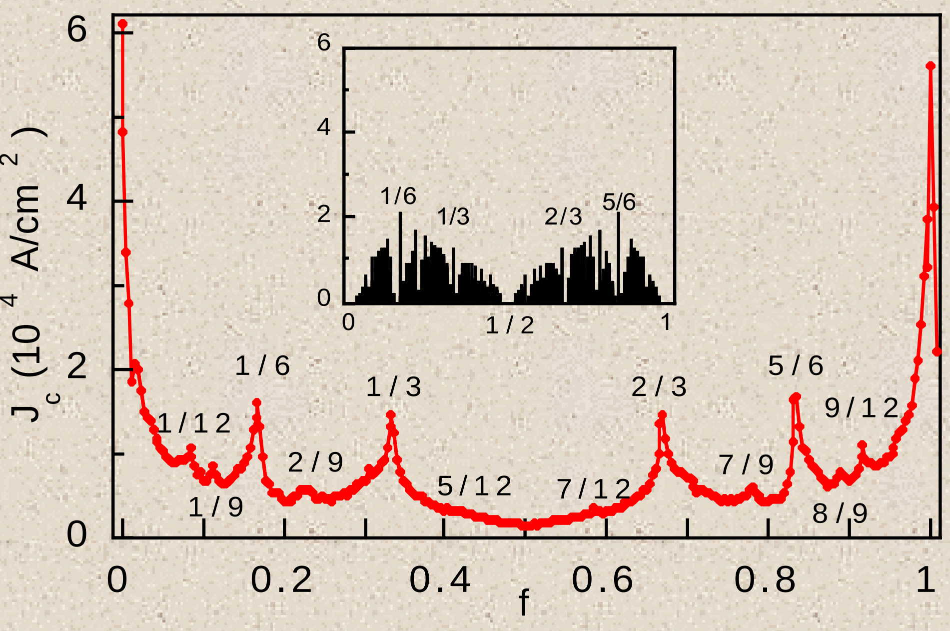
Superconducting Al wire network

• Critical temperature



$T_c(0)$=1.234 K

• Critical Current



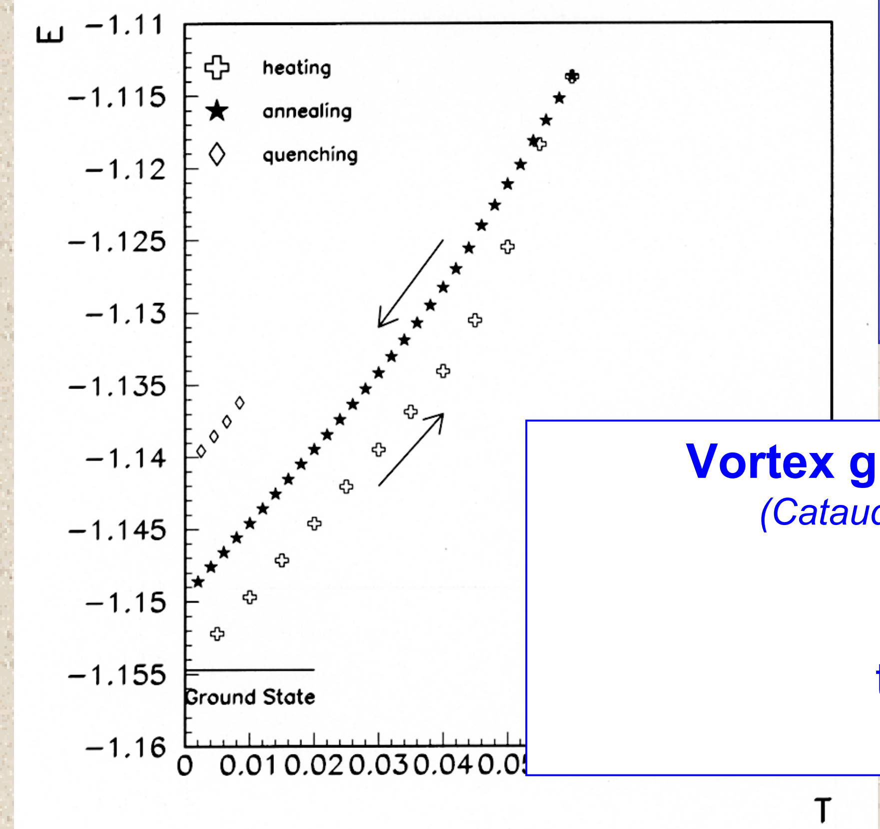
C. Abilio et al. PRL83, (1999) 5102

➡ at f=1/2 => « suppression » of superconducting order

The superconducting ground state at f=1/2

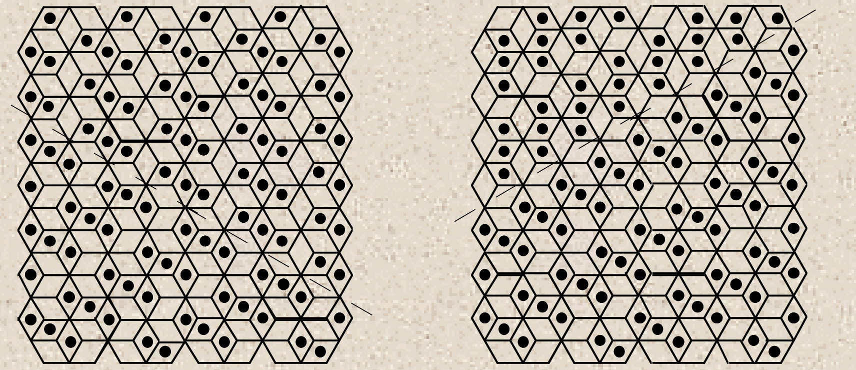
- **Classical spins on Kagomé lattice**
  disordered à T=0
  (Huse PRB45, 1992 p7536)

- **Josephson « dice » array** :
  highly degenerate metastable states



Theoretical Prediction:

S.Korshunov PRB, **63**, 134503 (2001)



ground state ➪ vortex triads

with zero energy domain walls

↪ S=(N+M)ln2 : non-extensive entropy

Vortex glass phase at T< T_{KTB}

(Cataudello and R. Fazio, 2002)

