Dislocation Structures in Disordered 2D Vortex Matter

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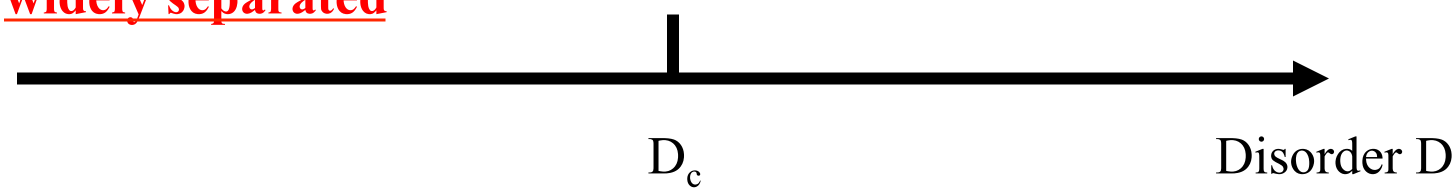
T=0 "Phase Diagram" of 2D Disordered Vortex Matter

Low Disorder/Low Fields:
quasi Bragg Glass (qBG)
(Giamarchi, Le Doussal):

Dislocations extremely widely separated

High disorder/High Fields:
Vortex Glass (VG) (M. Fisher, D. Fisher, D. Huse, P. Young):

Dislocations dense



Only crossover, not true phase transition

Picture of quasi Bragg Glass

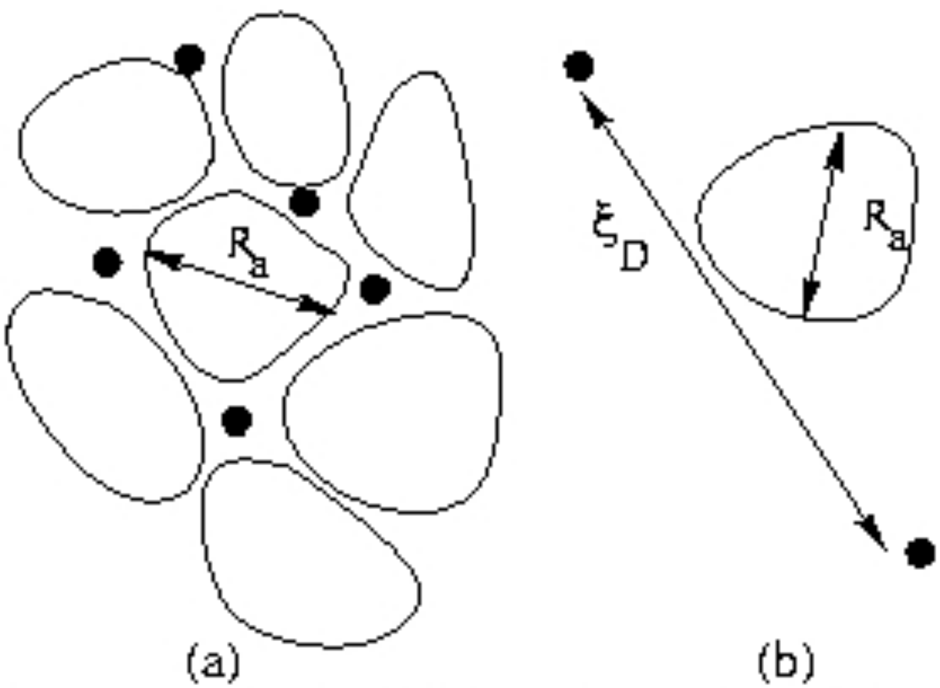


FIG. 1. (i) Conventional picture of a solid broken up by disorder in domains of size R_a with unpaired dislocations (black dots) appearing at the same scale. (ii) correct picture for weak disorder: the scale ξ_D at which unpaired dislocations appear is larger than the scale R_a at which translational order starts decaying slowly.

Dislocations are:

- **Distributed homogeneously**
- **Characterized by single length scale ξ_D**

Giamarchi-Le Doussal '00
Inspired by KT-Halperin-Nelson-Young theory of 2D melting

Numerical Simulation I.

- **Molecular Dynamics**
- **Overdamped Langevin equation**

$$\eta \frac{d\mathbf{r}_i}{dt} = -\sum_j \nabla U^{vv}(\mathbf{r}_i - \mathbf{r}_j) - \sum_k \nabla U^{vi}(\mathbf{r}_i - \mathbf{R}_k) + F_{ext} + \xi_i(t)$$

$$U^{vv}(r) = const. \times K_0(\tilde{r} / \lambda)$$

$$\tilde{r} = \sqrt{(r^2 + \xi^2)}$$

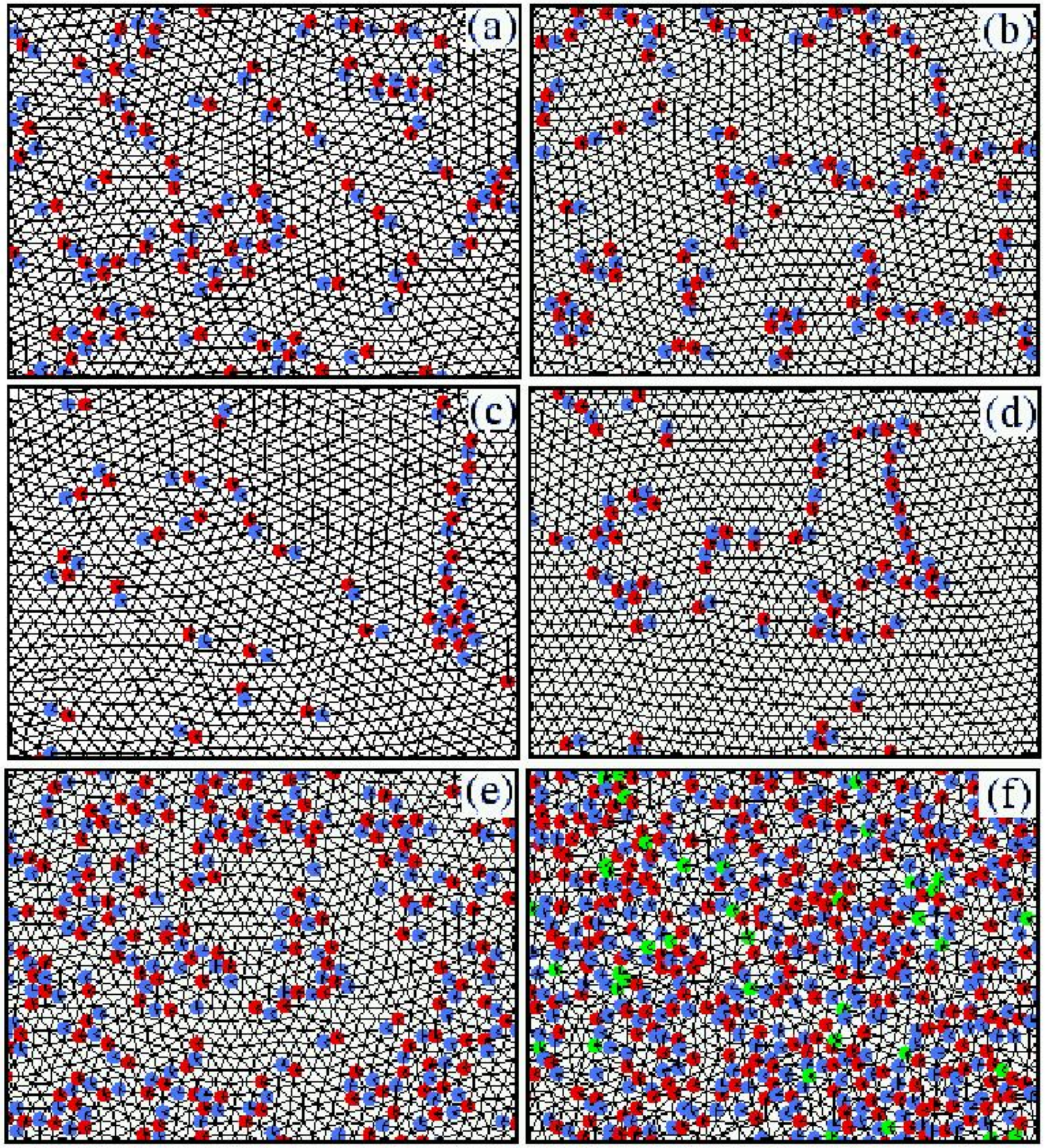
$$U^{vi}(r) = U_0(r^2 / r_p^2 - 1)$$

$$< \xi_i(t)\xi_j(t') >= 2kT\eta\delta_{ij}\delta(t - t')$$

Numerical simulations II.

- N(vortex)=1,000-6,400
- Disorder and Magnetic Field sweeps
- Vortex configurations prepared by current annealing and thermal annealing, results compared
- Albuquerque supercomputer center
- Results summarize runs of ~ **100 processor-year**

Magnetic Field Sweep



B/B_{c2} = 0.1 (a)
0.4 (b)
0.5 (c)
0.6 (d)
0.8 (e)
0.9 (f)

Δ = 0.02

N(v) = 4096

- **Blue & Red dots: 5 & 7 coordinated vortices: disclinations**

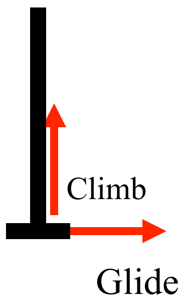
- **Come in pairs: dislocations**

Dislocations form domain walls at intermediate fields

What is the physics?

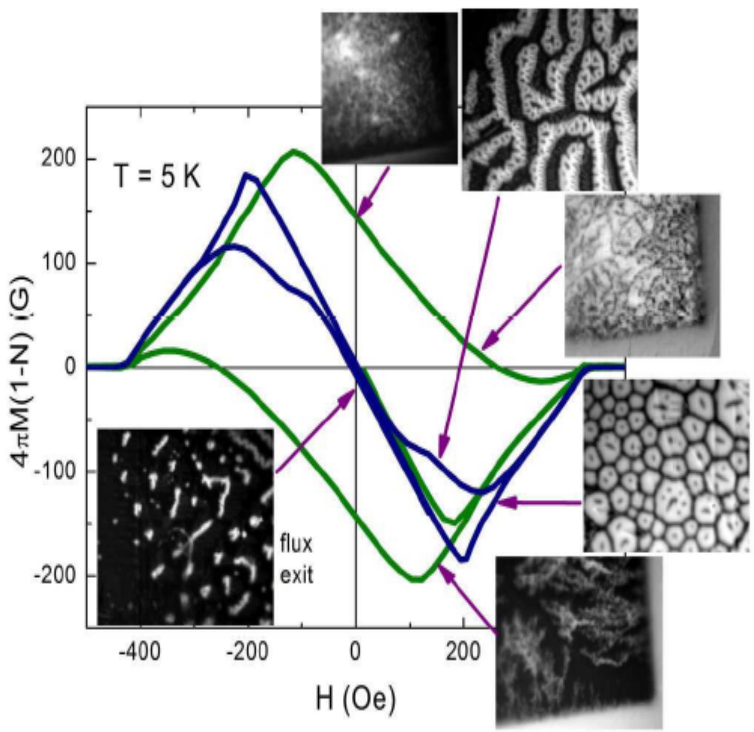
Dislocations are dipoles of disclinations, with anisotropic logarithmic interaction.

