

The Superconductor – Insulator Transition in Disordered Thin Films



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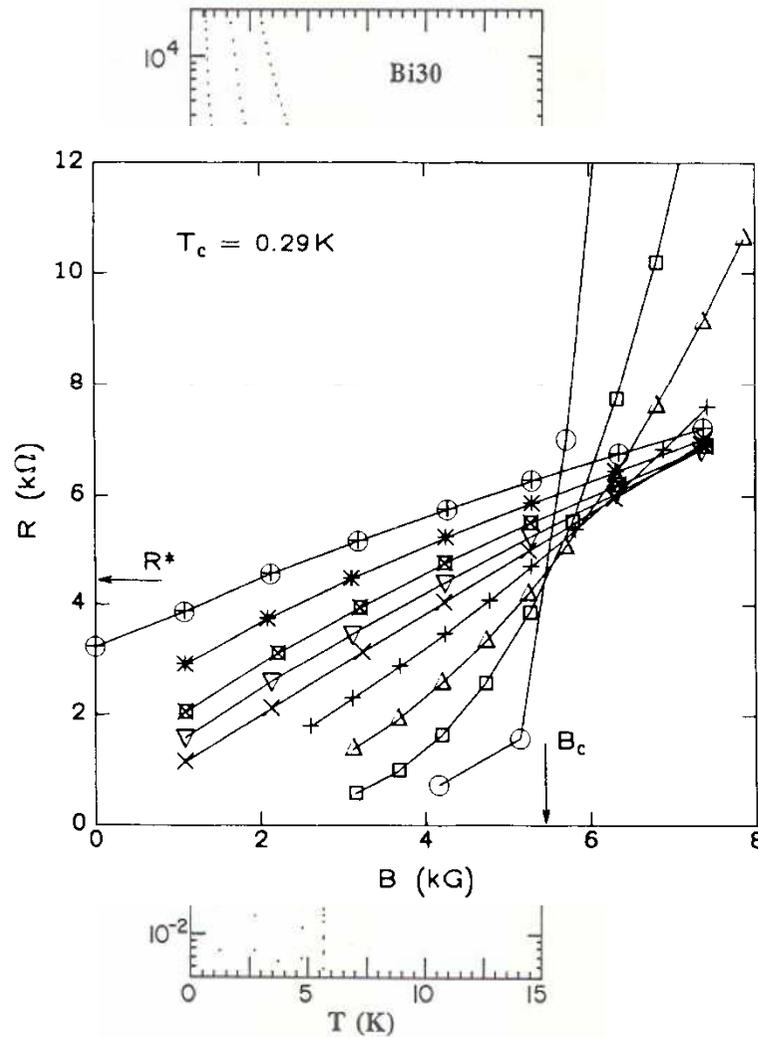
Elkana Porat

Argonne, Nov. 2012

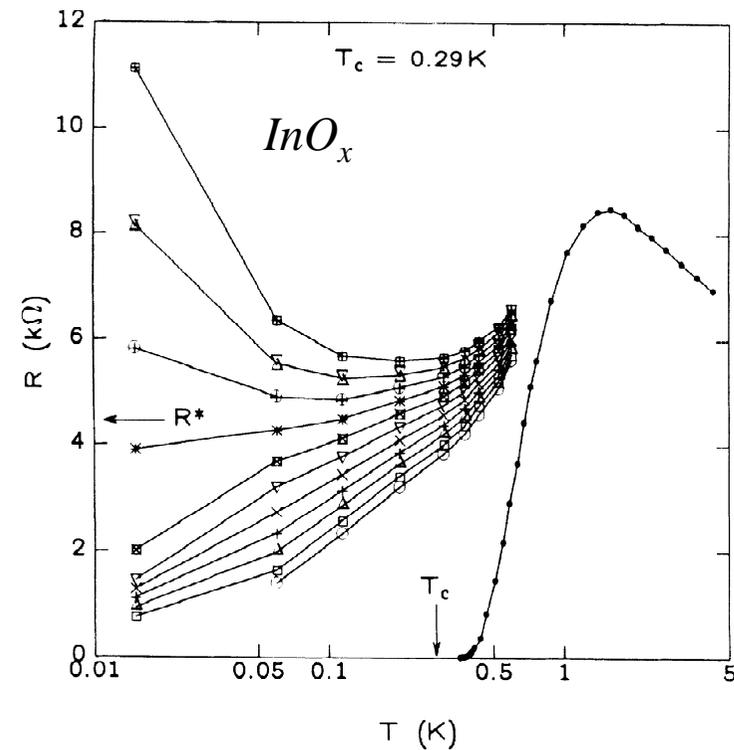
- *Motivation : superconductor-insulator transition in thin films*
- *Crash review on the theory of disordered SCs*
- *Formation and evolution of SC islands – A microscopic theory*
- *The Nature of the SIT – RG and percolation*
- *How to measure the spatial character of the transition ?*
- *Numerical calculation of the resistance*
- *A phenomenological model – transport in perpendicular magnetic fields*
- *Tilted magnetic fields*

Experiment: SC-insulator transition in thin films

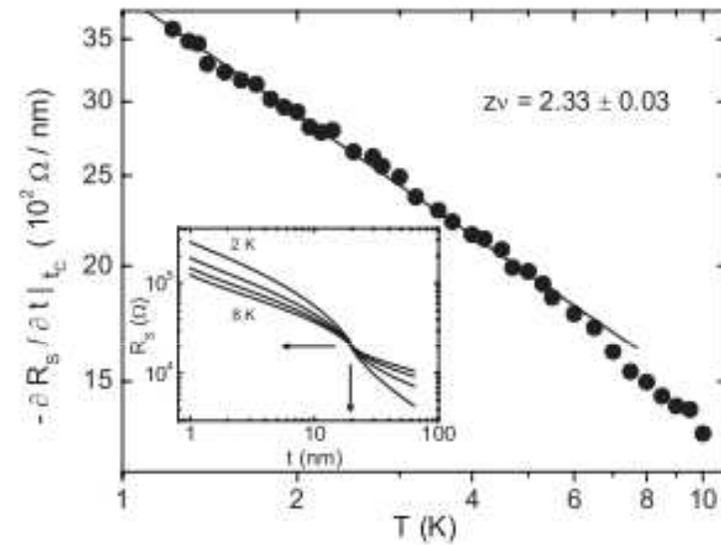
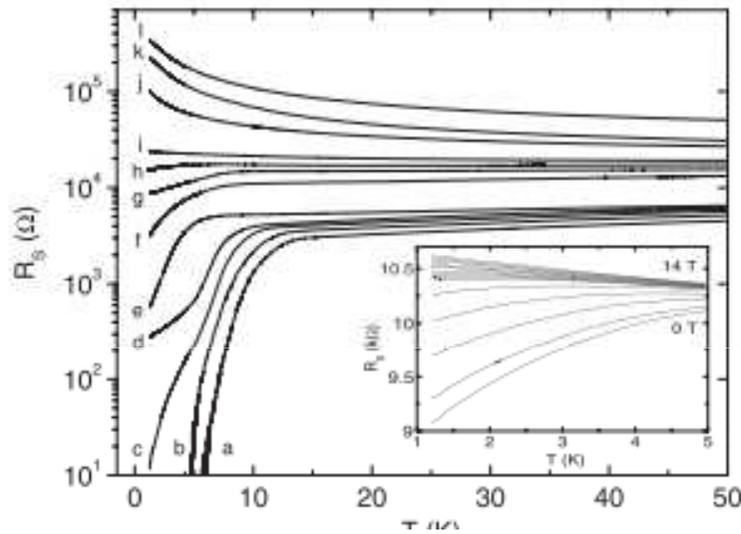
Haviland, Liu, Goldman [1989] –
thickness-driven transition



Hebard, Paalanen [1990] -
Field-driven transition



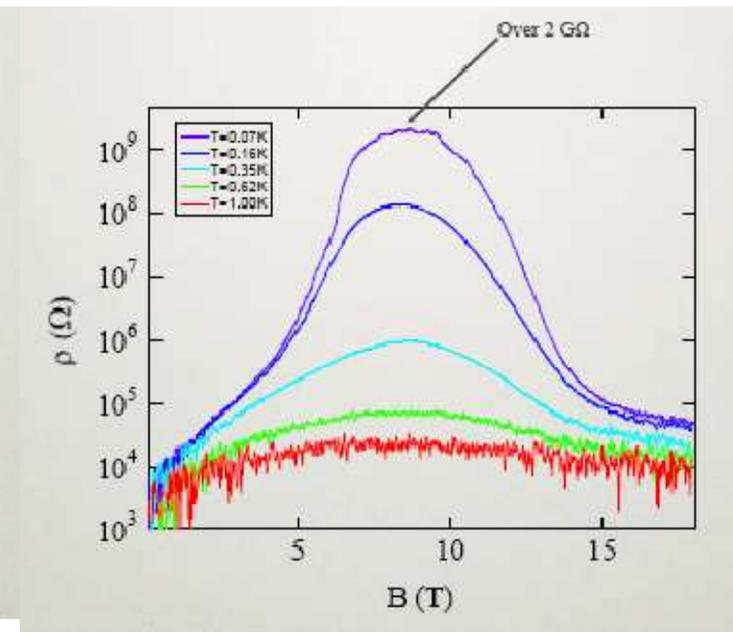
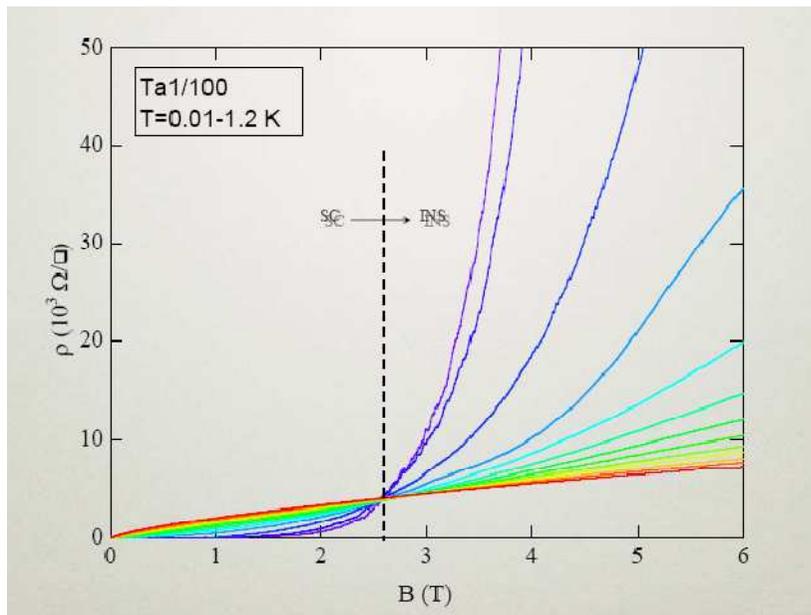
Experiment: Scaling at the transition



Schneider et al., PRL 2012

Prologue : Magneto-resistance of thin SC films

Field-driven transition...



*Sambandamurty, D.Shahar et.al. PRL
(2004)*

What drives the SC-Insulator transition ?

What is the source of non-monotonic magnetoresistance ?

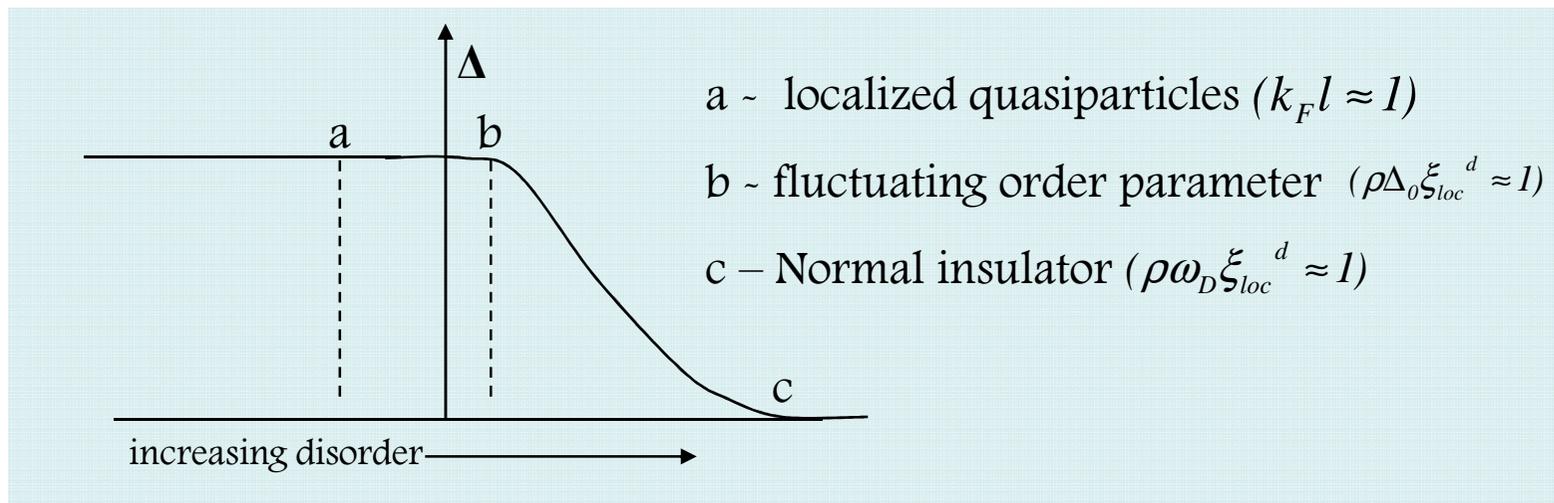
*Need to understand the interplay of
superconductivity and disorder !*

Crash review on the theory of disordered SCs

- *Anderson's theorem [1959]: weak disorder does nothing !*
(because one can pair eigenstates of the disordered system)
-

- *But strong disorder can induce a transition !*

[Lee & Ma 1985, Halperin, Lee & Ma 1986]



Crash review on the theory of disordered SCs

- A magnetic-field tuned transition – “Dirty boson” models

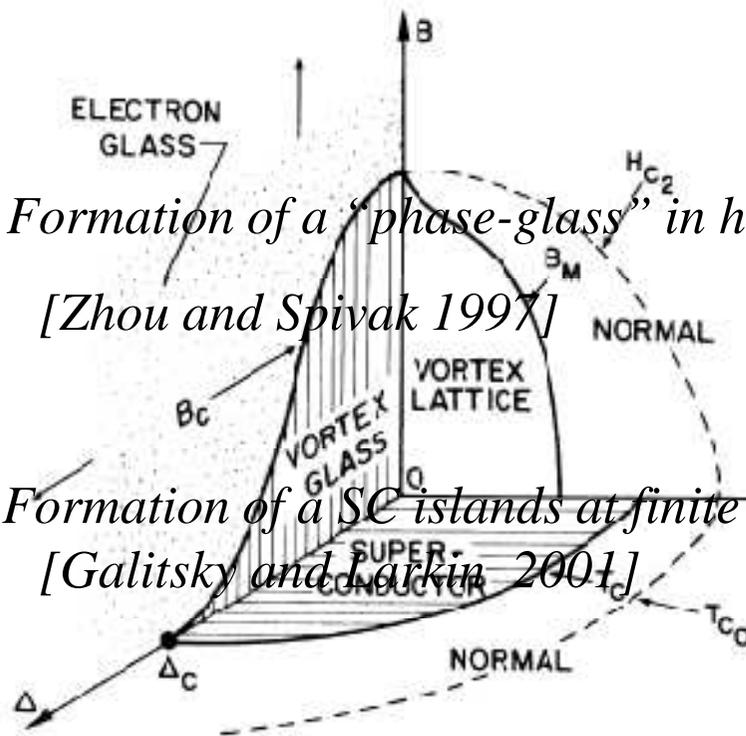
[Fisher 1990, Fisher, Grinstein and Girvin 1990]

- Formation of a “phase-glass” in high.

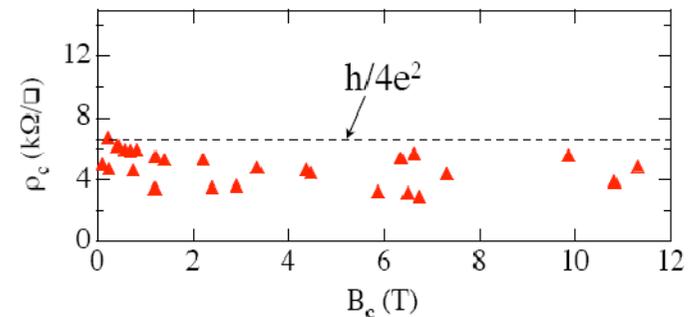
[Zhou and Spivak 1997]

- Formation of a SC islands at finite temperature and magnetic field

[Galitsky and Larkin 2001]



A quantum phase transition ?



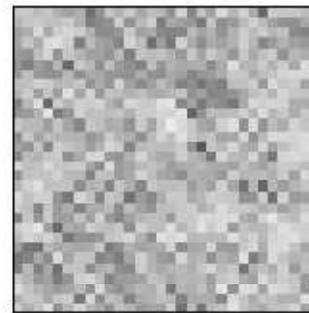
Critical exponent $\nu \sim 1.1$

Crash review on the theory of disordered SCs

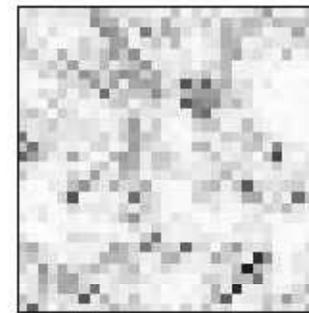
- *Formation of disorder-induced SC islands at $T=0$*

[Ghosal, Randeria and Trivedi 1998]

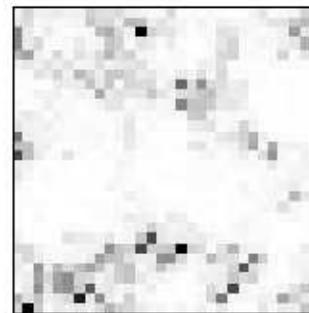
and more...



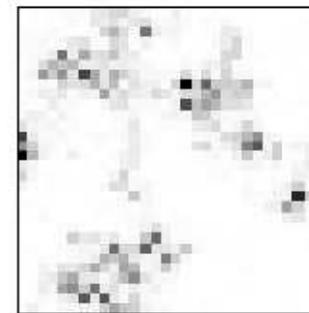
$V=t$



$V=2t$



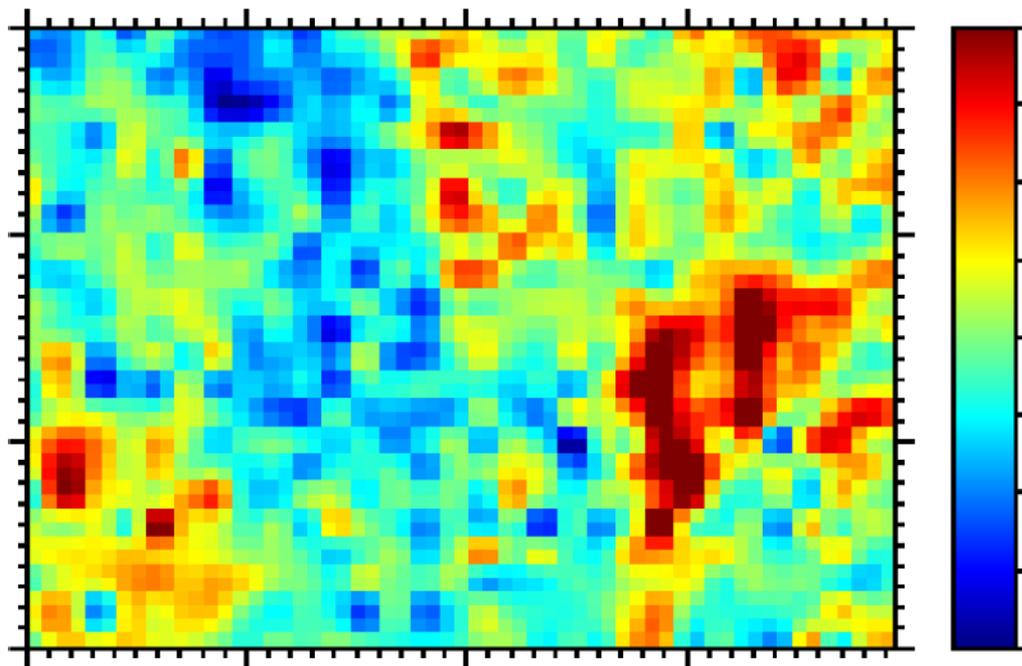
$V=2.5t$



$V=3t$

Nonuniformity – experimental evidence

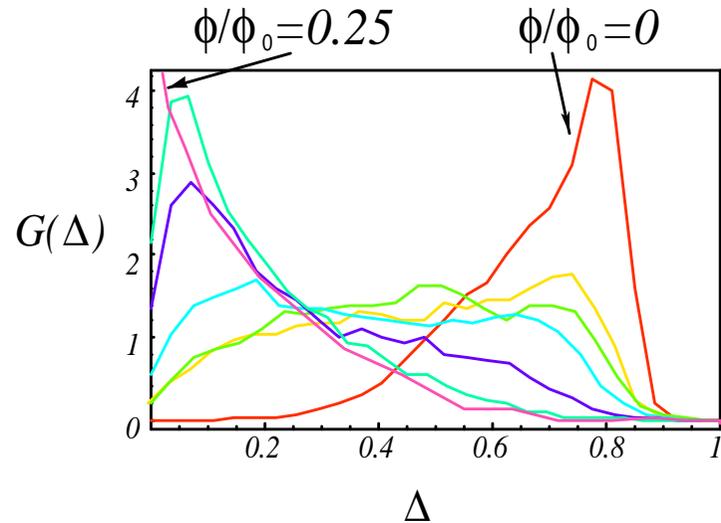
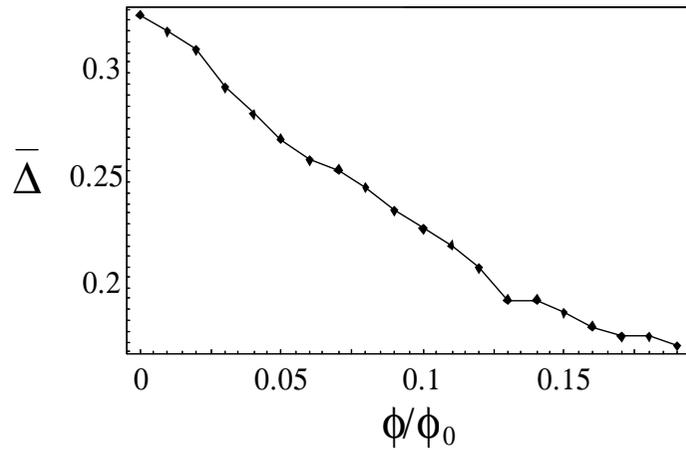
Experimental evidence for the existence of SC islands due to disorder



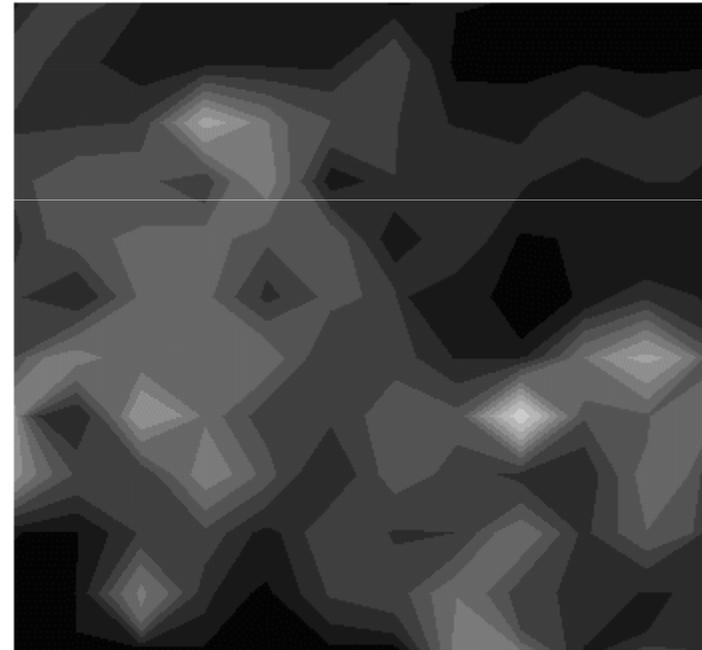
Sacepe *et.al.*, Phys. Rev. Lett. **101**, 157006 (2008)]

SC islands –mean-field (BdG) theory

perpendicular magnetic field



$B=0$.



Y.Dubi, Y. Meir and Y. Avishai, PRB [2008]

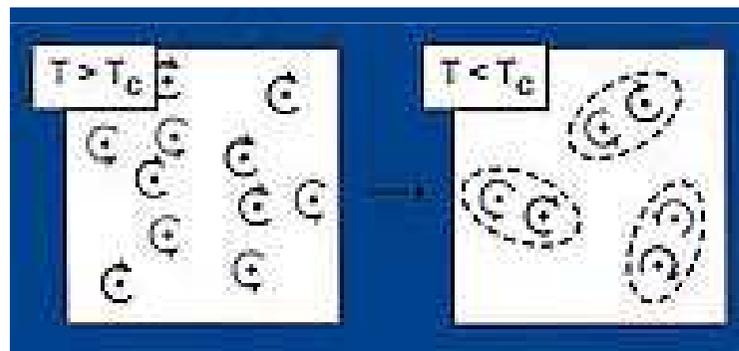
The problem

Problem: BCS theory is not appropriate to describe the loss of superconductivity at low dimensions due to phase fluctuations (Kosterlitz-Thouless transition).

Interplay of phase fluctuations and disorder ?

What happens in two dimensions ?