T_{KTB} =0.03 E_J

thermal hysteresis

slow dynamics

Magnetic imaging: Observed Configurations at f=1/2

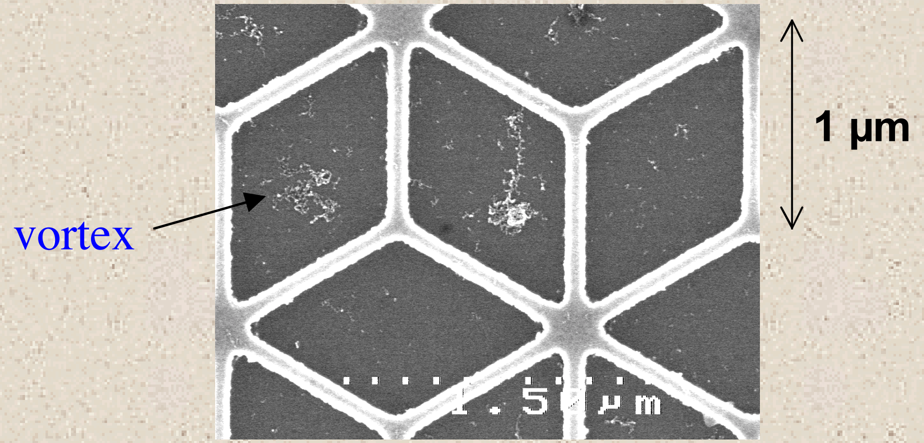
Magnetic decoration of vortices

Europhys. Lett. 59, 225 (2002)

field cooled epitaxial Nb wire array

Tc=9K

B = 11,93 Gauss for f=1/2

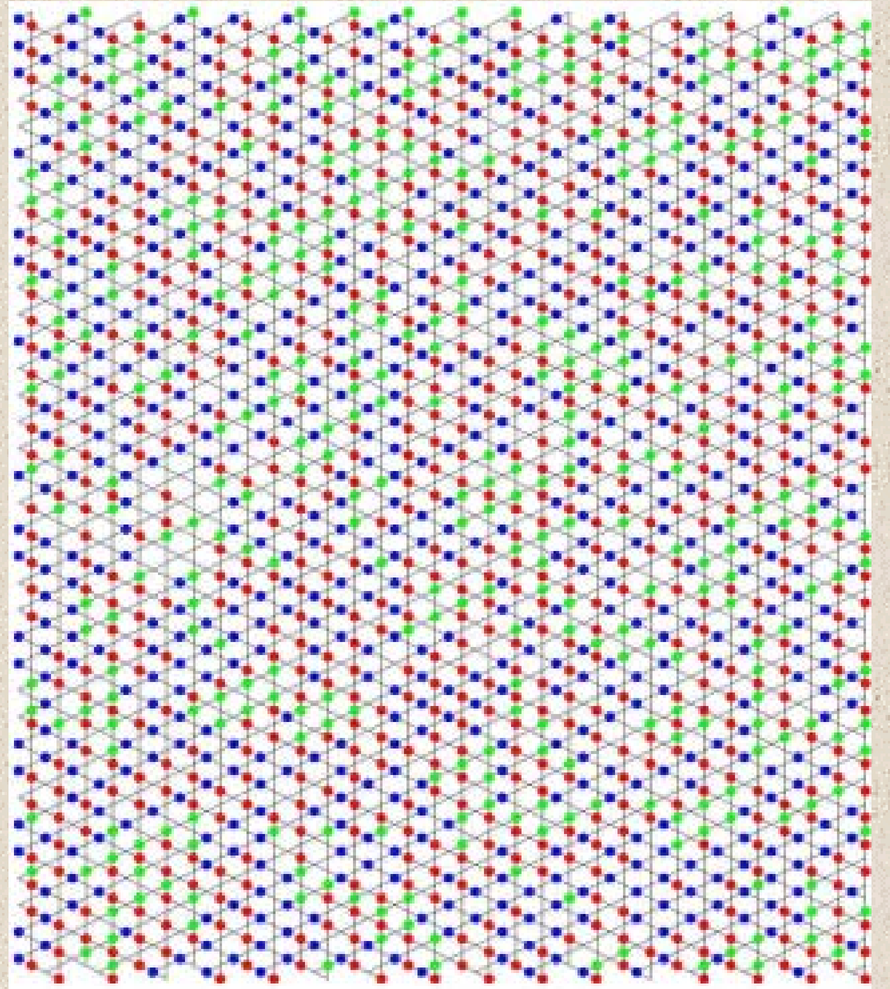


- ✦ No commensurate phase

⇒ disordered configuration?

Observed configuration

(reconstructed on the Kagomé lattice)



3 456 sites containing 1 725 vortices

↪ f=1/2-0,001

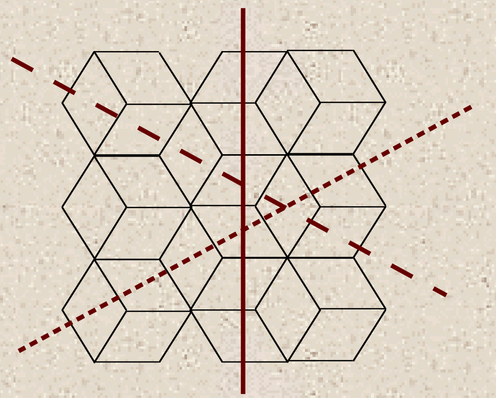
Magnetic imaging: Correlation function calculation