Previous theory	**However**
- Assumes isotropy, averages over anisotropy	- Structures profoundly anisotropic
- Only considered structures: pairs (~KTHNY pair unbinding)	- Domain walls minimize energy (No KTHNY energetics & scaling)
- Treats dynamics and statics independently	- Climb much harder than glide: dislocation annihilation hard: freezing influences structure



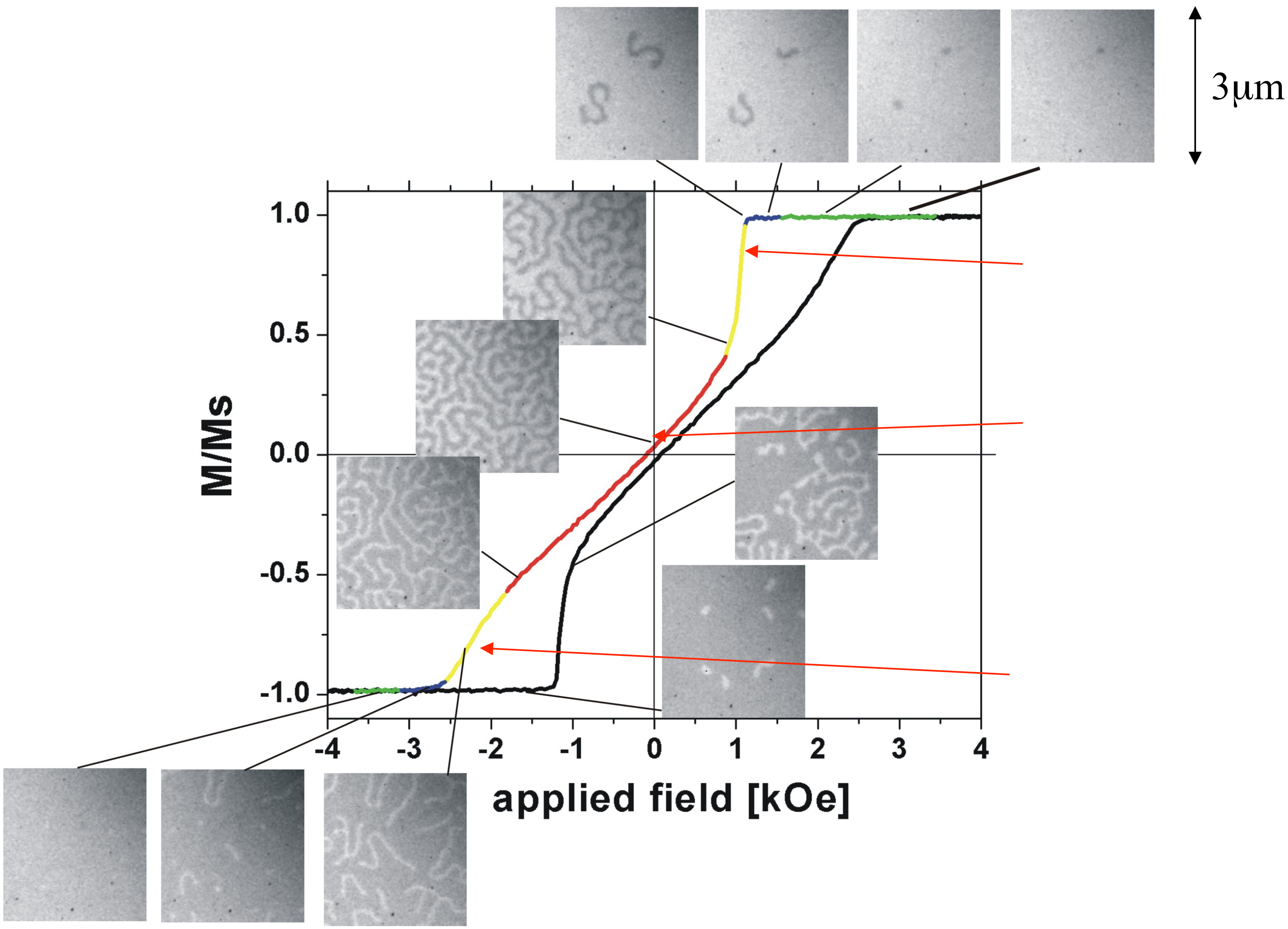
Also, at T=0 no entropy favors dislocation gas instead of structures.

Long range & anisotropic interactions & dynamics form dislocation structures

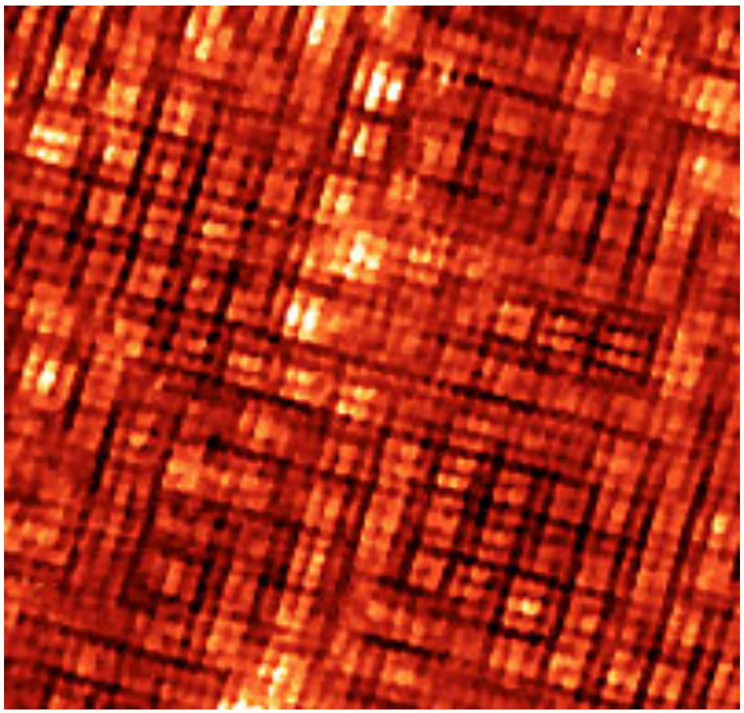


Lead (Prozorov et al 2004)

CoPt films by X-ray Microscopy



Structure Formation from Long Range Interactions



J.C. Davis,
Physics Today, September 2004

Competing interactions:

Kinetic energy
Short range magnetic

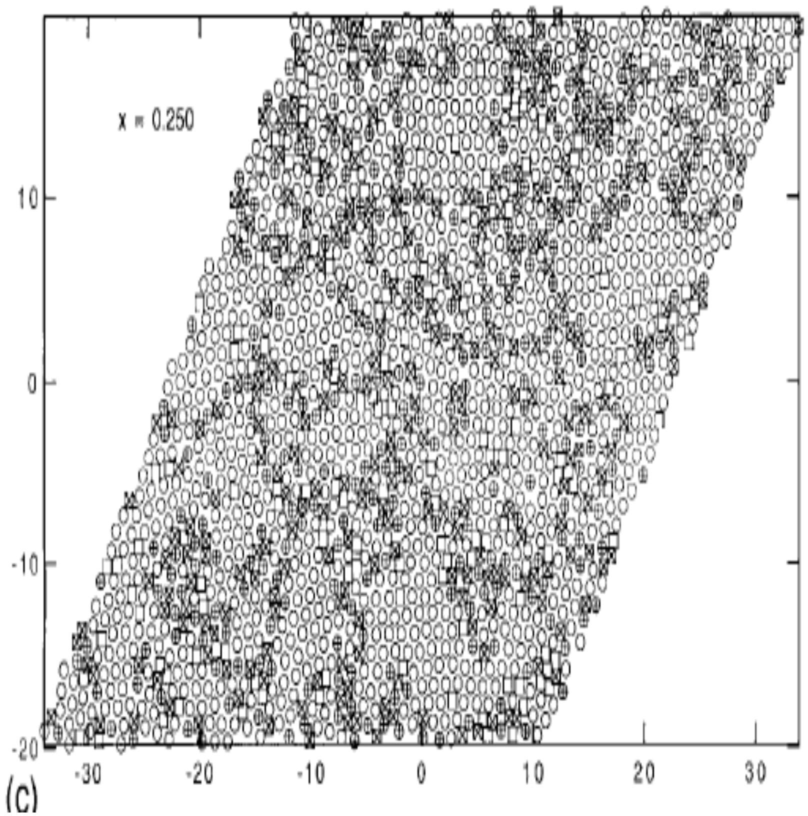
- Phase separation (Emery, Kivelson)

Additional interaction:

Long range Coulomb

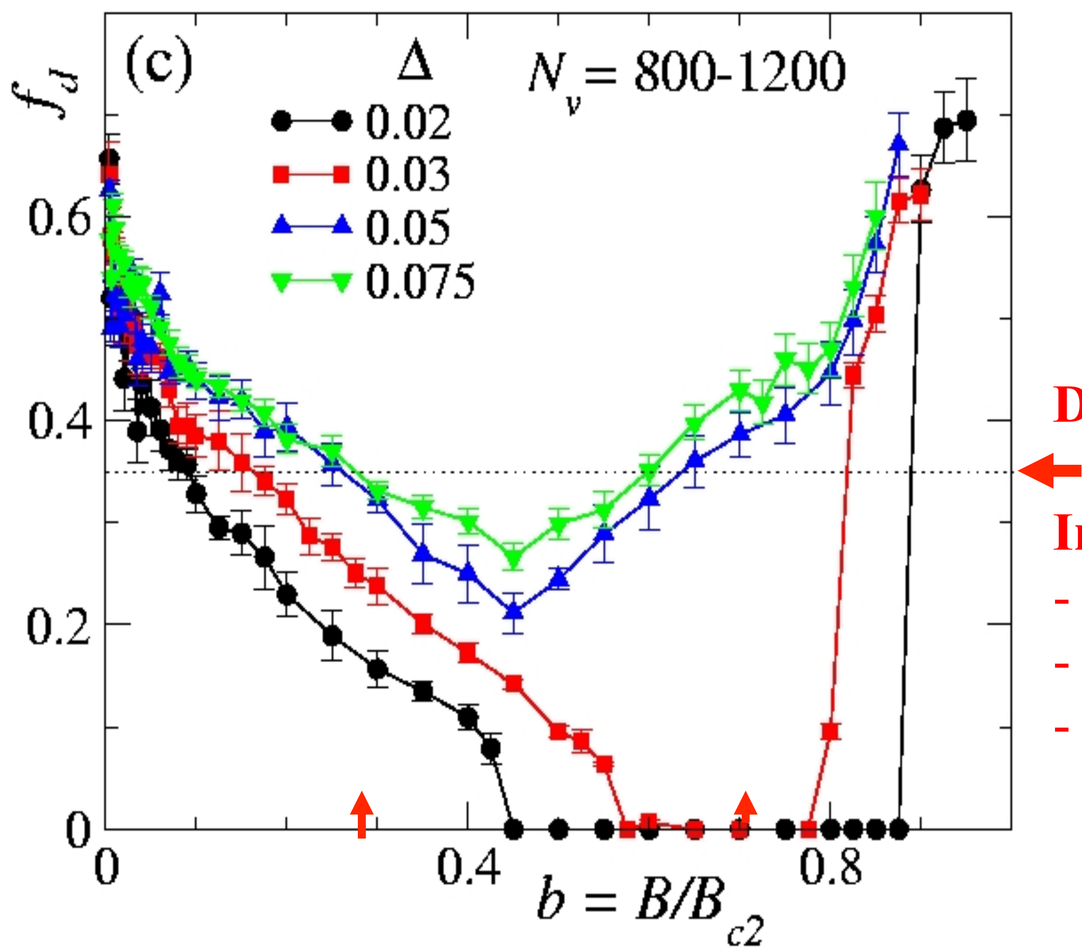
- Stripe formation (Littlewood, Zaanen Emery, Kivelson)