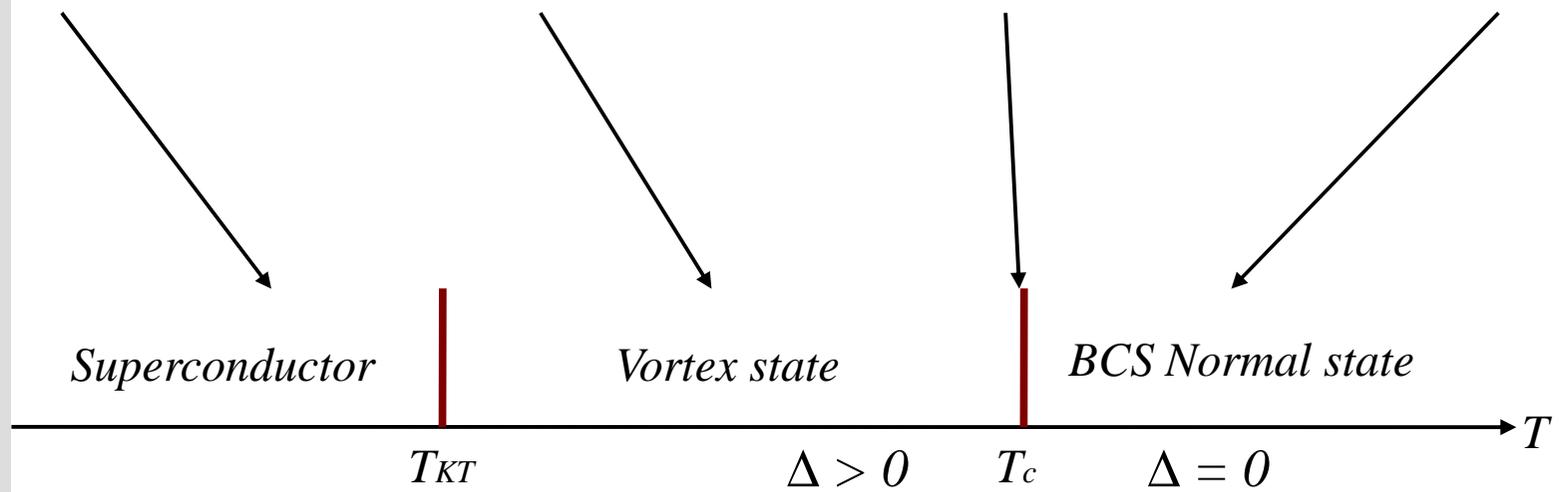
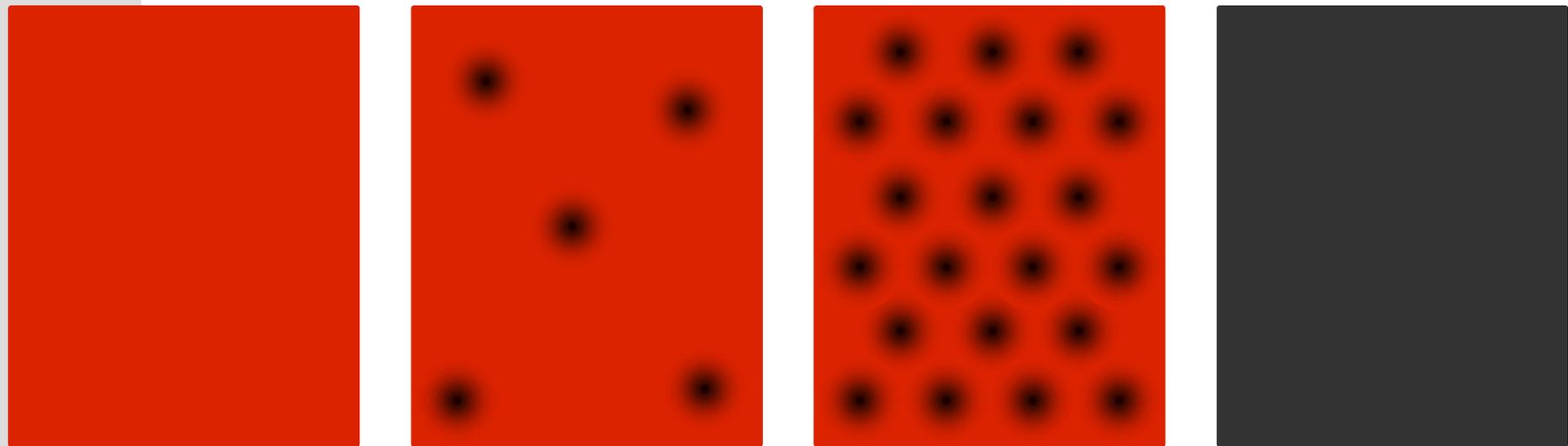
- *Mermin – Wagner theorem: no long range order at any finite T*
- *Kosterlitz – Thouless : a transition between power-law and exponentially decaying correlations*



*Binding energy of vortex- anti-vortex pair $\sim E_0 \text{ Log } R/a$
Entropy $\sim 2 \text{ Log } R/a$
So a transition at $T_{KT} = E_0/2$*

Transition driven by phase fluctuations

Kosterlitz-Thouless transition



Disorder and the Kosterlitz-Thouless transition

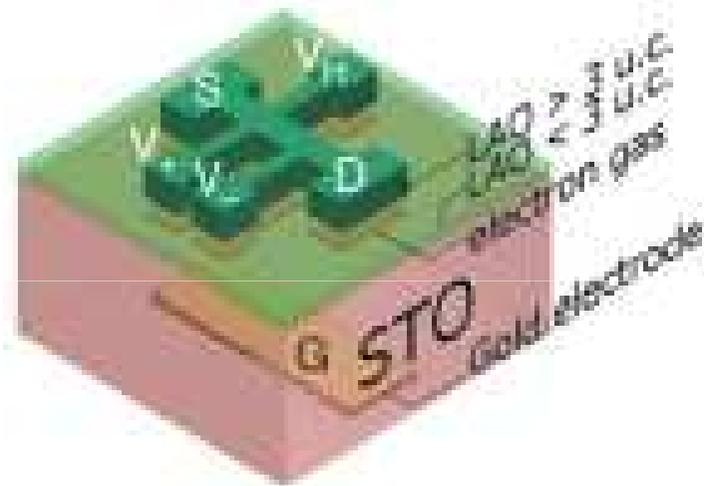
How does disorder affect the KT transition and the SC phase ?

- *Weak disorder is not relevant (Harris criterion)*
- *Strong disorder kills superconductivity (quantum phase transition)*
- *What happens at intermediate disorder ?*

Possible scenarios:

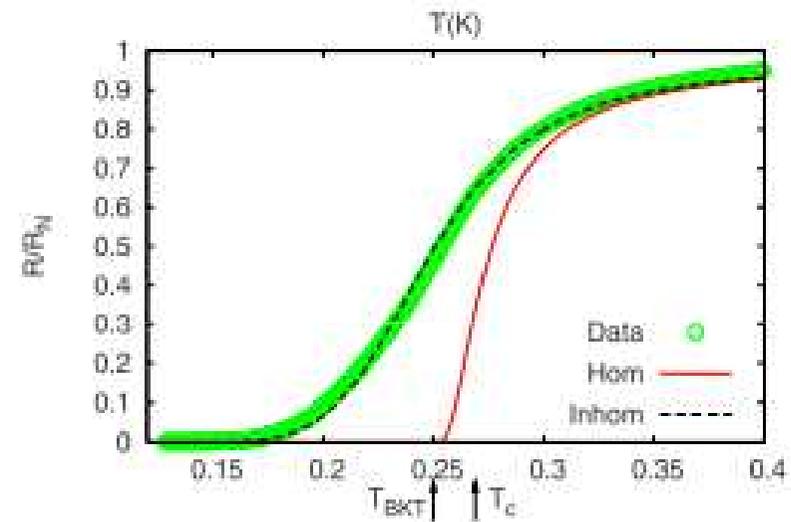
- *disorder does not affect the KT transition*
- *disorder smears the transition*
- *disorder changes the nature of the transition (percolation ?)*

Experiment: disorder and the Kosterlitz-Thouless transition



A. D. Caviglia, et al., Nature (2008)

Broadening of the transition



Nonzero pair-correlations are not sufficient for superconductivity: The system is a SC if the SC phases on the two sides of the system are correlated.

Problem – the BdG formalism does not capture phase fluctuations, so within this formalism every system with nonzero local gaps is a SC.

Solution – treat (thermal) phase fluctuations beyond BdG

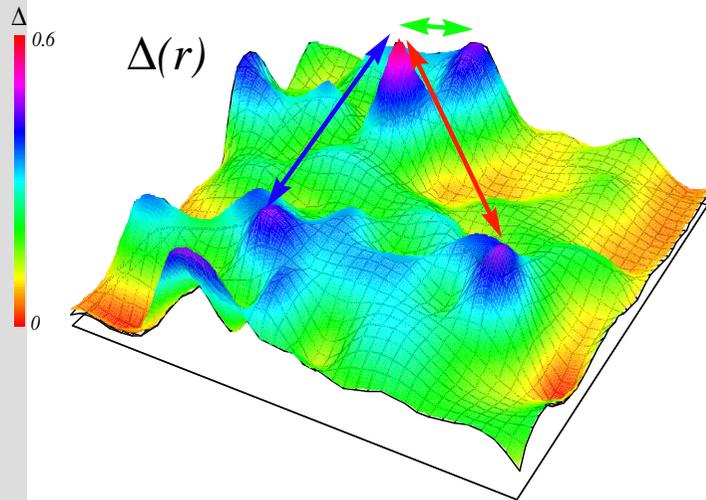
[M. Mayr *et al.*, *PRL* **94**, 217001 (2005)]

$$Z = \int \prod_i d|\Delta_i| d\vartheta_i \exp[-\beta S(\Delta_i, \beta)]$$

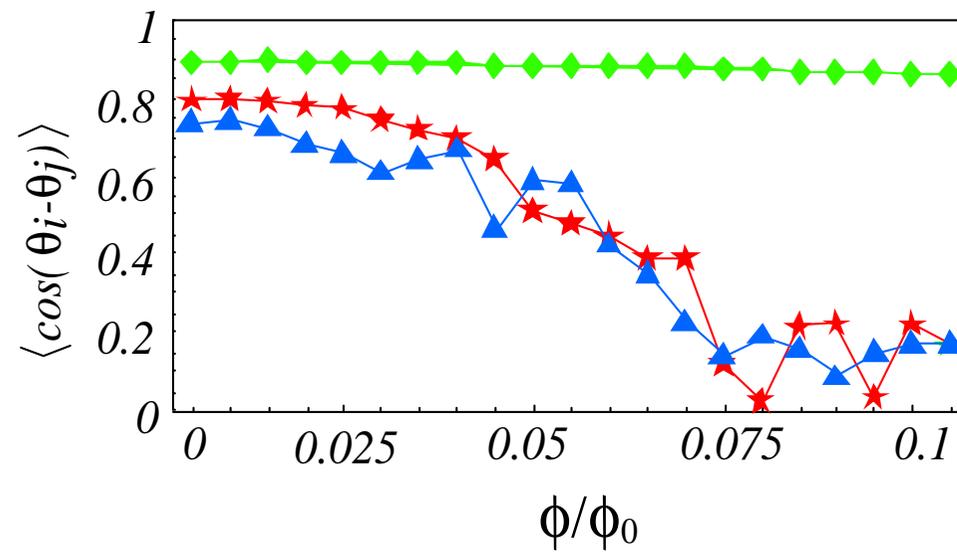
The finite-temperature BdG equations assume $\beta \longrightarrow \infty$

Evaluate the integral using a classical Monte Carlo (Metropolis) algorithm

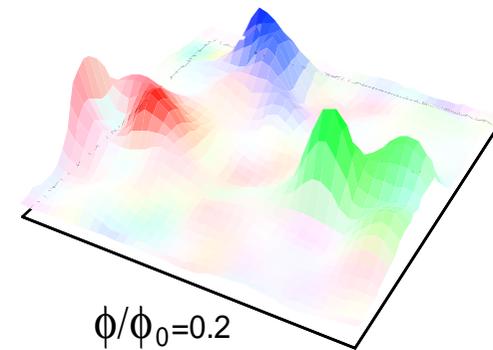
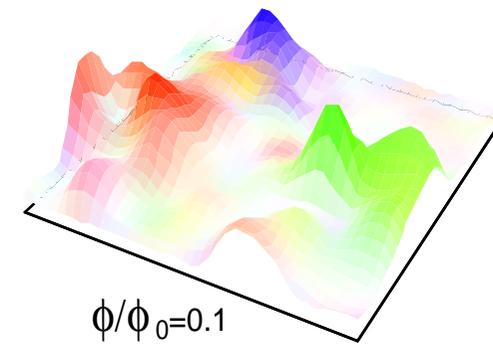
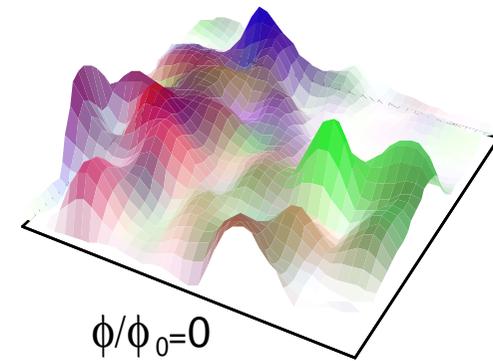
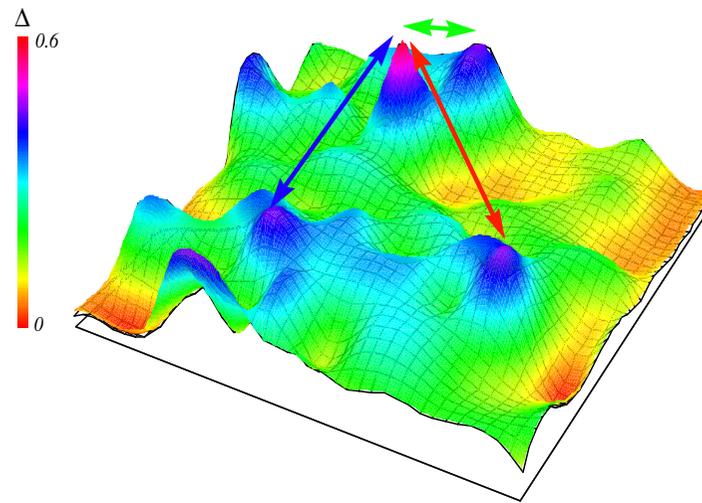
\mathcal{B} -induced phase fluctuations

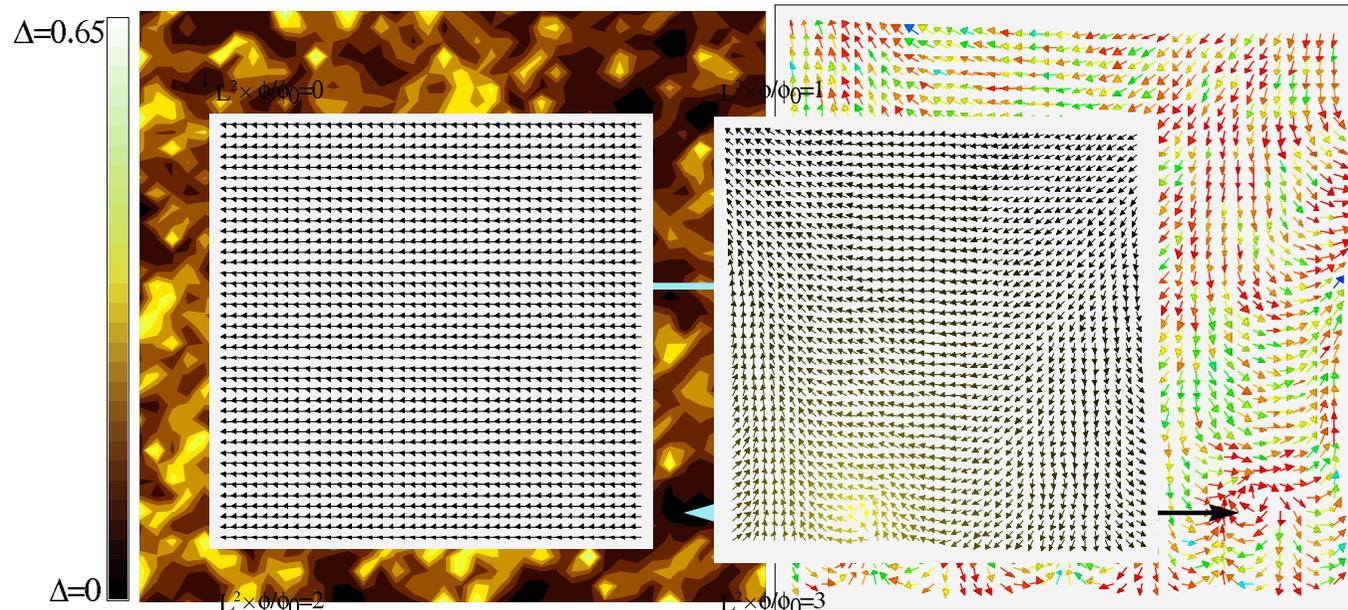


Y. Dubi, Y. Meir and Y. Avishai, Nature (2007)

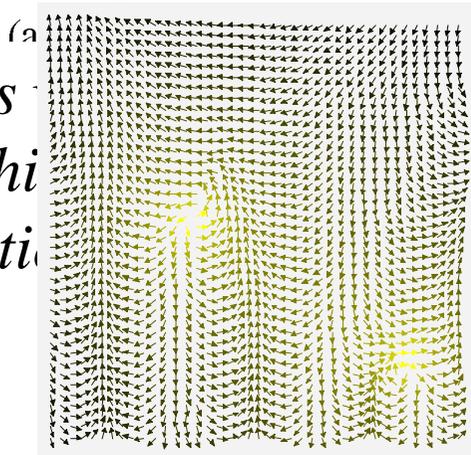


Emergence of SC islands

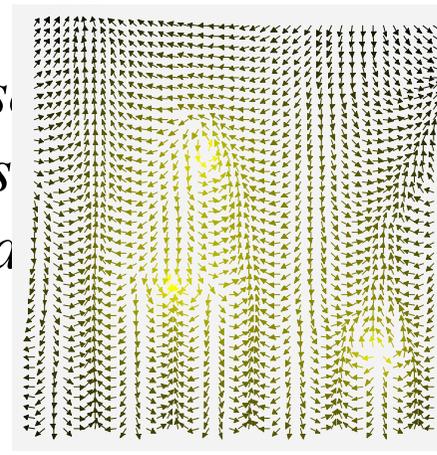




*Vortices
When the
correlati*



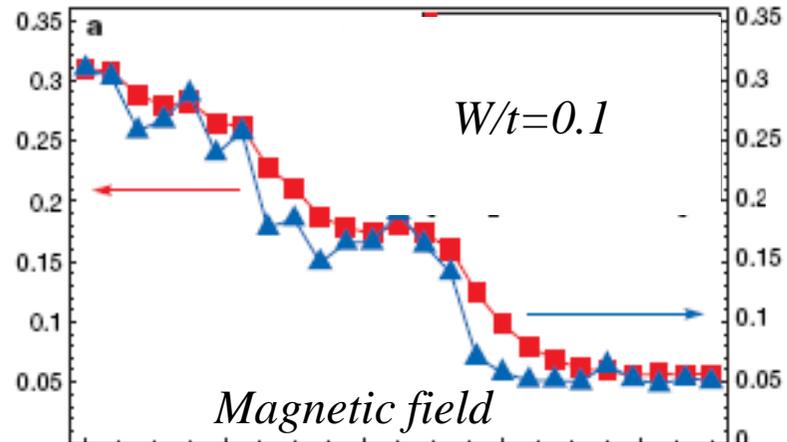
*hs
es
sla*



*ween the islands.
phase*

The SI transition

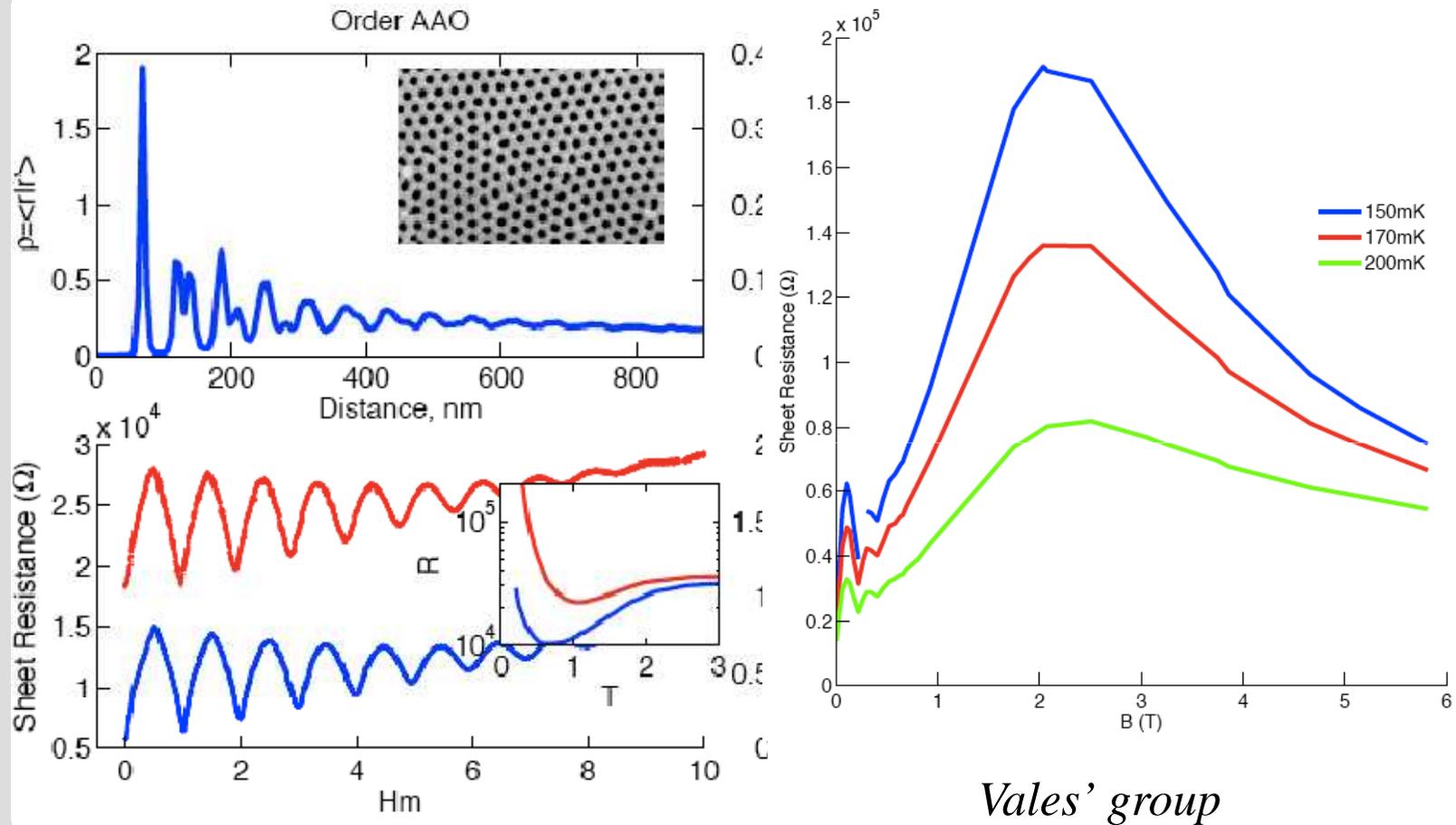
Phase rigidity



Average SC order

Both Cooper pairs and single electrons contribute to transport

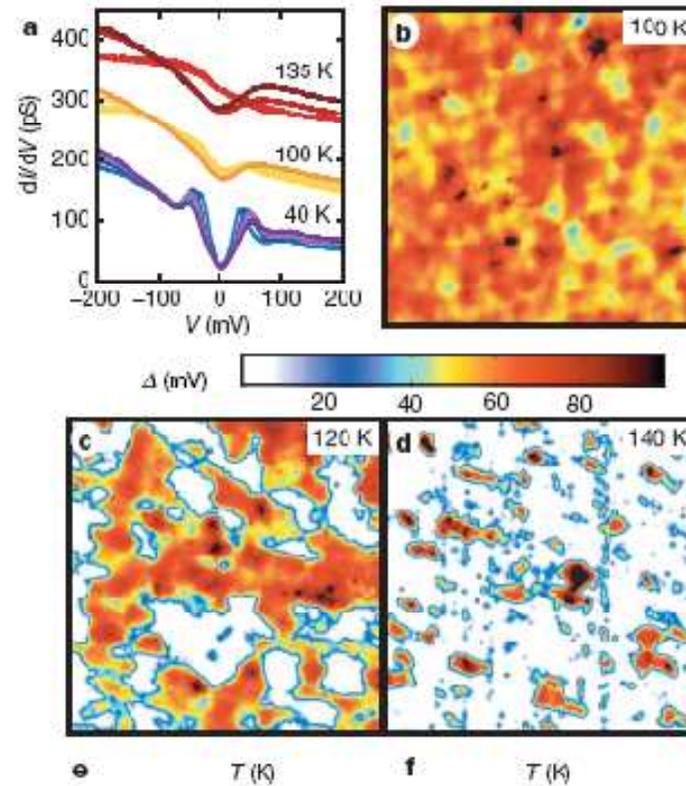
Superconducting correlations above T_c



Also, Nernst effect (Aubin)

