Superconducting ground state in an array of Josephson Junctions with dice lattice

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Outline

- ✓ Introduction
  - a new family of 2D JJ arrays with highly degenerate classical ground state
- ✓ classical superconducting dice arrays
  - T_c, I_c suppression, glassy vortex state
- ✓ quantum arrays
  - S-I transition, metallic phase
- ✓ Conclusion and perspectives

- **Collaborators**
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  - P.Butaud, J. Vidal
  - O. Buisson, K. Hasselbach
  - Th. Fournier

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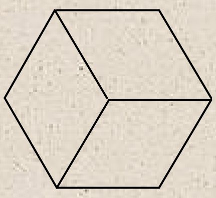
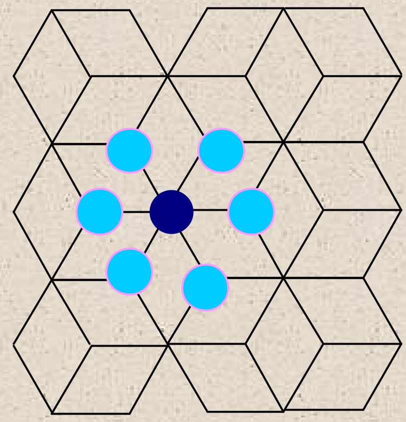
  - B. Douçot, P. Martinoli, L. Ioffe, M. Feigel'man, S. Korshunov, R. Fazio
  - " CEA-LETI-PLATO"

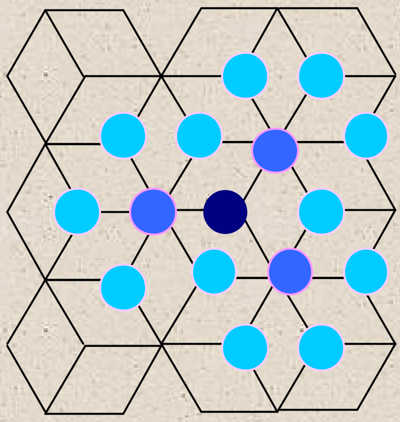
localisation effect in the « dice » lattice



Bravais cell

$f=\phi/\phi_0$
ϕ_0 :flux quantum





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

  f=1/2 $\Rightarrow$ localisation due to quantum interferences (AB cages)

  cage effect suppressed by : disorder, edge states , interaction.