Experiment: Davis, Yazdani



Goddard

Fraction of Defected Vortices



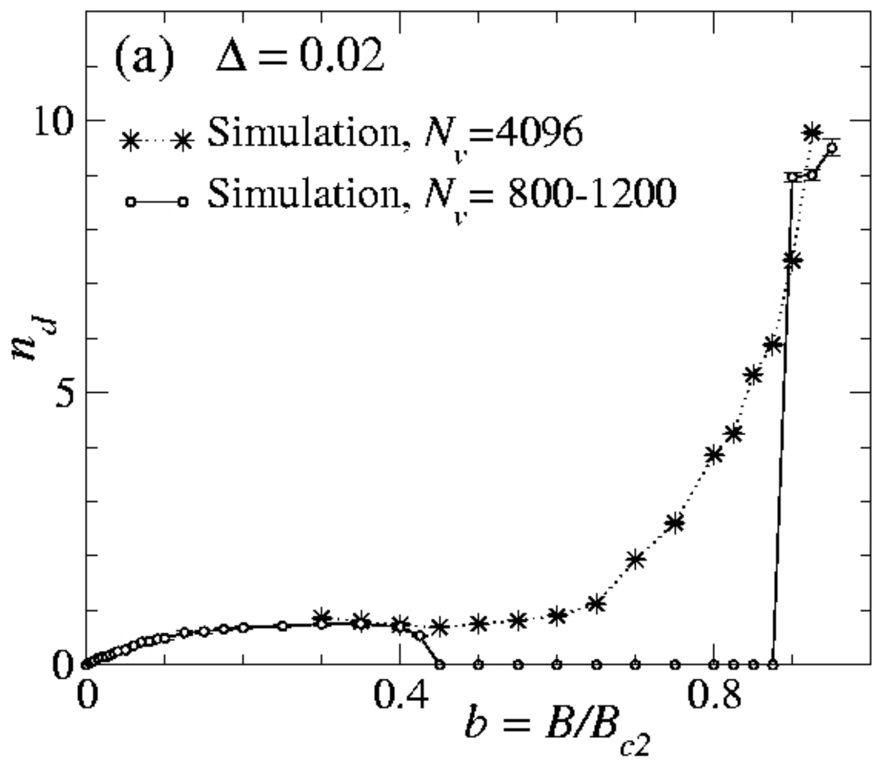
Domain formation dominant:

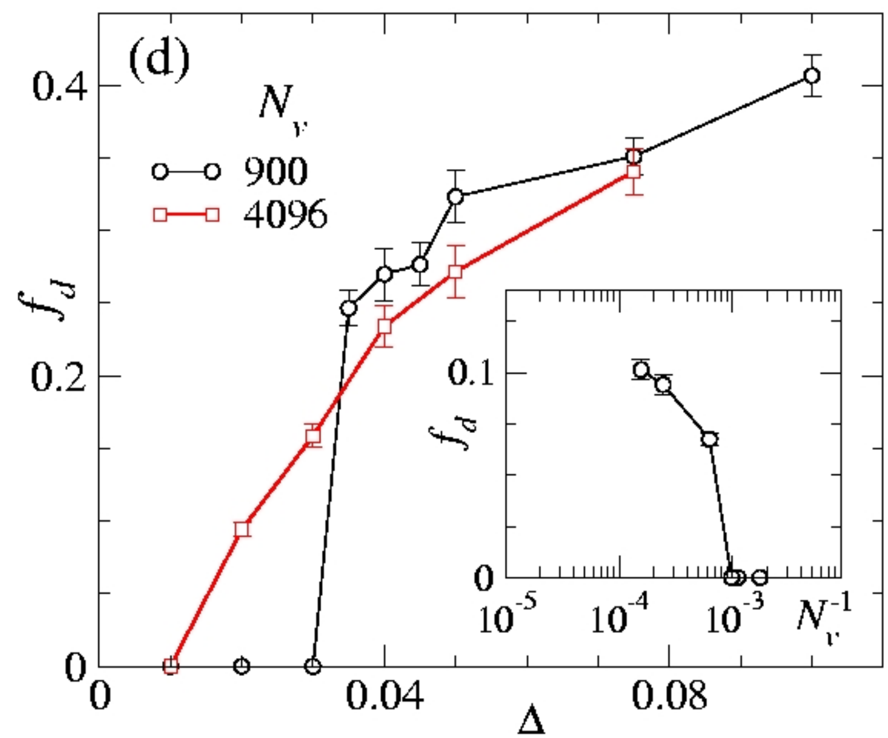
In Domain Regime

- **~83% of vortices inside domains**
- **~15% in domain walls**
- **~2% in individual dislocations**

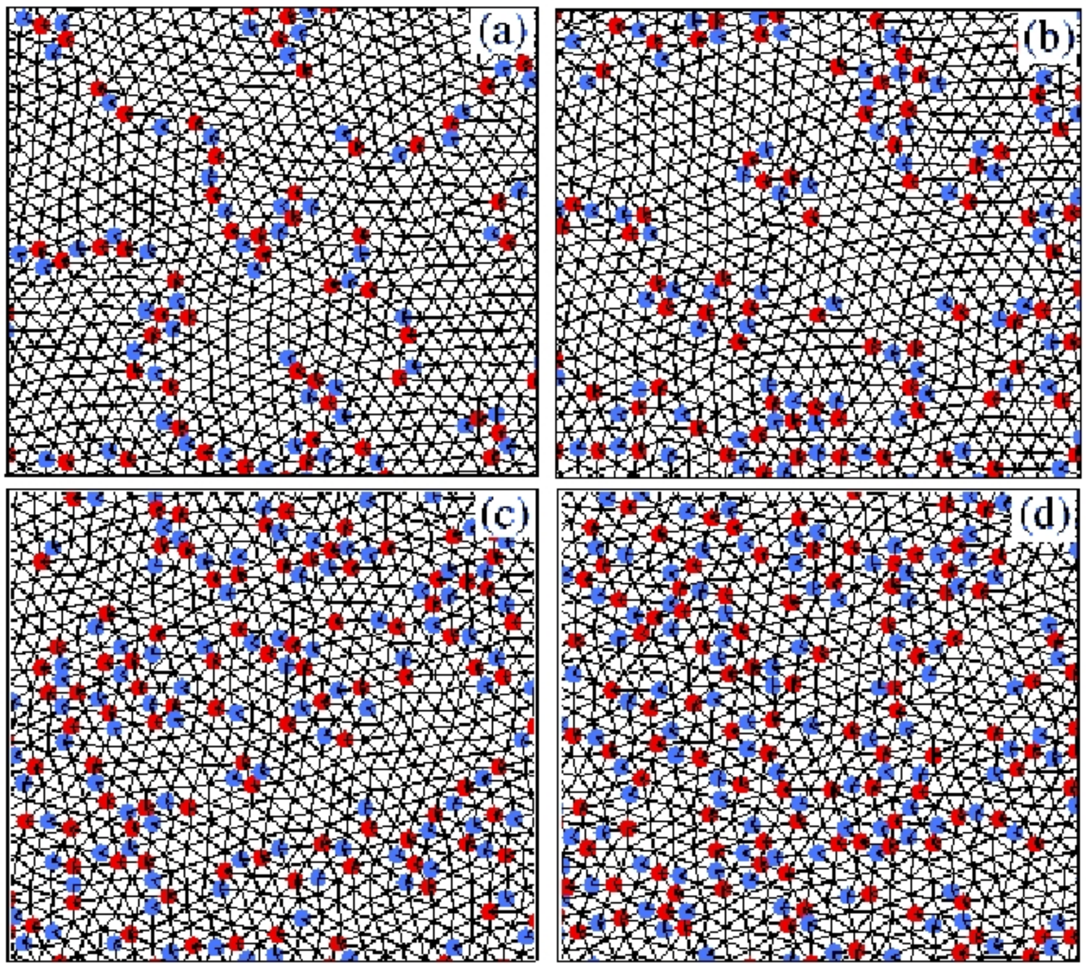
Finite Size Effects

- The measured values show little variation as N(v) is increased from 4,096 to 6,400
- At low vortex numbers and intermediate fields dislocation formation is suppressed





Disorder Sweep



Δ = 0.03 (a)
0.04 (b)
0.05 (c)
0.075(d)