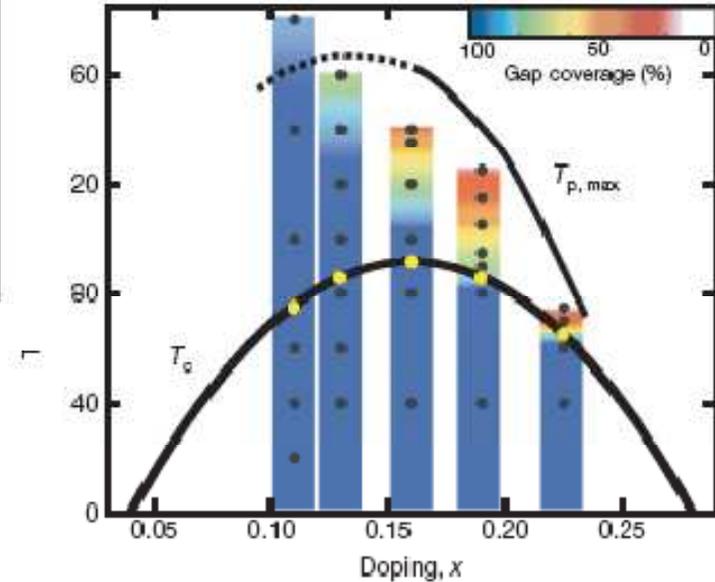
Vales' group

Superconducting islands in high- T_c materials

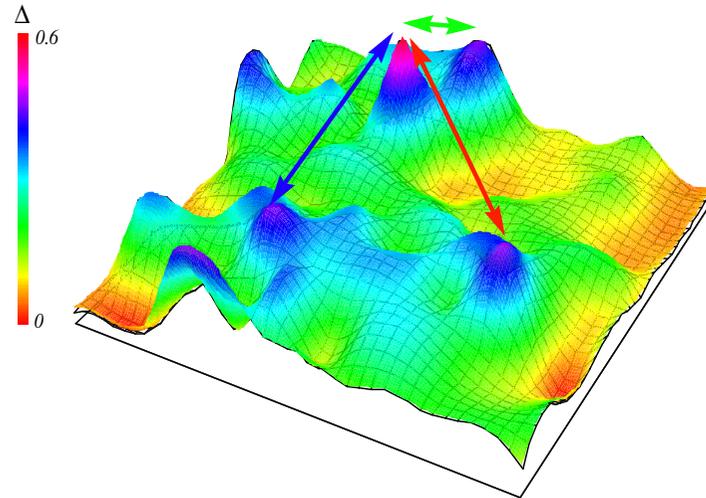


Gomez et al., Nature (2007)

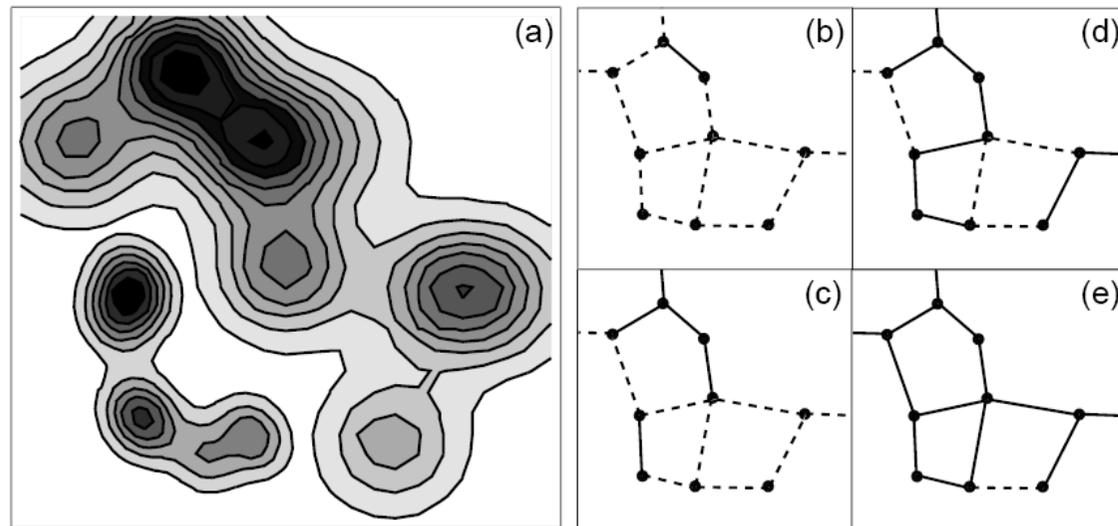
Gaps persist to well above the critical temperature



Nature of the transition

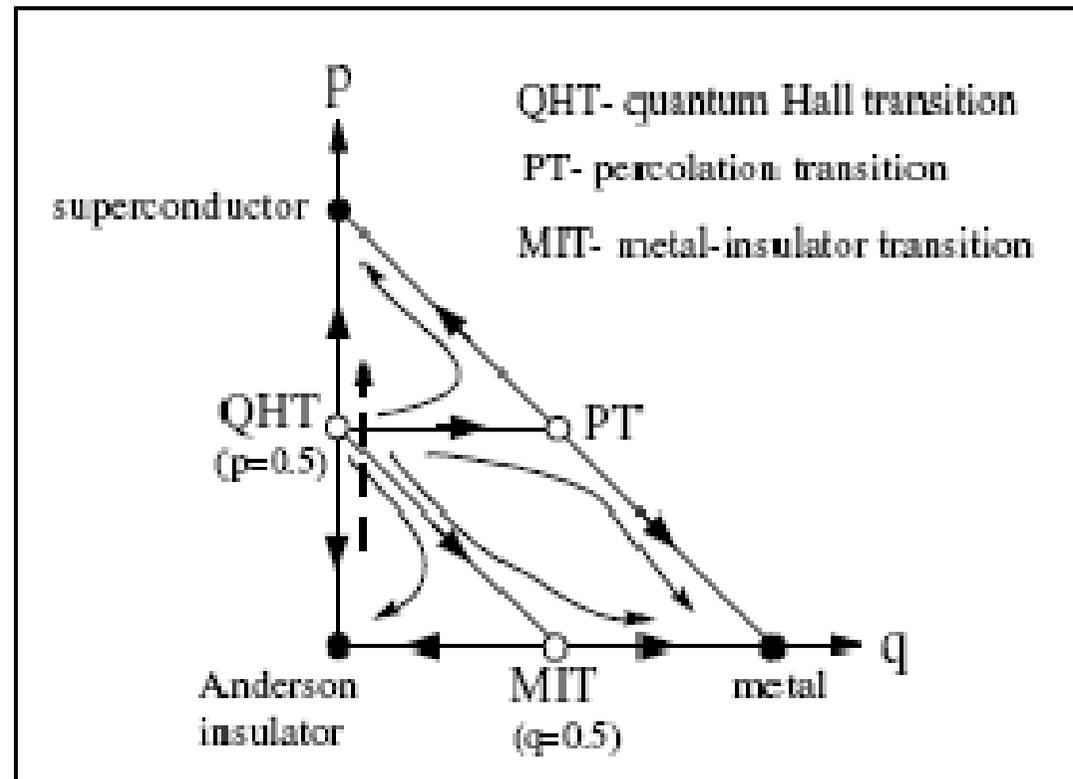


Similar to the QH transition



Y. Dubi, Y. Meir and Y. Avishai, Phys, Rev. B (2005)

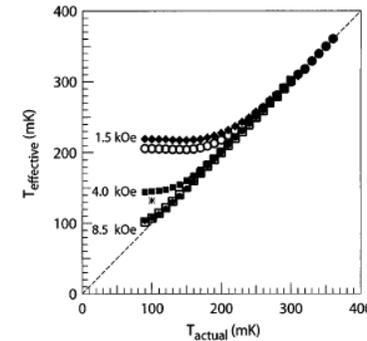
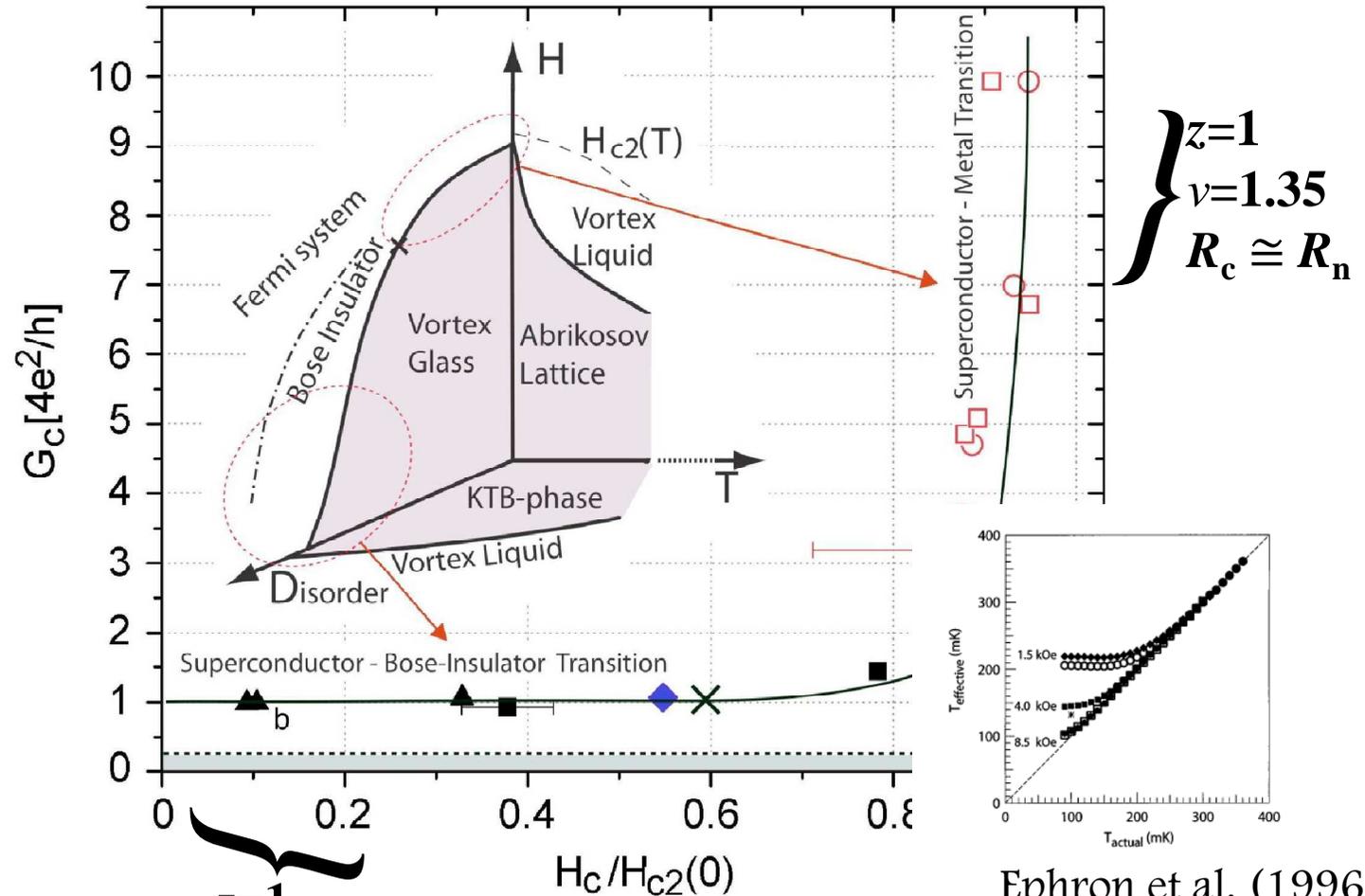
Including decoherence



Y, Y & Y, Phys, Rev. Lett. (2005)

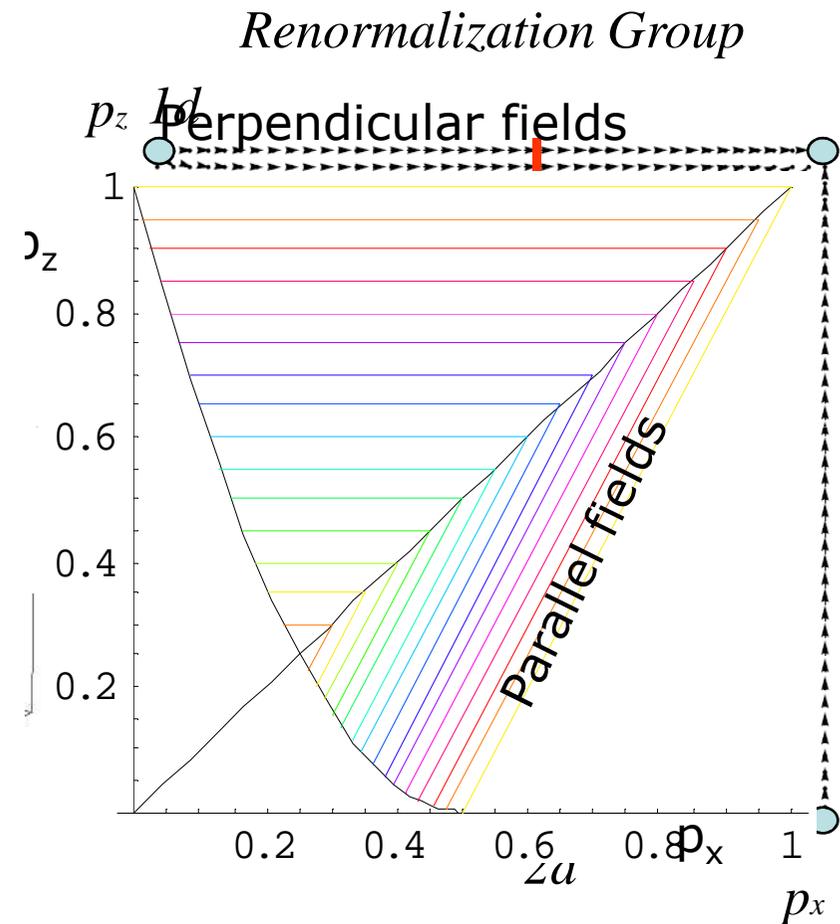
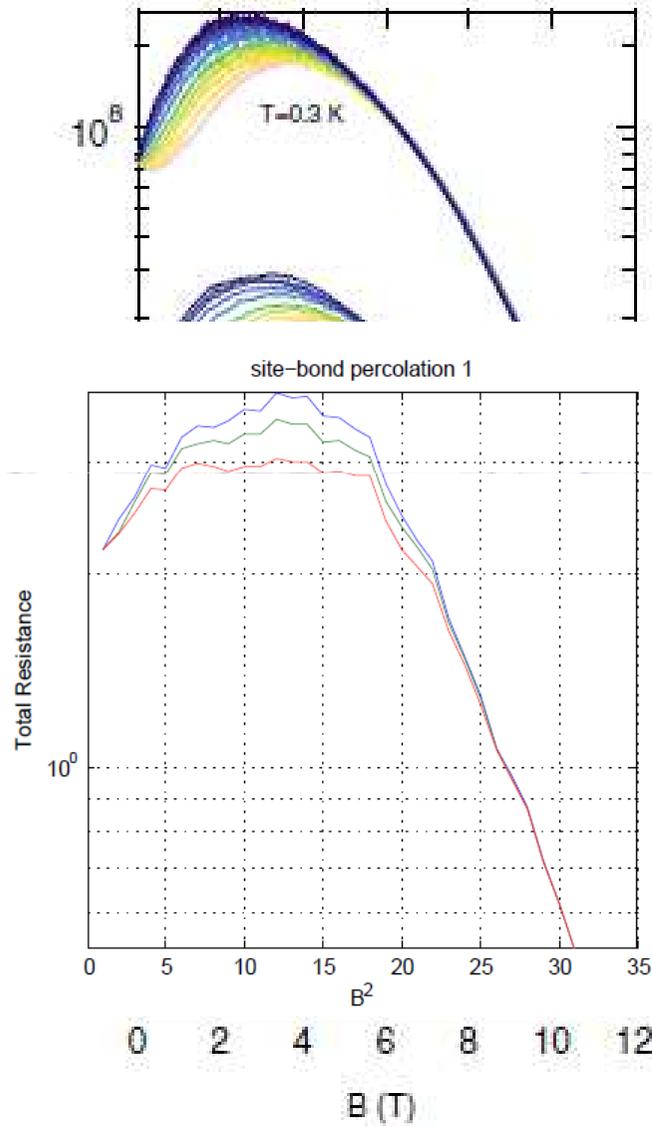
Experimental phase diagram

Kapitulnik et al.



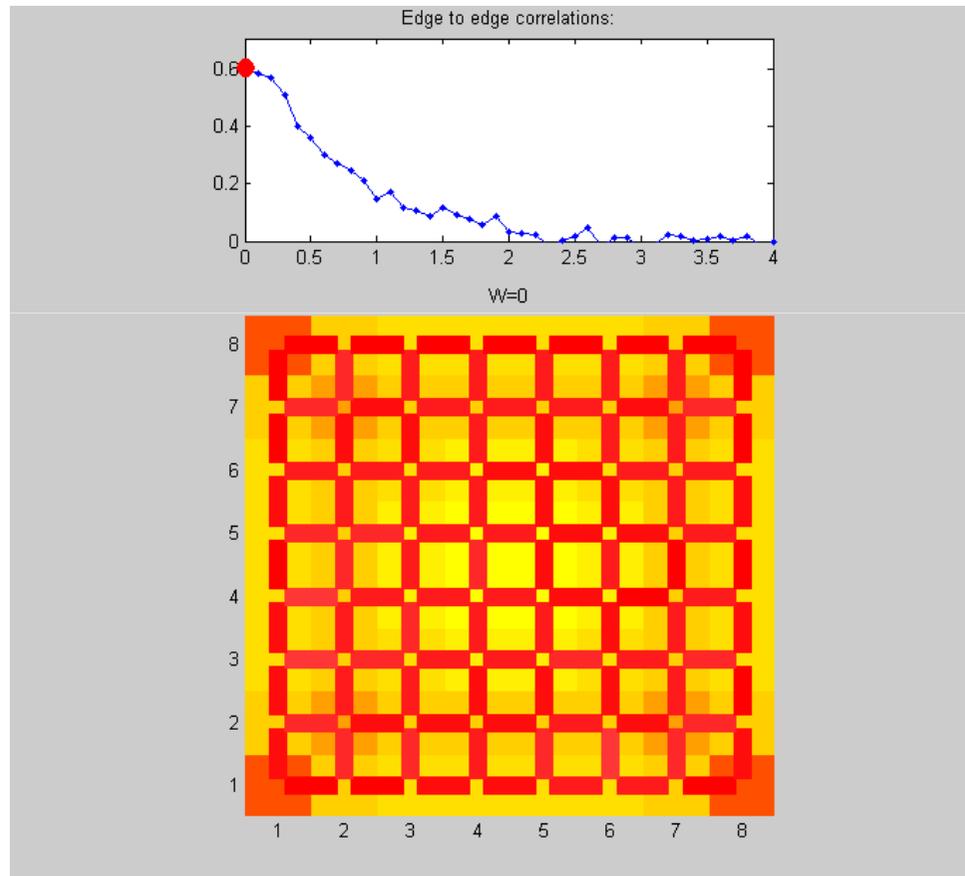
Ephron et al. (1996)

Finite thickness

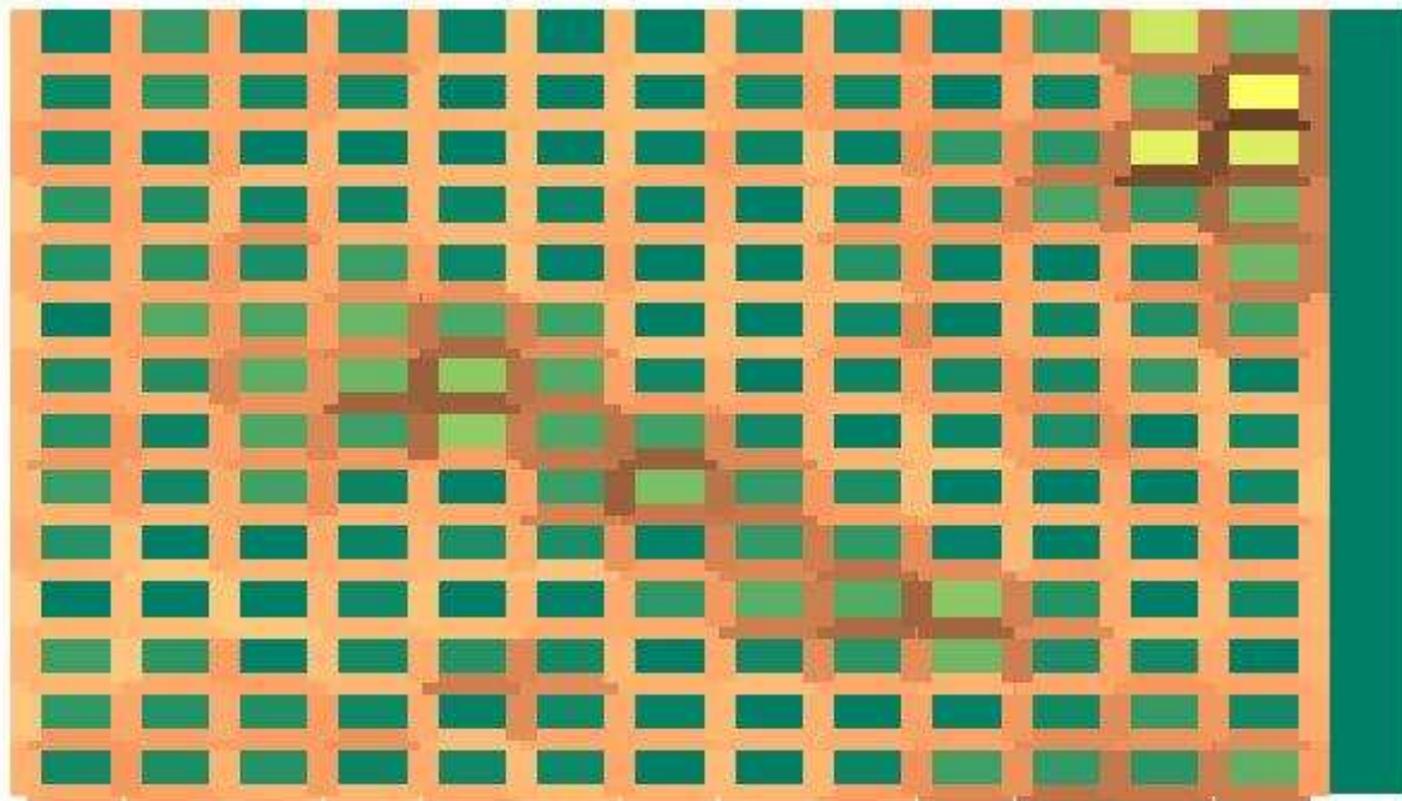
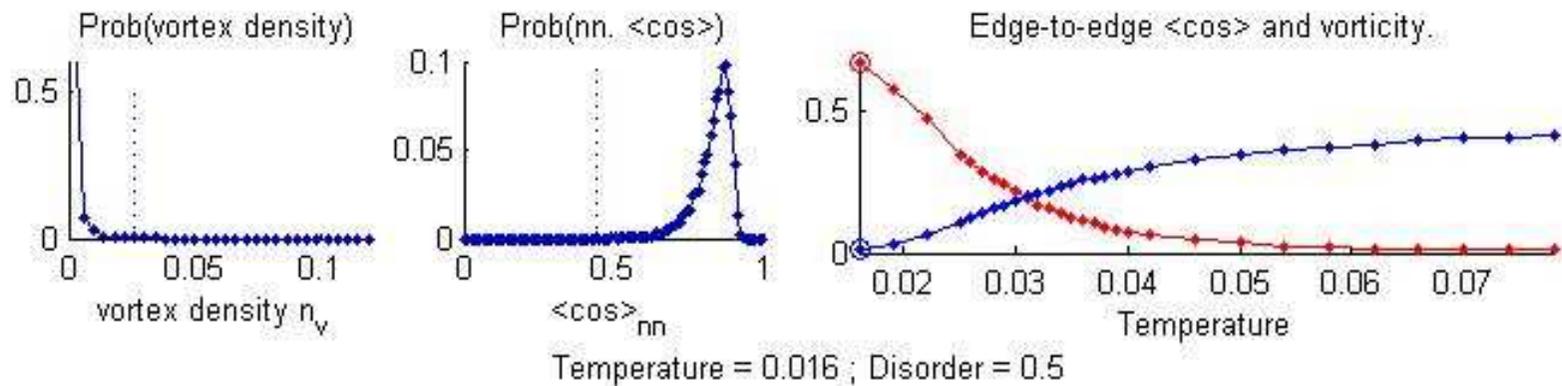