- 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 JJ array

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

  dice array : vortices on the Kagomé (dual) lattice

- quantum JJ array

  Josephson coupling + Coulomb blockade

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

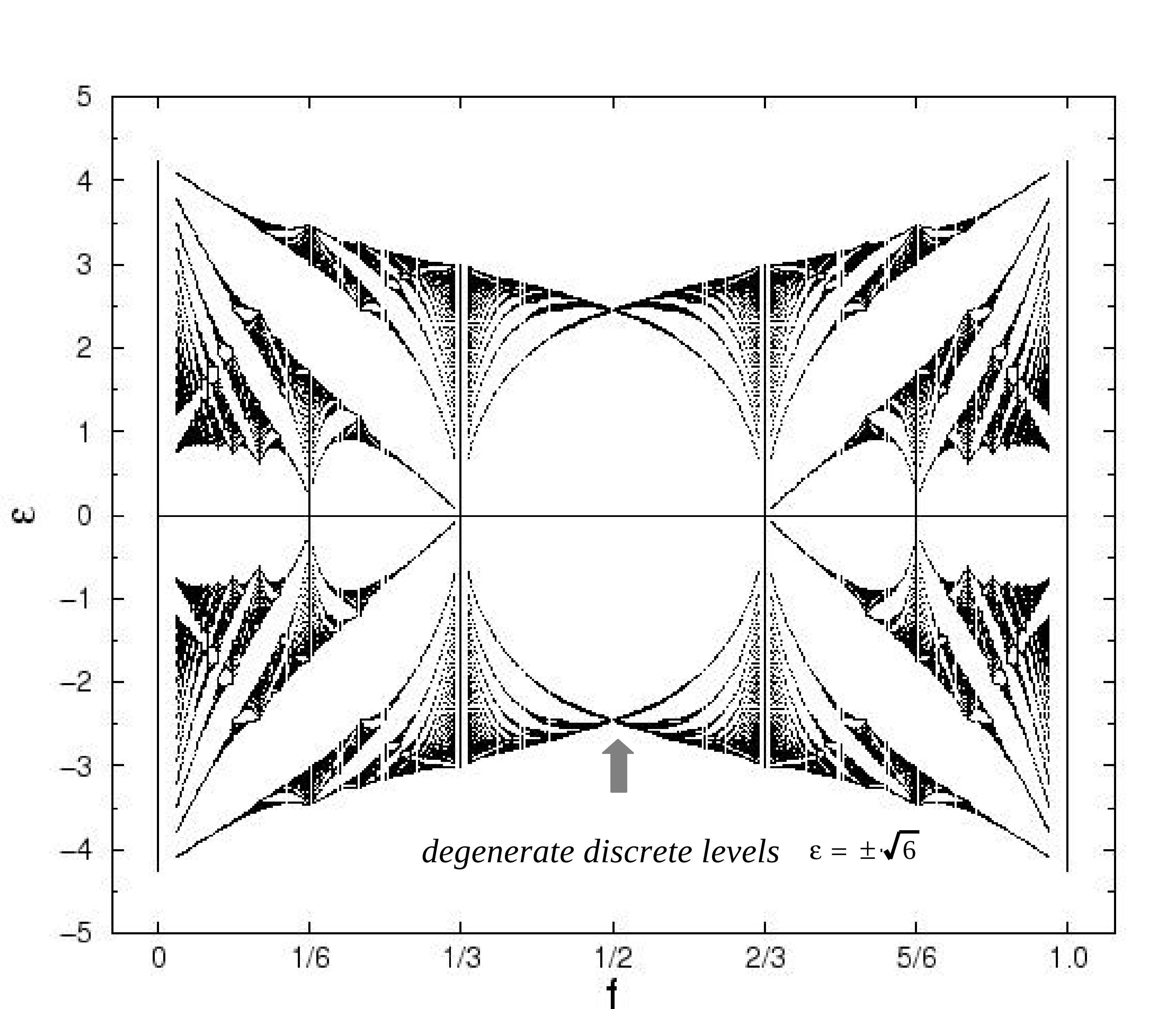
Hubbard

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

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

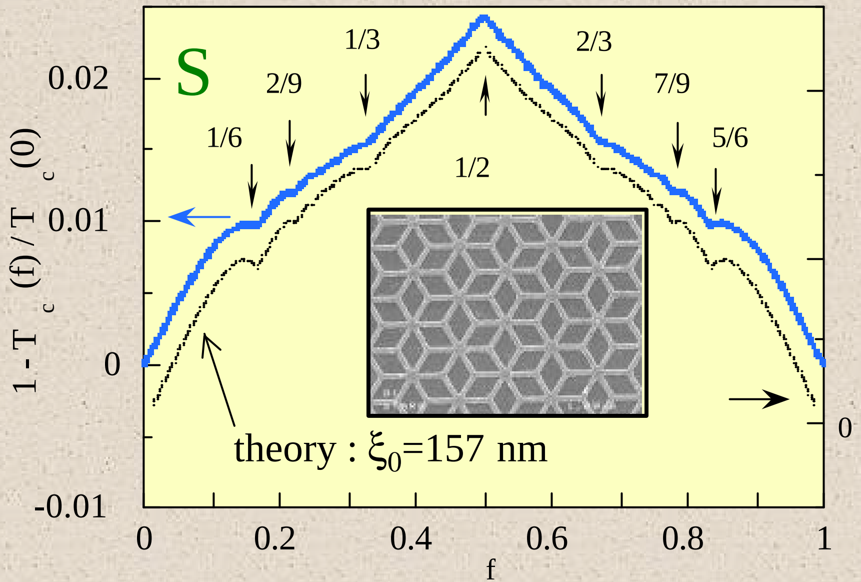
hopping of Cooper pairs

Landau levels of the 'dice' array

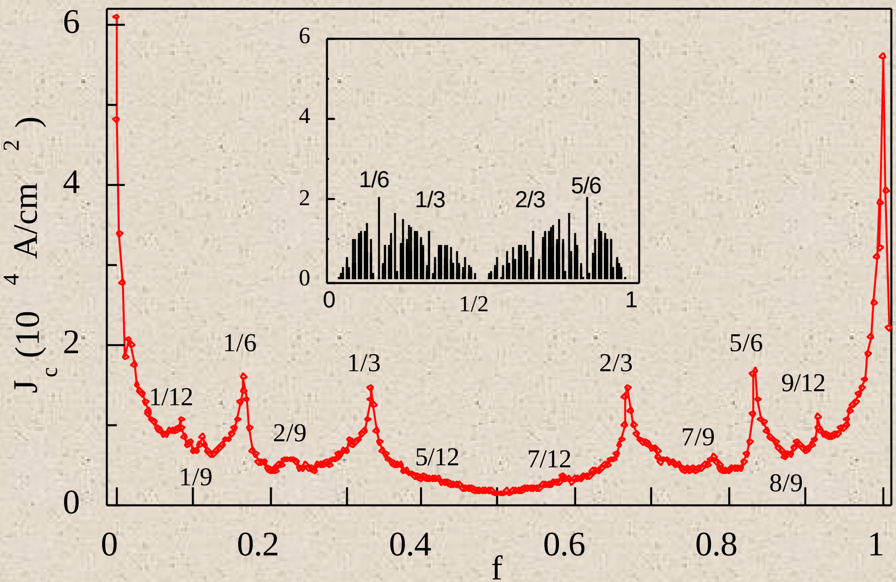


Superconducting Al wire network

- Critical temperature
- Critical Current



$T_c(0)$=1.234 K



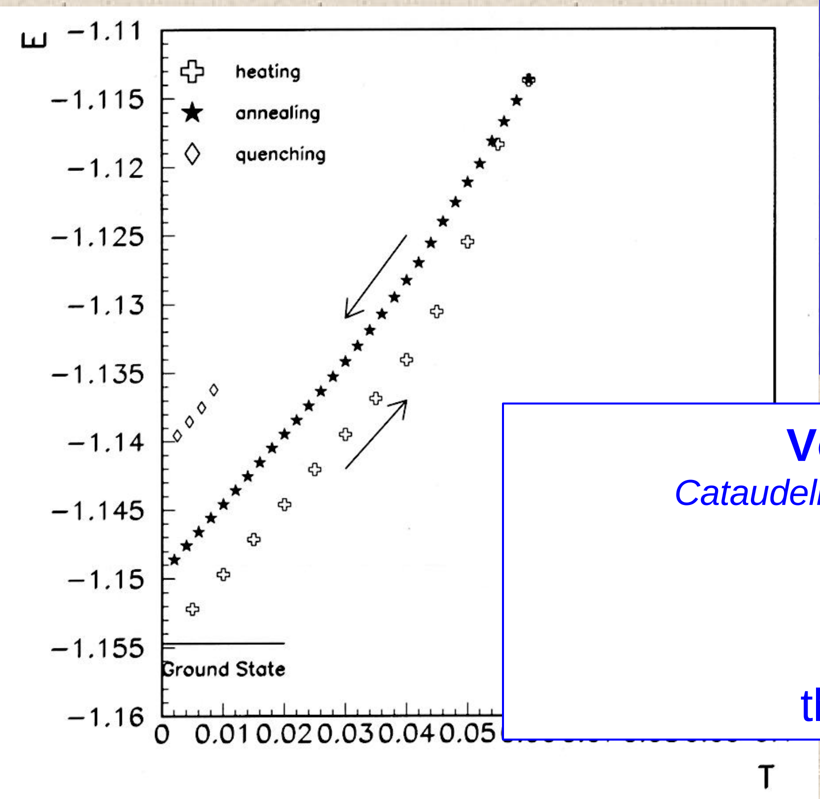
C. Abilio et al. PRL83, (1999) 5102

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

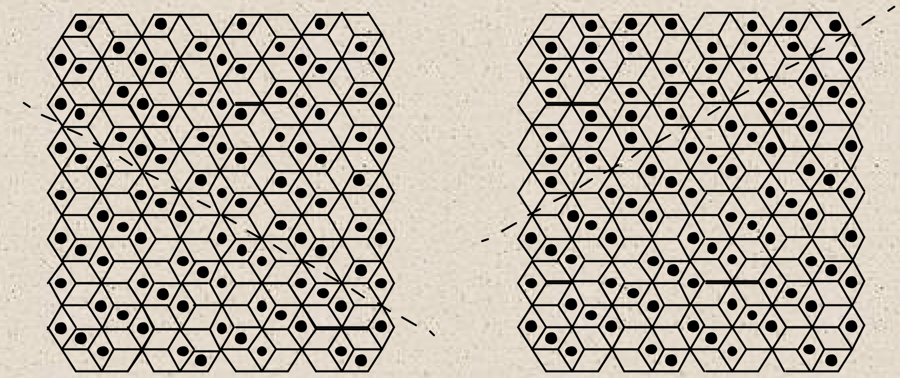
The superconducting ground state at f=1/2

- **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}
Cataudella and R. Fazio, Europhys. Lett. 61 (2002) 341

T_{KTB} =0.03 E_J

thermal hysteresis, slow dynamics

Magnetic imaging: Observed Configurations at f=1/2

Magnetic decoration of vortices

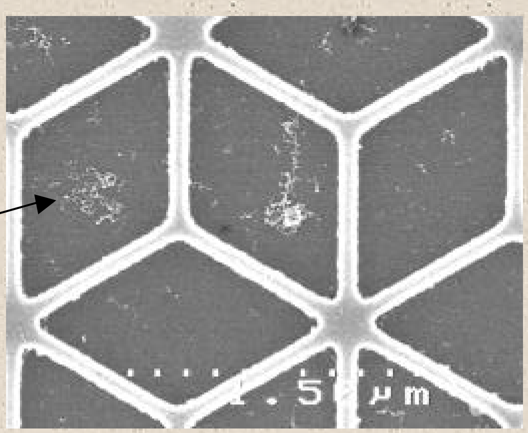
Europhys. Lett. 59, 225 (2002)

field cooled epitaxial Nb wire array

Tc=9K

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

vortex



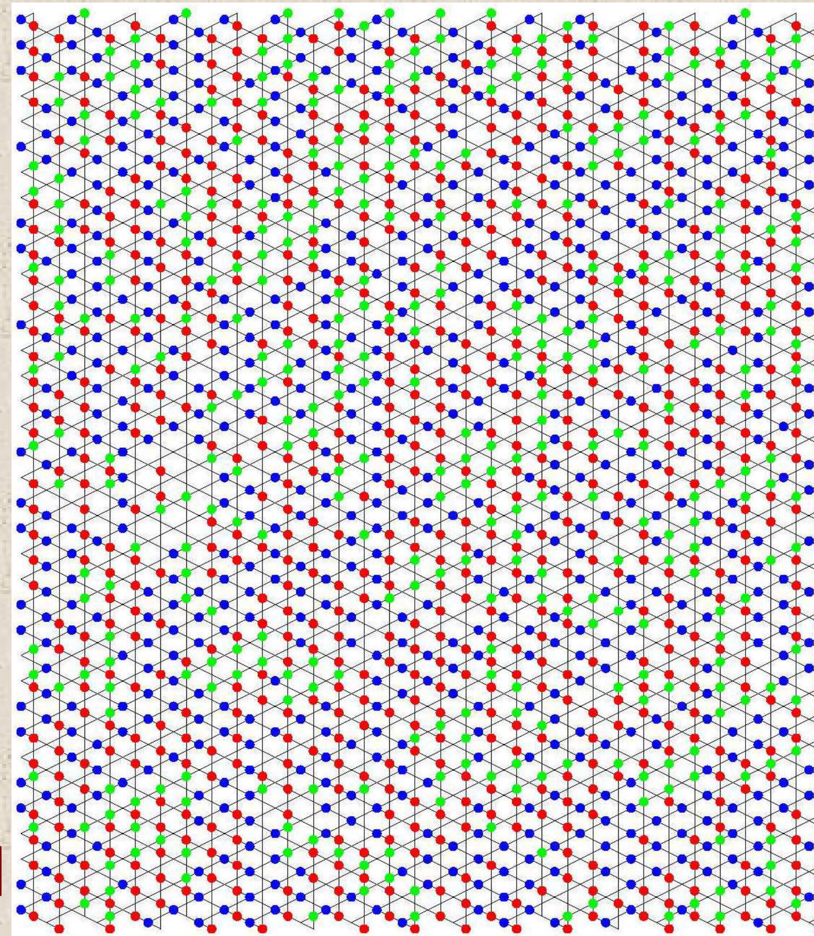
1 µm

- ☞ No commensurate phase

Þ disordered configuration?