$$C_{\alpha,\beta,\gamma}(r) = \langle V_i . V_{i+r} \rangle$$

V_i : « vortex » variable

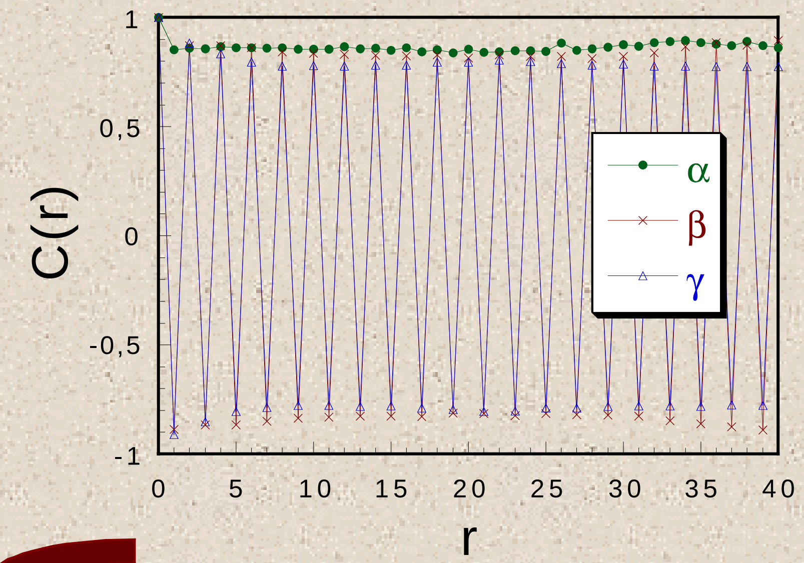
= 1 if a vortex is in the i cell

= -1 if not

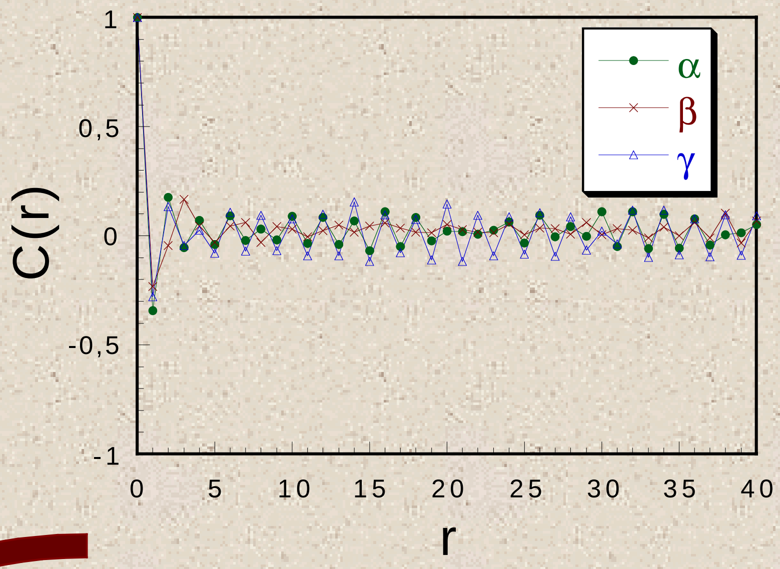


Collaboration. P.Butaud

✦ f=1/3



✦ f=1/2

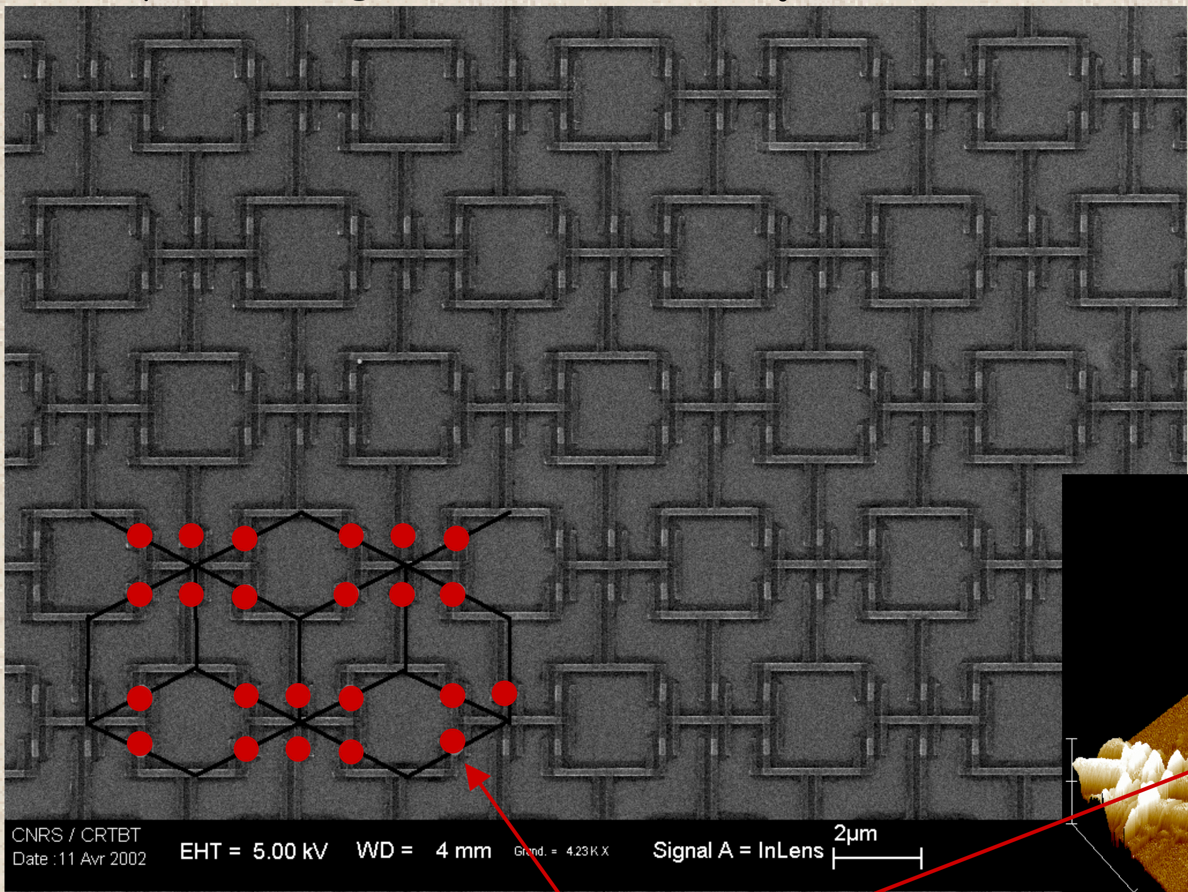


Long range order:
C(r) > 0,8 until r = 40

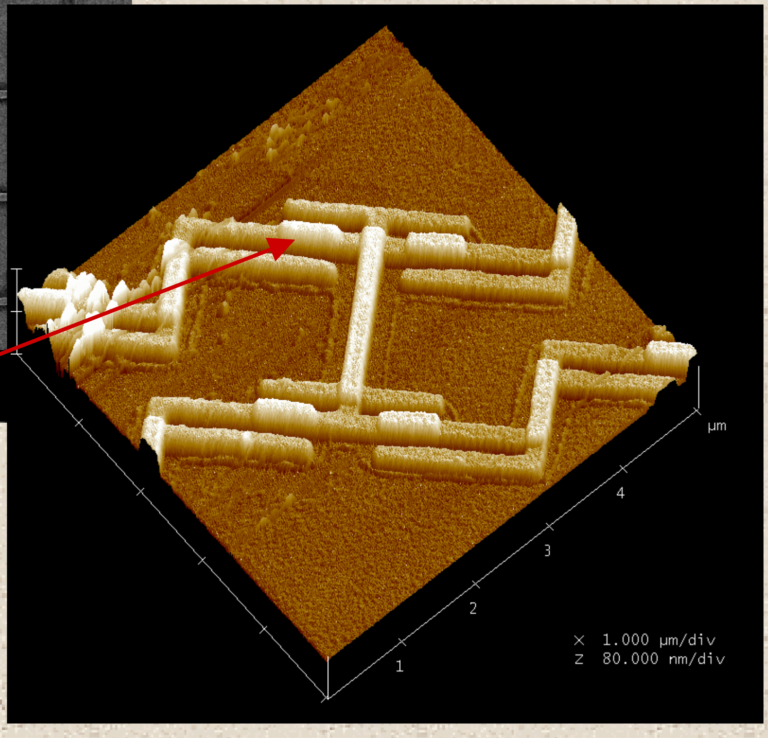
No long range order:
$\xi \approx 1{,}5$

Nanofabrication: Samples

(Array containing more than 127 000 junctions)



Chain of « cages »



Josephson junctions

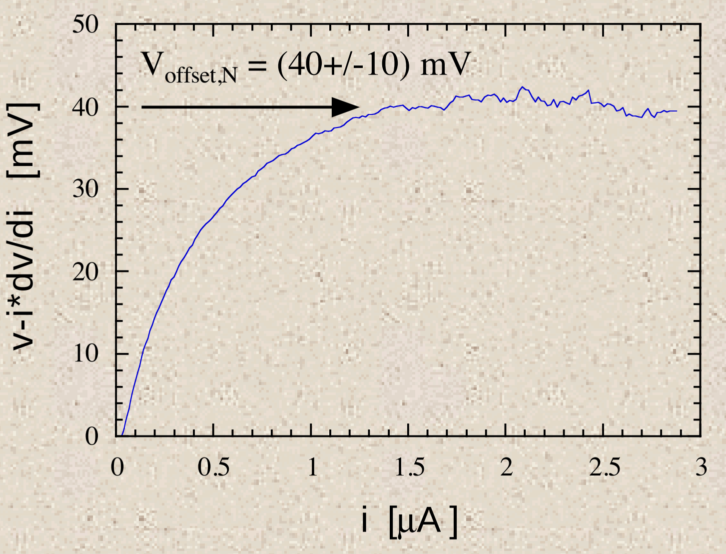
Transport: Samples overview

- Estimation of E_J with R_n measured at 4K