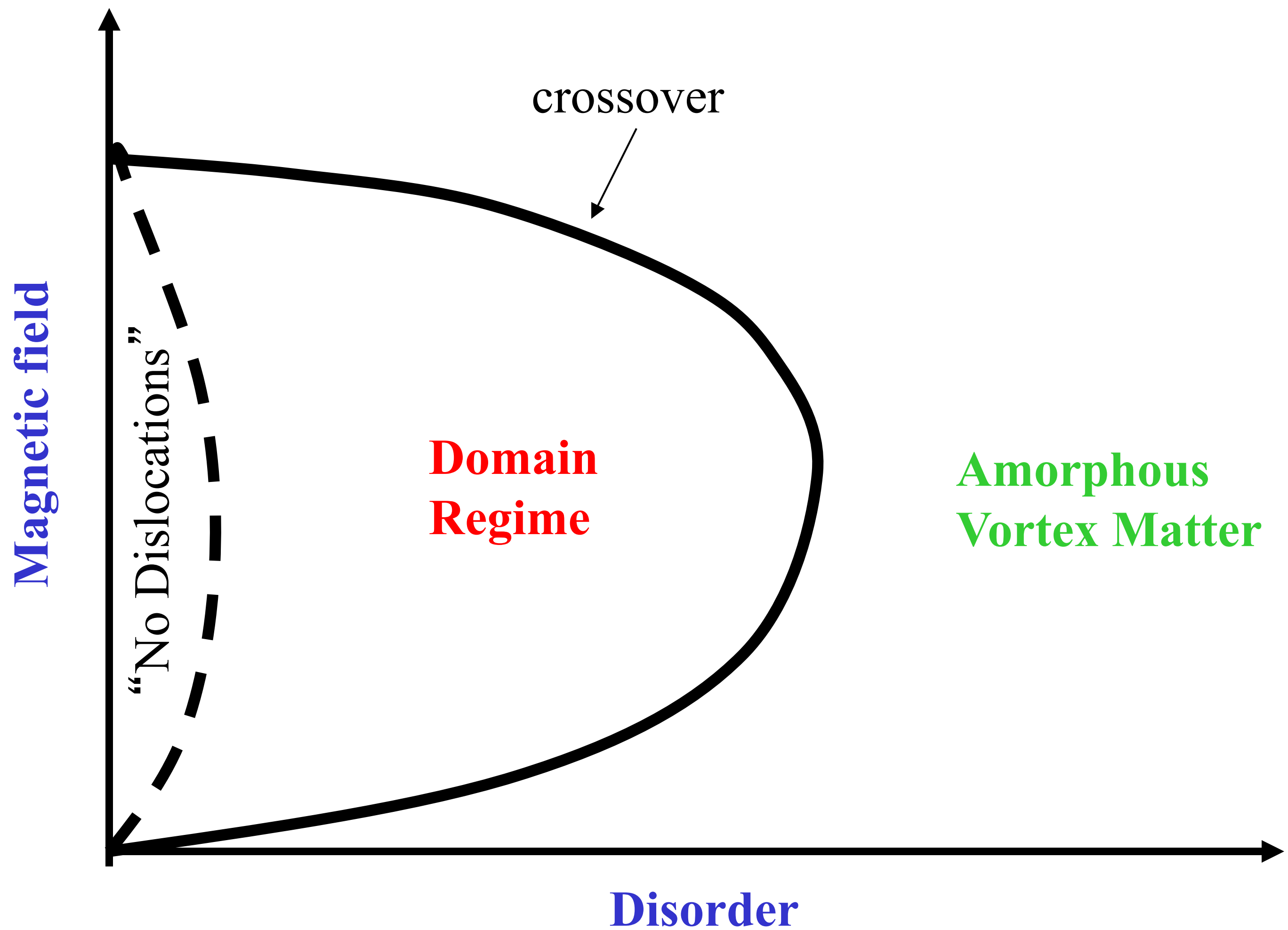
N(v) = 4096

Small disorder: Domain Regime

Large Disorder: Amorphous Vortex Matter

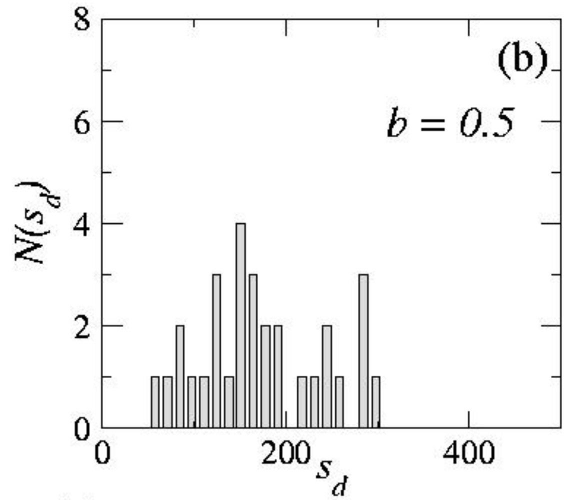
Domains are stable against moderate amount of shaking

T=0 “Phase Diagram”

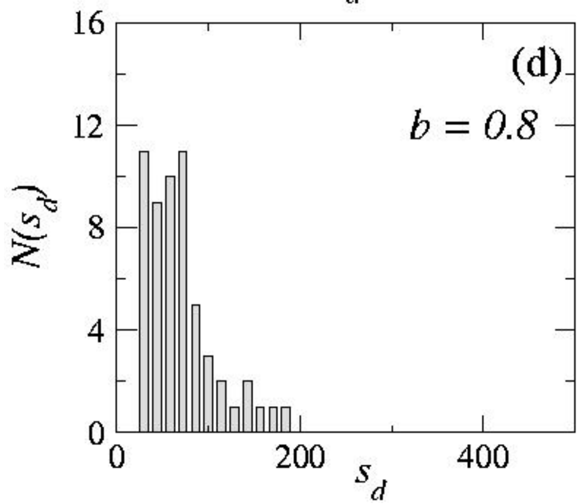


Domain Size Distribution

Domain Regime



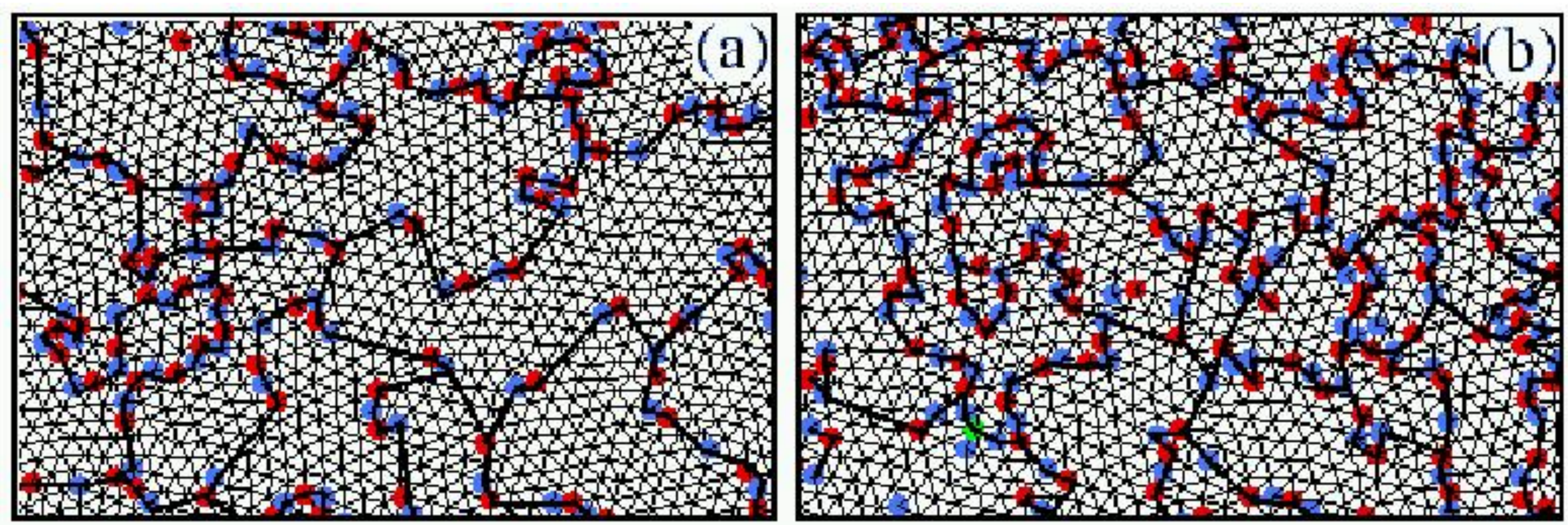
Amorphous Regime



- **Domain Size distribution is broad, besides mean higher moments are needed to characterize distribution ("rare events")**

- **Domain size distribution falls off quickly, mean characterizes distribution satisfactorily.**

Transition from Domain Regime to Amorphous Vortex Matter



Domain Regime:
Domain walls are <u>smooth</u>

Transition Regime:
Domain walls are <u>rough</u>

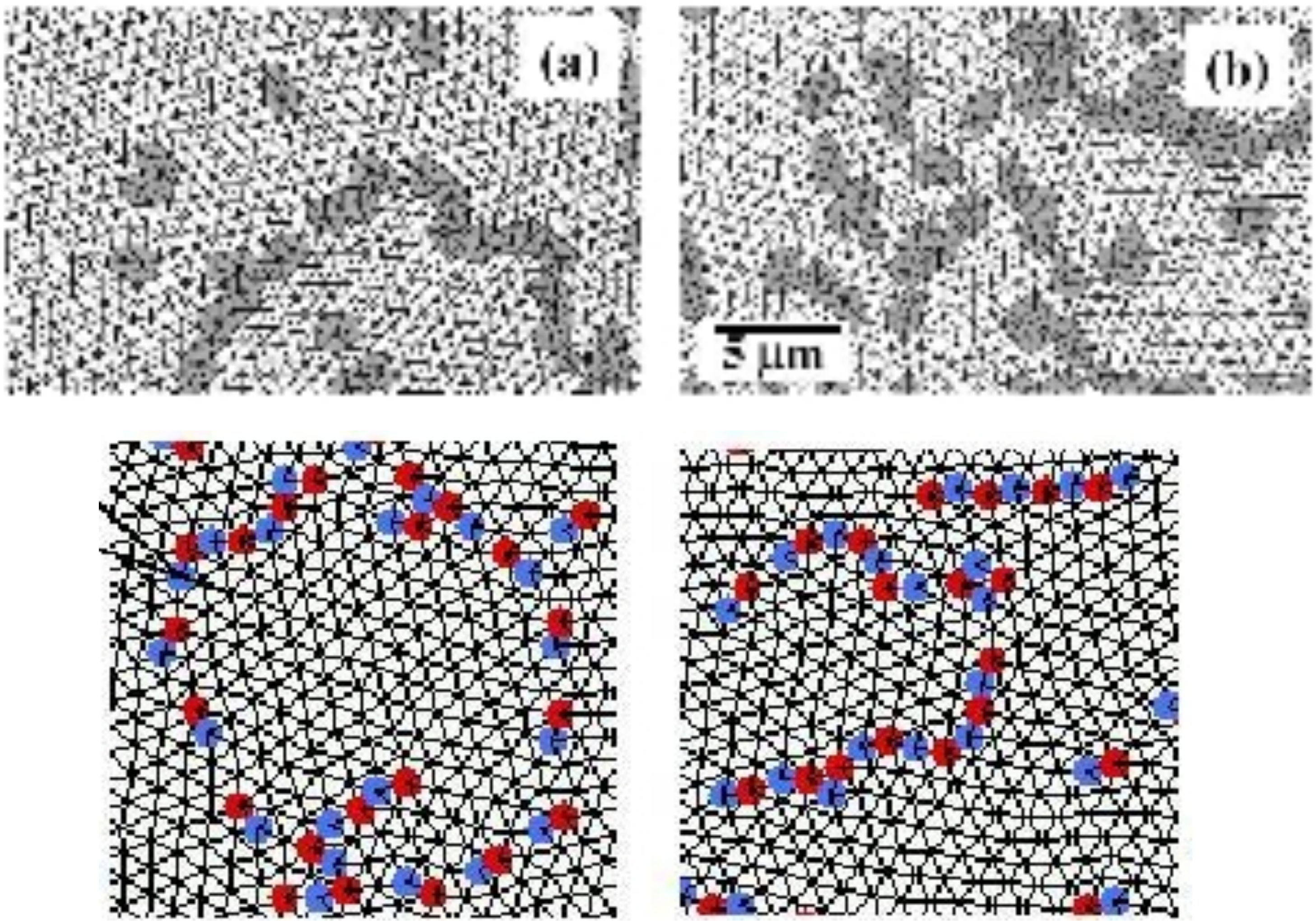
“Absence of Amorphous Vortex Matter”

Fasano, Menghini, de La Cruz, Paltiel, Myasoedov, Zeldov, Higgins, Bhattacharya, PRB, 66, 020512 (2002)