Observed configuration

(reconstructed on the Kagomé lattice)



3 456 sites containing 1 725 vortices

↙ f=1/2-0,001

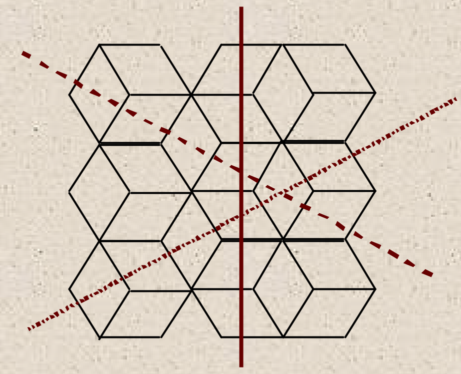
Magnetic imaging: Correlation function calculation

$$C_{a,b,g}(r) = \langle V_i \, . V_{i+r} \rangle$$

V_i : « vortex » variable

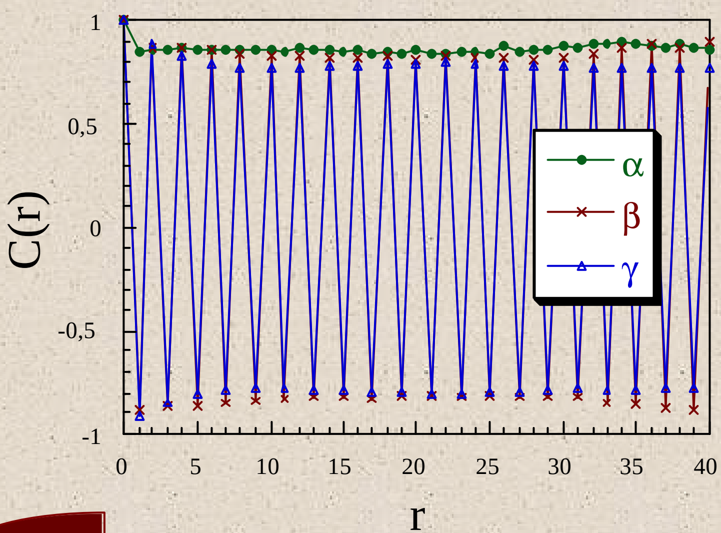
= 1 if a vortex is in the i cell

= -1 if not



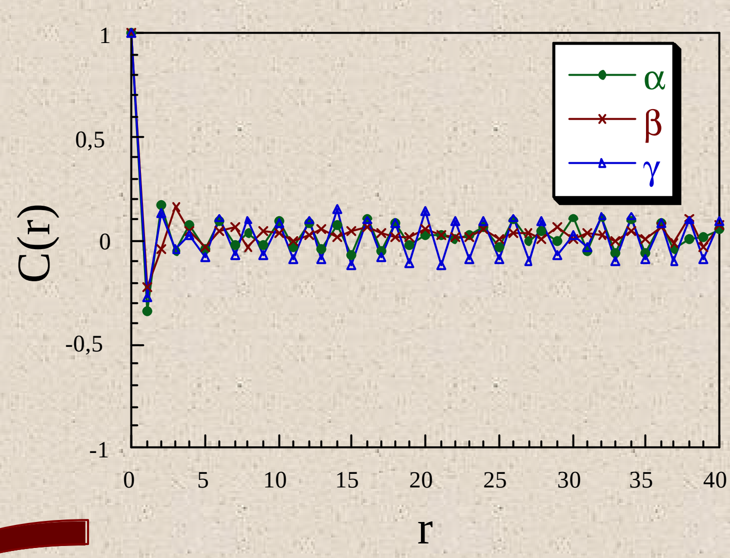
Collaboration. P.Butaud

☞ f=1/3



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

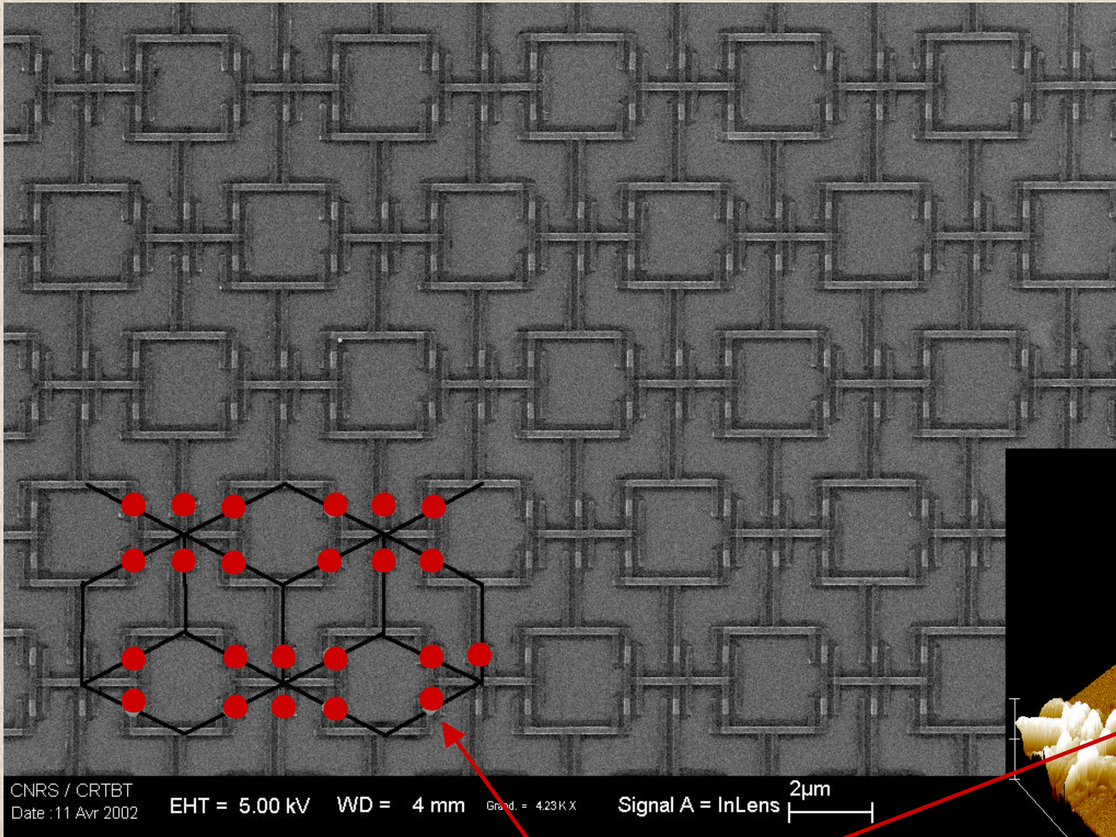
☞ f=1/2



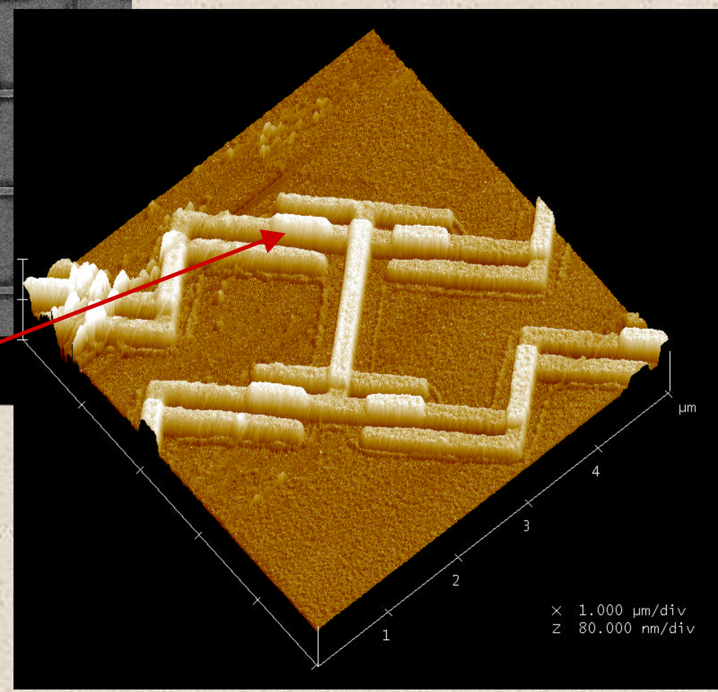
No long range order:
$\xi \approx 1{,}5$

Nanofabrication: Samples

(Array containing more than 127 000 junctions)



Chain of « cages »

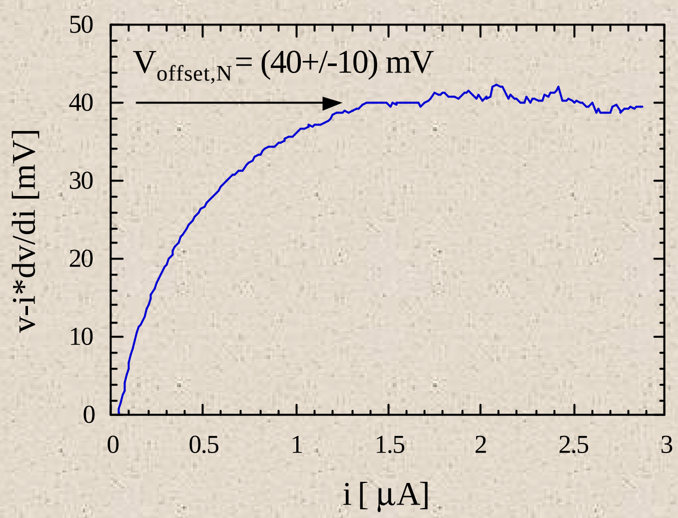


Josephson junctions

- ➔ 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/μm²



Sample	S [μm²]	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 μm² => f=1 ^{o} B=0,3716 mT