- Estimation of E_c with the offset voltage:

$$V_{offset} = N\frac{e}{2C}$$

i.e. about 50fF/μm^2



Sample	S [μm^2]	R_n [kΩ]	E_J [μeV]	C [fF]	E_c [μeV]	E_J/E_c	Regime
A	0,06	4,93	130	3	27	**4,9**	Classical
B	0,023	20,4	32	1,3	61	**0,5**	Quantum
C	0,015	53,3	12	0,5	160	**0,05**	Charge

Cell area = 5,57 μm^2 => f=1 ≡ B=0,3716 mT

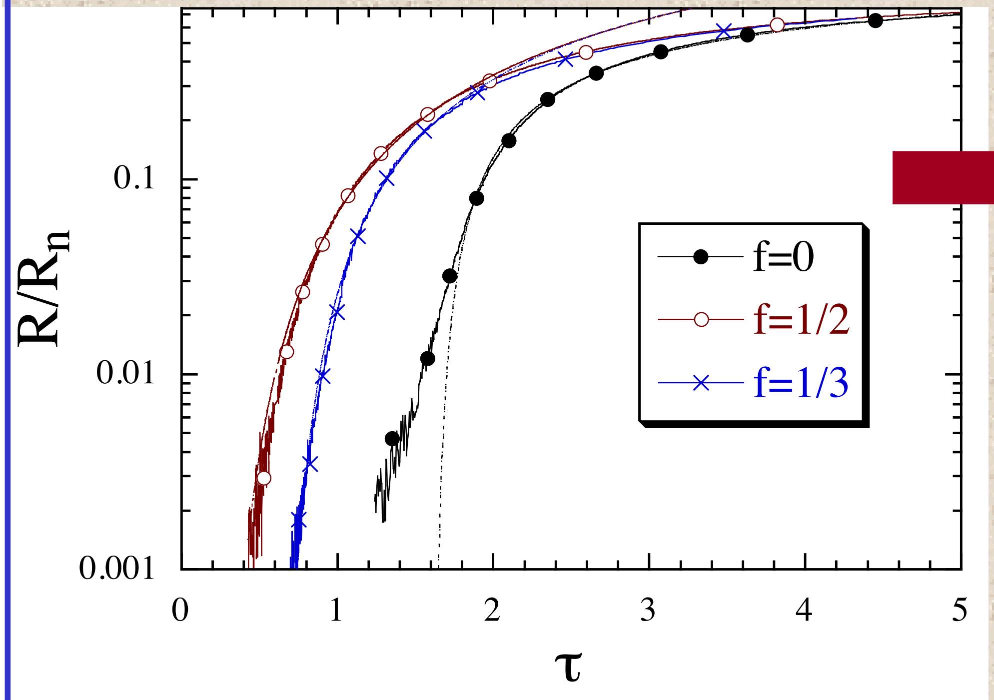
Transport: Classical array with E_J/E_C=4,9

Study of the KTB transition:

if $T>T_{KTB}$, $$\frac{R(T)}{R_n} = b_1 \exp\left[\frac{-b_2}{\sqrt{\tau - \tau_{KTB}}}\right]$$

with $\tau = {k_B T}/{E_J(T)}$, and $b_1, b_2 \approx 1$

	τ_{KTB} theoretical	τ_{KTB} measured
f=0	1,8	1,68
f=1/3	0,36	0,57
f=1/2	0,108	0,155



