「Avalanches, plasticity, and nonlinear response in nonequilibrium solids」
7 Mar 2016 京都大学基礎物理学研究所

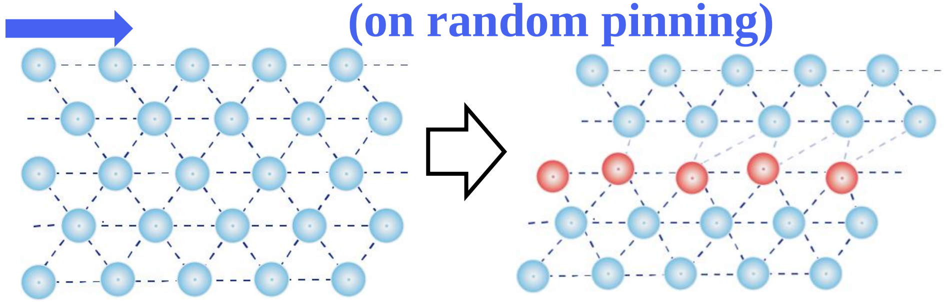
Plastic Flow and Dynamic Transitions of Vortex Solids in Superconductors

S. Okuma, Y. Kawamura, A. Motohashi, and S. Kaneko
Department of Physics,Tokyo Institute of Technology, Tokyo, Japan

Acknowledgments: **N. Kokubo, C. Reichhardt, K. Takeuchi**

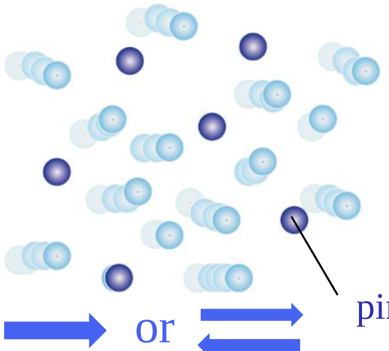
Introduction

Lattice subject to shearing force (on random pinning)



- Plastic deformation
- Plastic flow of solid
- Slip

Interacting particles driven over a random substrate (pinning)



pinned particle

Driving force

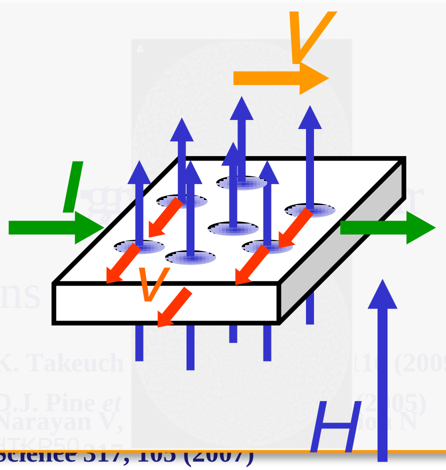
Elastic media responding to an external shearing force

- drift of earth plates
- avalanches

Non-equilibrium phenomena in many-particle systems

- turbulent fluids
- granular matter

A vortex system is a general model system for studying **plasticity of solids** and various **non-equilibrium phenomena in interacting many particle** systems