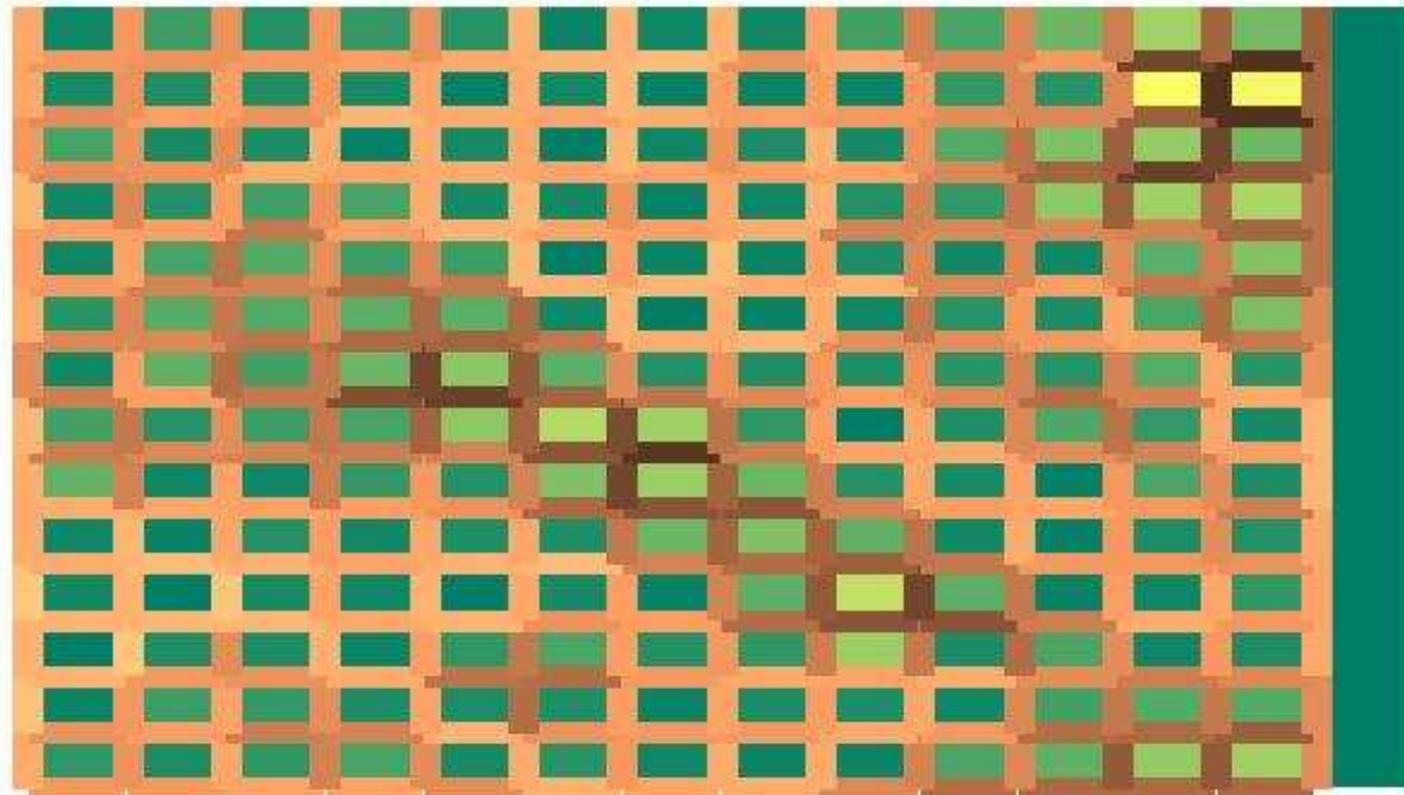
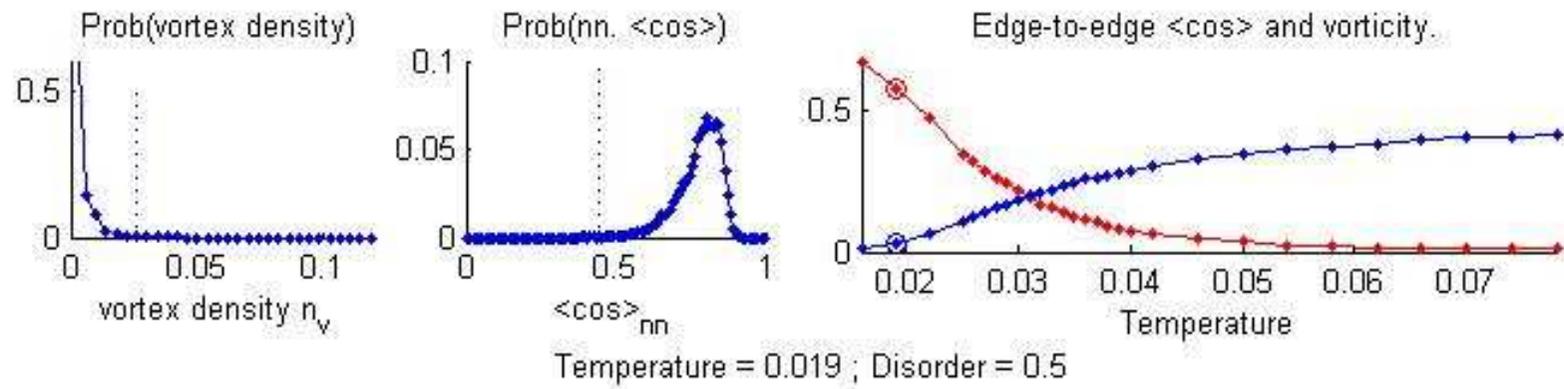
E. Porat, unpublished

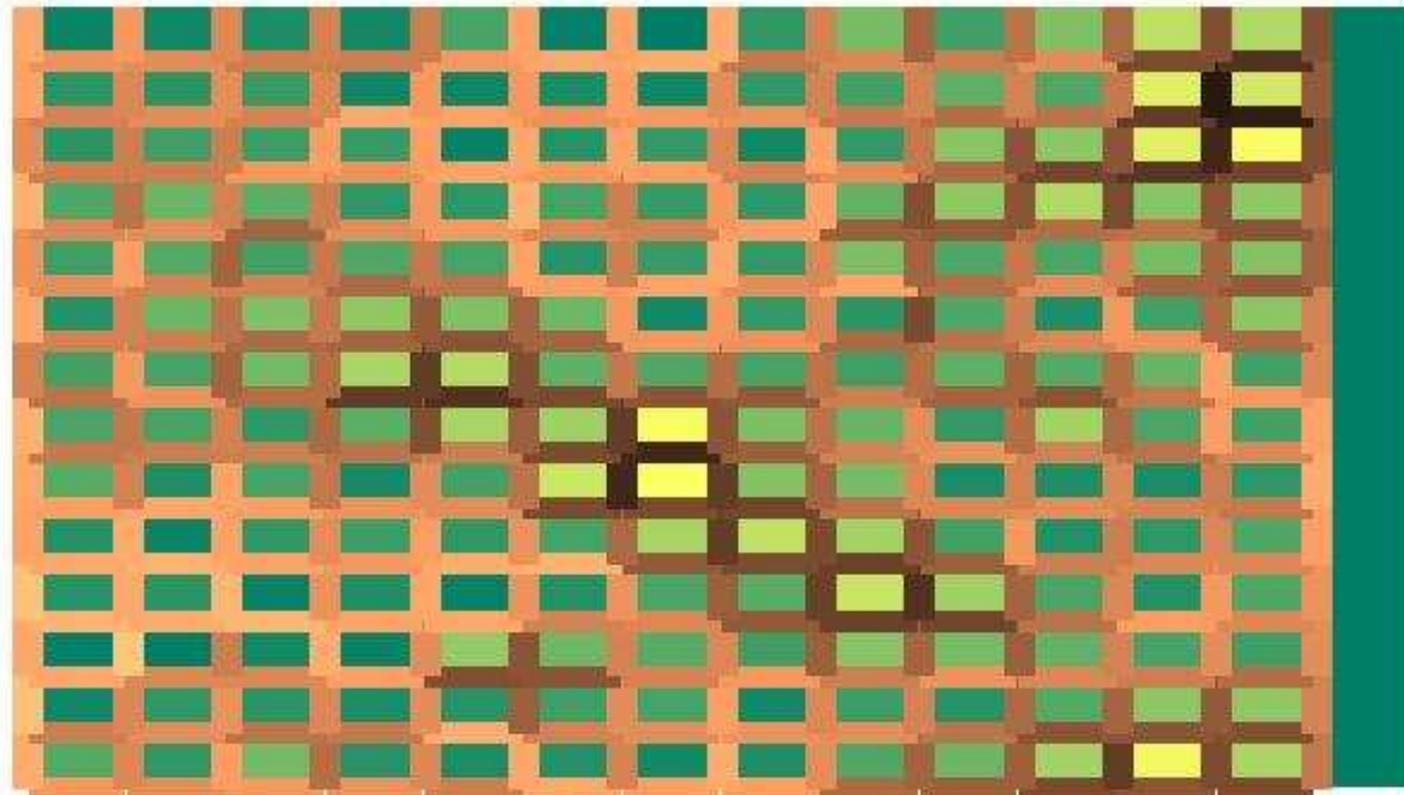
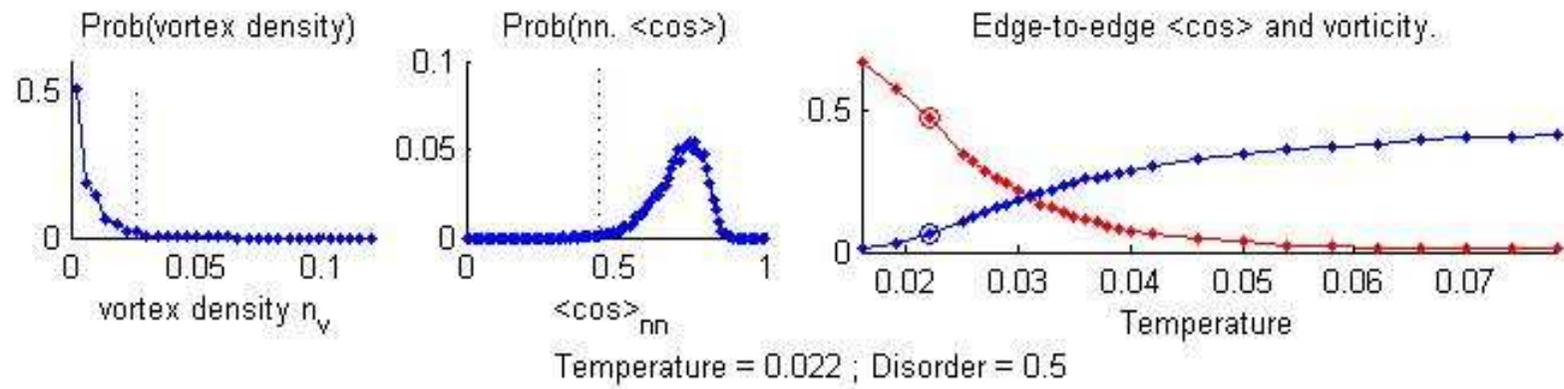
*The SIT in the disordered XY model:
KT vs percolation transition*

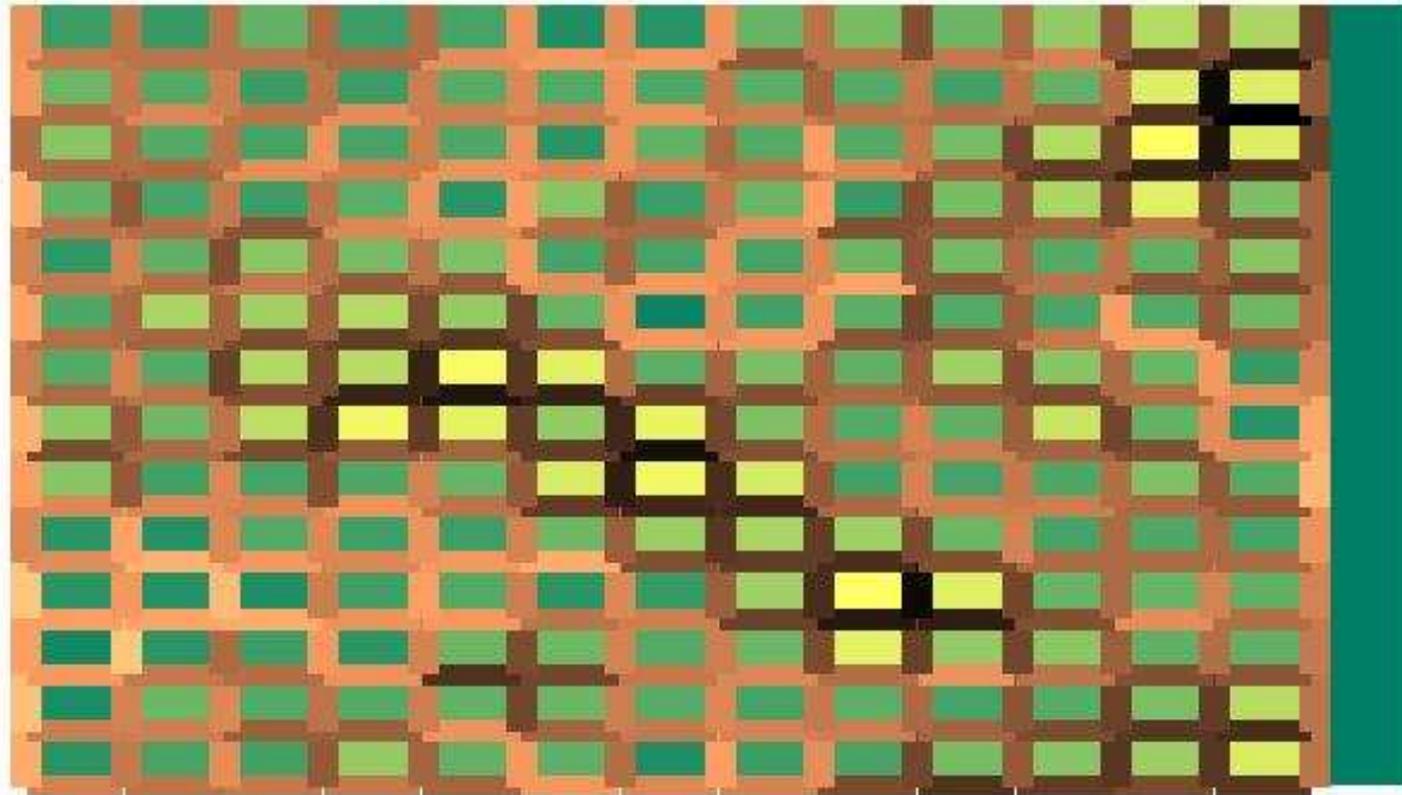
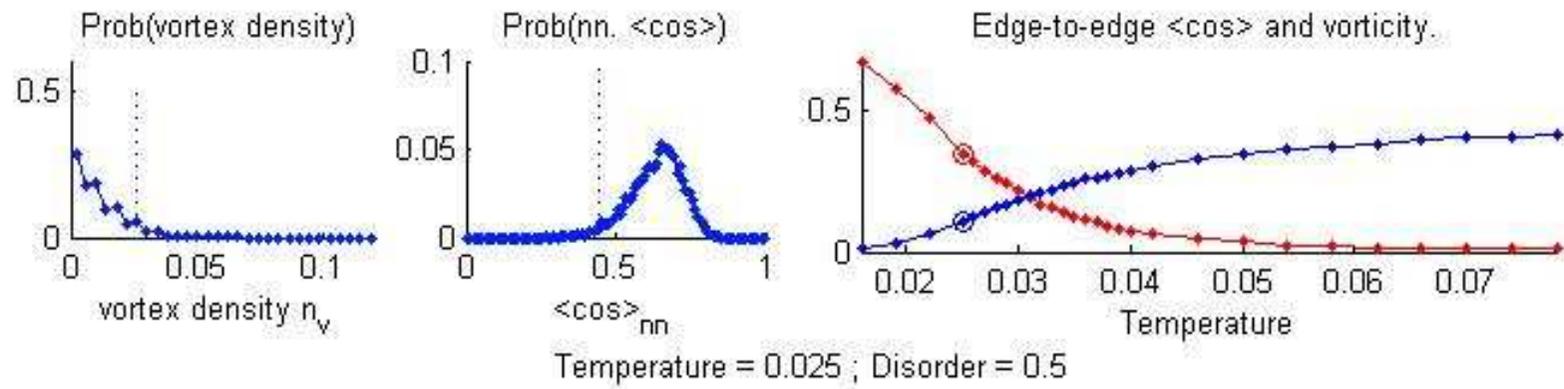


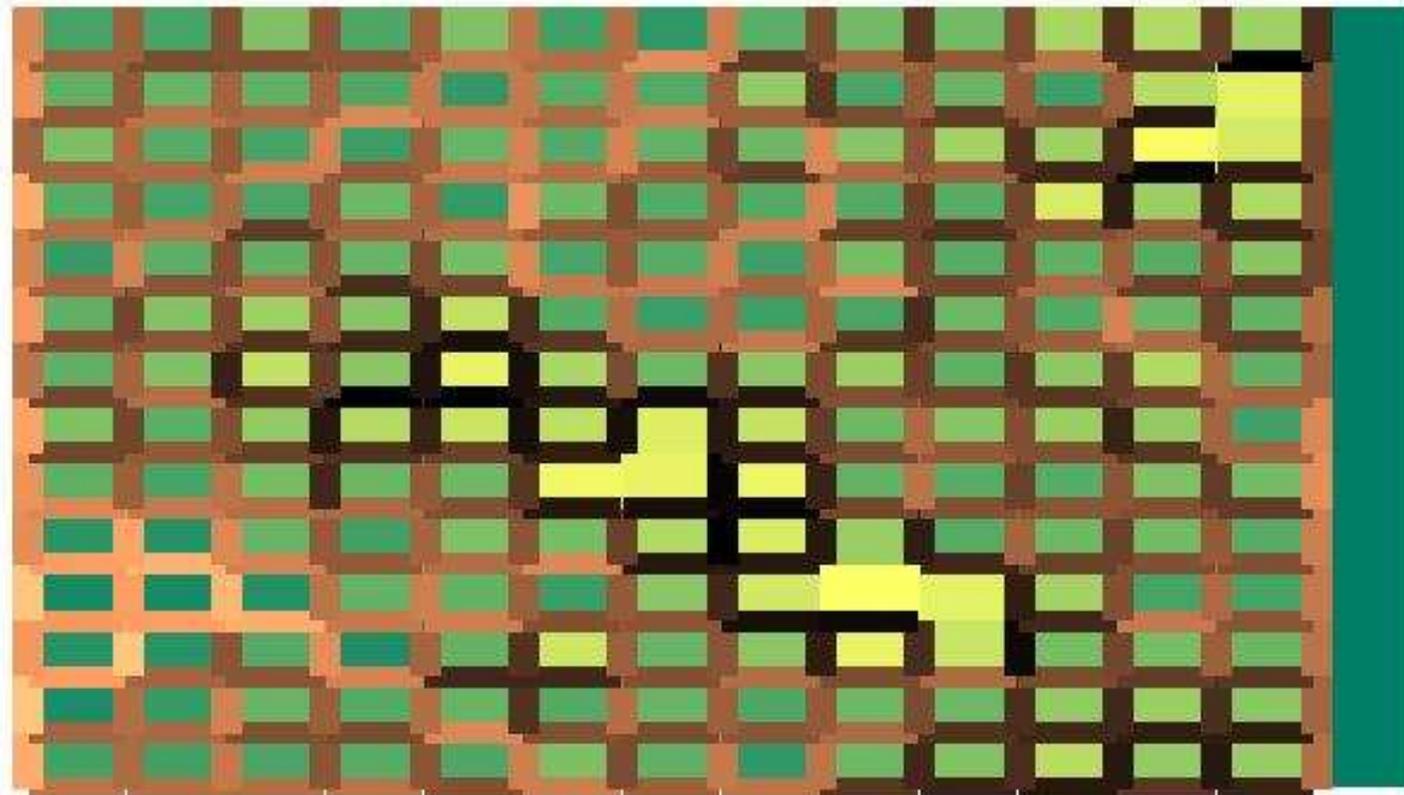
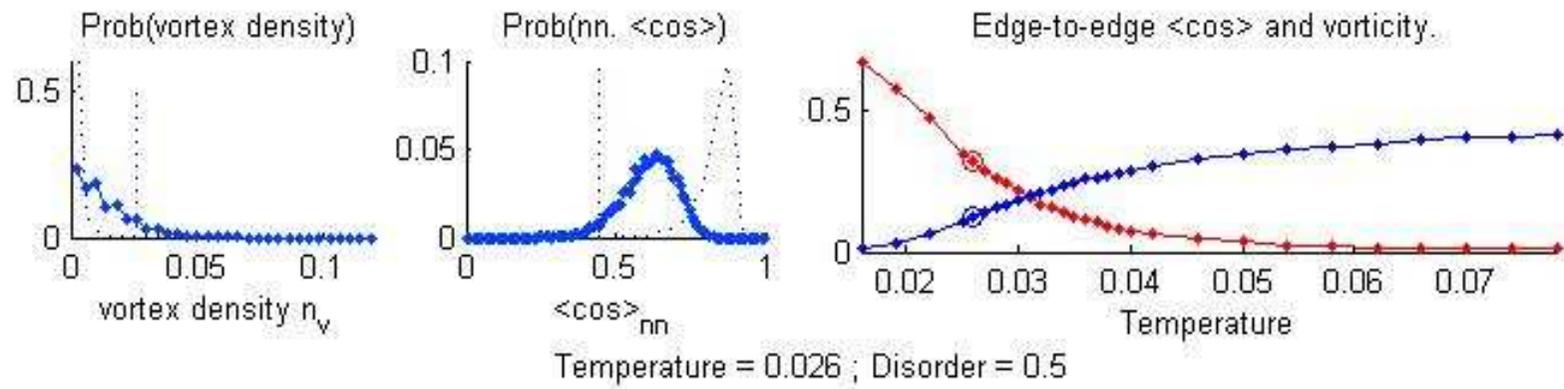
*A. Erez and Y. Meir,
EPL (2011)*

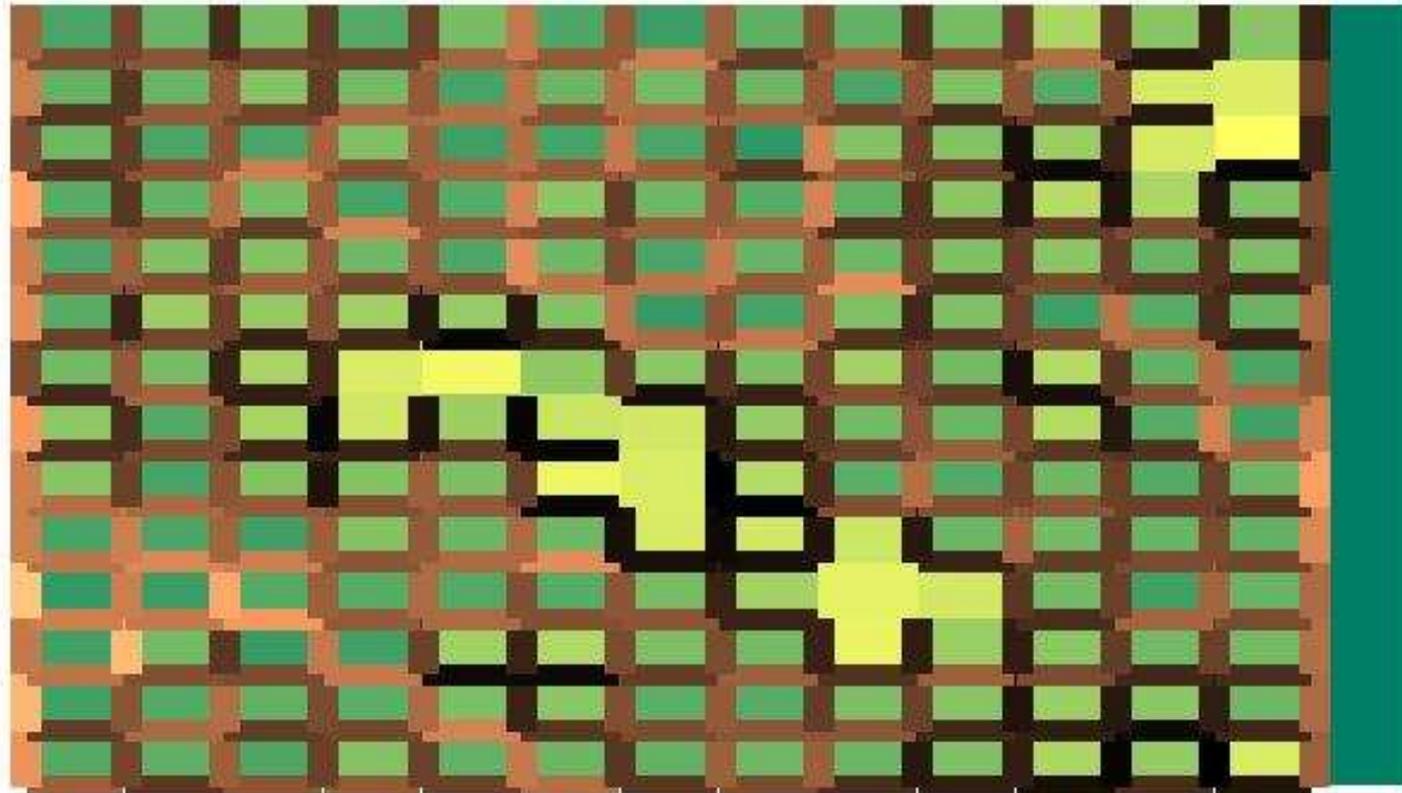
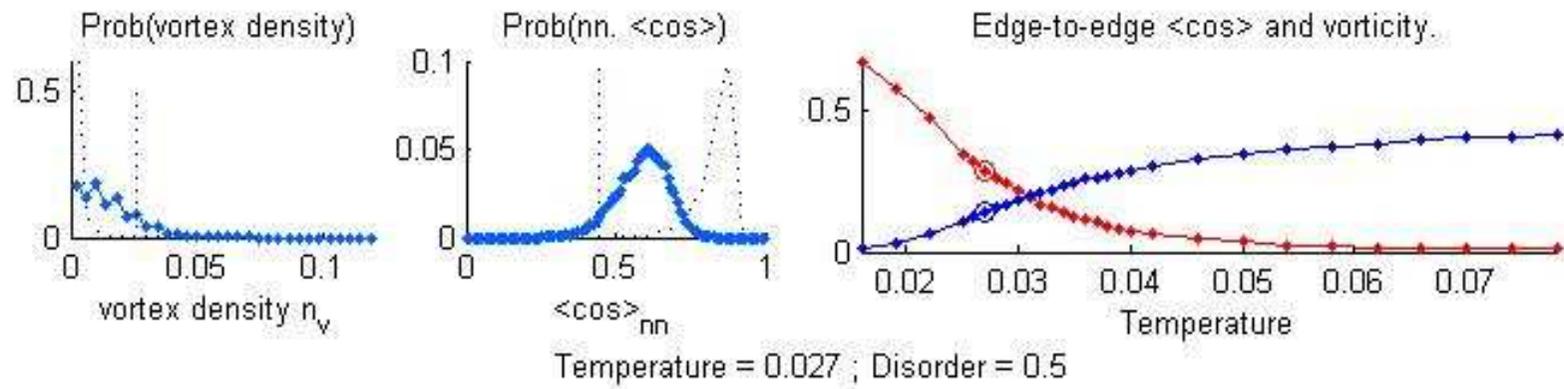