- $NbSe_2$
- T= 3-7K
- H= 36-72 Oe

$NbSe_2$

Simulations

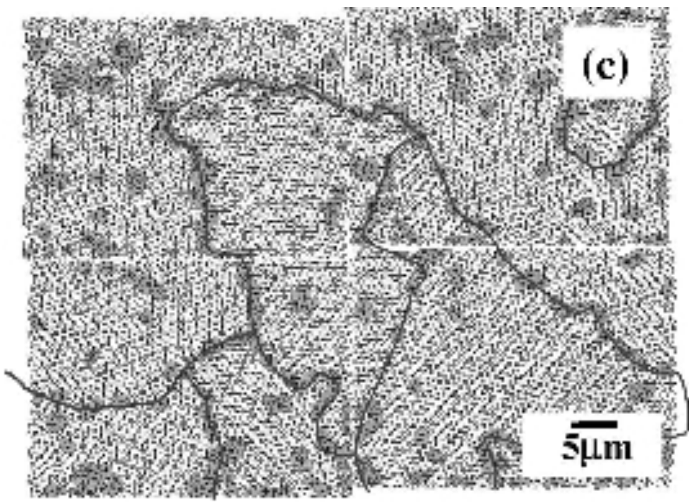


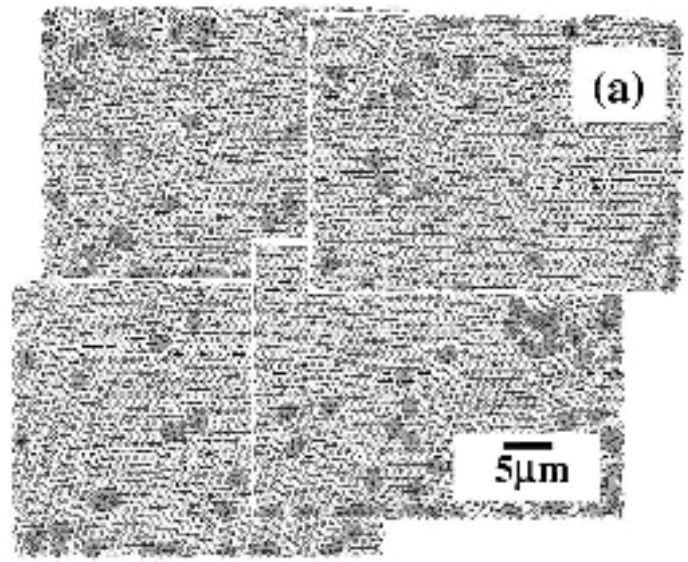
Domain Configurations

Medium Disorder

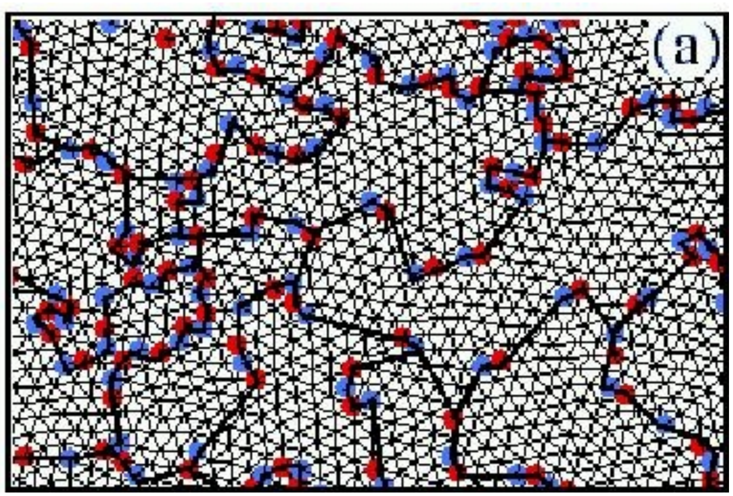
Low Disorder

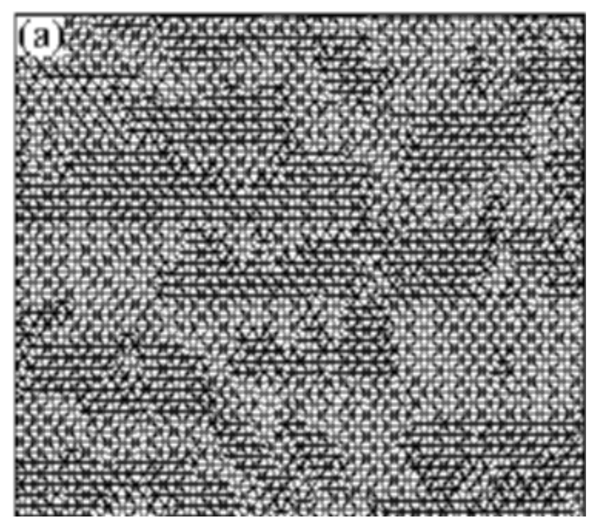
$NbSe_2$





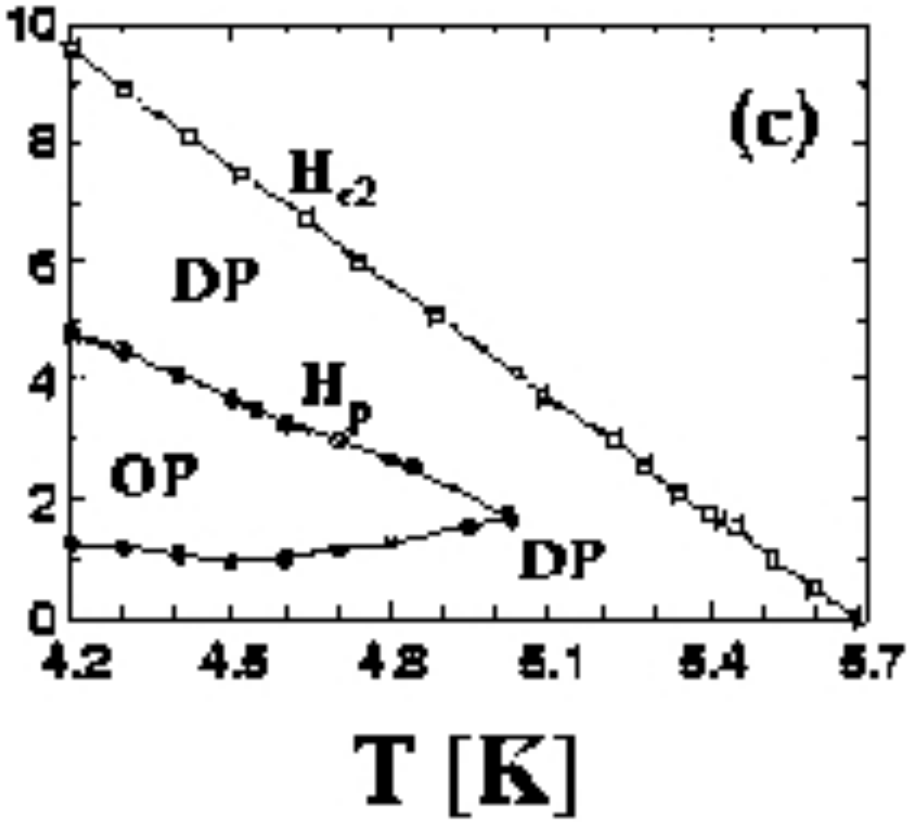
Simulation





We accessed lowest
dislocation densities

Experimentalists' Phase Diagram



• We also observe a region with exceedingly low dislocation density, which may appear as an "Ordered Phase"

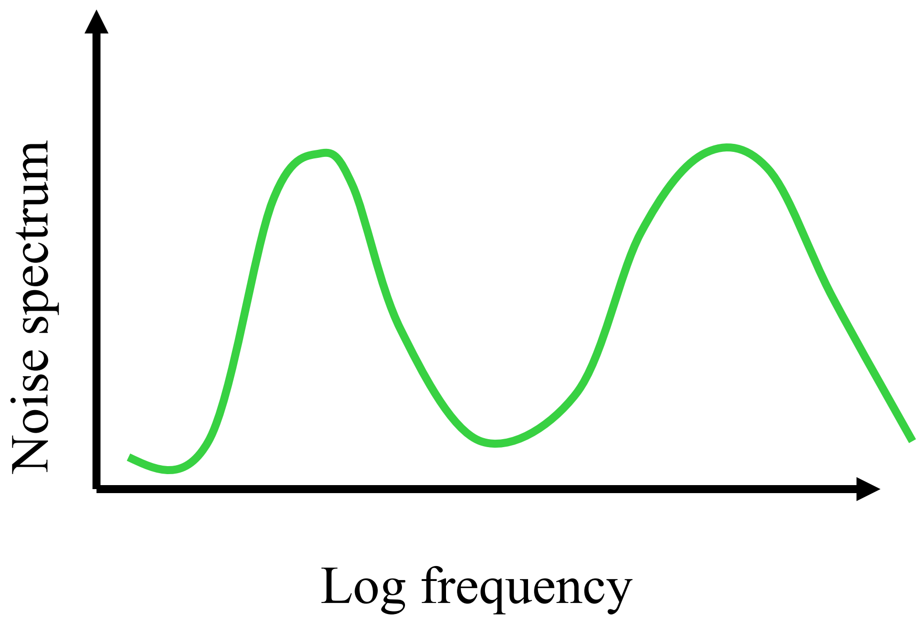
• One interpretation:
Experiment probes only Domain Regime, but with varying domain sizes

• **Very large domains: "Ordered Phase"**
• **Observable domains: Disordered Phase**

Note: we accessed lowest dislocation density regime, where dislocation unbinding could dominate. When in any meaningful density, dislocations form structures/domains instead of unbound gas.

Improvement in Statistics

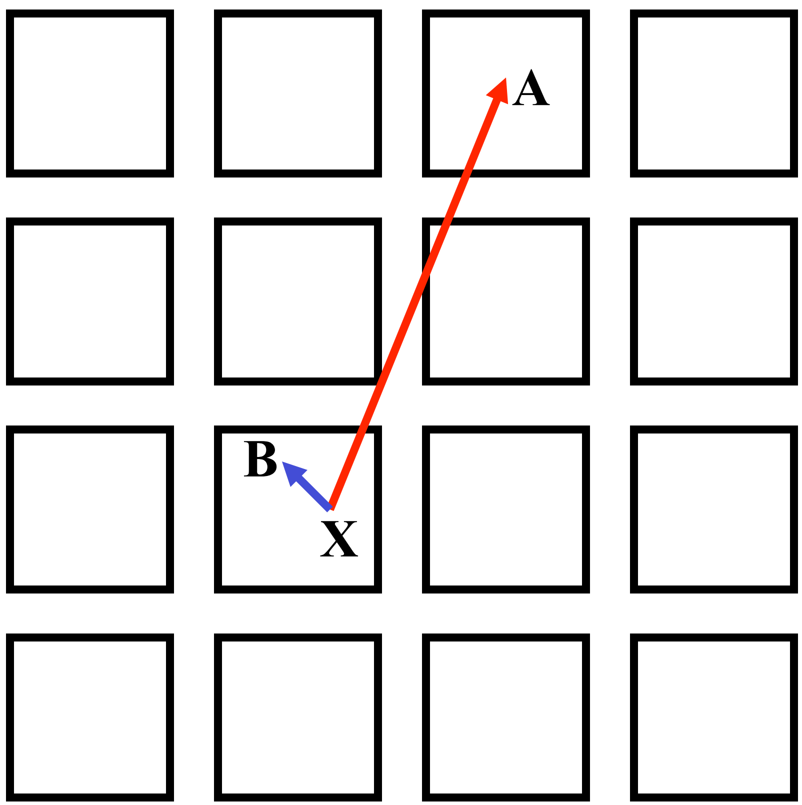
- **5,000 vortices, 200 dislocations: our results are indicative, not definitive**
- **I. Groma: import a very useful method, introduced in astrophysics to study galaxy distributions, and implemented in plasma physics**
- **Rests on analyzing noise in simulations: apparently two, well-separable frequency regimes dominate**



Develop a two-stage approximation ~ Born-Oppenheimer

Stochastic Coarse Graining I.

with G. Gyorgyi and I. Groma

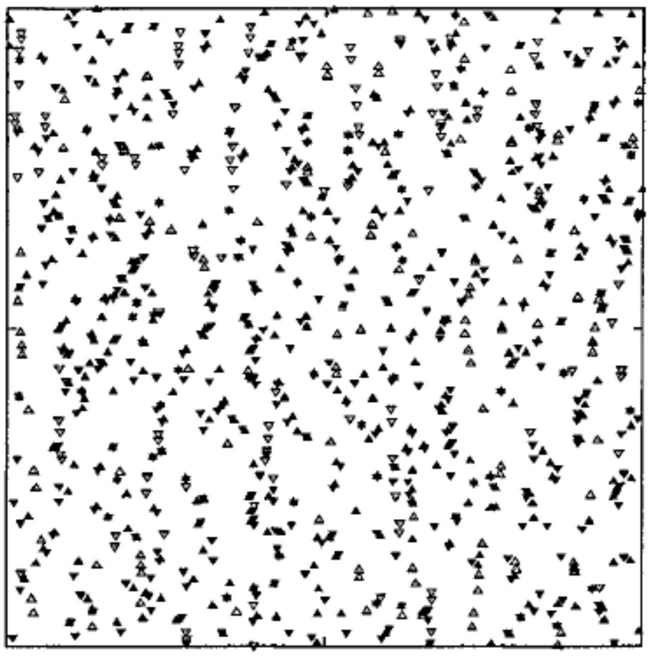


- Divide simulation space into boxes
- Calculate "center of mass" for each box
- Interaction of dislocation X with
  all dislocations A in other box:
  approximate with same center of mass
- Interaction of dislocation X with
  dislocations B in same box:
  approximate with white noise + non
  linear viscosity to reproduce a pre
  calculated dislocation (stress)
  distribution.