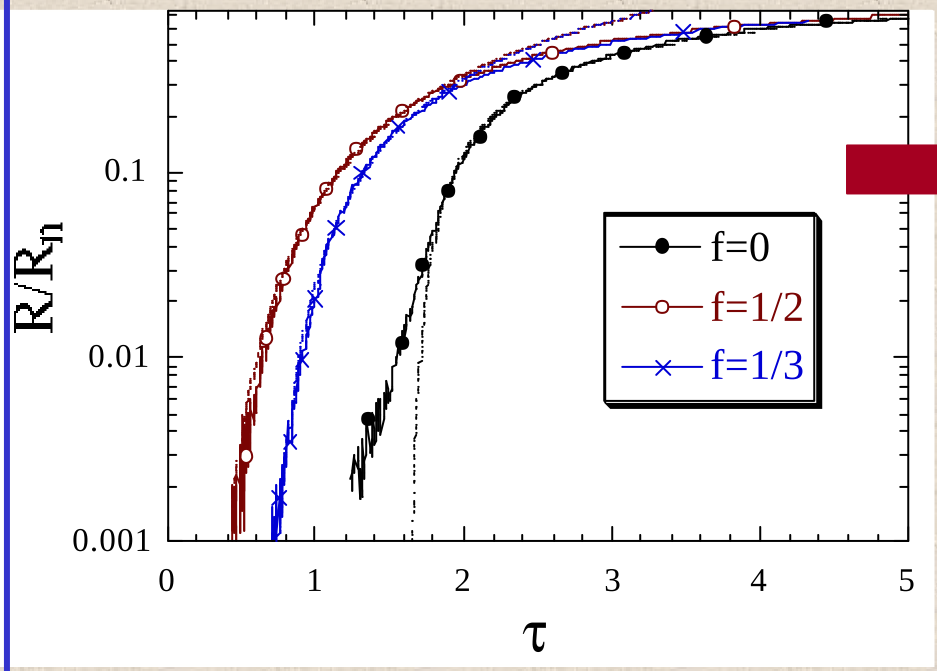
Transport: Classical array with E_J/E_C=4,9

Study of the KTB transition:

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

with $t = {k_B T}/{E_J(T)}$, 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



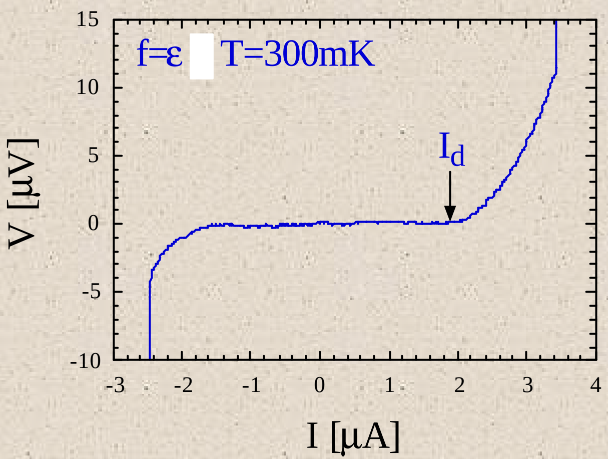
- At f=1/2, the array undergoes a KTB transition
- Relatively good agreement with theory (uncertainty on ? (T))

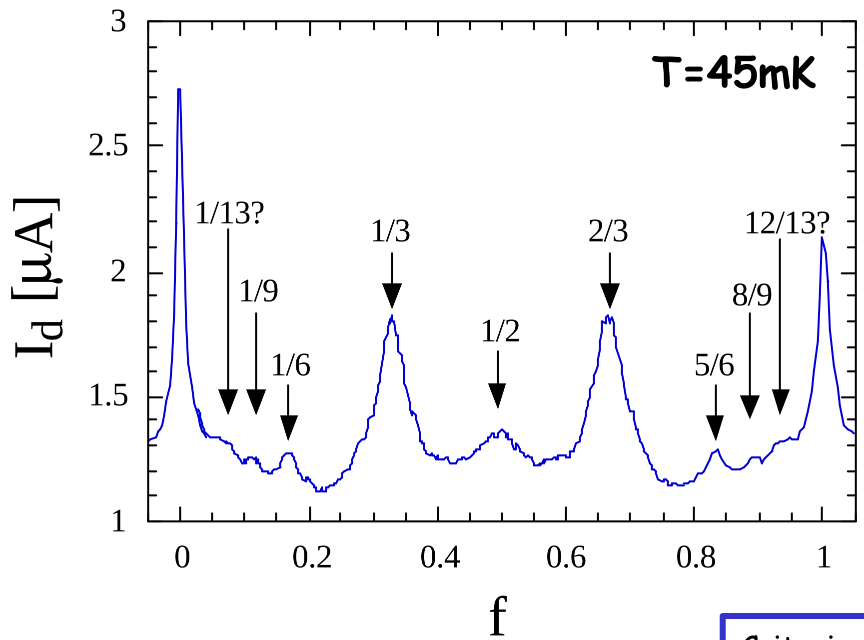
Is the f=1/2 state a vortex glass?

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

Study of the superconducting phase at f=1/2

Þ vortex configuration pinning force measurement





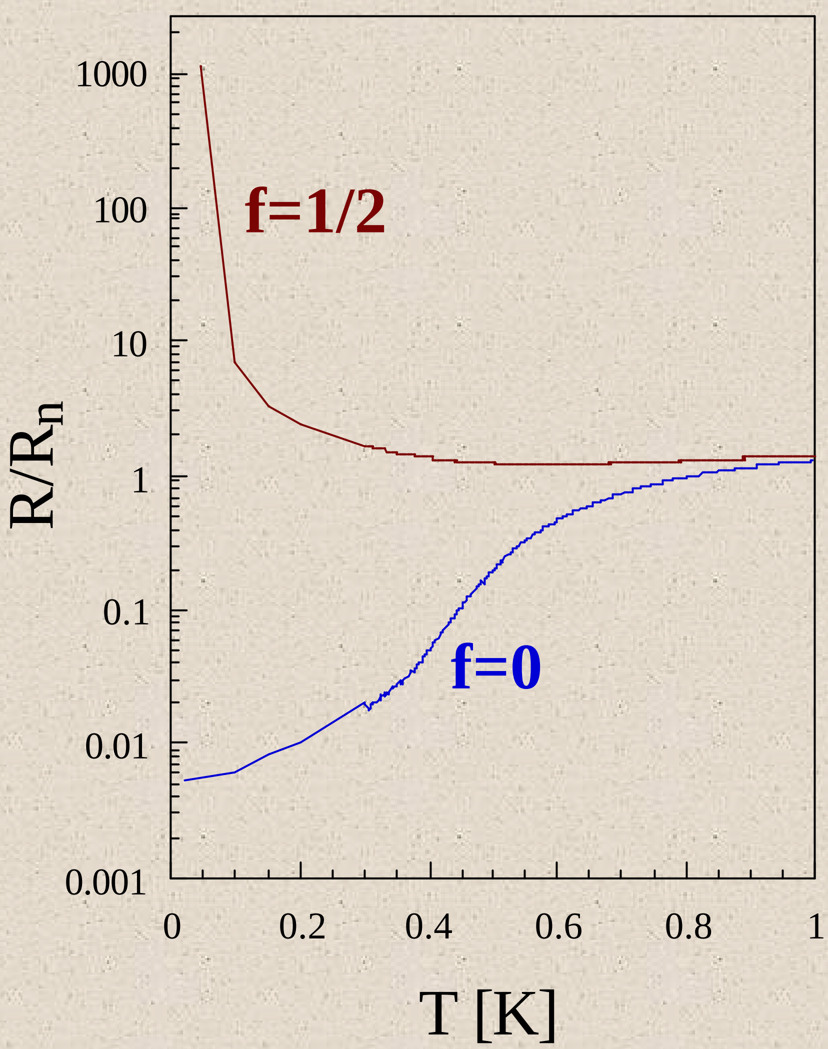
Criterion 1μV

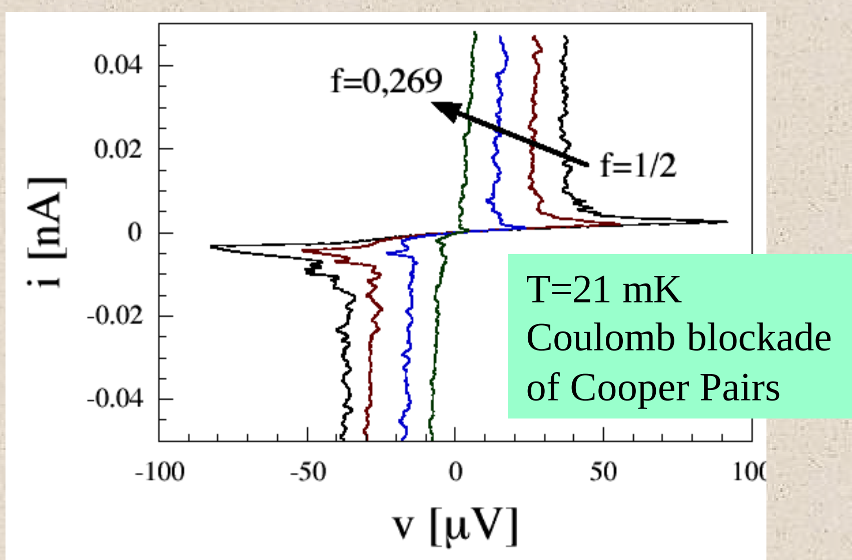
1. Max of I_d at
   f = 0 , 1/13 , 1/9 , 1/6 , 1/3 , 2/3 , 5/6....