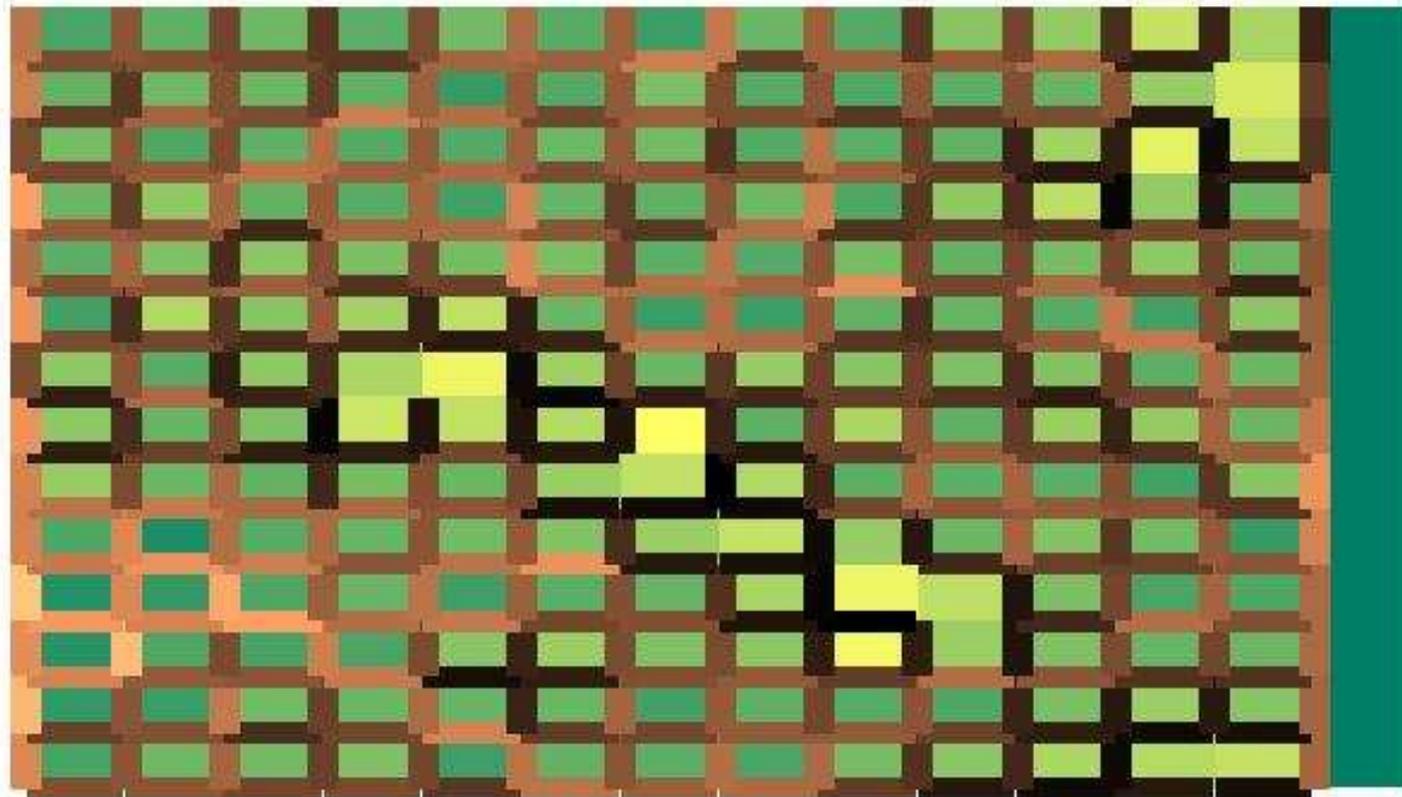
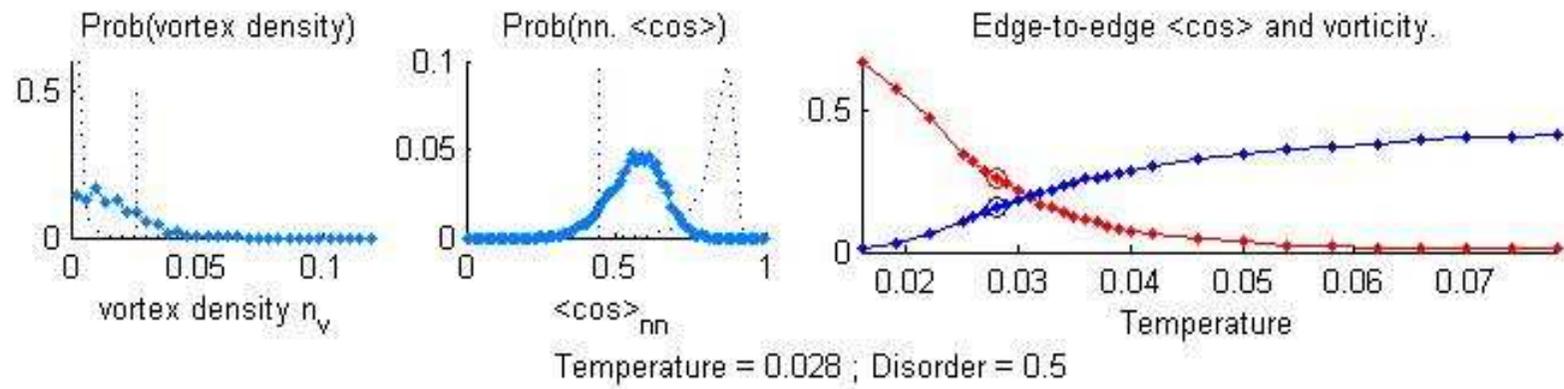


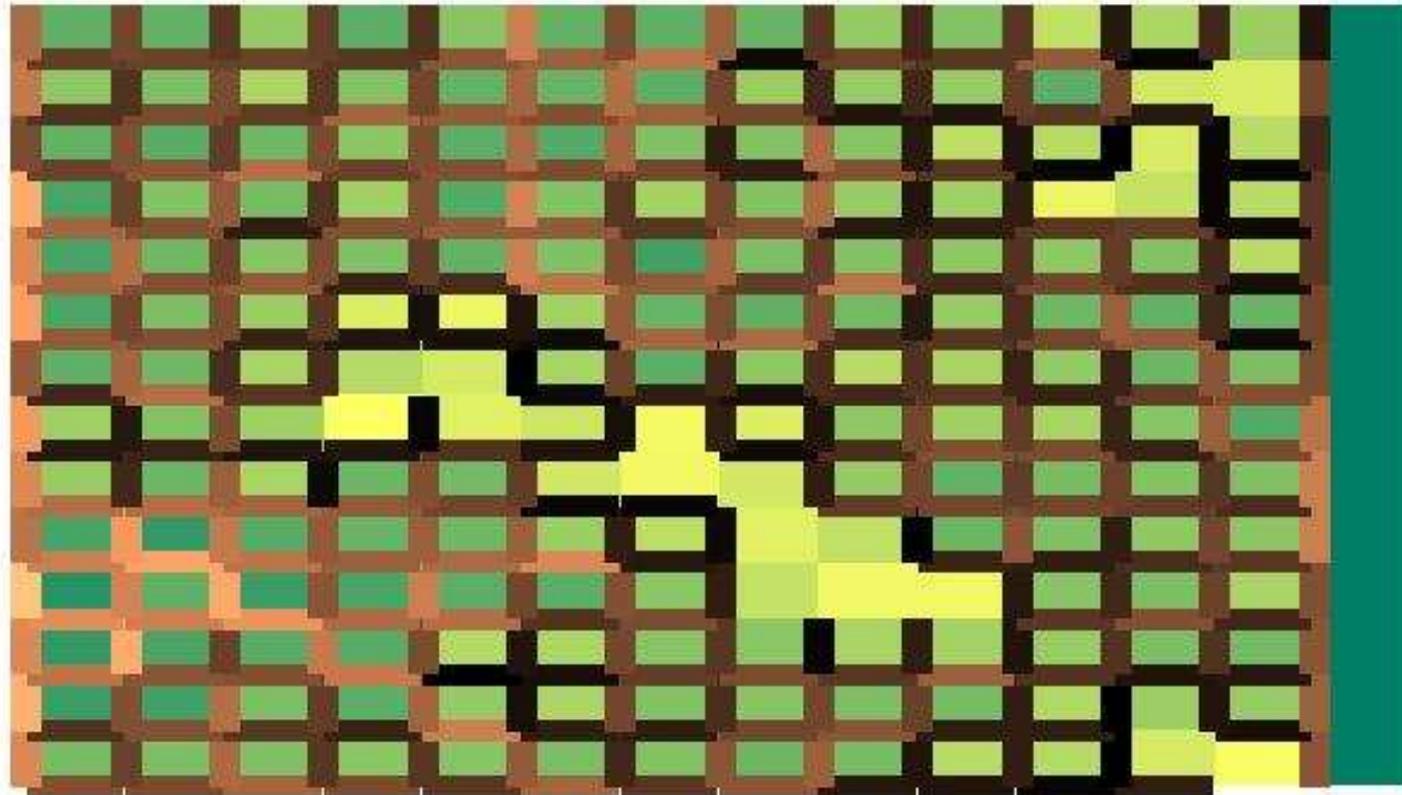
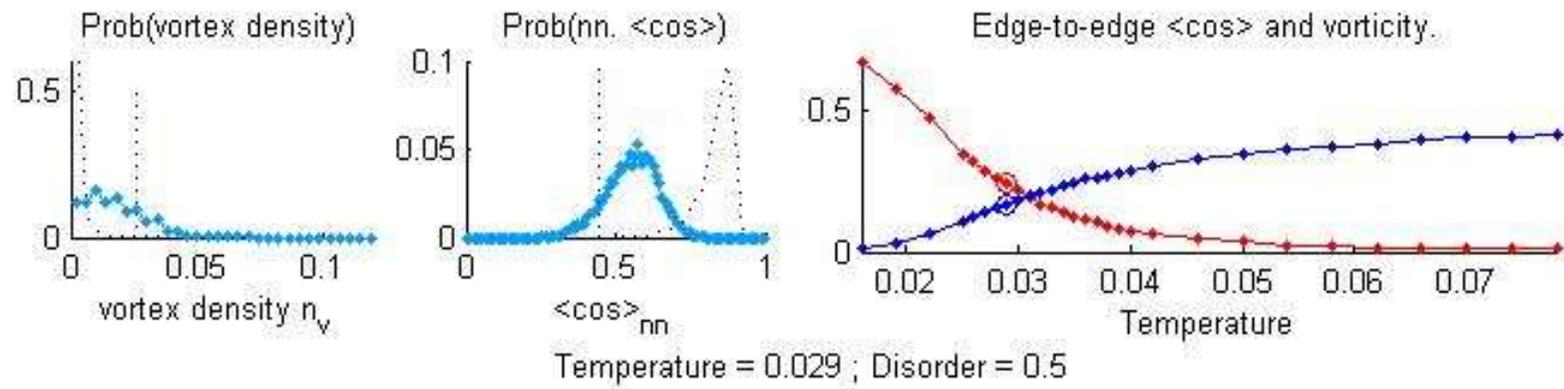


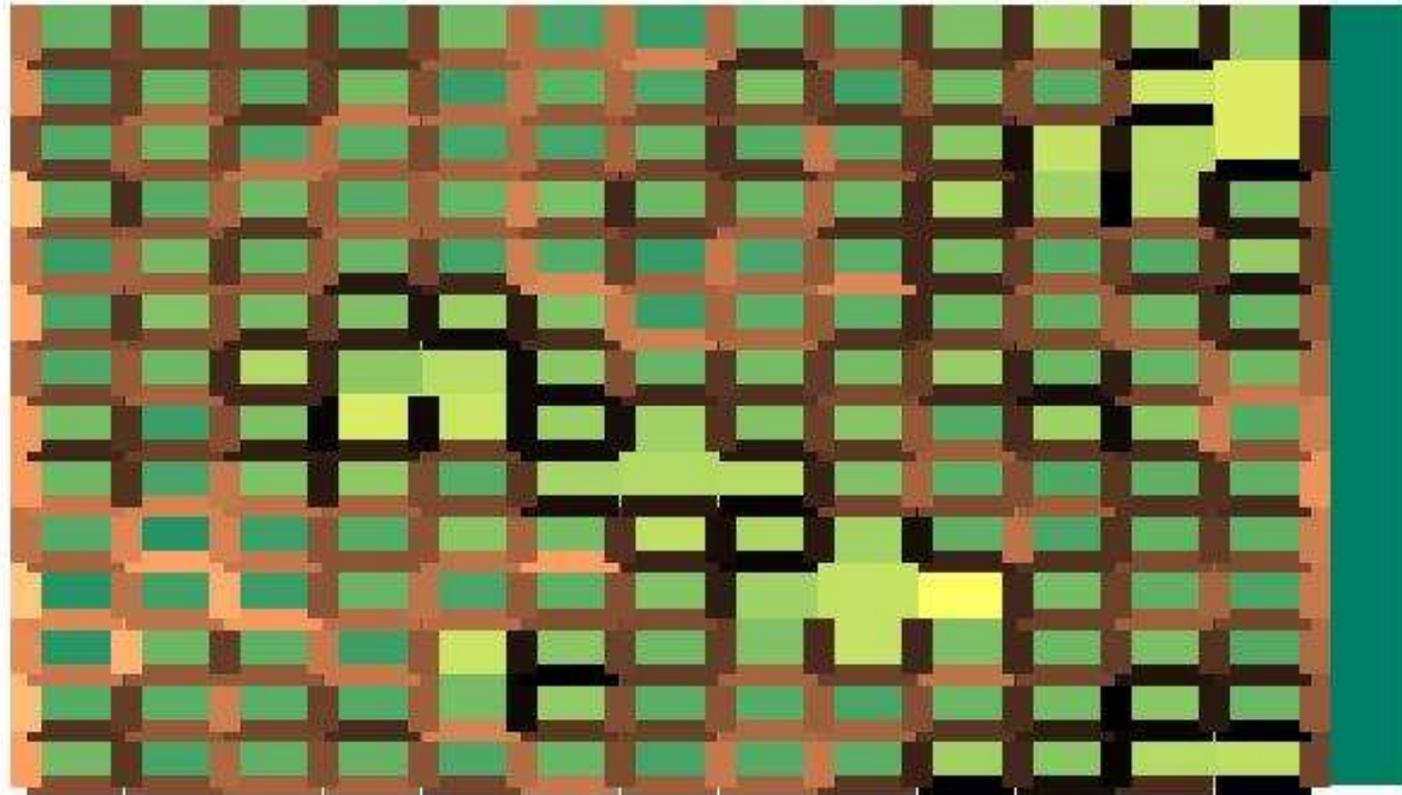
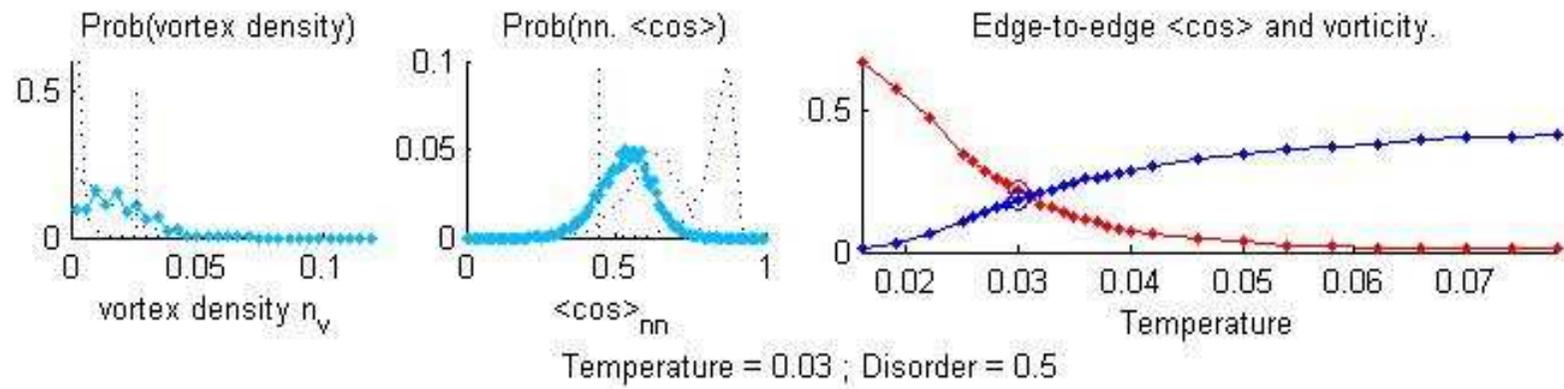


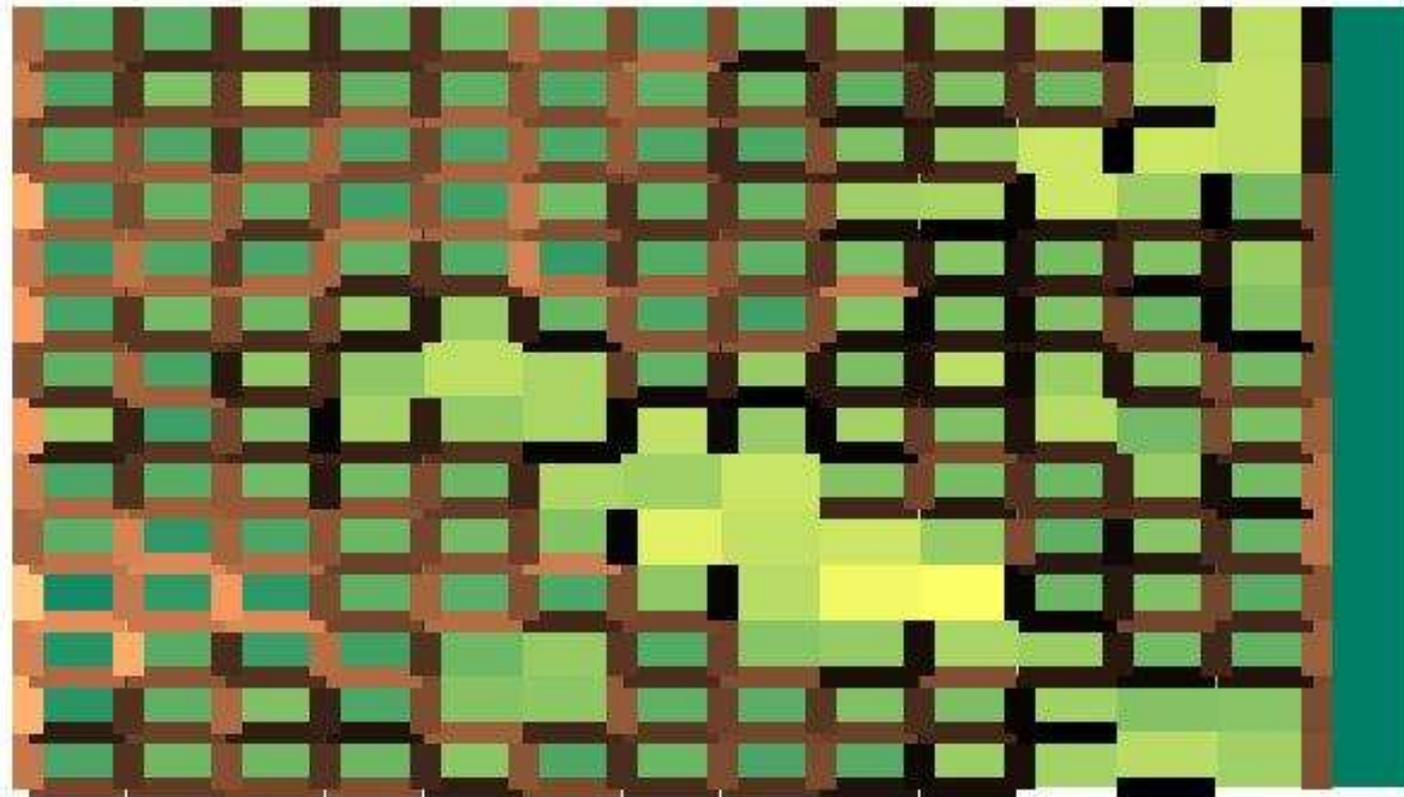
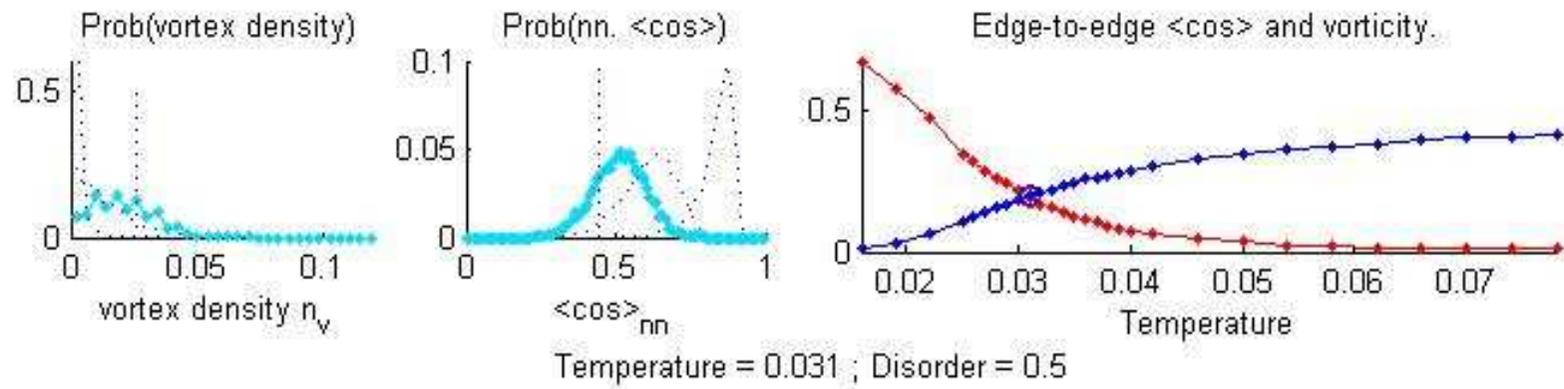


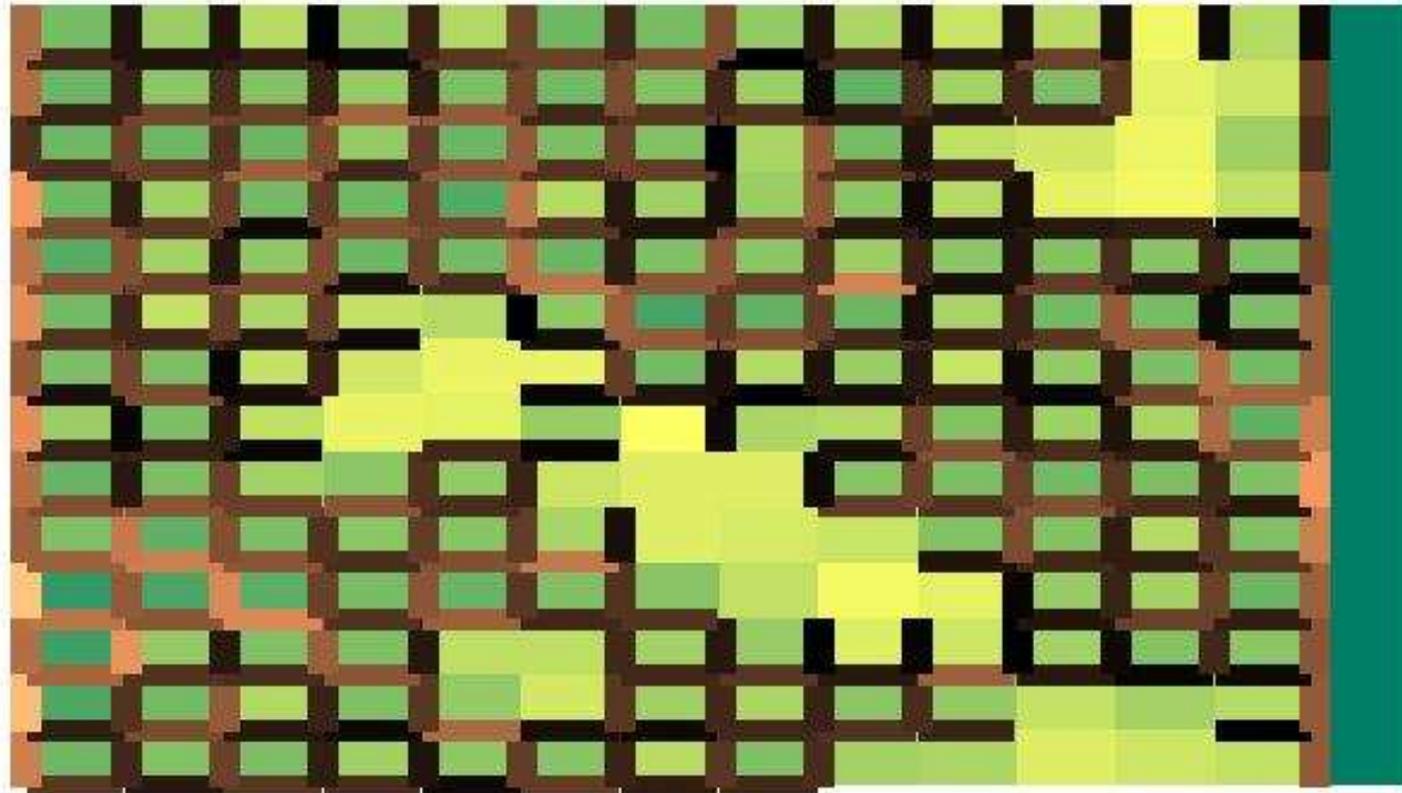
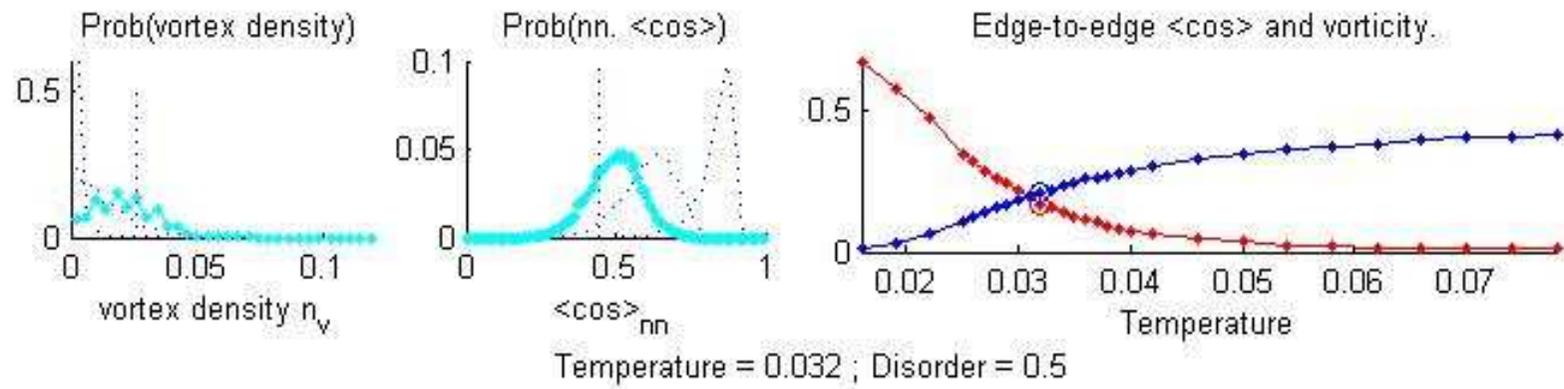