30*30*1,000=1-10 million dislocations are
simulated

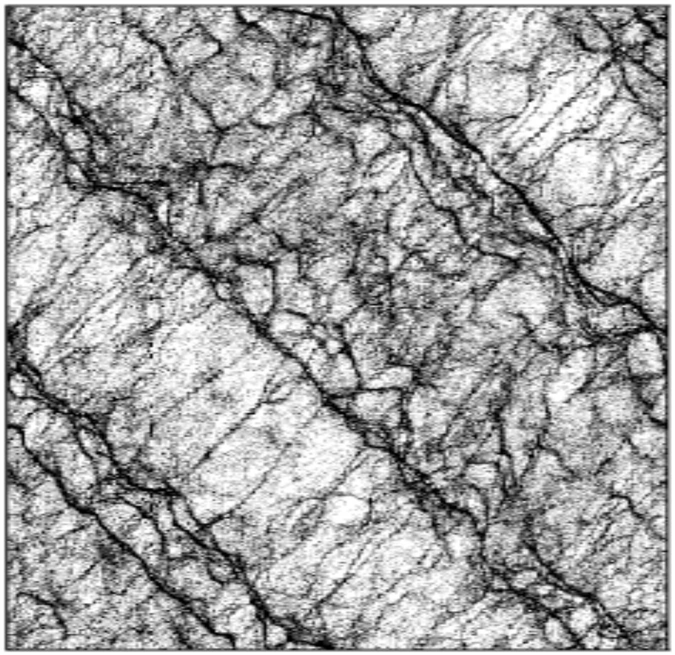
Add how to generate proper, non-white noise

Stochastic Coarse Graining II.



- Calibration simulation for (stress) distribution: N~1,000 dislocations

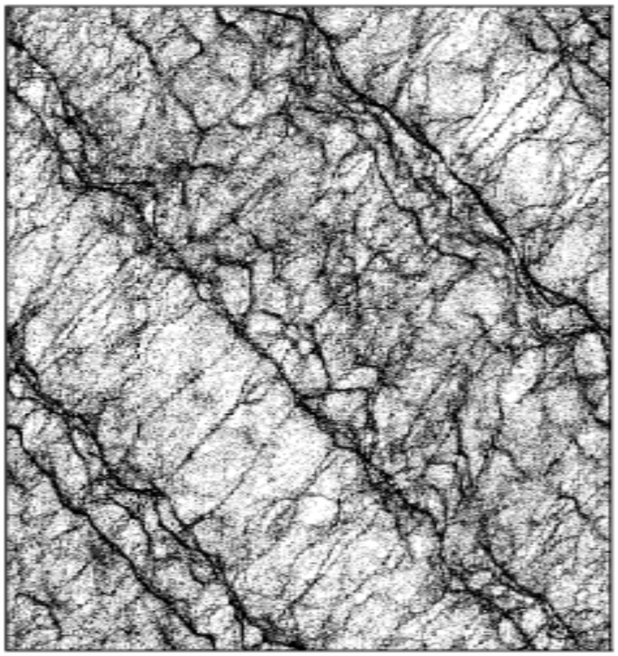
- Moderate structure formation



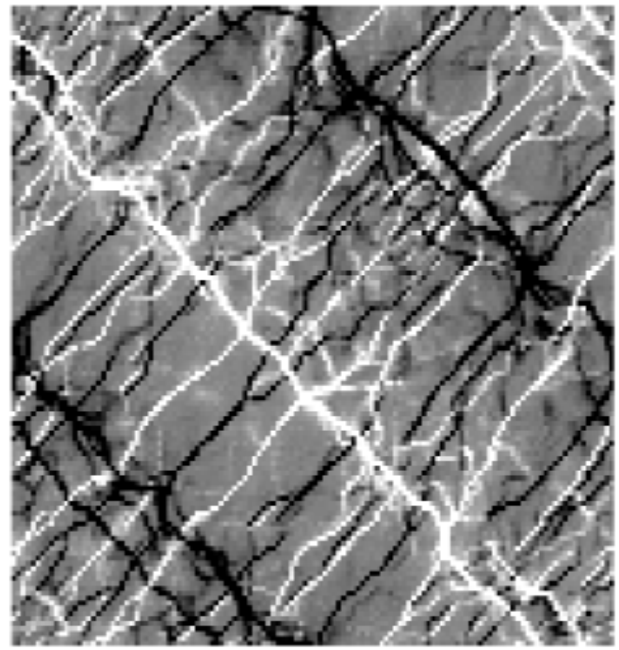
-Full simulations N~5 million dislocations

-Profound structure formation
-Sensitive to boundary, history:
-Work/current hardening

Stochastic Coarse Graining III.

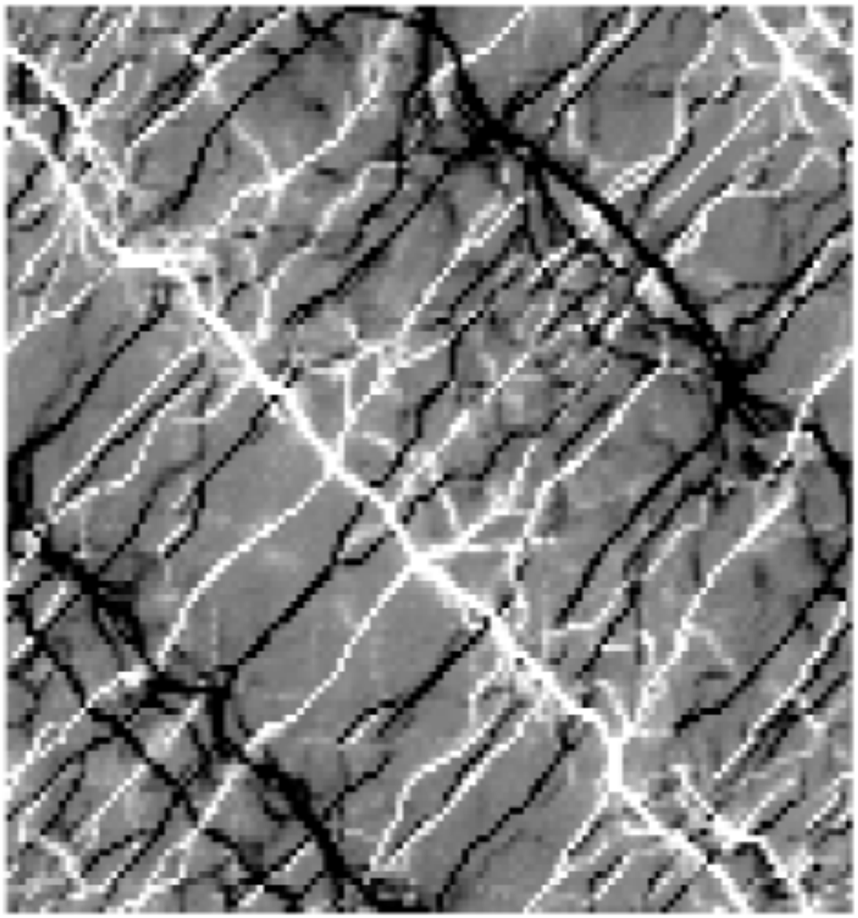


Dislocation structures
(all black)

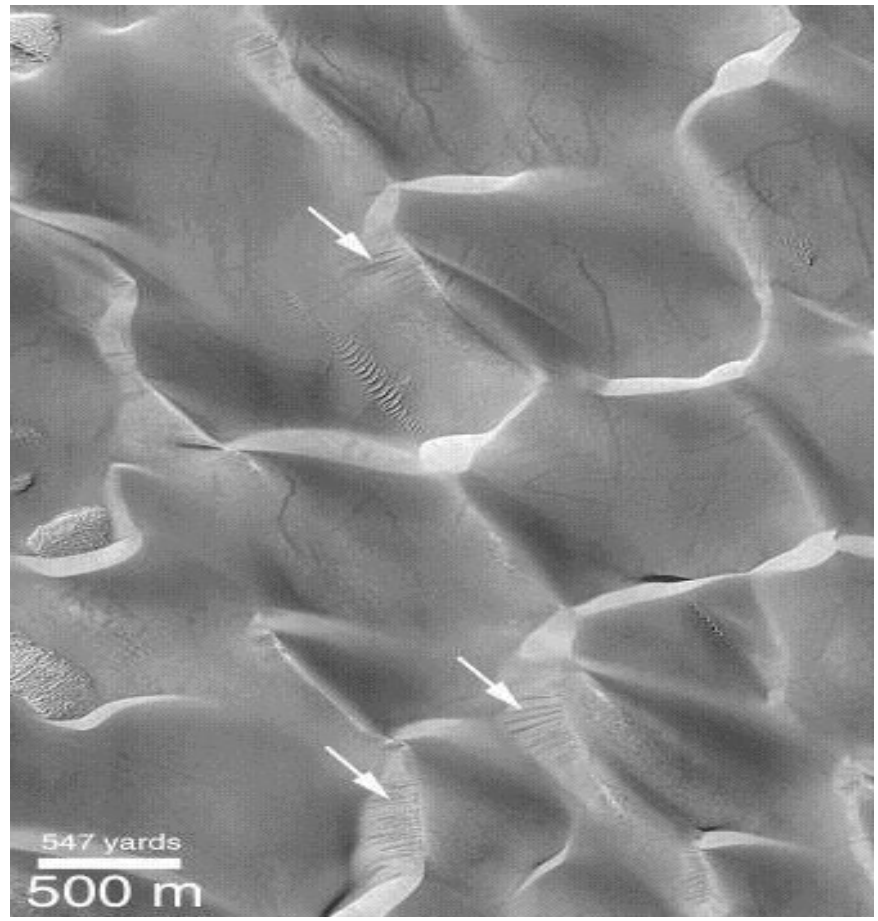


Dislocation structures
(sign color coded)