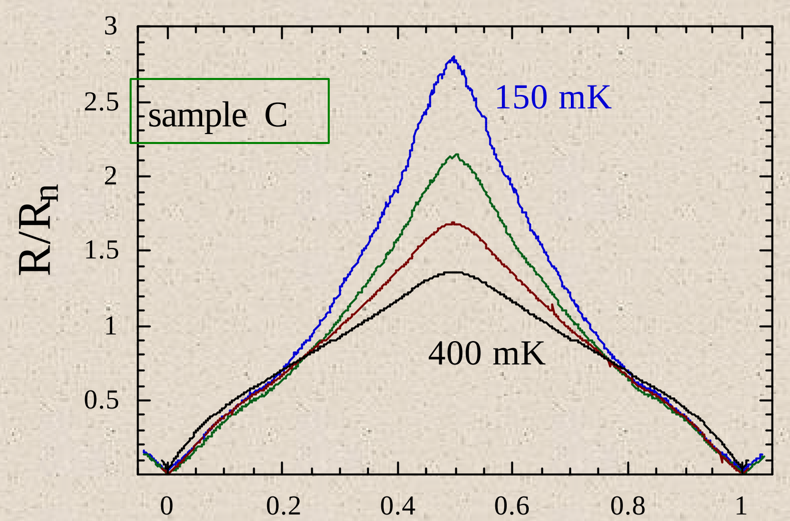
2. Max of I_d at f=1/2 ≠ wire arrays

Commensurate state at f=1/2

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

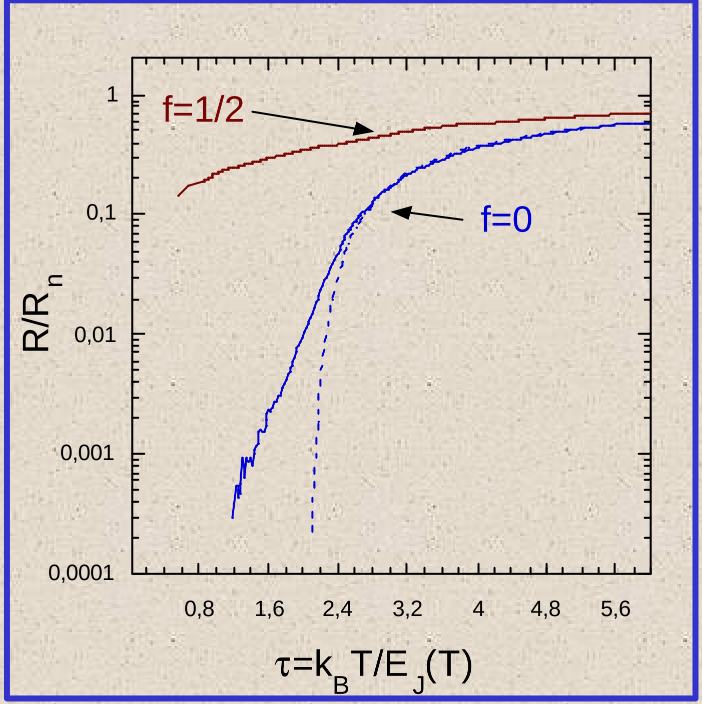






Metal-Insulator transition induced by B at $f_{c,1}$ = 0,23 and $f_{c,2}$ = 0,76

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

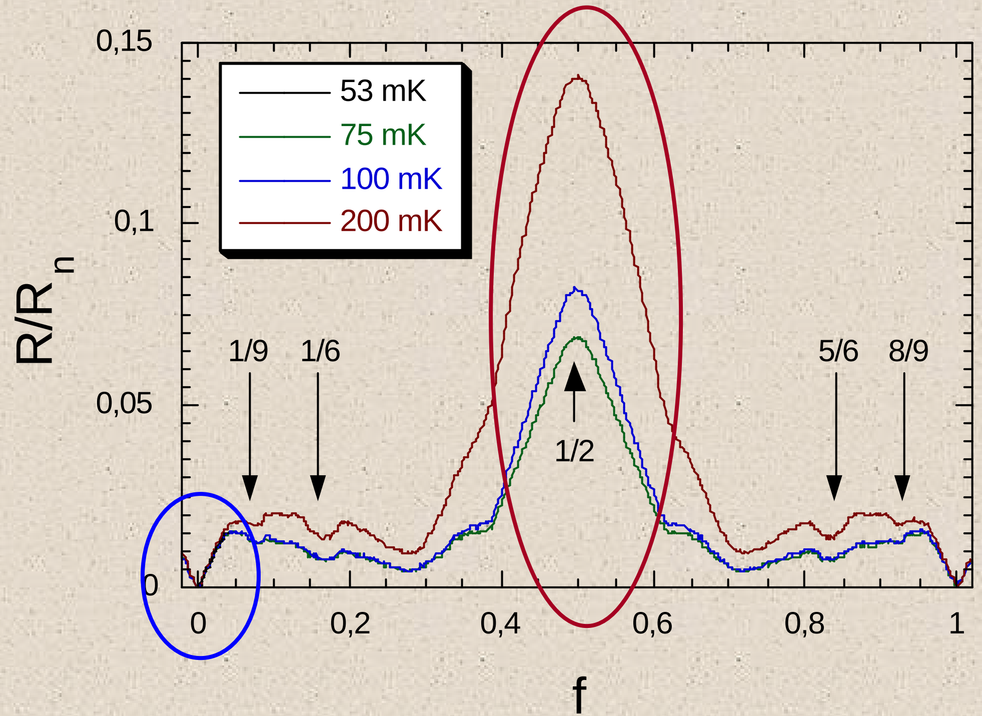


☞ **At f=0: KTB transition**

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 :**

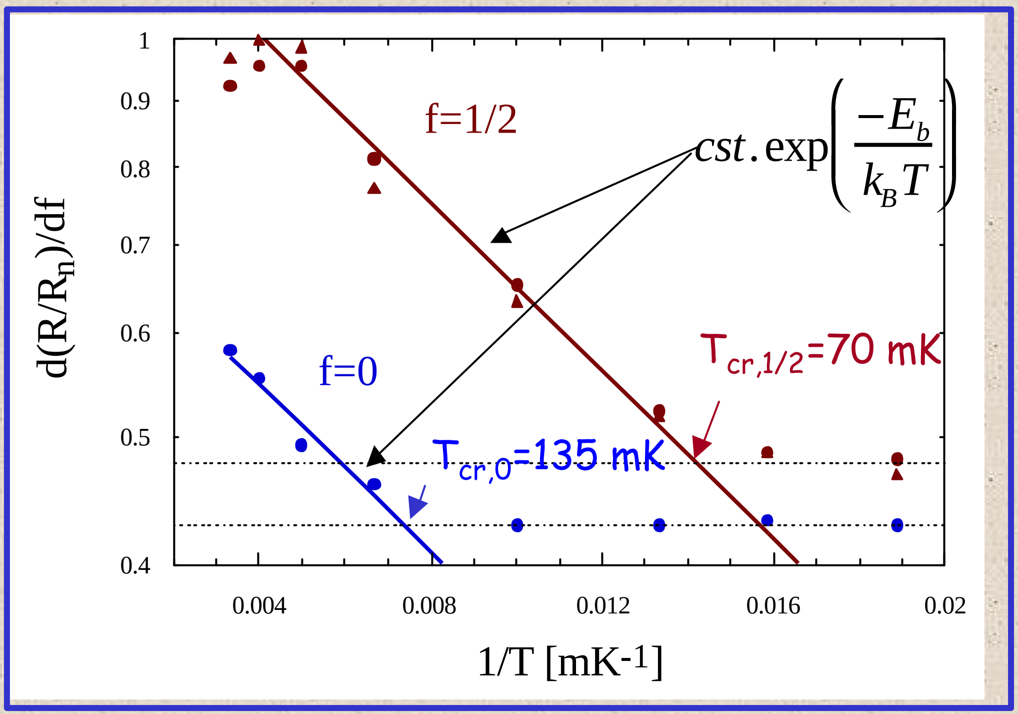
differential Resistance is :

- T- independent
- proportionnal to f

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

Study of the resistive phase at f=1/2

Þ 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}:

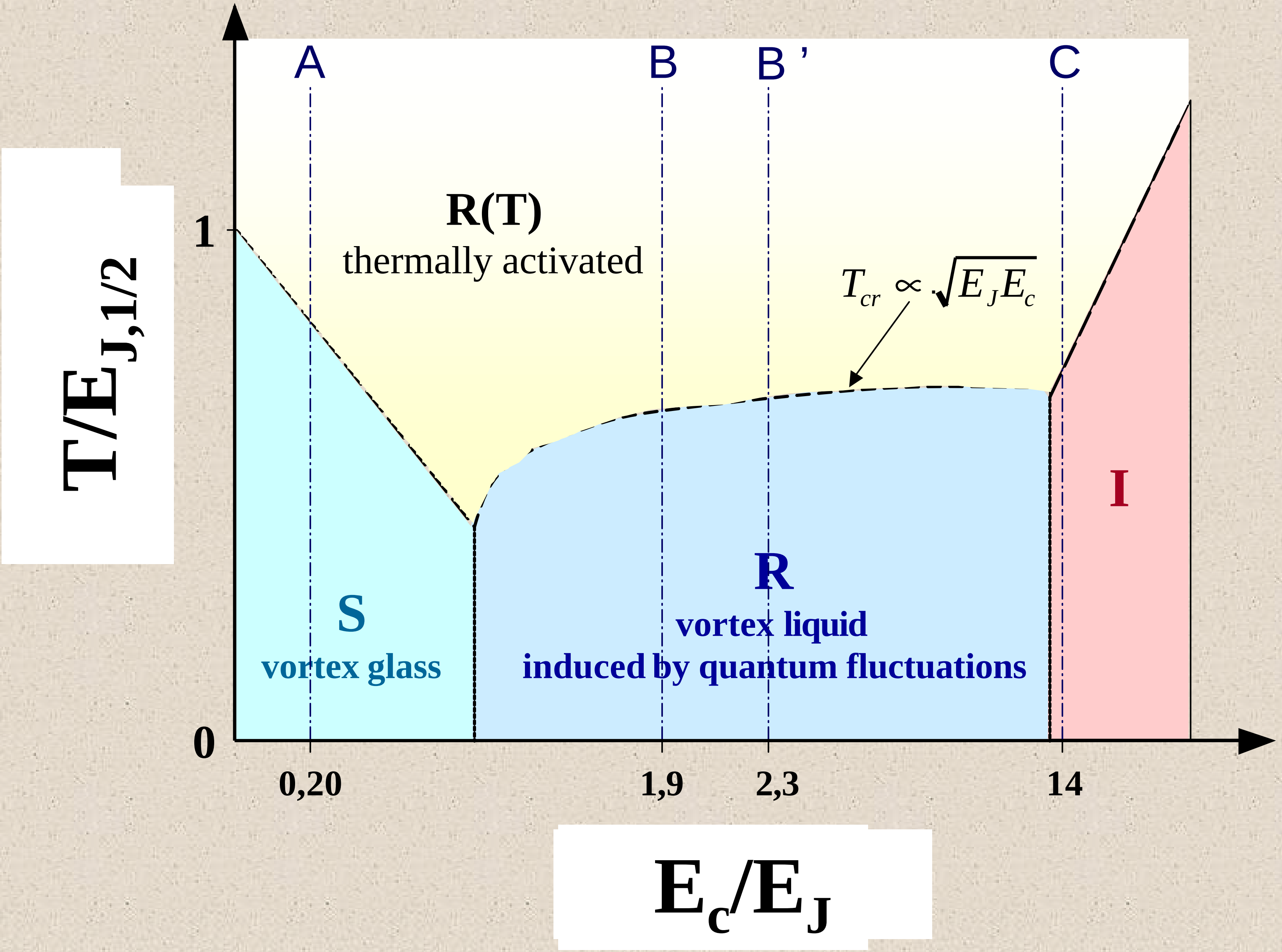
$$T_{cr,th} \approx \sqrt{E_b E_c} = 230\,mK$$

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=1/2



Conclusions

Vertex imaging : at f=1/3 commensurable state
at f=1/2 very short range order (triades)

Transport at f=0: dice array found robust against quantum fluctuations

Transport in JJ arrays at f=1/2:

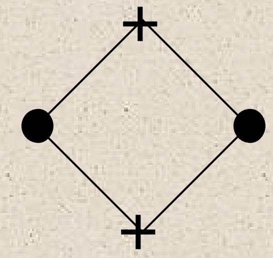
- charge array :
  insulating phase with Coulomb gap for Cooper pairs
- classical array :
  Indications of a commensurate phase at f=1/2 at very low temperature
  no glassy behavior
- quantum array:
  some evidence of a vortex liquid induced by quantum fluctuations

More : search for the "4e phase" in chains of rhombuses

role of elementary rhombuses (dimers)

- loop with two junctions

SQUID geometry, E_J is suppressed at f=1/2

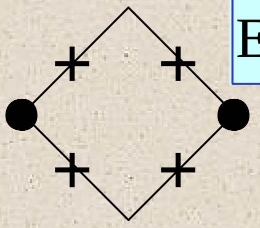


equivalent to 1 single junction with renormalized Josephson coupling

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

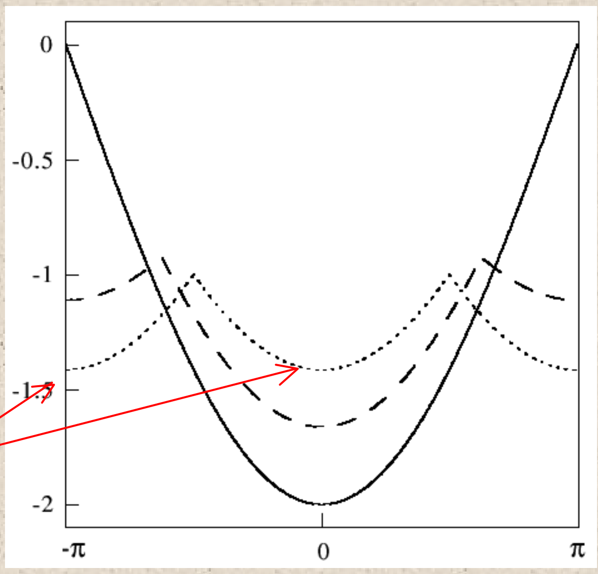
- the loop with 4 junctions

Rhombus : phases of intermediate islands lead to additionnal degrees of freedom



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

2 degenerate ground states at f=1/2

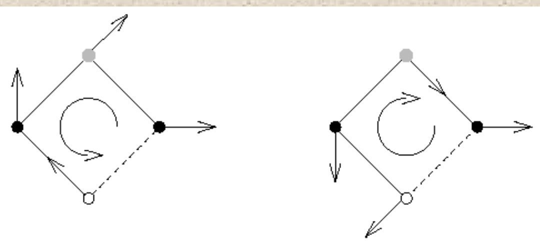


B. Douçot and J. Vidal, PRL88, 227005 (2002)

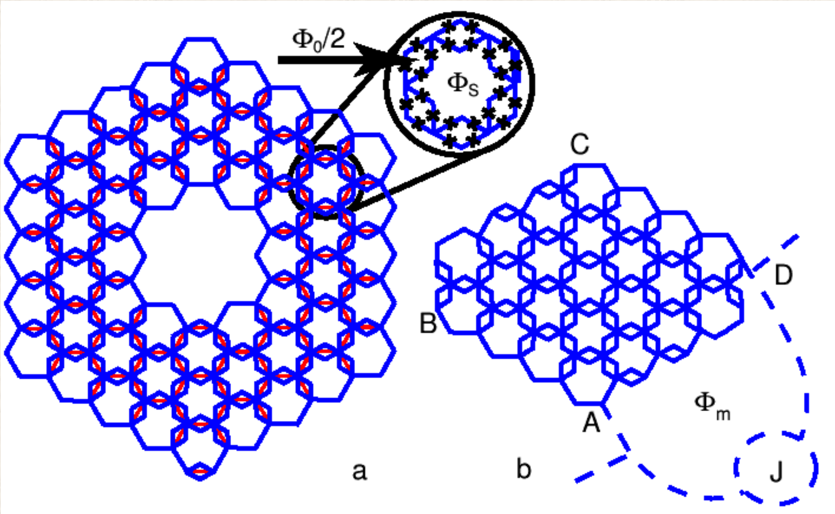
Arrays of Josephson rhombuses

At f=1/2 :

- •classical system is highly frustrated (extensive entropy)
- •quantum : topological order parameter
- •"protected" ground state (gap for 2e excitations)
- •Exotic S-state with 4e charges (cos2ϕ LRO)