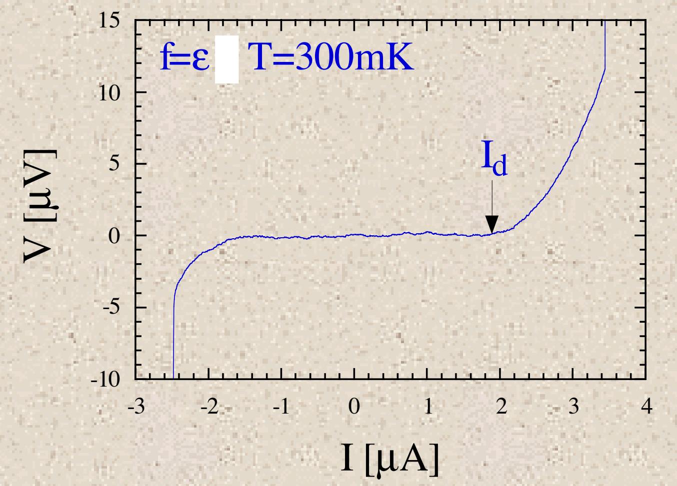
- At f=1/2, the array undergoes a KTB transition
- Relatively good agreement with theory (uncertainty on Δ(T))

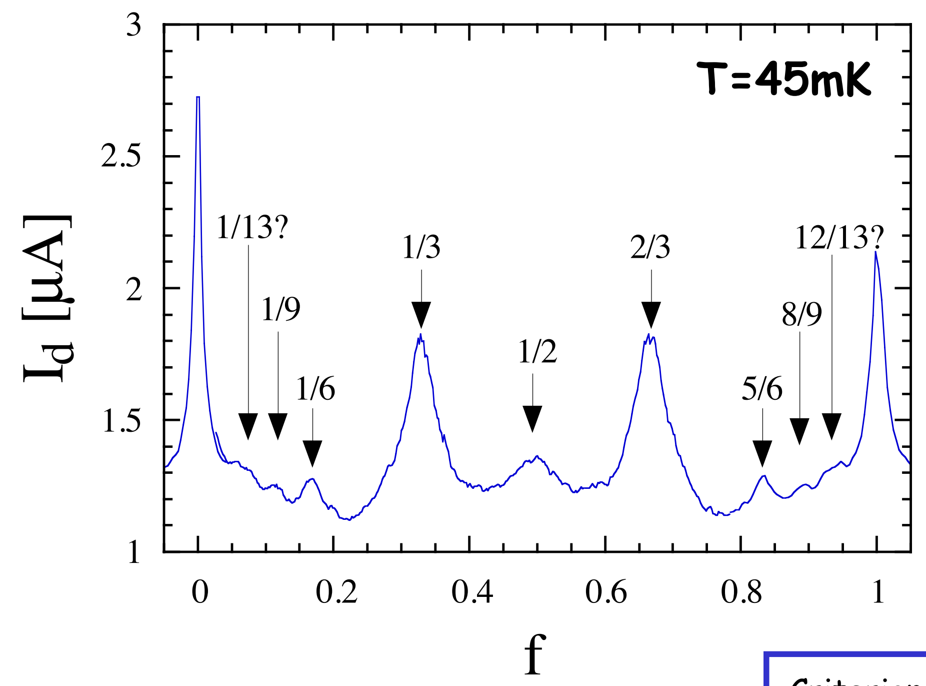
Is the f=1/2 state a vortex glass?