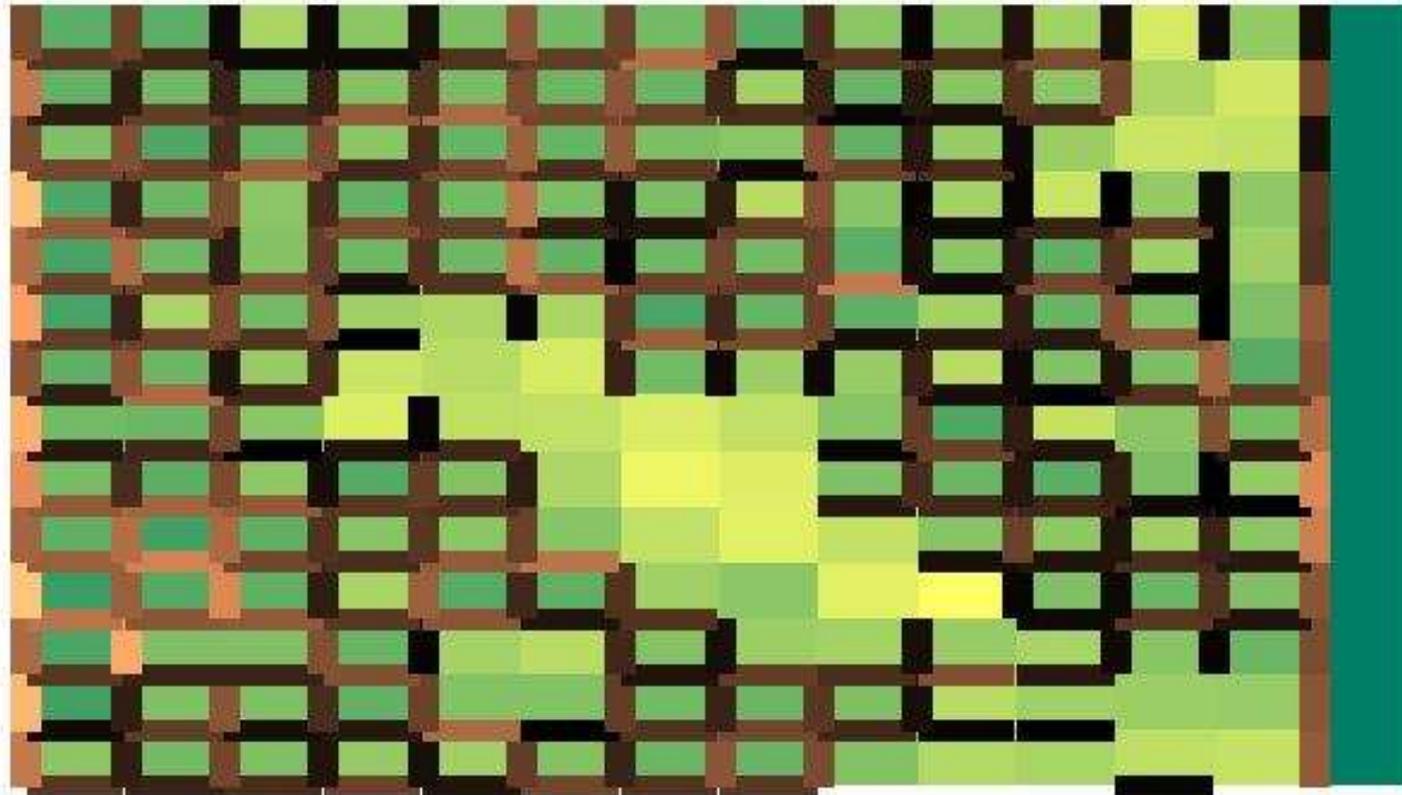
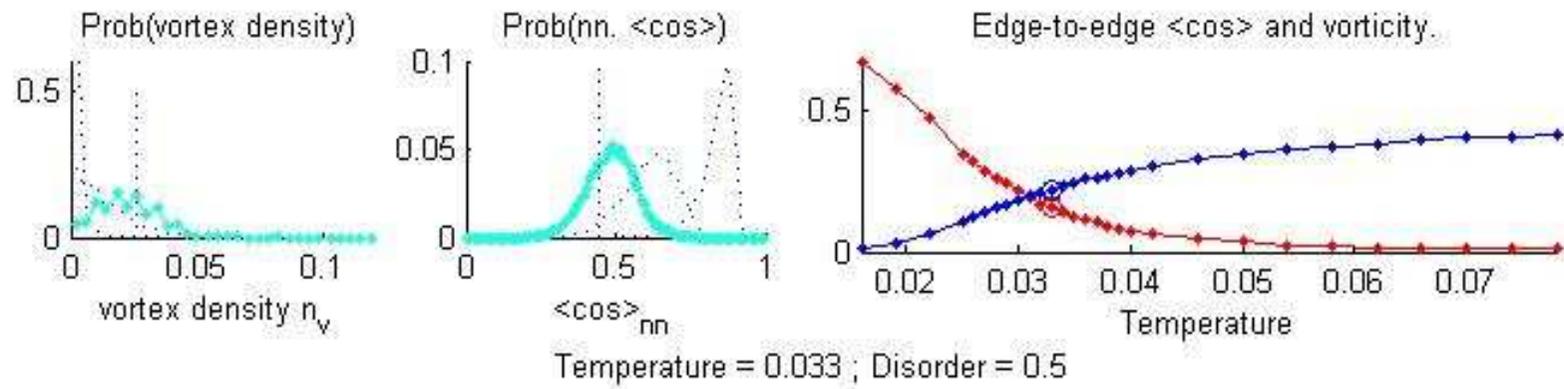


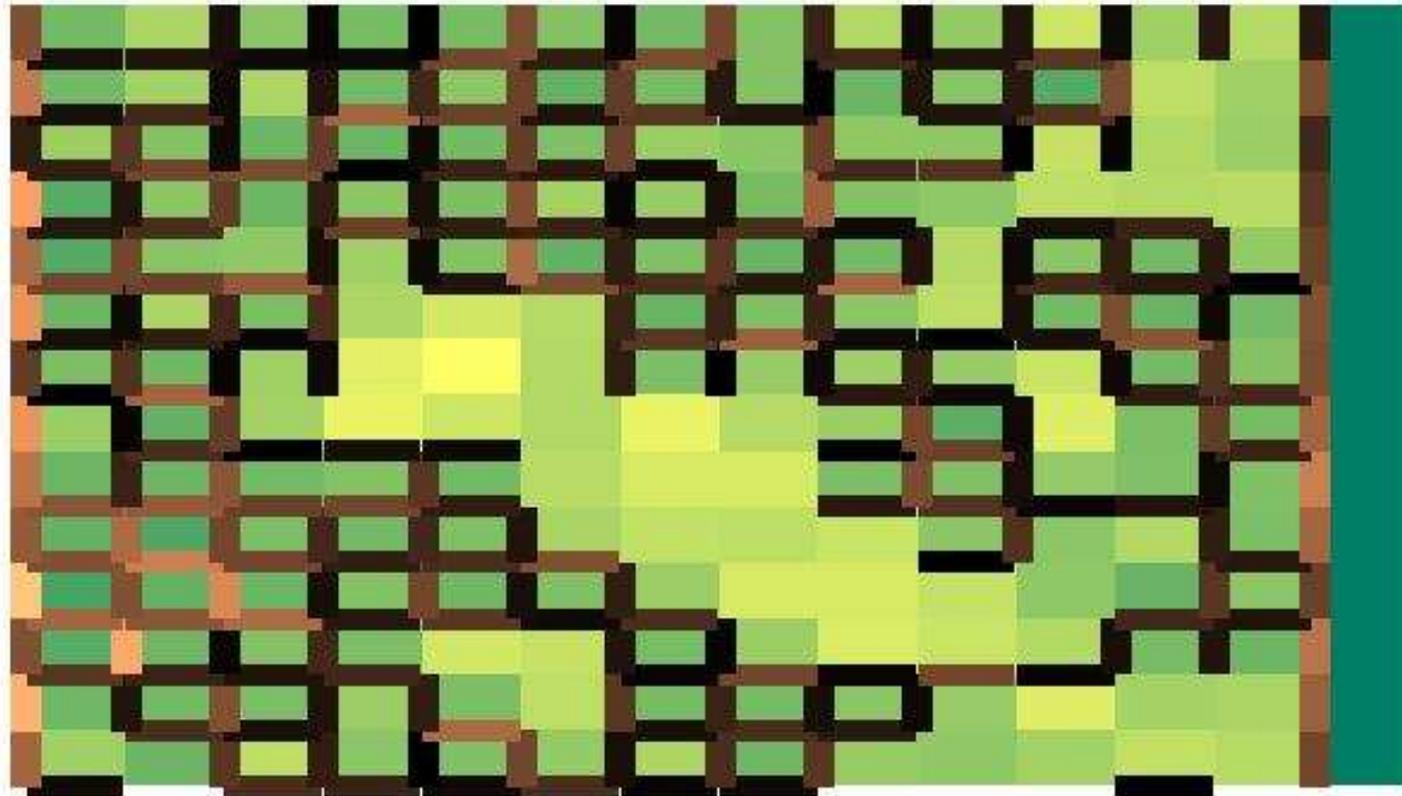
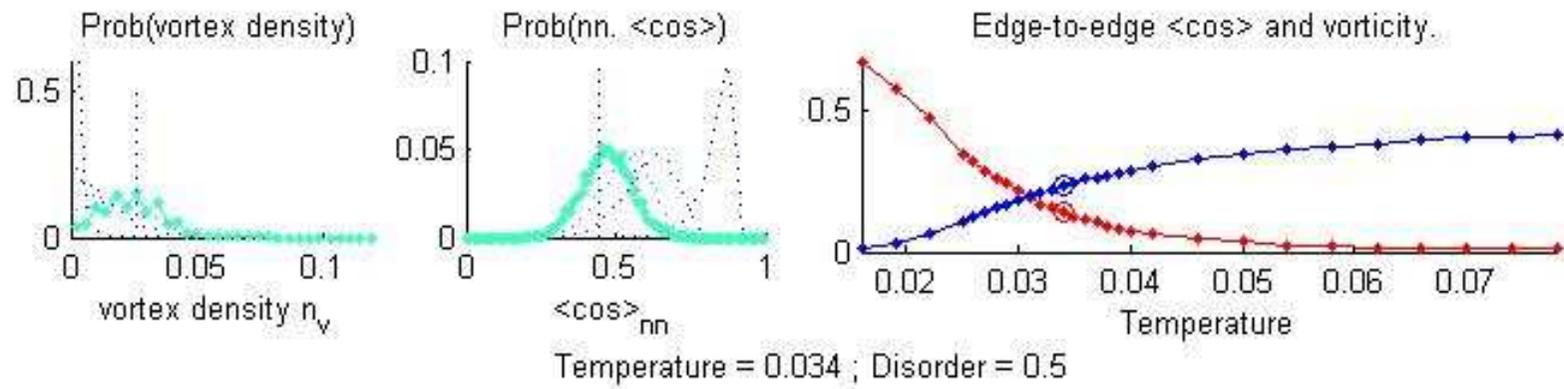


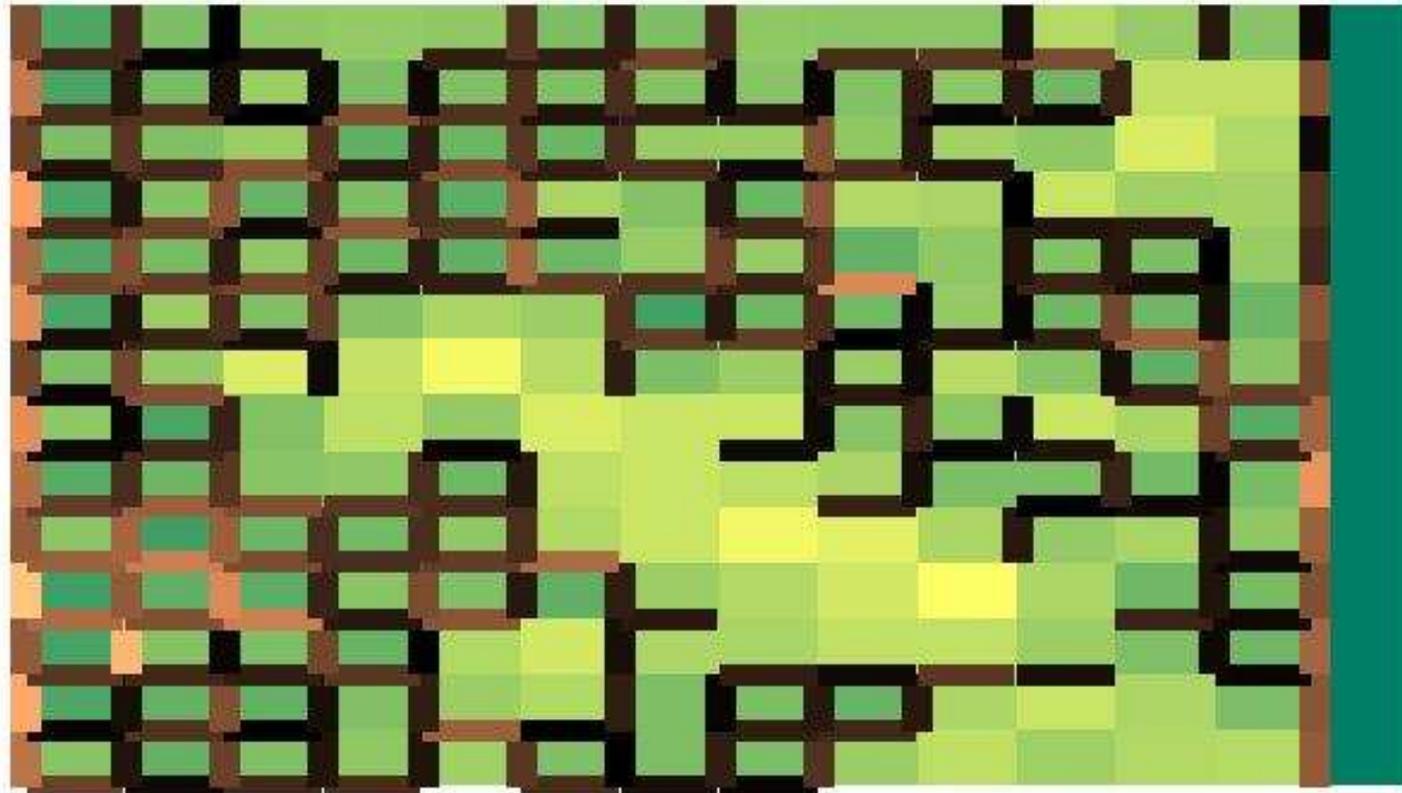
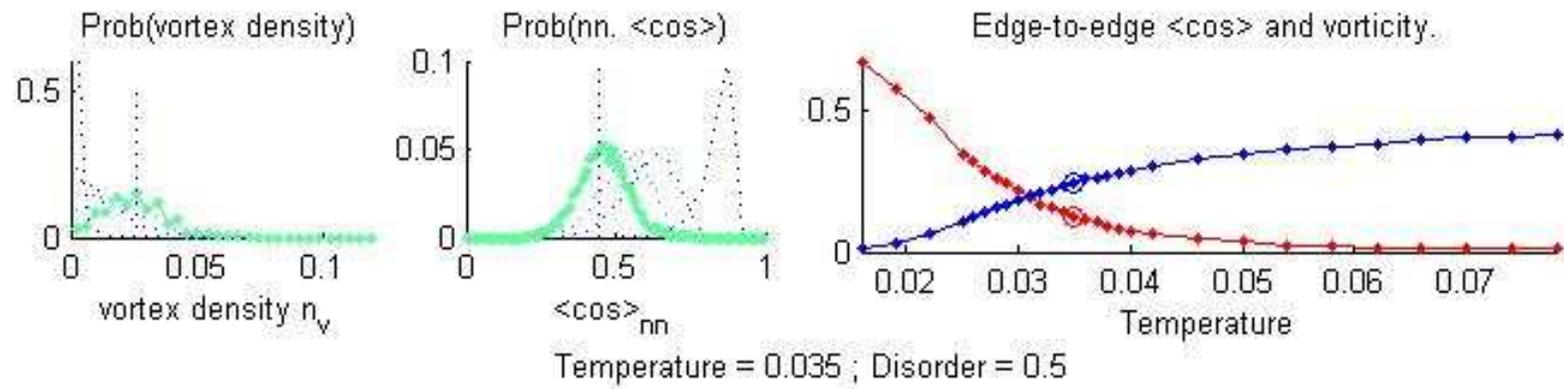


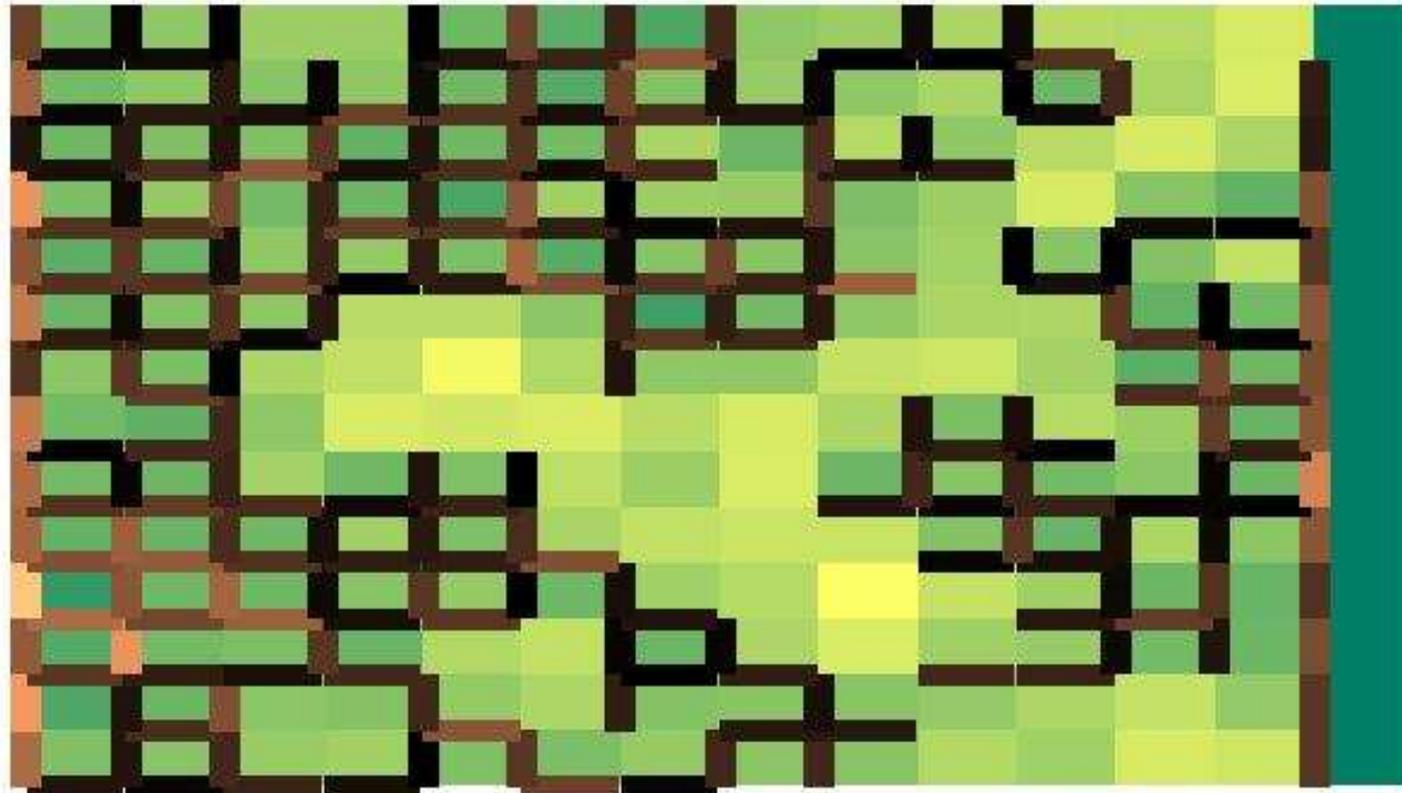
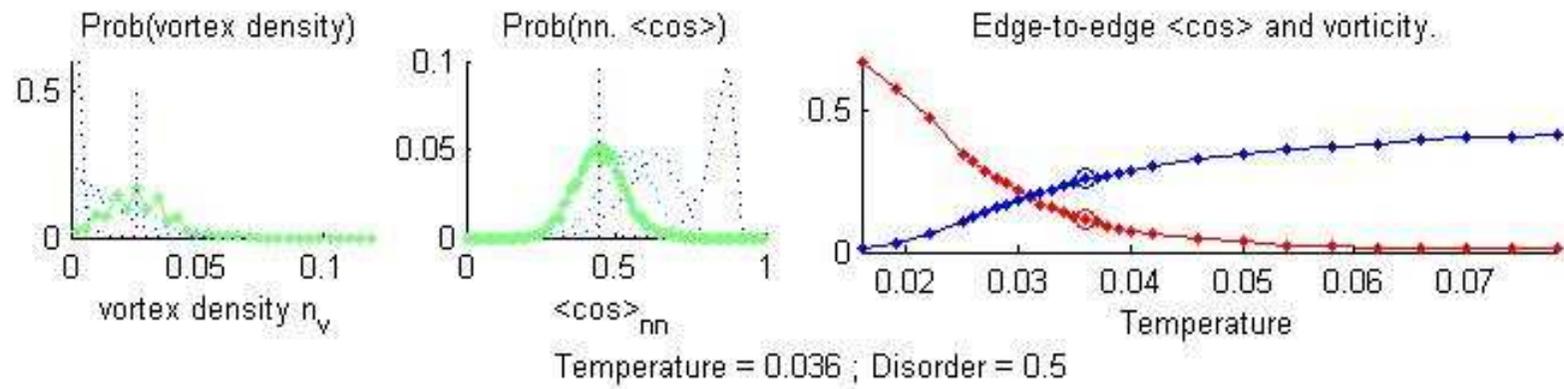


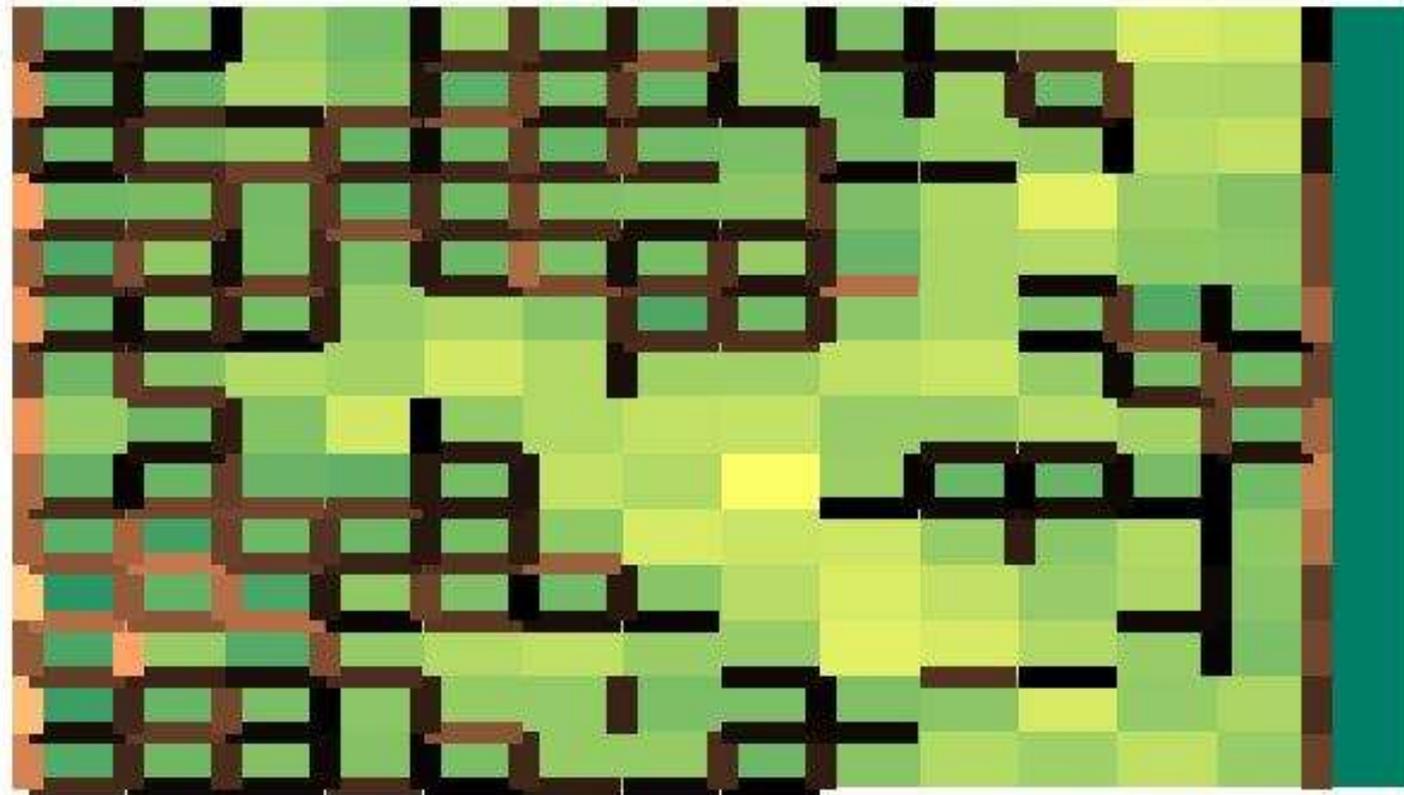
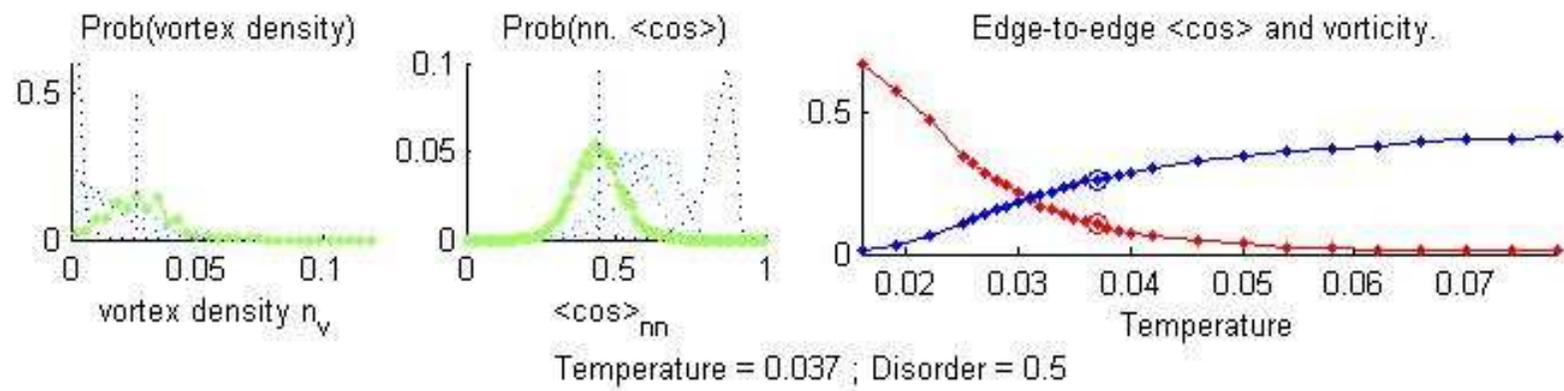