Dislocation Structure



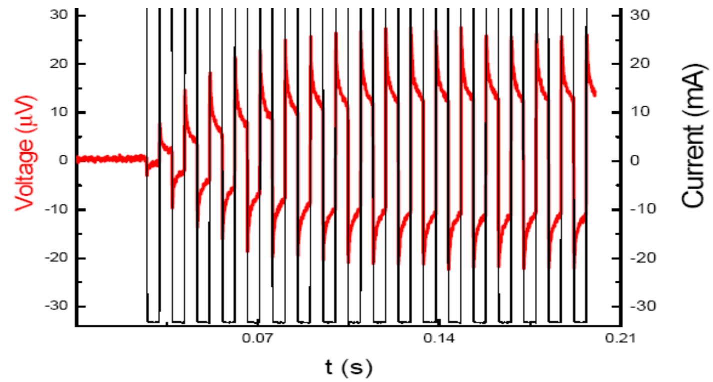
Sand Dunes on Mars

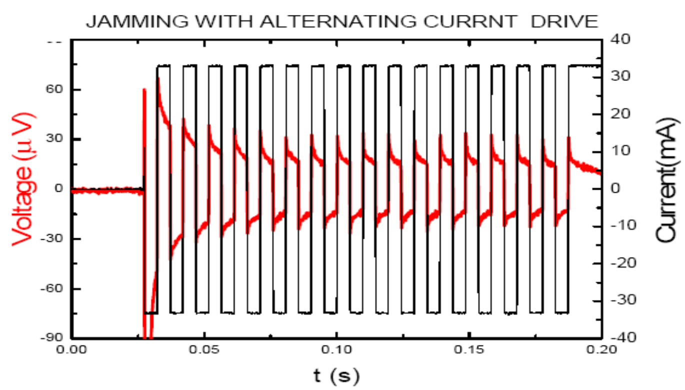


Dislocations form

Dislocations form domain walls

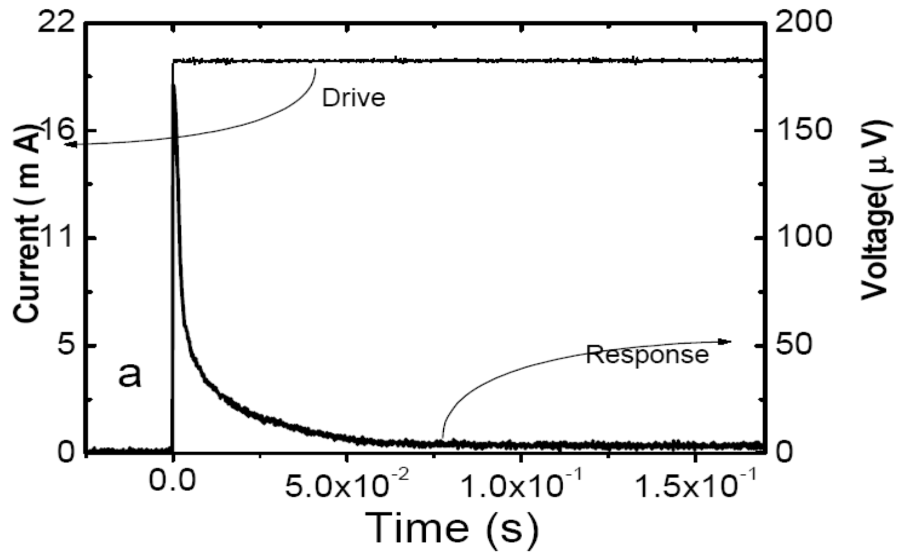
Dislocation density

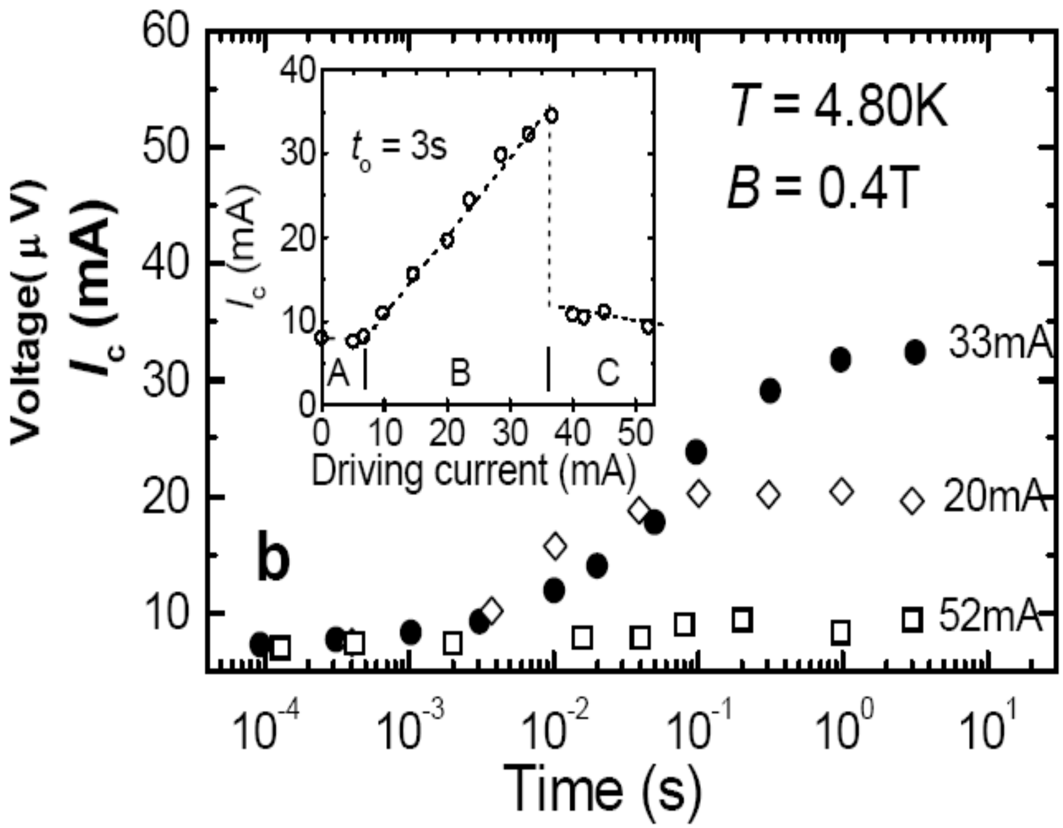

Voltage (μV)
Current (mA)
t (s)
0.07
0.14
0.21


JAMMING WITH ALTERNATING CURRNT DRIVE
Voltage (μ V)
Current(mA)
t (s)
0.00
0.05
0.10
0.15
0.20

Phys. Rev. Lett. **83**, 1664, (1999)

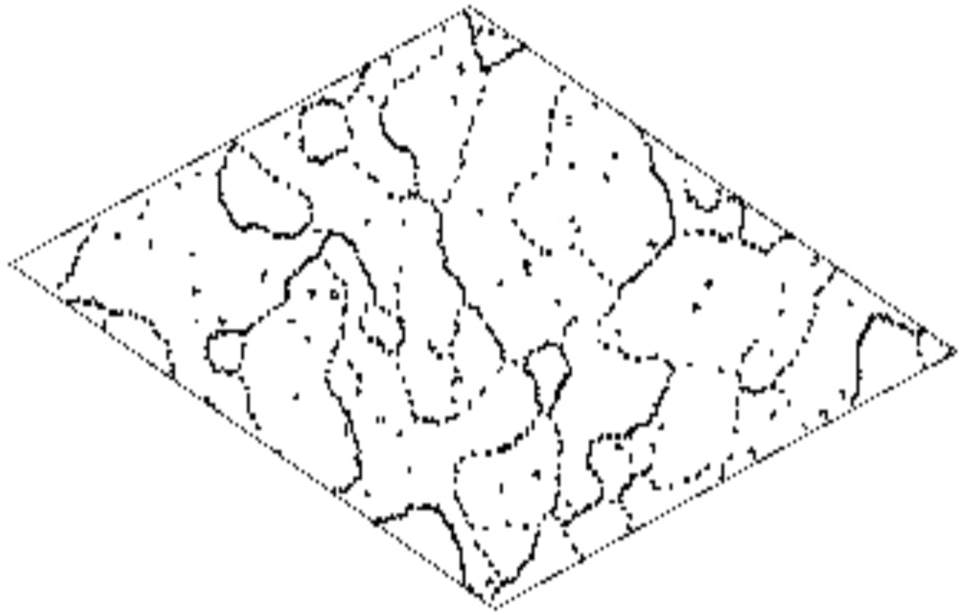
Z.L. Xiao, E. Y. Andrei and M. J. Higgins
Phys. Rev. Lett. 83, 1664, (1999)





Voltage(μ V)
I_c (mA)
60
50
40
30
20
10
T = 4.80K
B = 0.4T
33mA
20mA
52mA
b
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
Time (s)
t_o = 3s
I_c (mA)
A
B
C
Driving current (mA)

"Inherent Structures" in 2D Melting



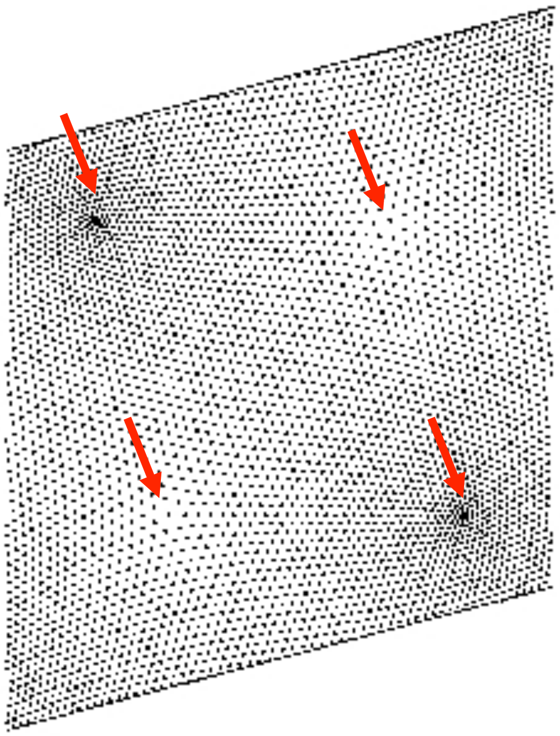
Somer, Canright, Kaplan
PRL 79, 3431 (1997)

- **Clean 2D L-J liquid**
- **T=2.17**
- **36,000 particles**

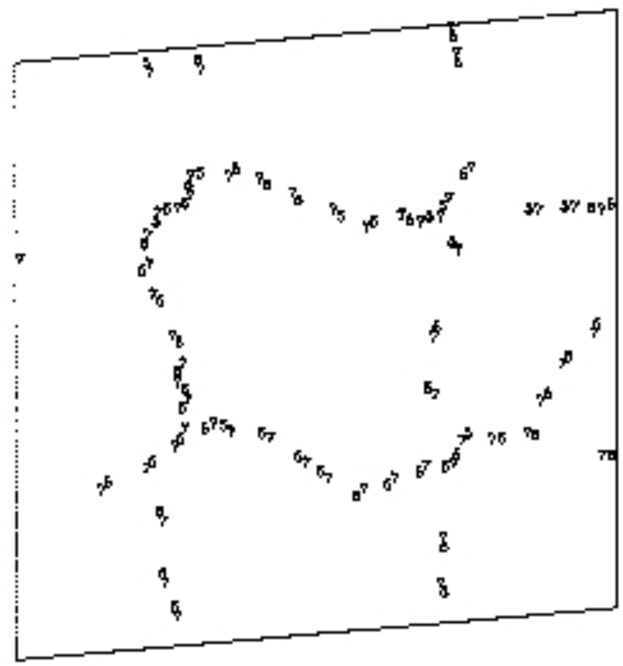
- **Potential energy landscape is governed by large basins in configuration space, corresponding to "Inherent Structures"**
- **Inherent structures turn out to be**
  Domain Walls, formed by Dislocations
- **Free disclinations in nodes**

Free Disclinations Generate Domain Walls

- Start with four free disclinations
- Relax potential energy
- Domain walls of 5-7 disclination pairs develop
- Free disclination at nodes
- Olson & Reichhardt report similar results (2004 PRL)



(a)



Dislocation structures in clean 2D melting?