Transport: Classical array with E_J/E_C=4,9

Study of the superconducting phase at f=1/2

⇒ vortex configuration pinning force measurement





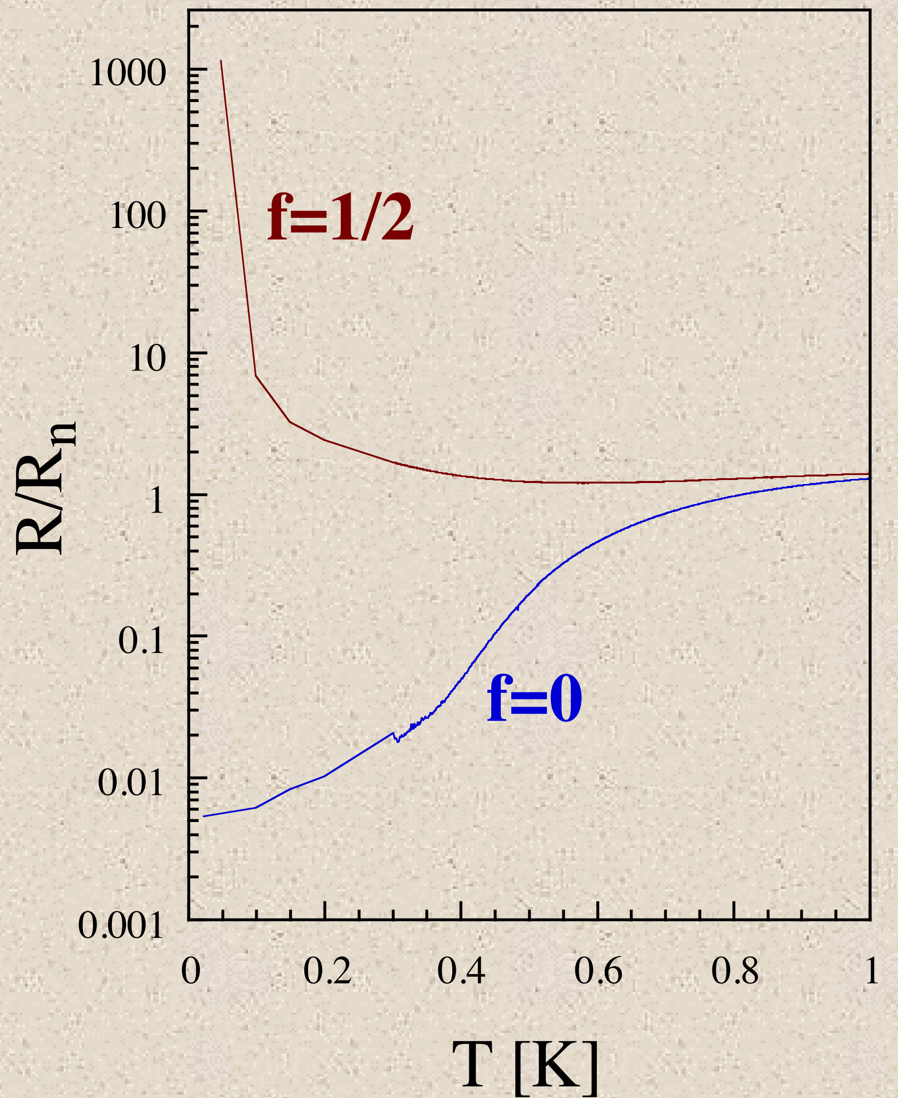
Criterion 1μV

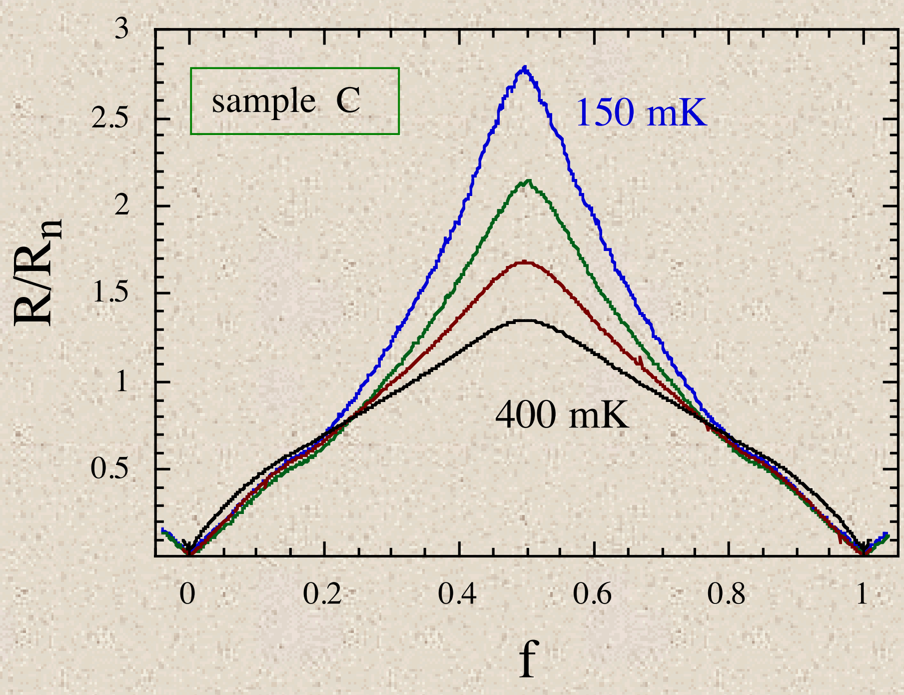
1. Max of I_d at
   f = 0 , 1/13 , 1/9 , 1/6 , 1/3 , 2/3 , 5/6....

2. Max of I_d at f=1/2 ≠ wire arrays

Commensurate state at f=1/2

Transport: Charge array with E_J/E_C=0,05



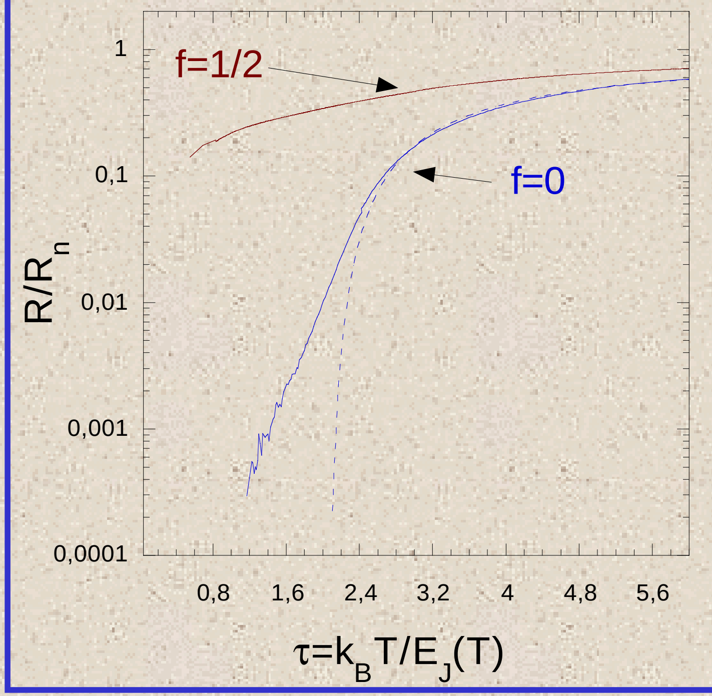


Metal-Insulator transition induced by B
at $f_{c,1}$ = 0,23 and $f_{c,2}$ = 0,76

At f=1/2: insulator (R > 50MΩ)