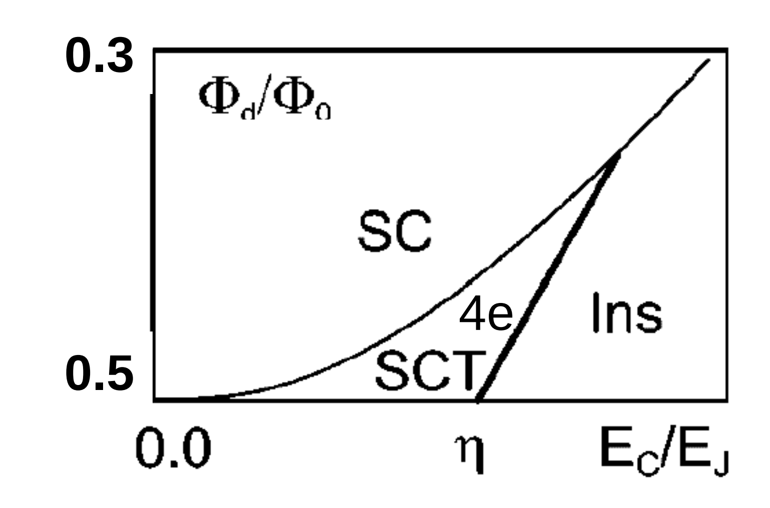


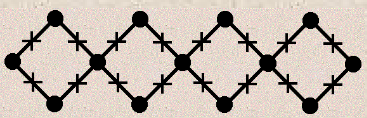
2 degenerate classical ground states



Ioffe et al; PRB66, 224503 (2002), Nature, 415, 2002 p503

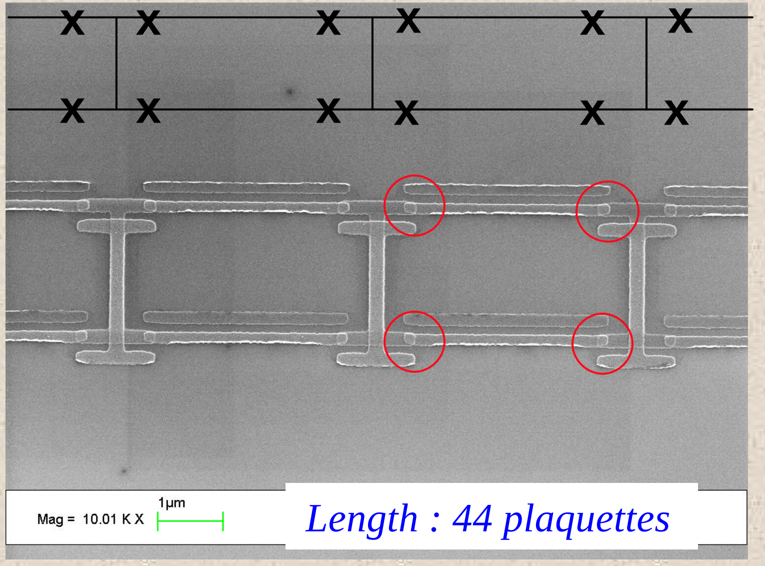
Predicted phase diagram

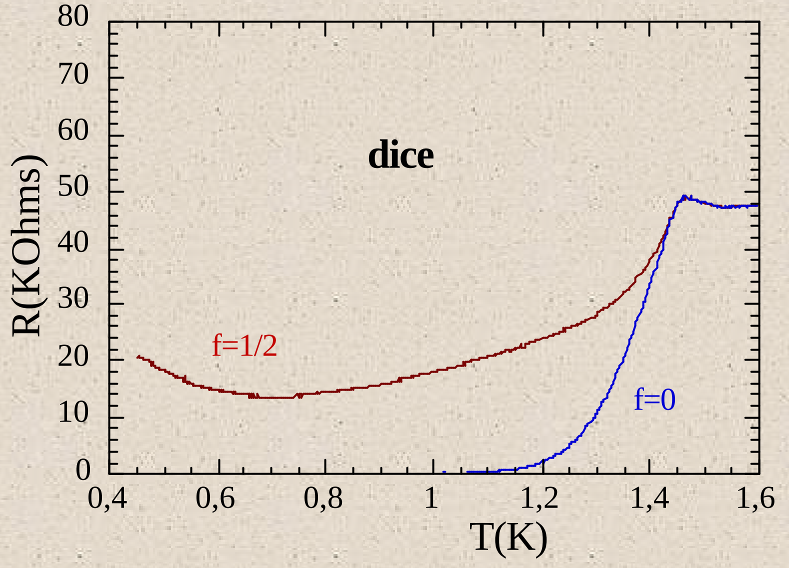


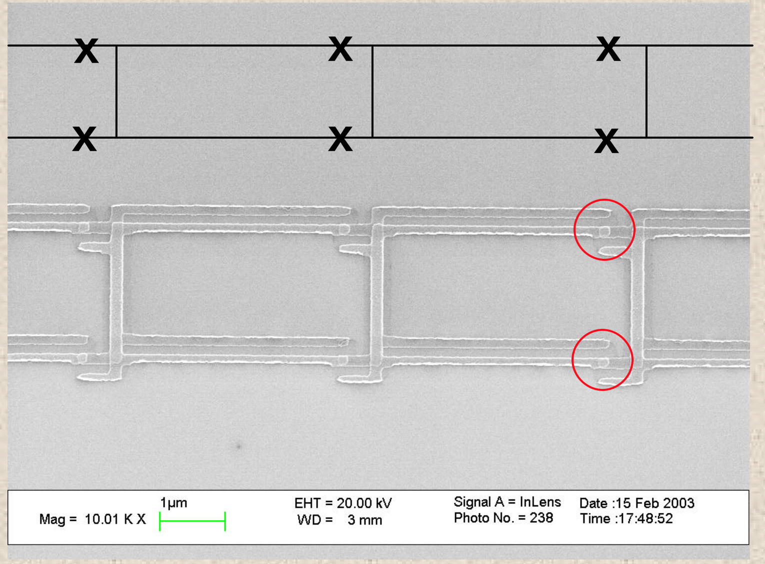


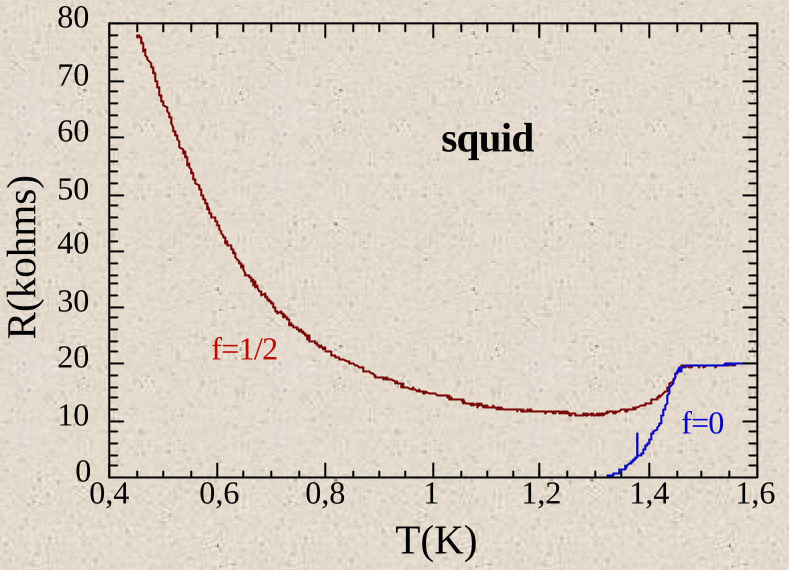
B. Douçot and J. Vidal, PRL88, 227005 (2002)