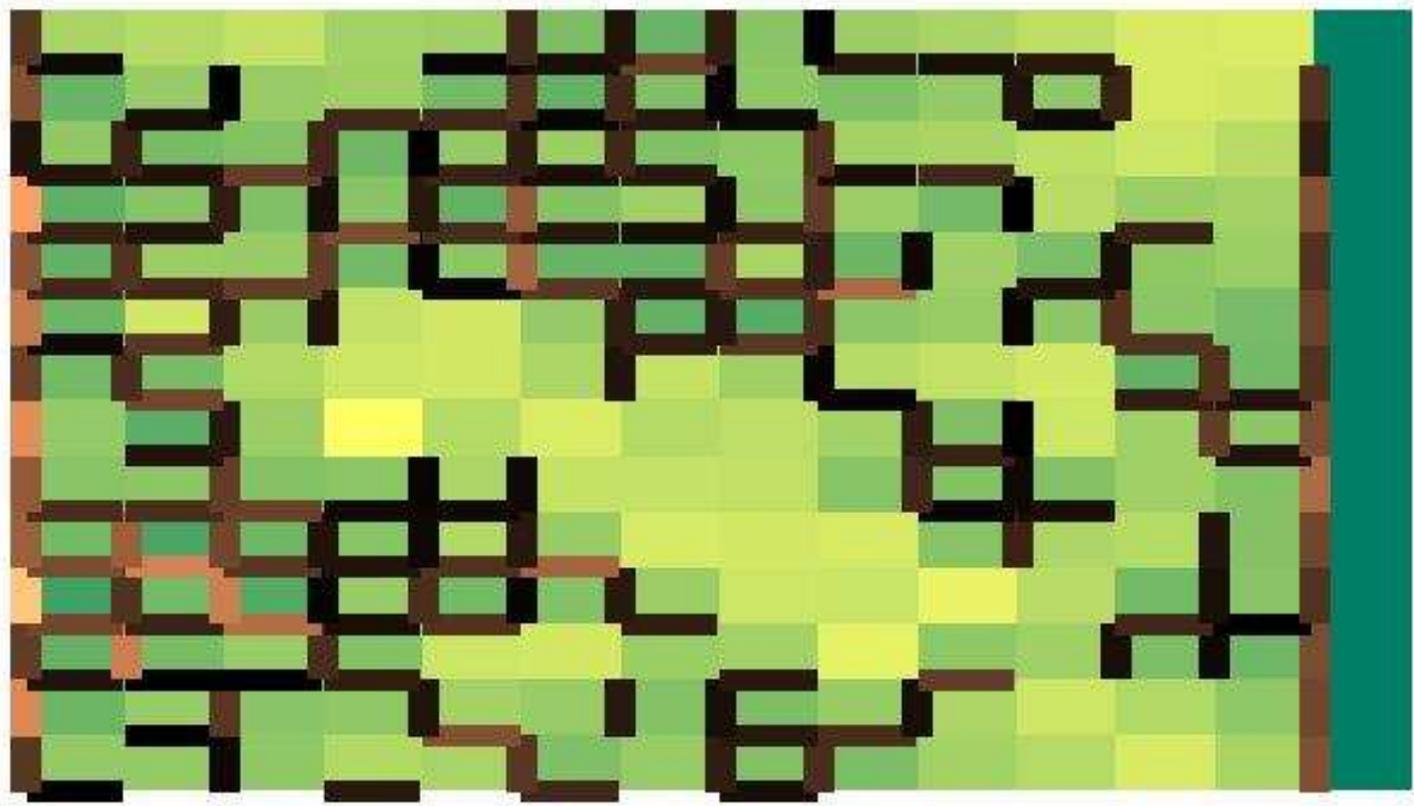
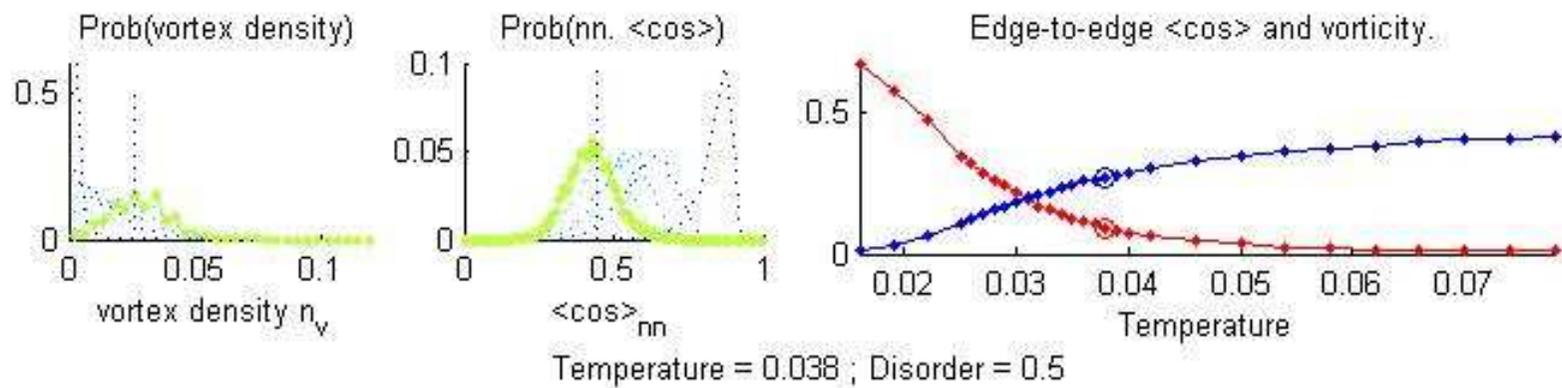


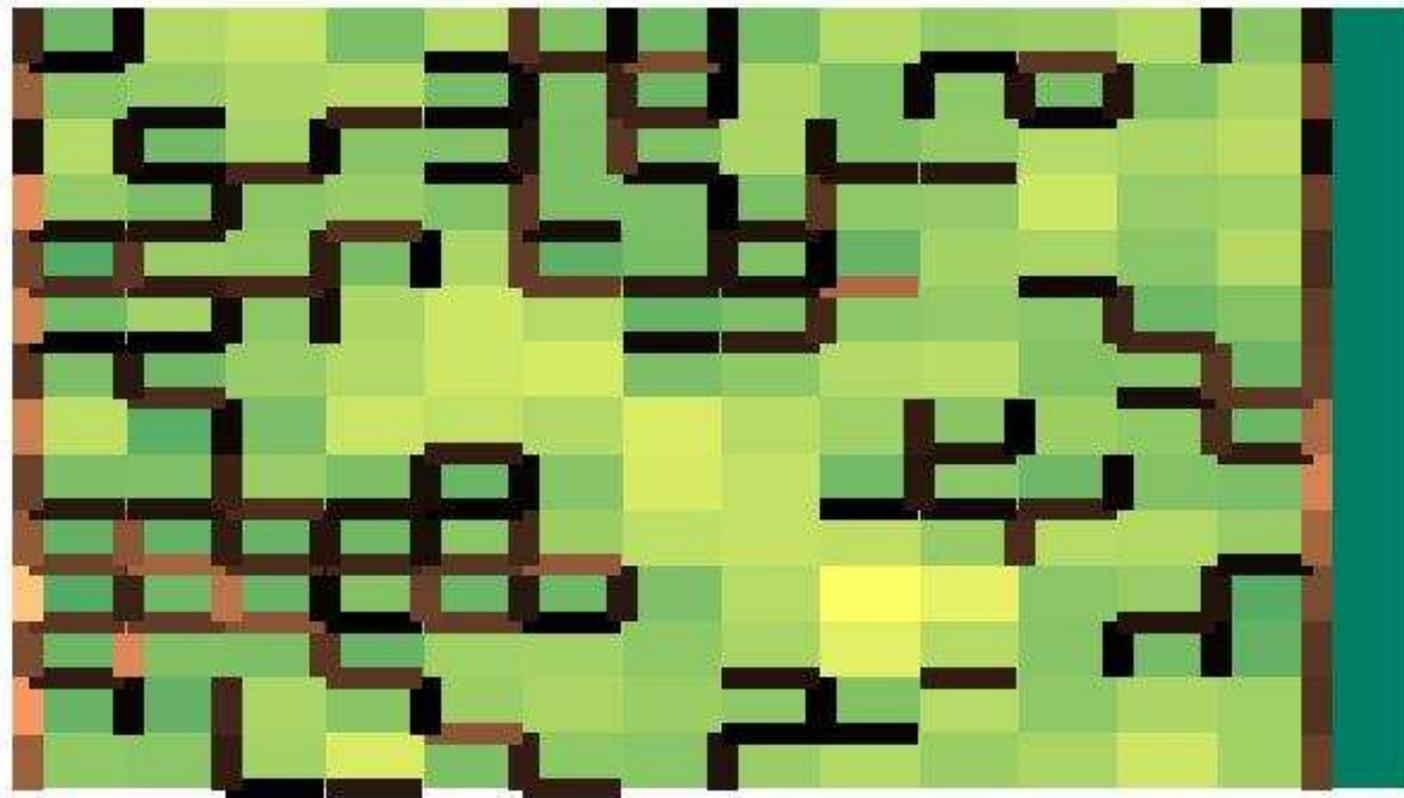
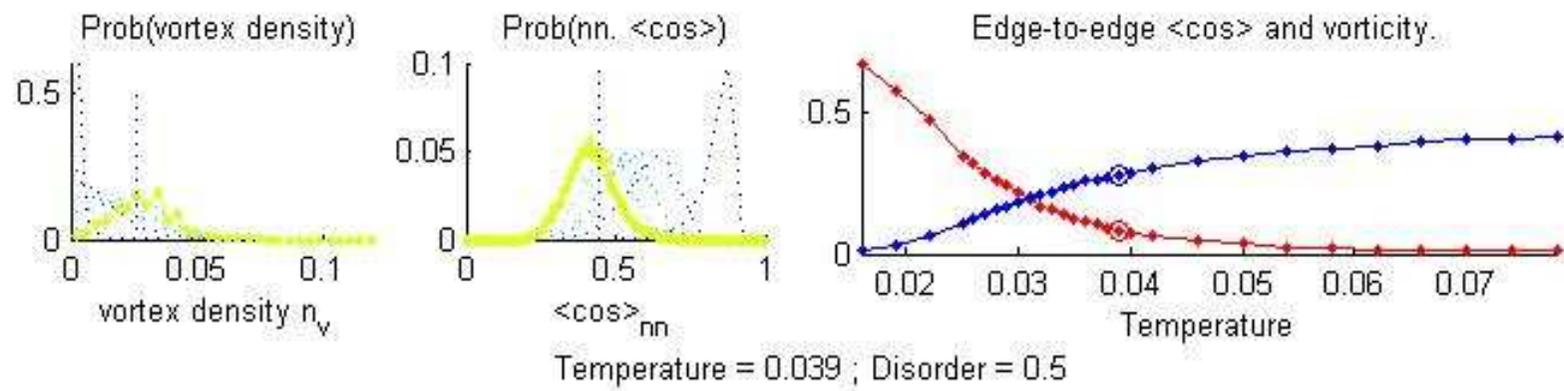


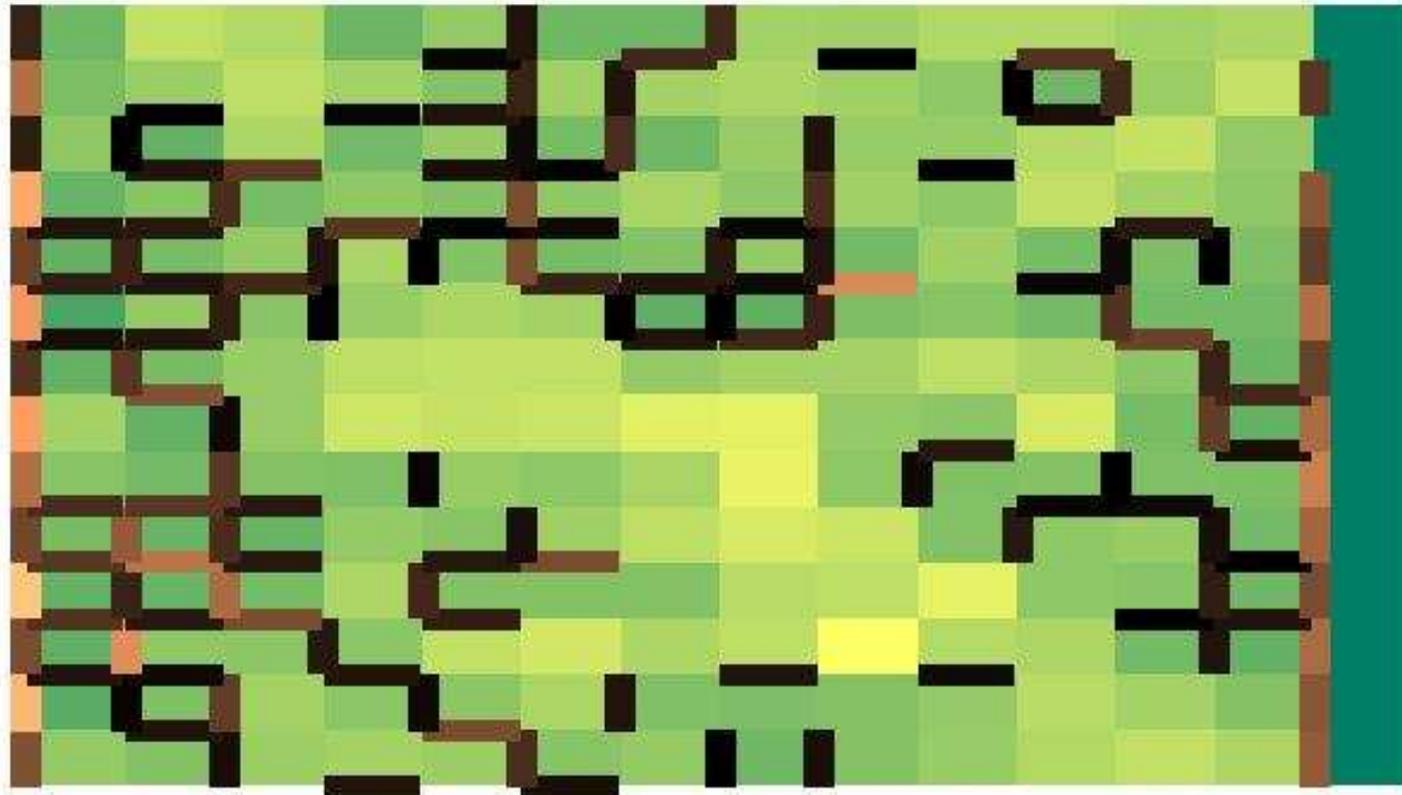
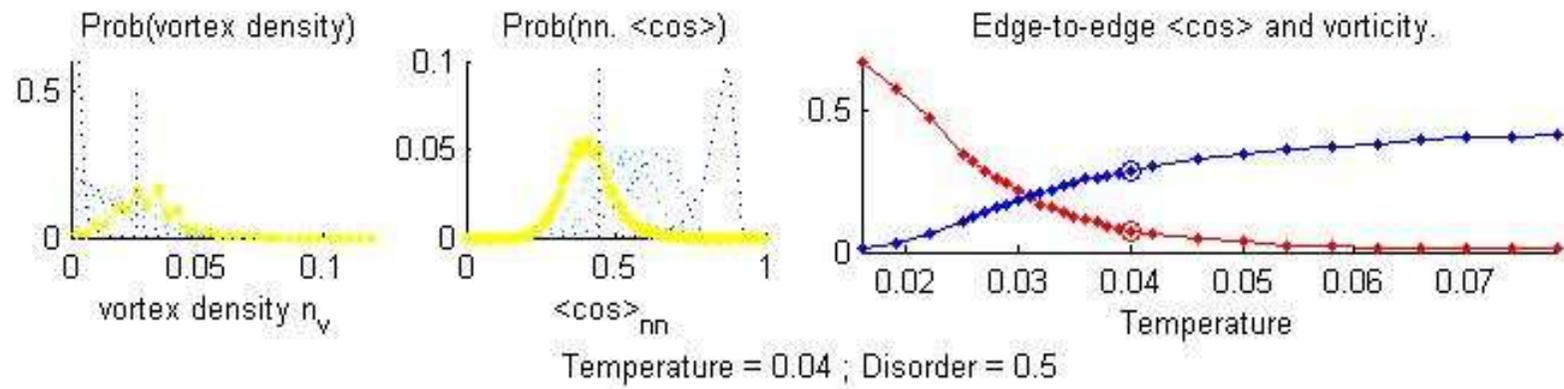


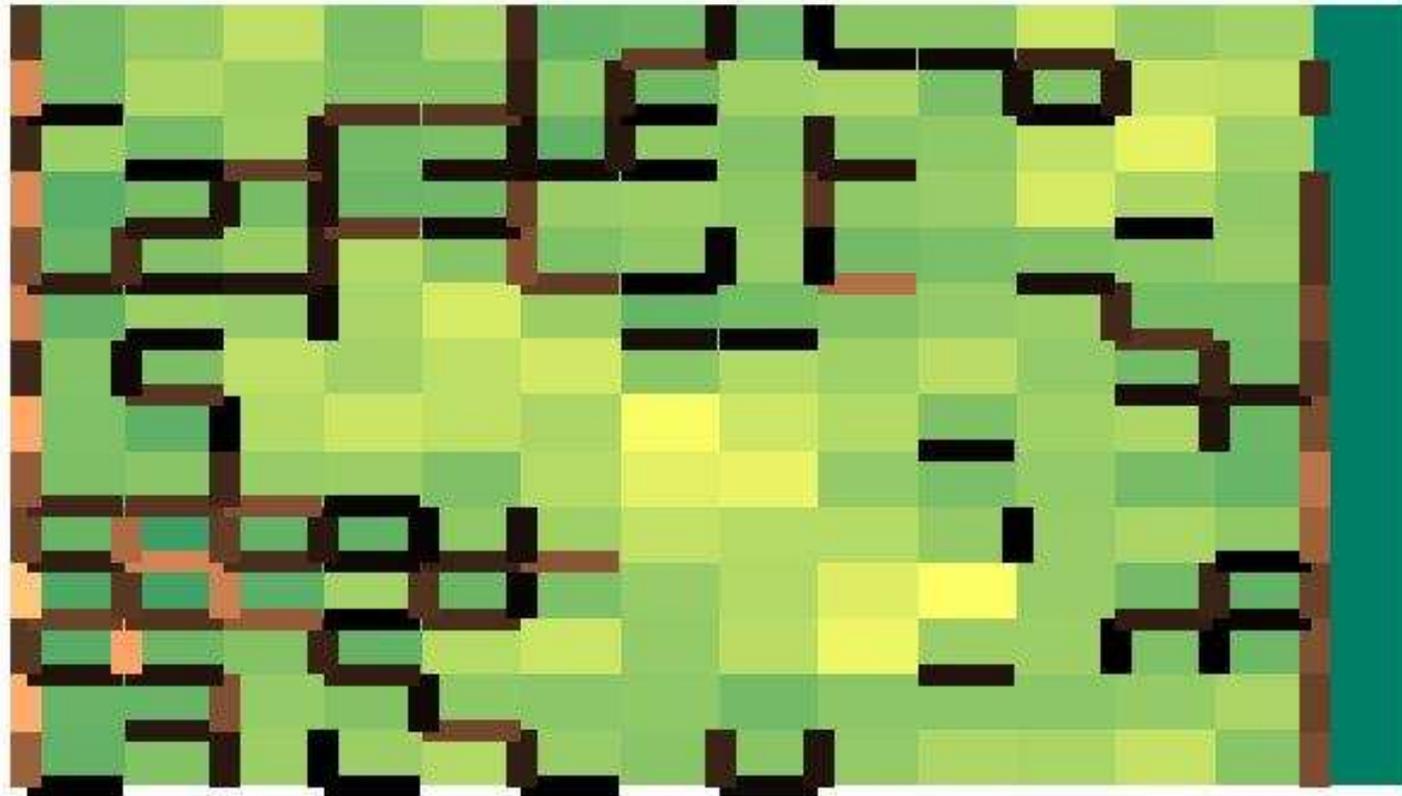
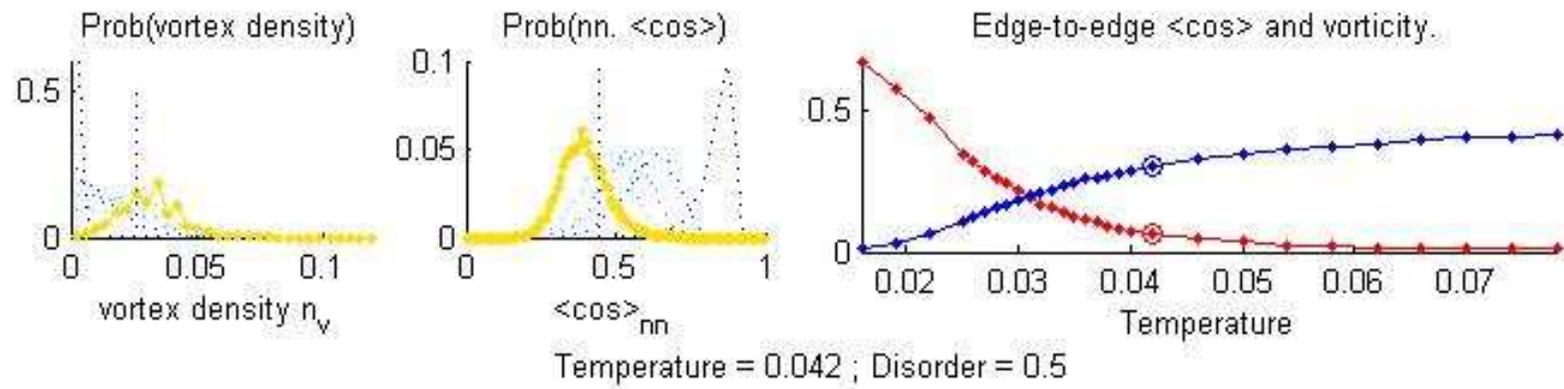


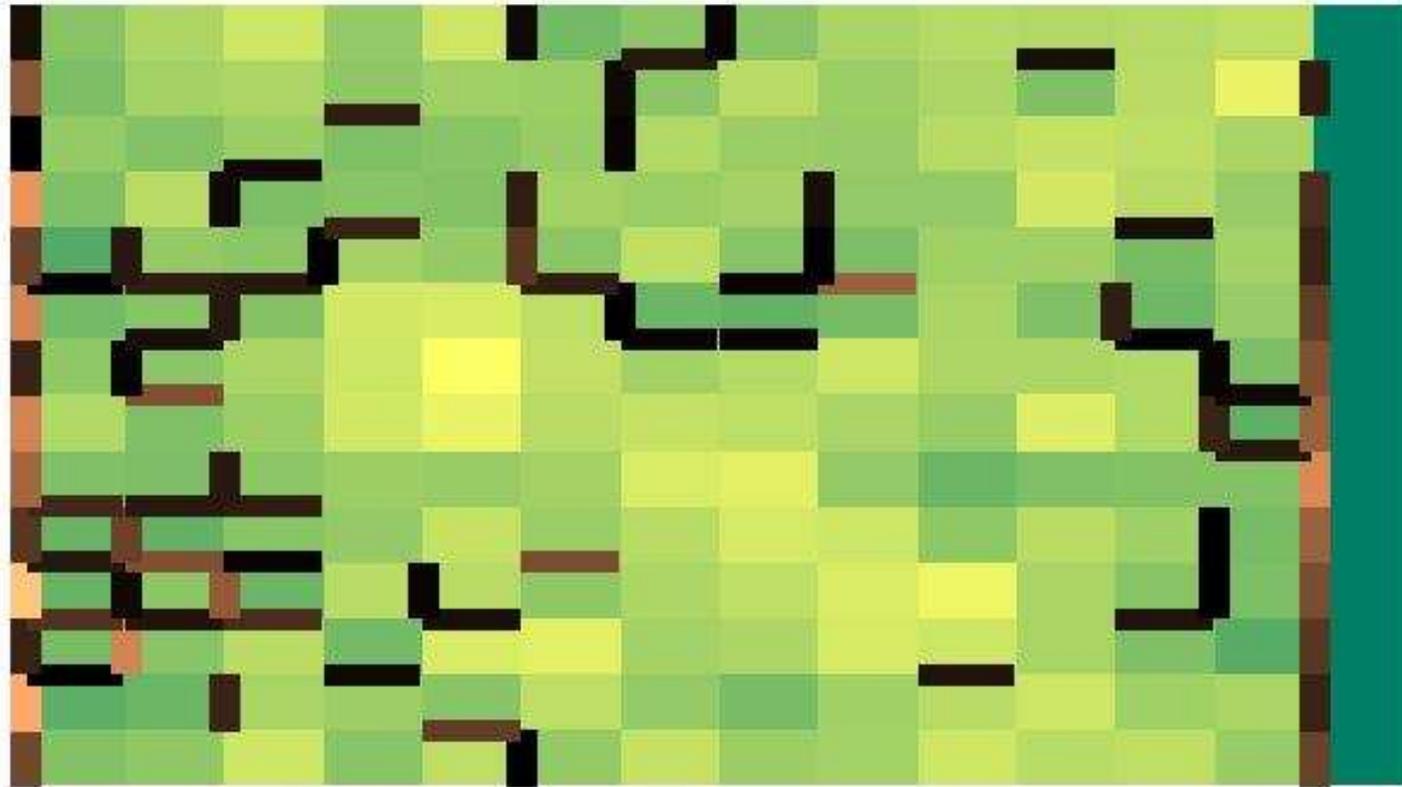
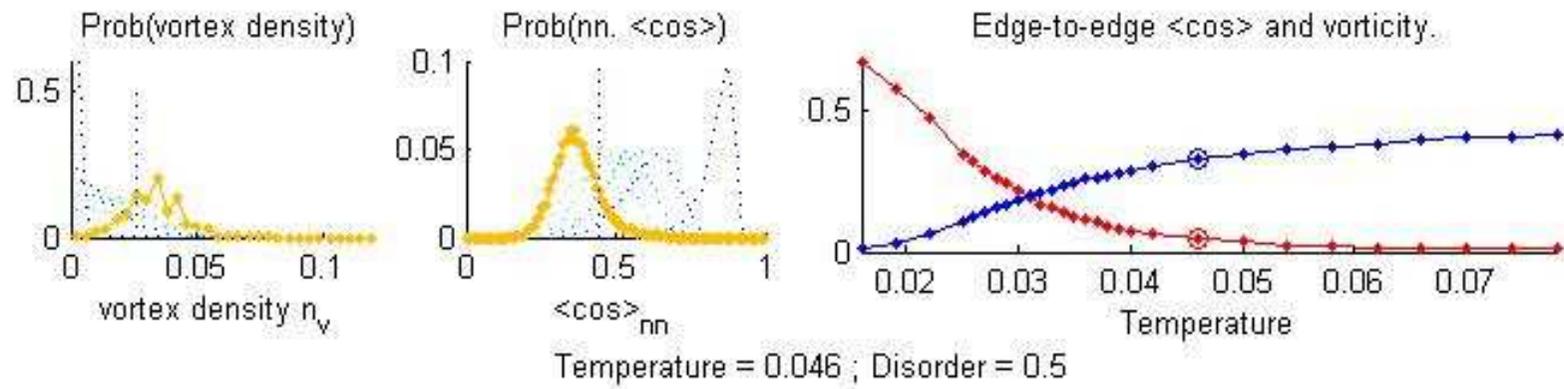