At f=0: low resistance state

Transport: Quantum array with E_J/E_C=0,5

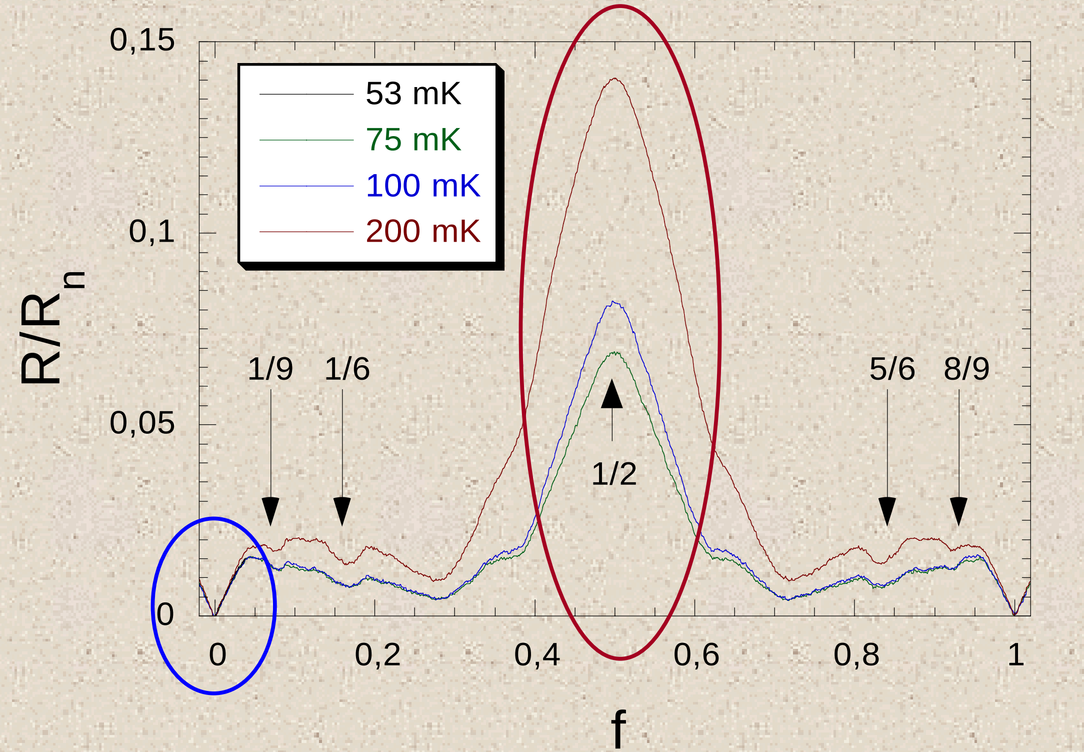


✦At f=0: KTB transition

fit $R_0(T)$ => $\tau_{KTB,mes}$=1,58

theory with quantum fluctuations => $\tau_{KTB,th}$=1,47

✦At f=1/2 : saturation of $R_0(T)$



✦ **both near f=0 and 1/2 :**

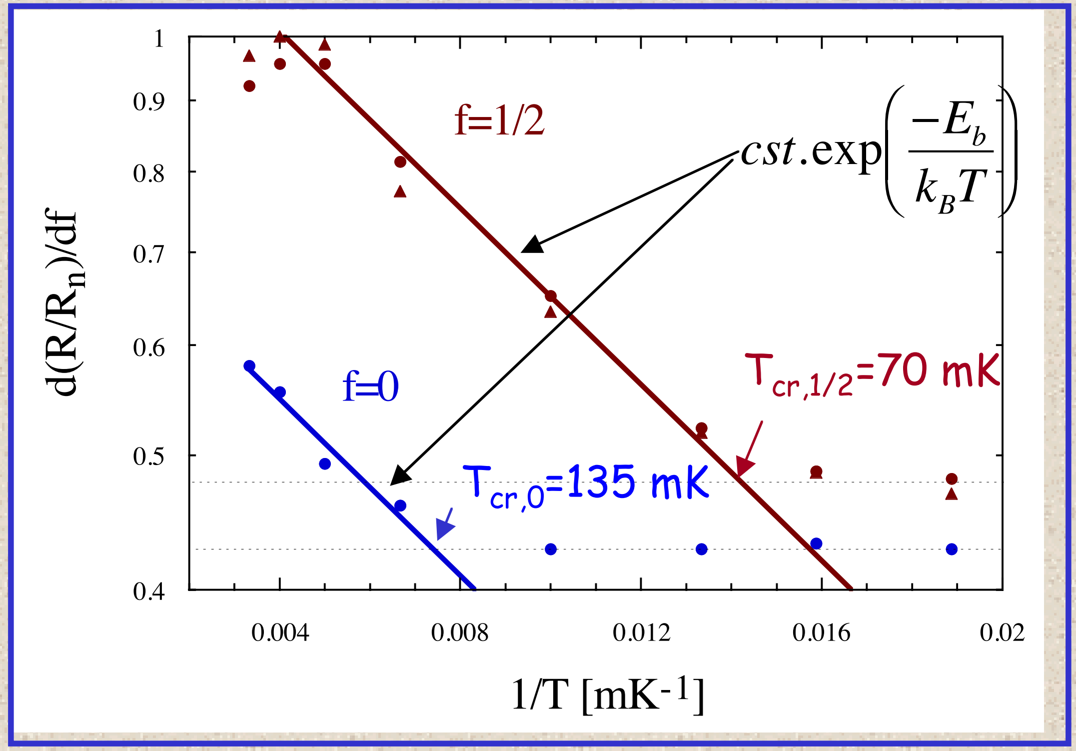
differential Resistance is :

- T- independent
- proportionnal to f

Transport: Quantum array with E_J/E_C=0,5

Study of the resistive phase at f=1/2

⇒ Behavior comparison between f=0 and f=1/2



✦ If T>T_{cr}, thermal activation behavior:

Same energy barrier at f=0 and 1/2:

E_b = 73 mK = 0,2E_J

(theory : 0.19 E_J)

✦ Theoretical prediction for T_{cr}:

$$T_{cr,th} \approx \sqrt{E_b E_c} = 230mK$$

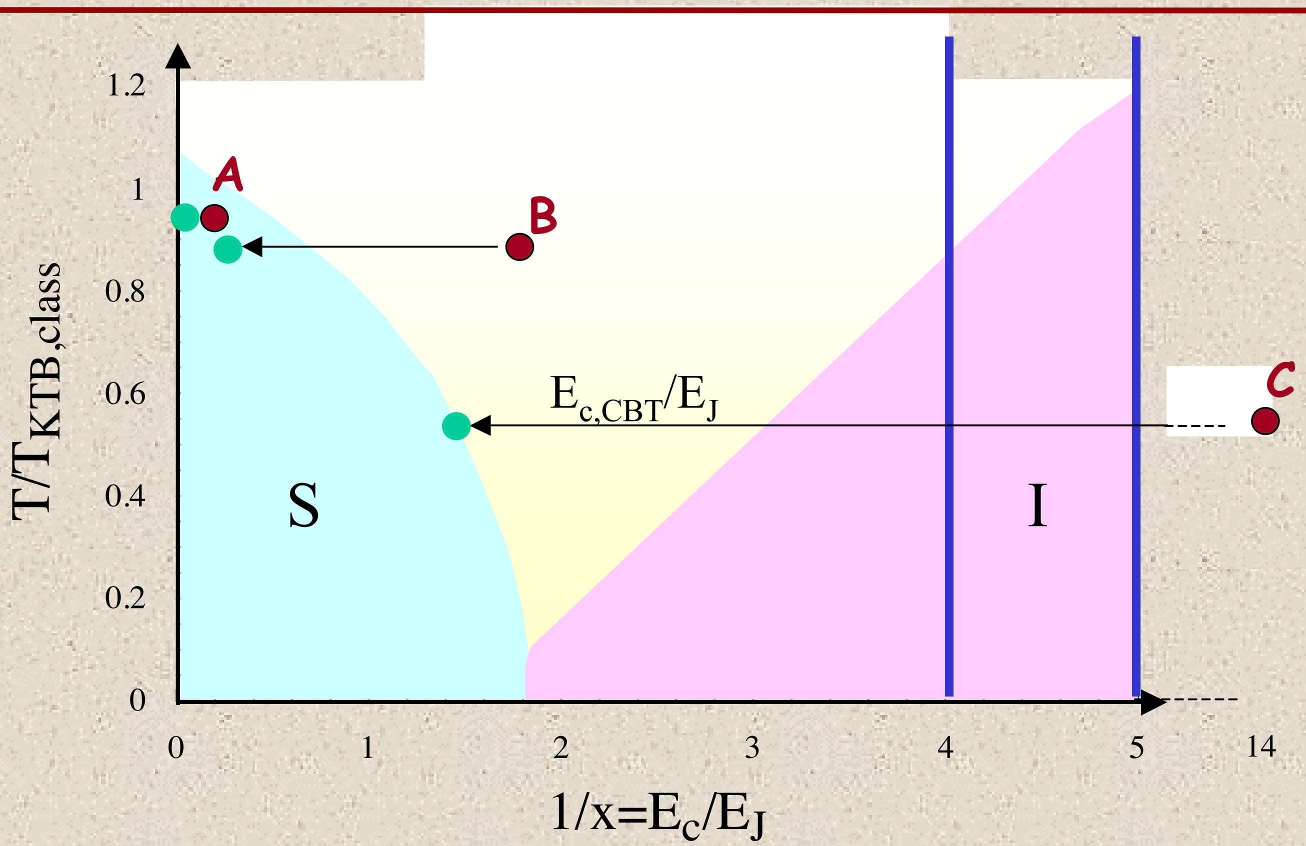
Observed T_{cr} is smaller (dissipation effect)