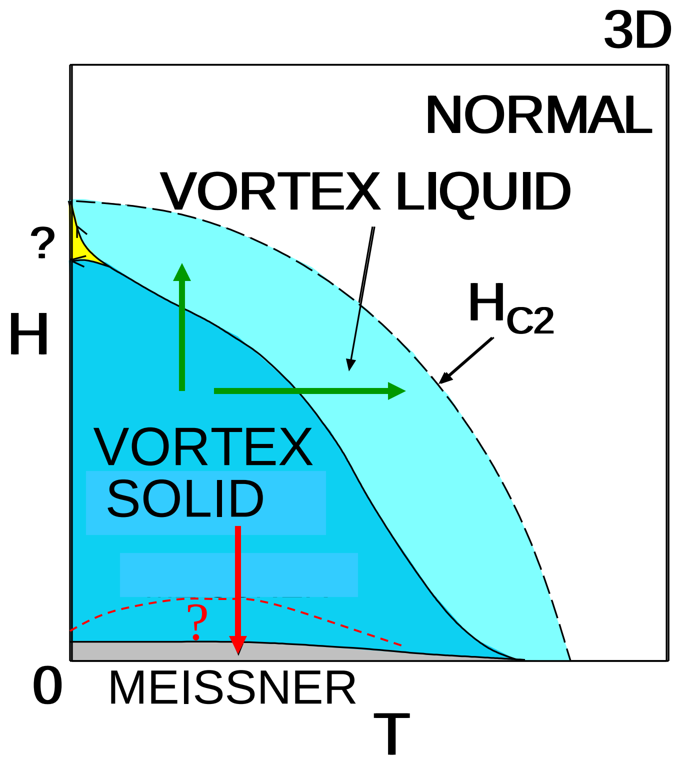
Introduction

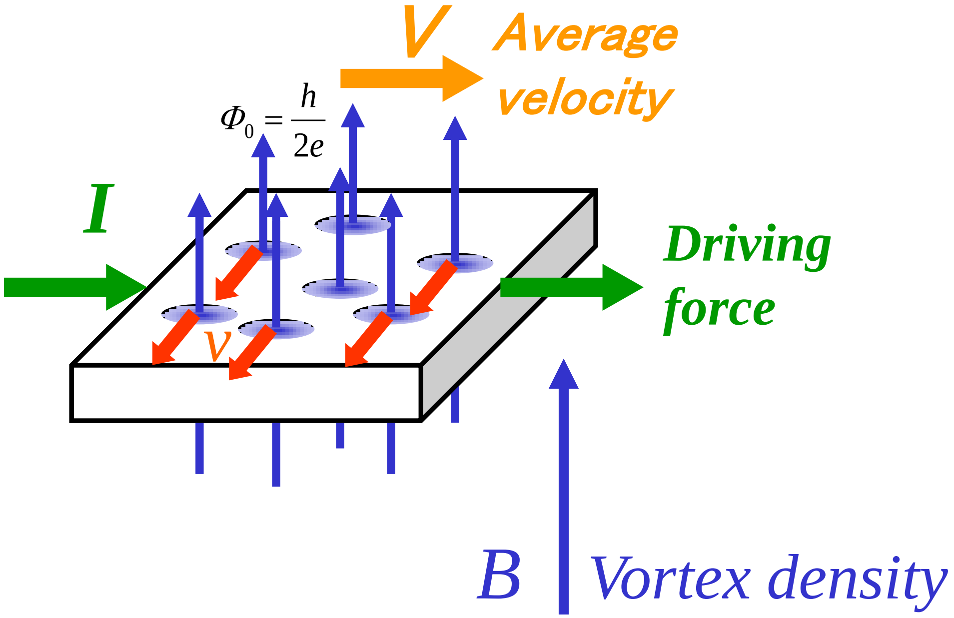
Vortex states (phase diagram) in type-II superconductors