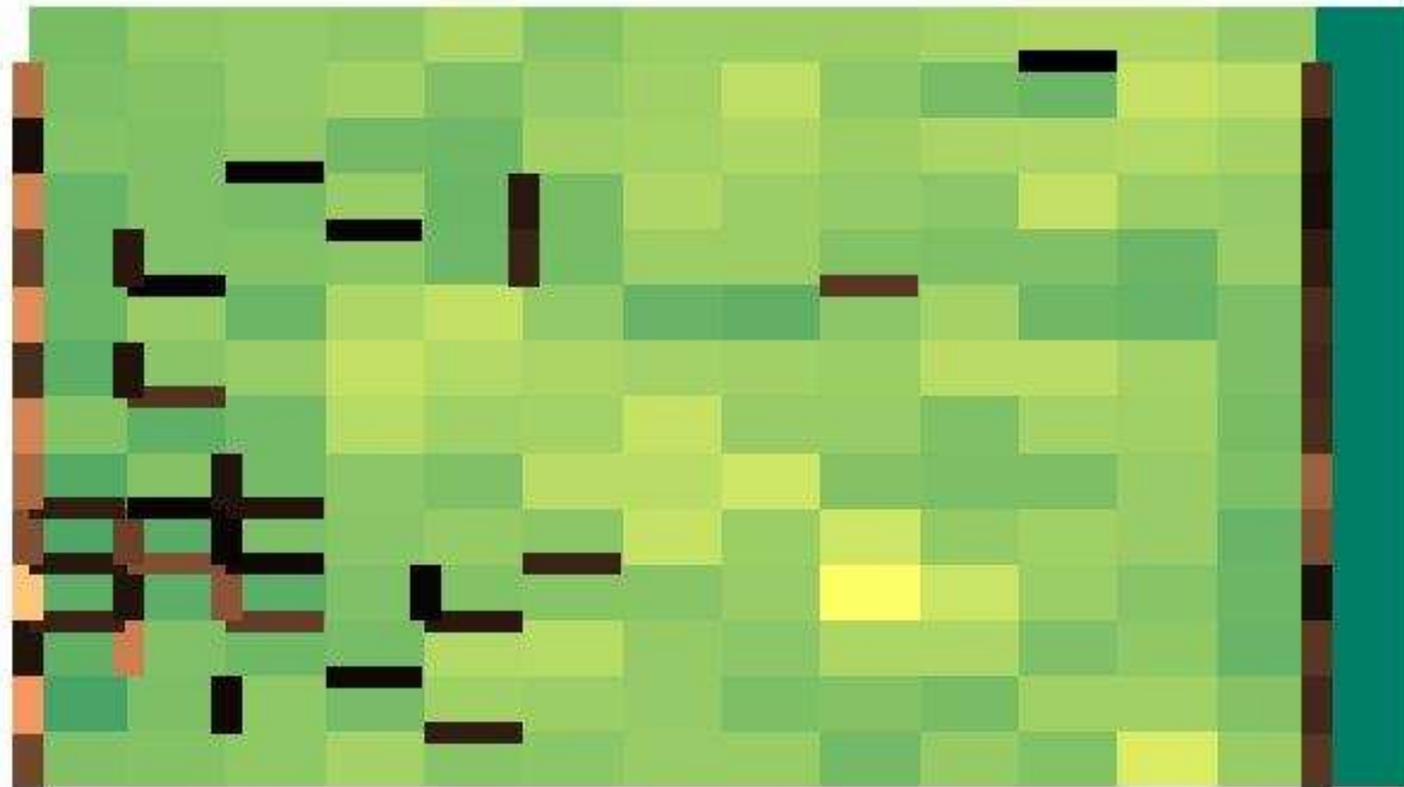
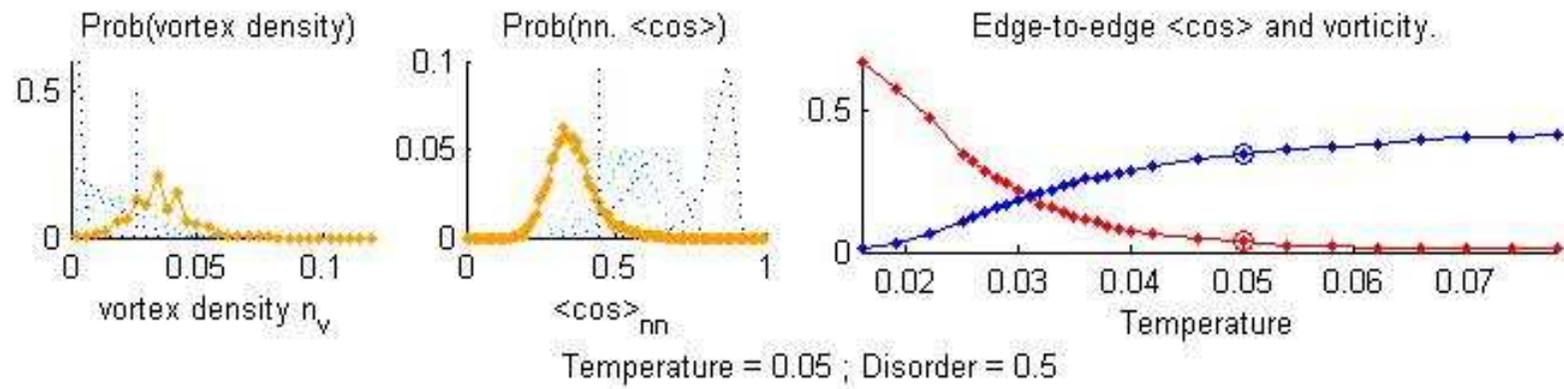




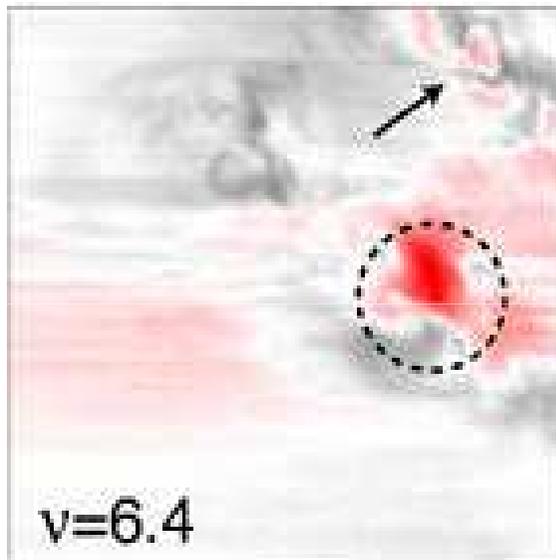




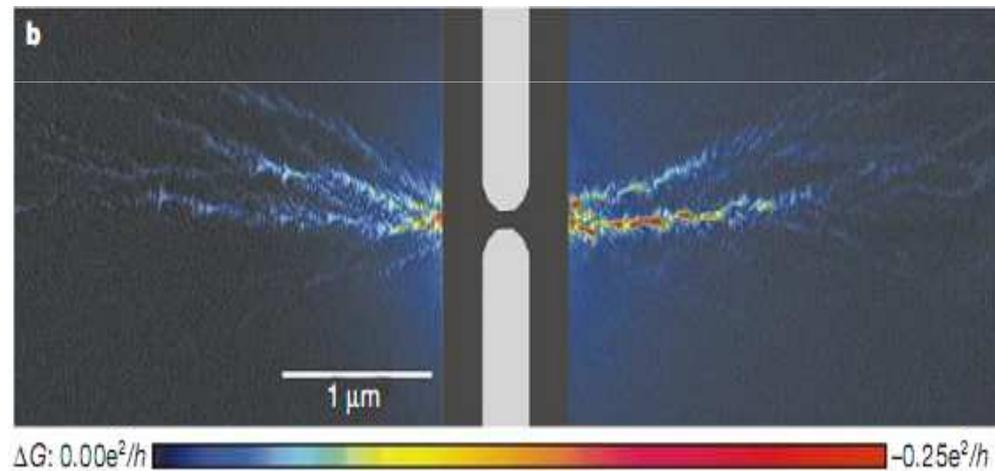
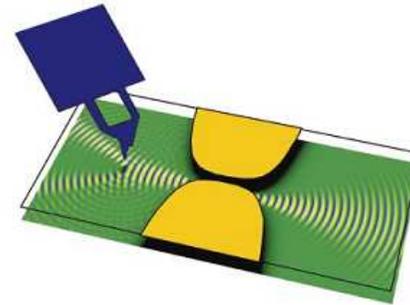




Probing the critical percolation path

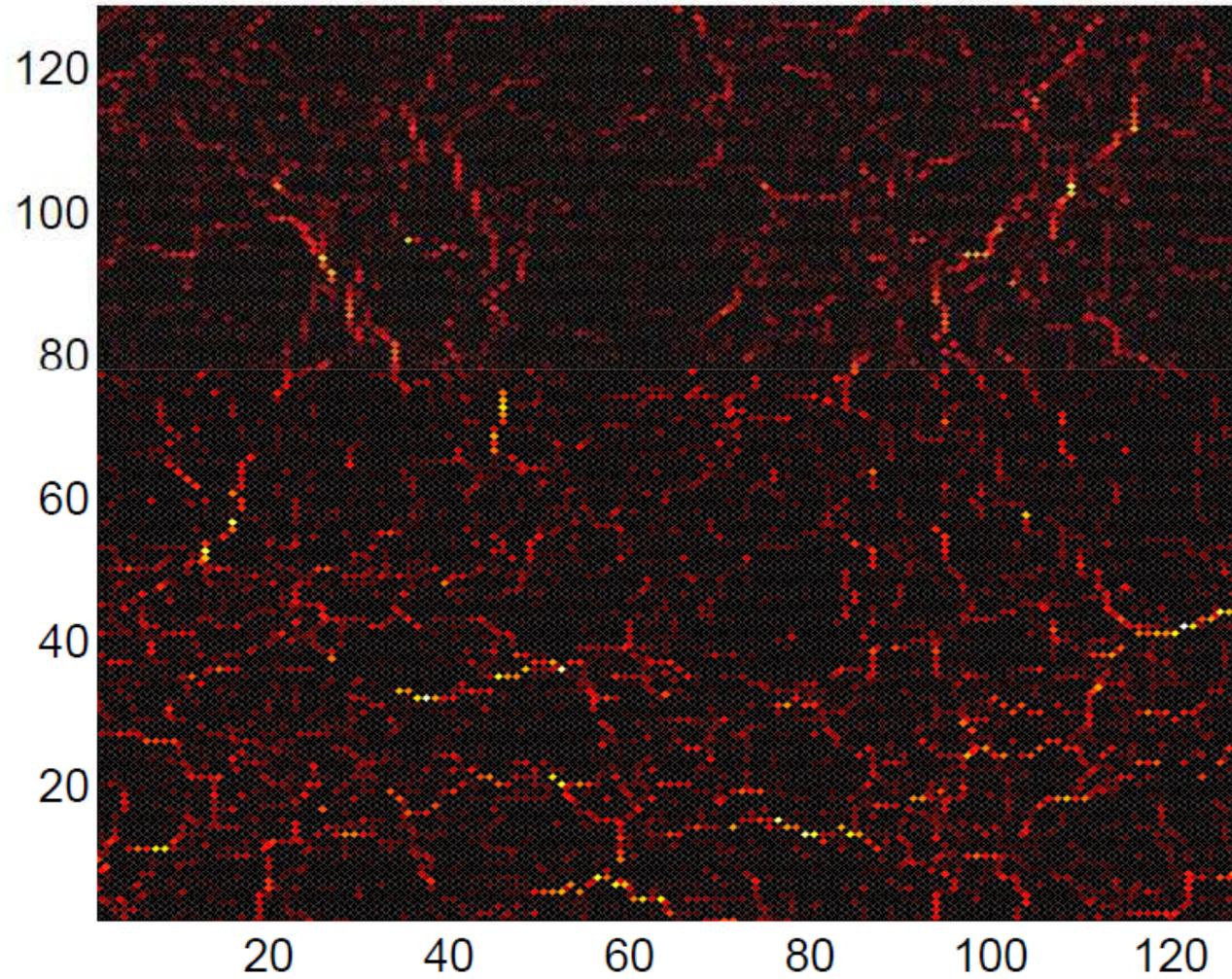


Ensslin et al.
PRB, 2004



Topinka et al. Nature, 2001

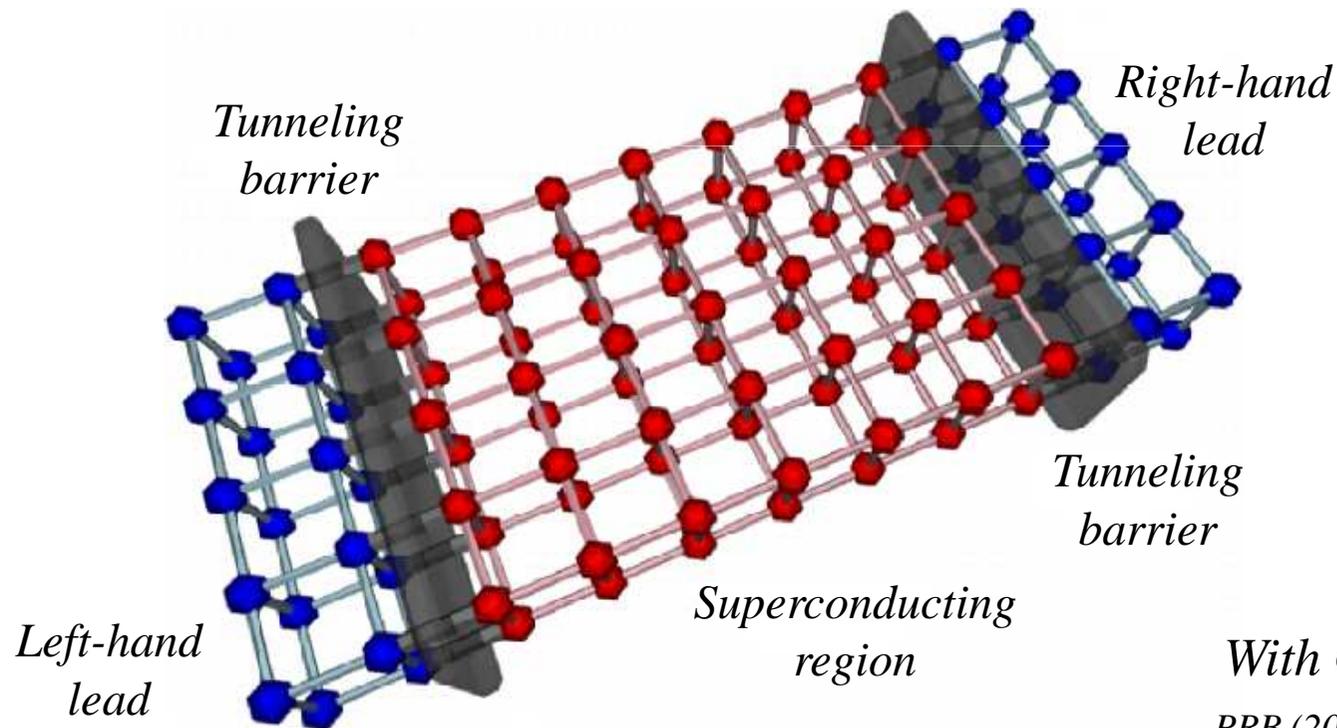
Disordered System, Near T_c



*Amir Erez,
unpublished*

General expression for the current [Meir & Wingreen, PRL (1992)]

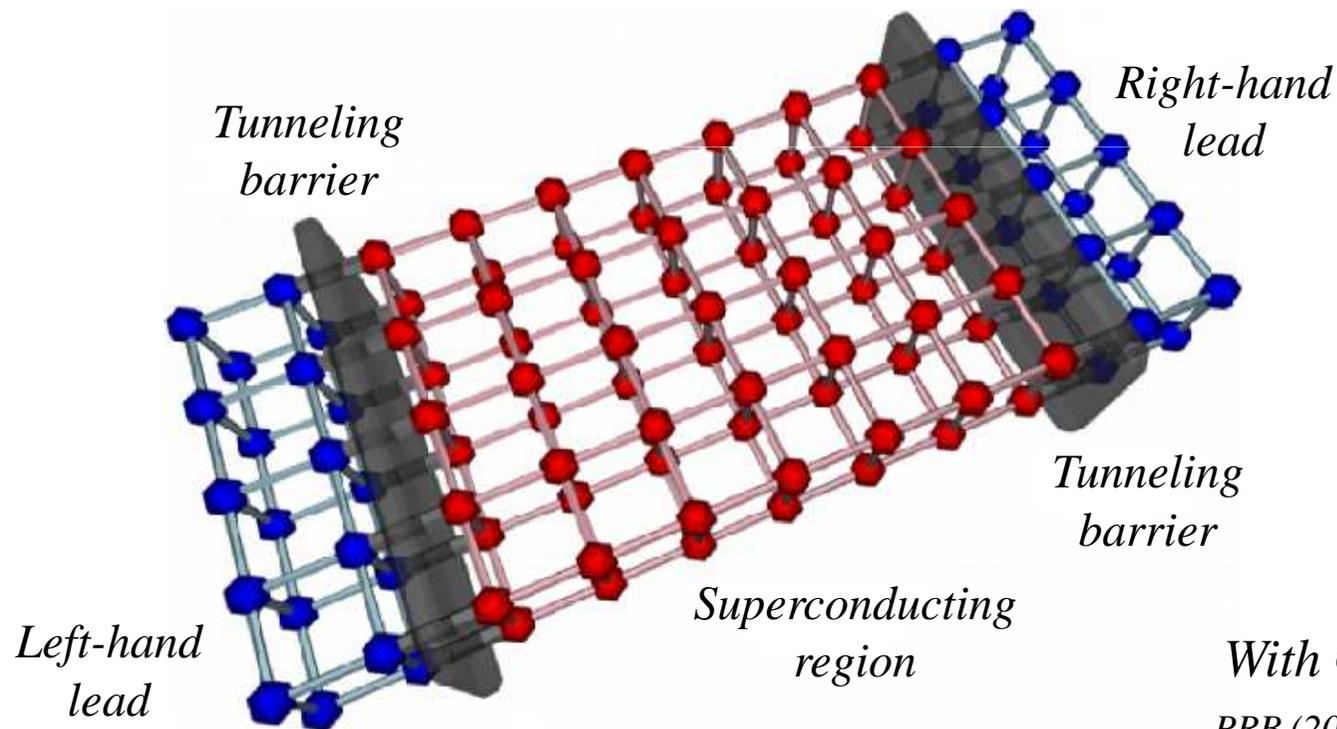
$$J = \frac{ie}{2h} \int d\epsilon \left[\text{Tr} \left\{ (f_L(\epsilon)\Gamma^L - f_R(\epsilon)\Gamma^R) (G_{e\sigma}^r - G_e^{a\sigma}) \right\} + \text{Tr} \left\{ (\Gamma^L - \Gamma^R) G_{e\sigma}^< \right\} \right]$$



With G. Conduit
PRB (2011), PRL (2012)

General expression for the current [Meir & Wingreen, PRL (1992)]

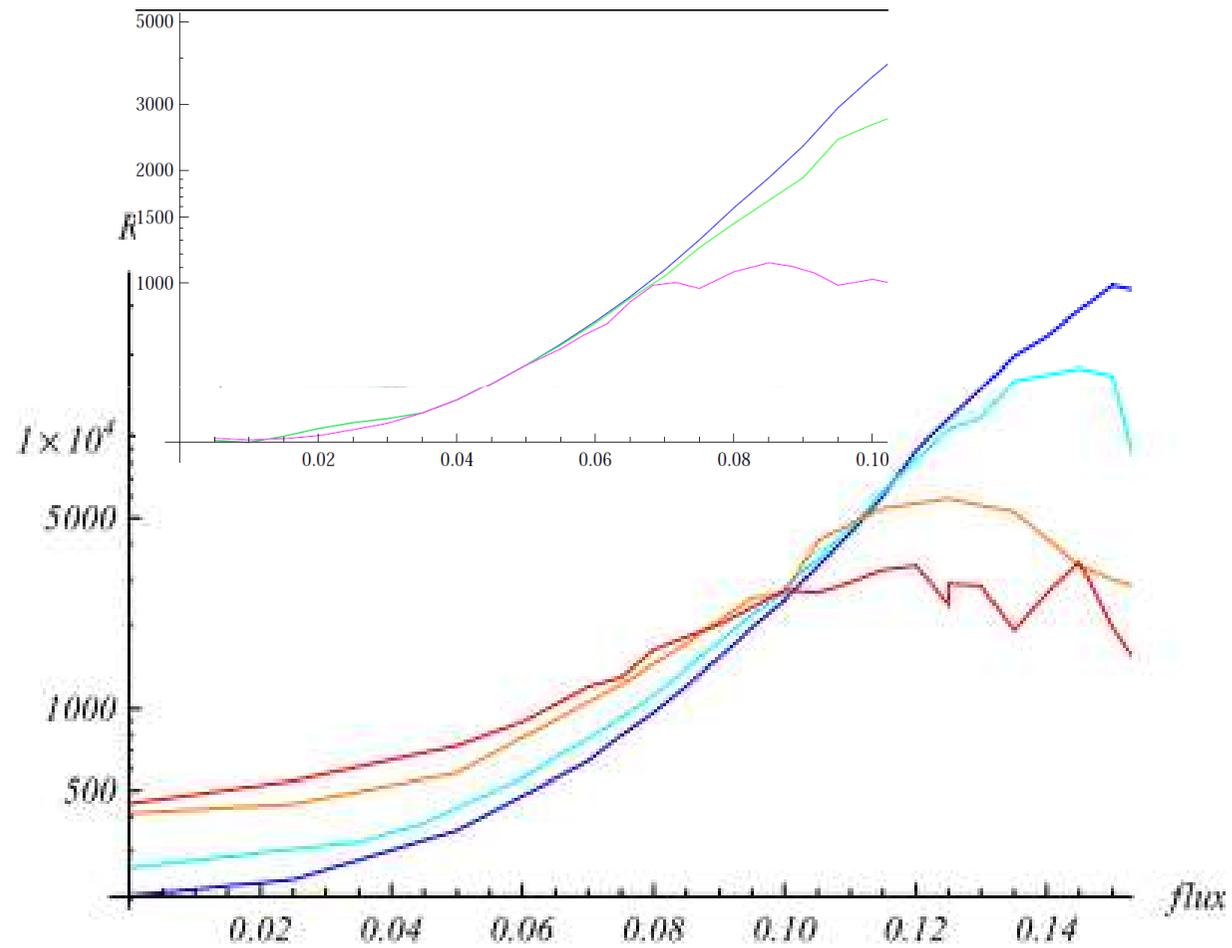
$$J = \frac{ie}{2h} \int d\epsilon \left[\text{Tr} \left\{ (f_L(\epsilon)\Gamma^L - f_R(\epsilon)\Gamma^R) (G_{e\sigma}^r - G_e^{a\sigma}) \right\} + \text{Tr} \left\{ (\Gamma^L - \Gamma^R) G_{e\sigma}^< \right\} \right]$$



With G. Conduit
PRB (2011), PRL (2012)

Preliminary results

same temperature, scaling by V^4



Conclusion:

Phase fluctuations and SC islands may be crucial in understanding the SIT in disordered SC films. Results indicate the relevance of quantum percolation to describe the transition



"Hey! Is this little stylus thingie what you're looking for?"

Challenges and work in progress

- *Tilted fields*
- *The role of repulsive interactions: Coulomb blockade, antiferromagnetism*
- *Extension to disordered d-wave and p-wave superconductors*
- *Layered superconductors*

Thank you for your attention