Comparison between 1D Josephson chains



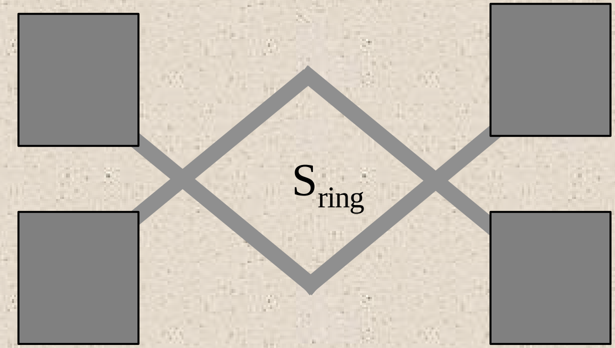


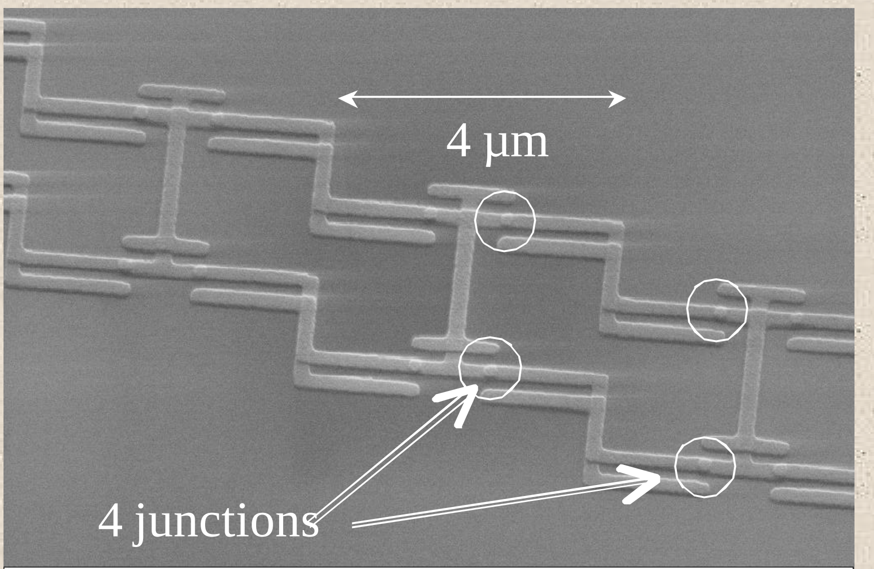




Search for state 4e : preliminary experiments

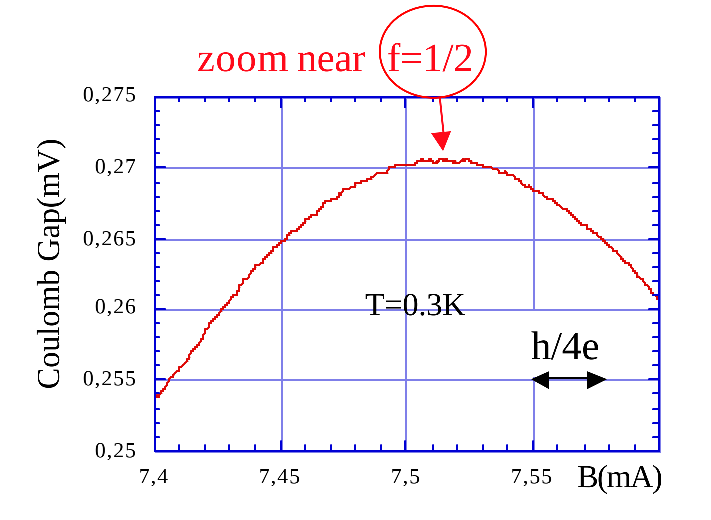
Aharonov Bohm ring



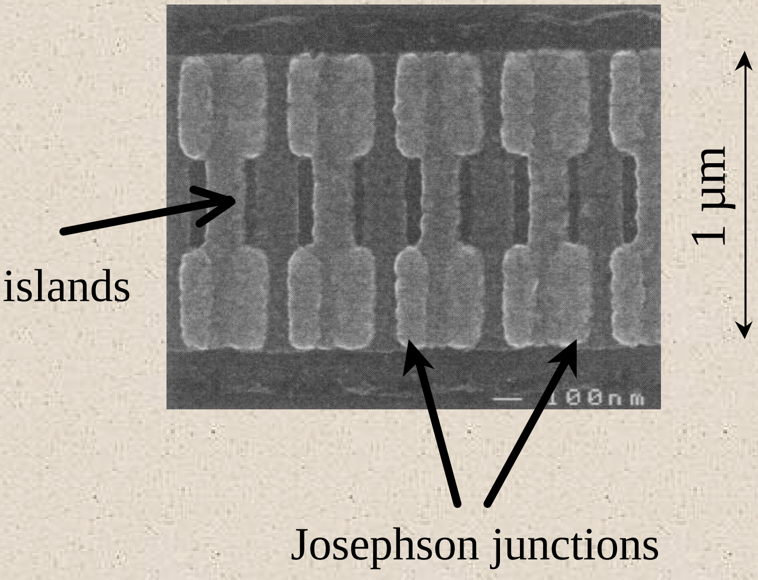


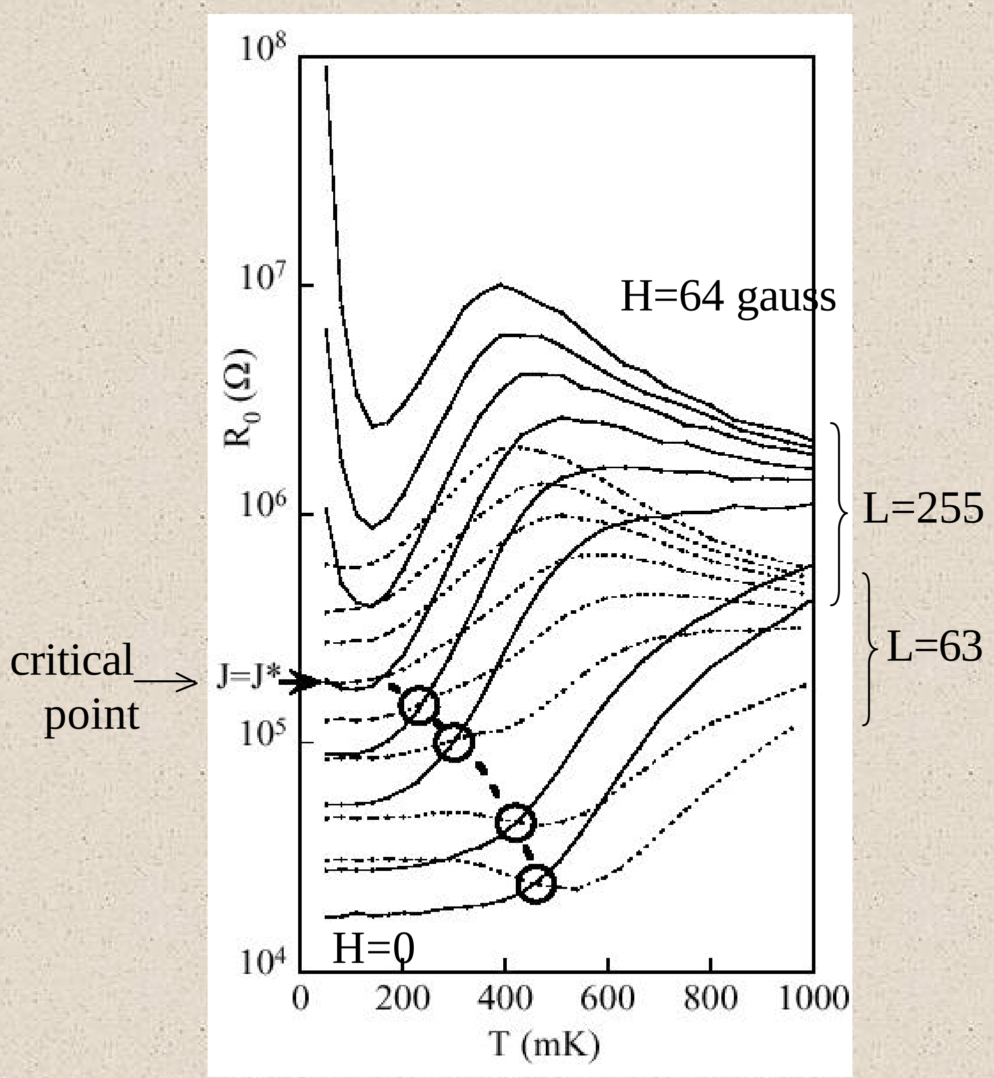
s_{cage} =8µm^2 S_{ring} =2048 µm^2

sample	r_N kΩ	E_J µV	E_c µV	E_J / E_c	state at f=1/2
A	1..2	570	18	33	S
B	2.5	287	35.5	8	M
C	6.4	100	71	1.4	I, *Coulomb Gap*



S-I transition in 1D Josephson arrays

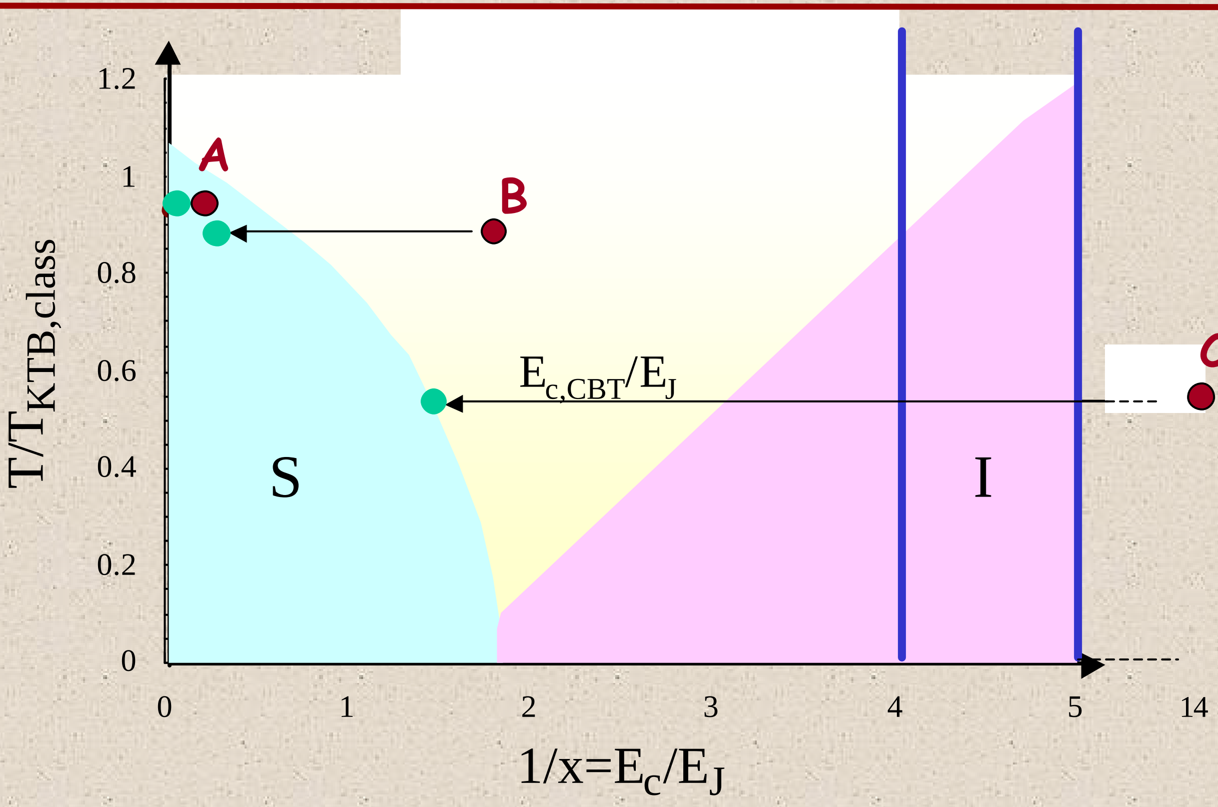




E_J/E_c = 6.1 cos pf tunable by magnetic field

Haviland, PRL81, (1998) 204
see also
Miyasaki et al. PRL89, (2002), 197001

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 !**