- **KTHNY melting theory: governed by dislocation unbinding.**
  - Applies, when dislocation core energy is high enough to keep dislocation density low. Otherwise: first order transition.
  - Many numerical work reports first order transition (Sandburg 89)

- **Our work I: Role of anisotropy in interactions and dynamics:**
  Can they favor the formation of dislocation structures instead of the formation of pairs?

- **Our work II: Even if upon cooling in principle dislocations may want to bind into pairs, above T_{melt} they form structures, which freeze into a "stripe/labyrinth glass". This glass formation may prevent the system from carrying out the KTHNY scenario.**
  We will study the possible divergence of characteristic times upon approaching the melting transition (in analogy to spin glasses)

Summary of Domain Regime – quasi Bragg Glass Results

- Dislocations form structures, defining domain walls and creating a Domain Regime, driven by the anisotropy of the interactions and the dynamics.

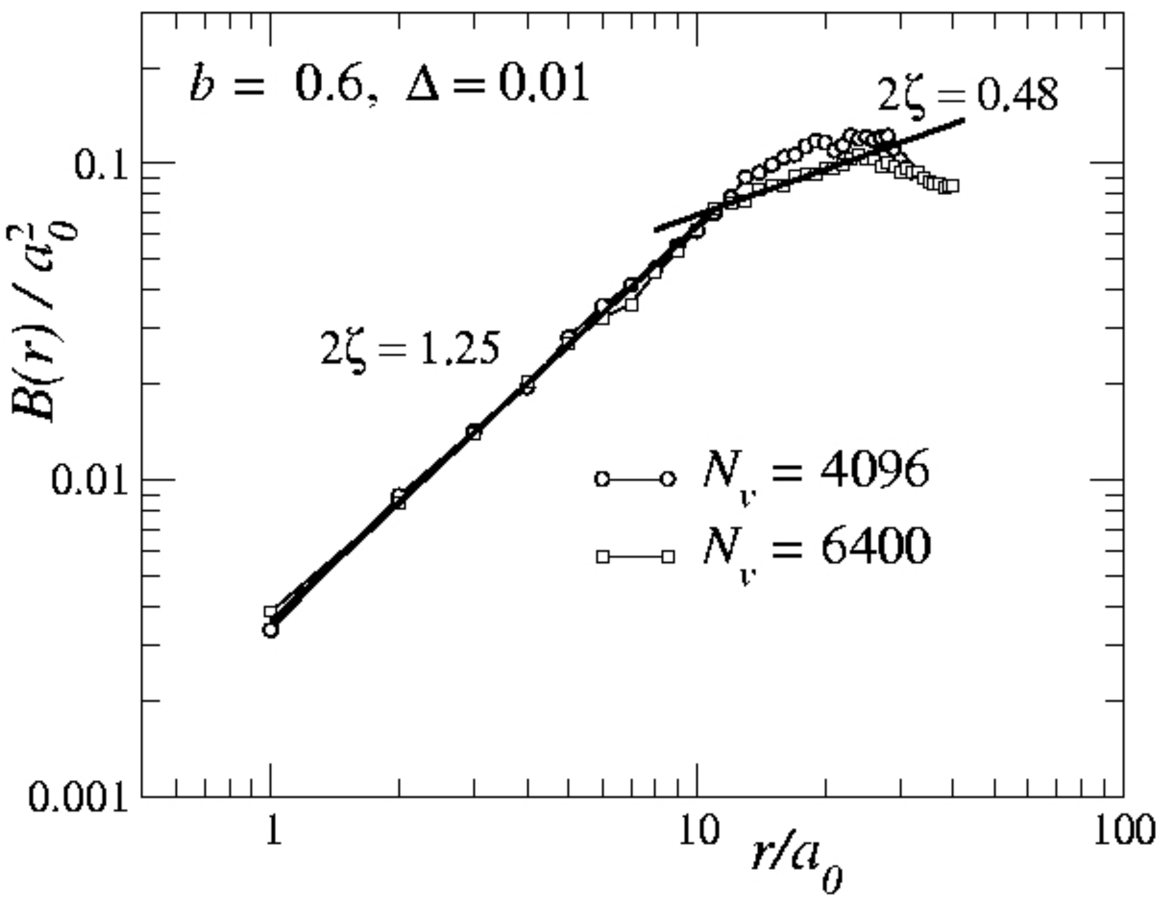
- Distribution of domain sizes is broad, more than one moment is required to characterize the distribution.

- Increasing field/disorder drives an apparent Ordered Phase – Domain Regime – Amorphous Vortex Matter sequence.

- Domain Regime melts by roughening of the domain walls.

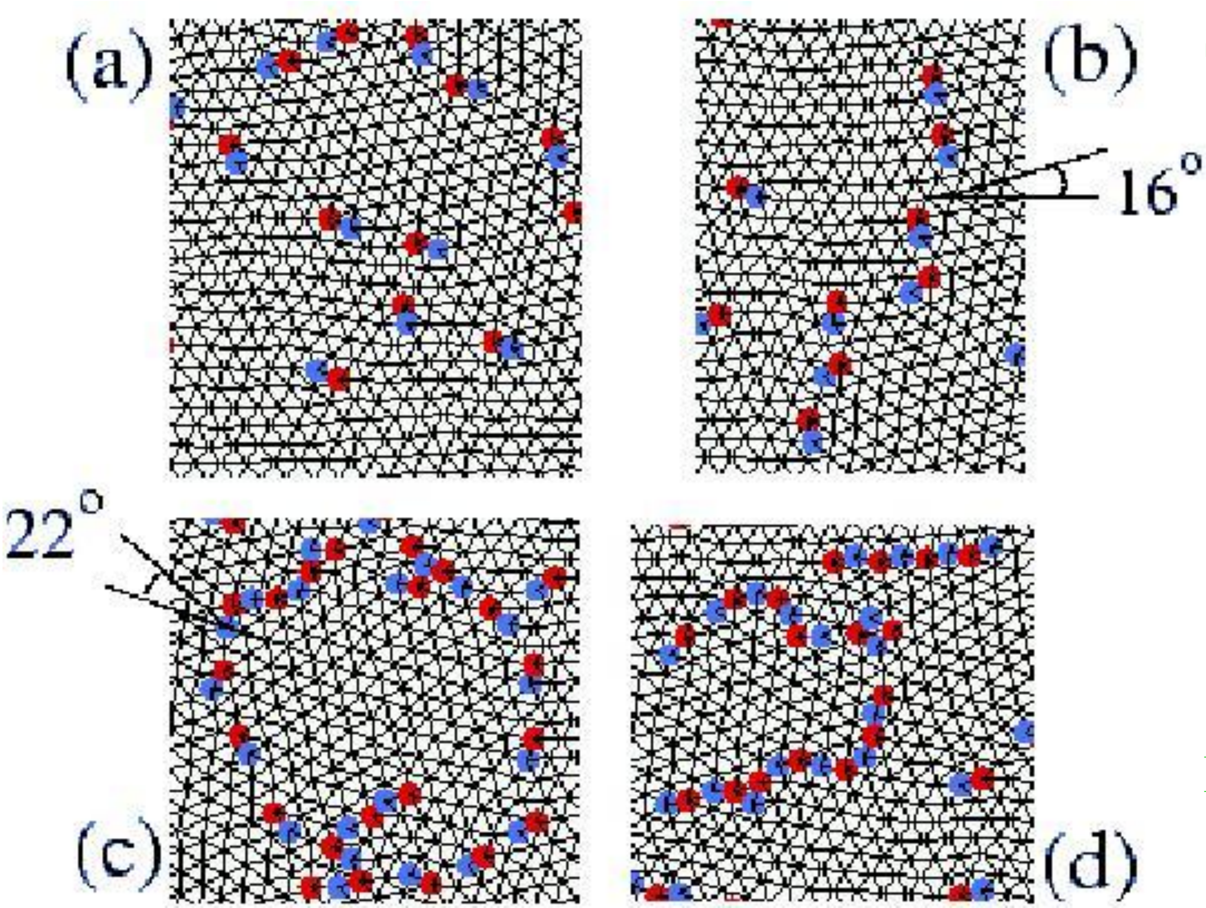
- Relation to Inherent Structures in clean 2D melting?

- Stochastic Coarse Graining method brings large improvements.



b = 0.6, Δ = 0.01
2ζ = 0.48
2ζ = 1.25
N_v = 4096
N_v = 6400
B(r) / a_0^2
r/a_0
0.1
0.01
0.001
1
10
100

Determination of Domain Walls



Small angle domain boundary:

- Bond angle deviation between 10-18 degrees
- Dislocations are 3-5 lattice spacing apart
- Domain wall can be interpolated

Large angle domain boundary:

- Dislocations form filaments

Previous Work

Random manifold

Fleury estimates, review — Halpin-Healey

Functional RG — Balents-Fisher, Emig-Nattermann

Two loop — Le Doussal-Chauve-Wiese

Dislocations

Appear only at extremely long scales

Replica variational study — Giamarchi-Le Doussal

Functional RG — Balents-Marchetti-Radzihovsky

Scaling — Sheidl-Vinokur

Nattermann

Numerical work

XY model, established Bragg glass — Gingras-Huse

two dislocations interact ~ log ^{2}(r) — Zeng-Leath-Fisher

other dislocations screen log ^{2}(r) — Middleton

P. Young, Rieger

Moon-G.T.Z. (2D moving)

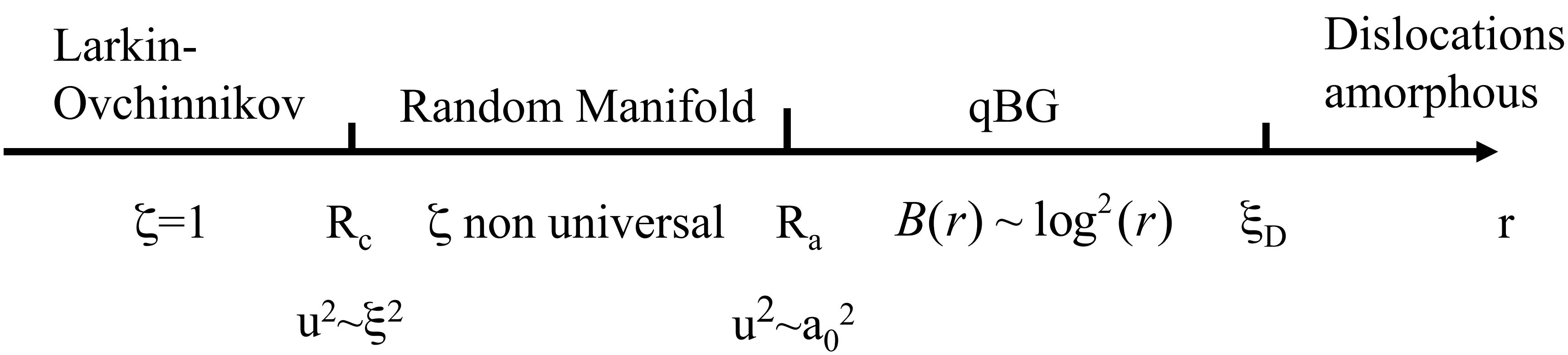
v.Otterlo-G.T.Z. (3D static)

The 2D quasi Bragg Glass

qBG has several relevant length scales:

$$B(r) = \left\langle [u(r) - u(0)]^2 \right\rangle \sim r^{2\varsigma}$$

$$C(r) \sim \exp(-k^2 B(r))$$



Structure Formation in Nature