At f=1/2, resistive phase at T->0 :

evidence of a vortex liquid induced by the quantum fluctuations

Phase diagram:

At f=0



disagreement between dice and square phase diagrams

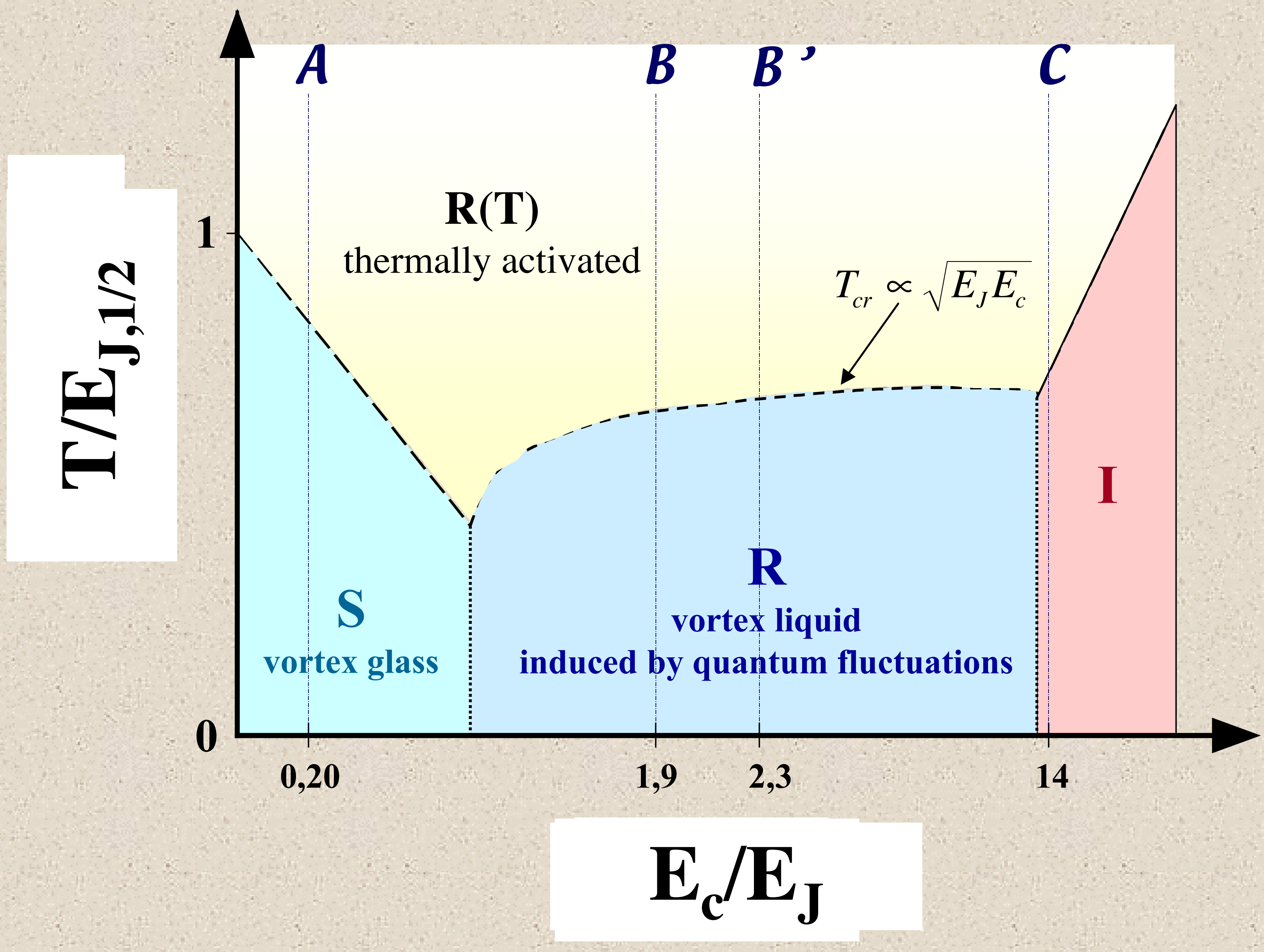
✦ $E_{c,eff}$ measure with CBT for sample C => $E_{c,CBT} = E_c / 10$ ➡ what is $E_{c,eff}$?

✦ fabrication and measurements of other samples: $E_{c,CBT} \approx E_c$

and for 1/x=4 et 5 => superconducting at f=0

➡ **Suppression of the quantum fluctuations in the dice array at f=0 !**

Phase diagram: At f=1/2



Conclusions

Imaging: at f=1/3 observation of a commensurable state
at f=1/2 very short range order (triades)

Transport at f=0: suppression of the quantum fluctuations in the dice array
compared to the square array

Transport at f=1/2:

- charge array:
  observation of an insulating phase
- classical array:
  evidence of a commensurate phase at f=1/2
  no thermal hysteresis
  no ordering induced by electrical excitation ($\neq$ f=1)
- quantum array:
  evidence of a vortex liquid induced by quantum fluctuations