Solid-liquid (melting) transition

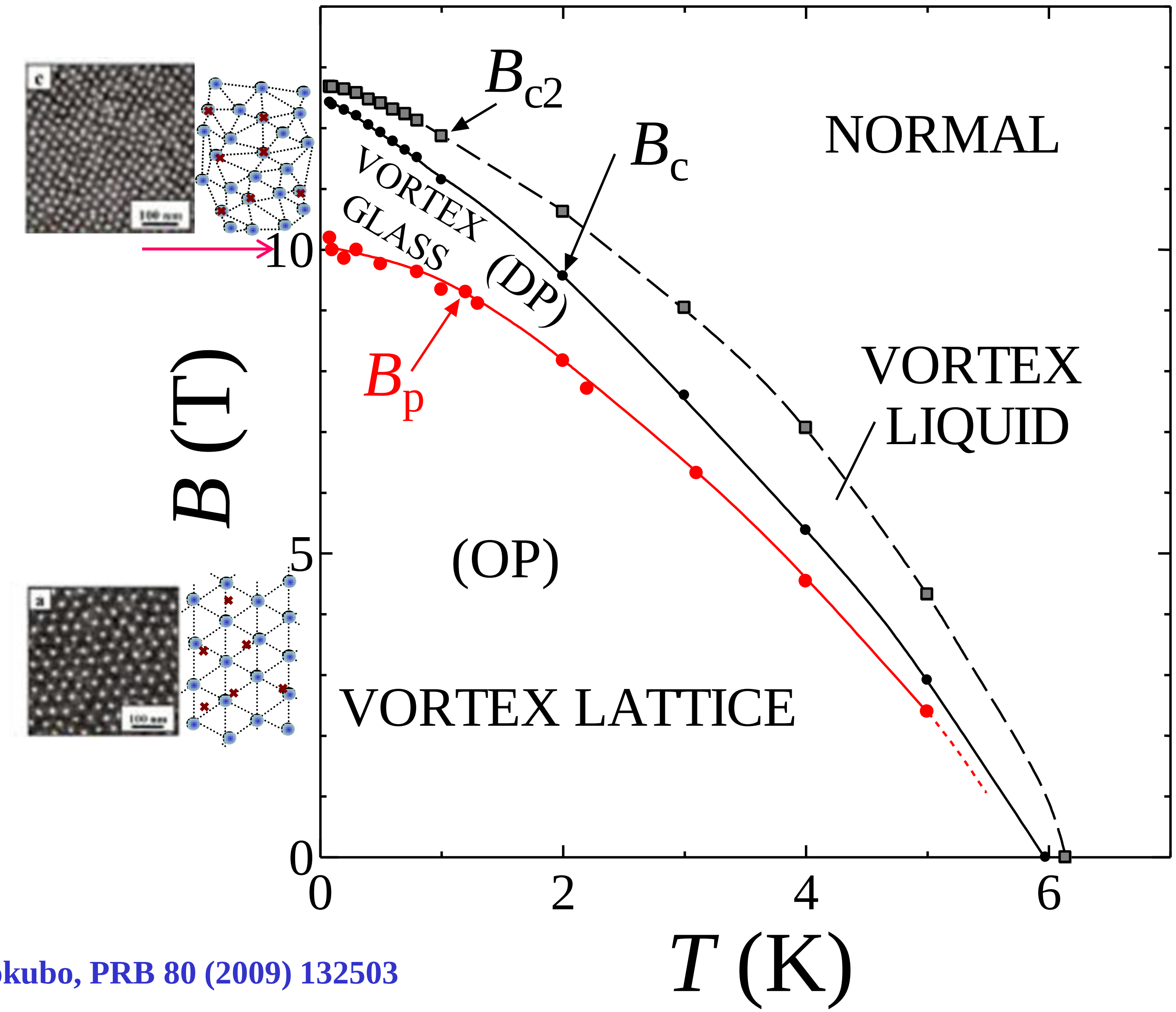
with increasing *T* / *H* (thermal fluctuations) or

with decreasing *H* (vanishing shear modulus)



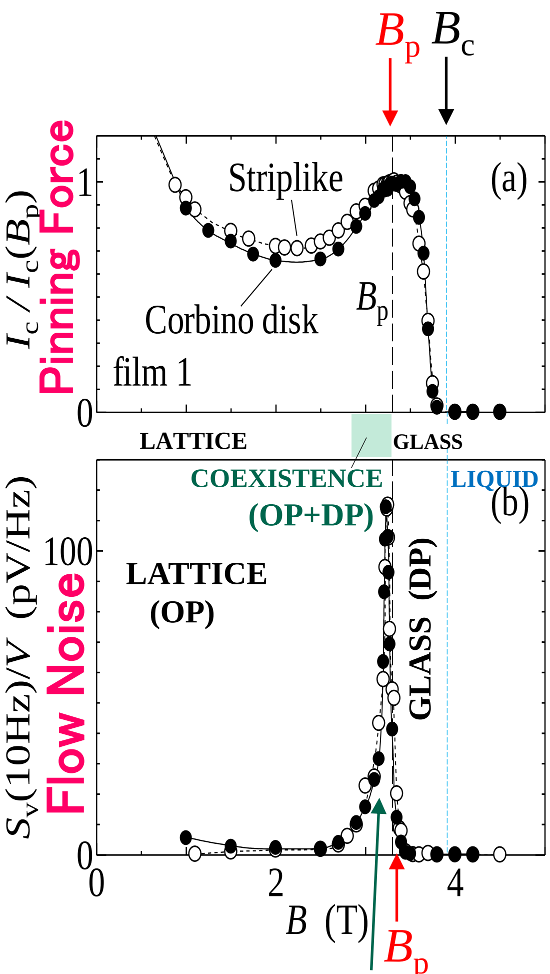


Static vortex phases for *a*-Mo_xGe_{1-x} film with **weak random pinning**



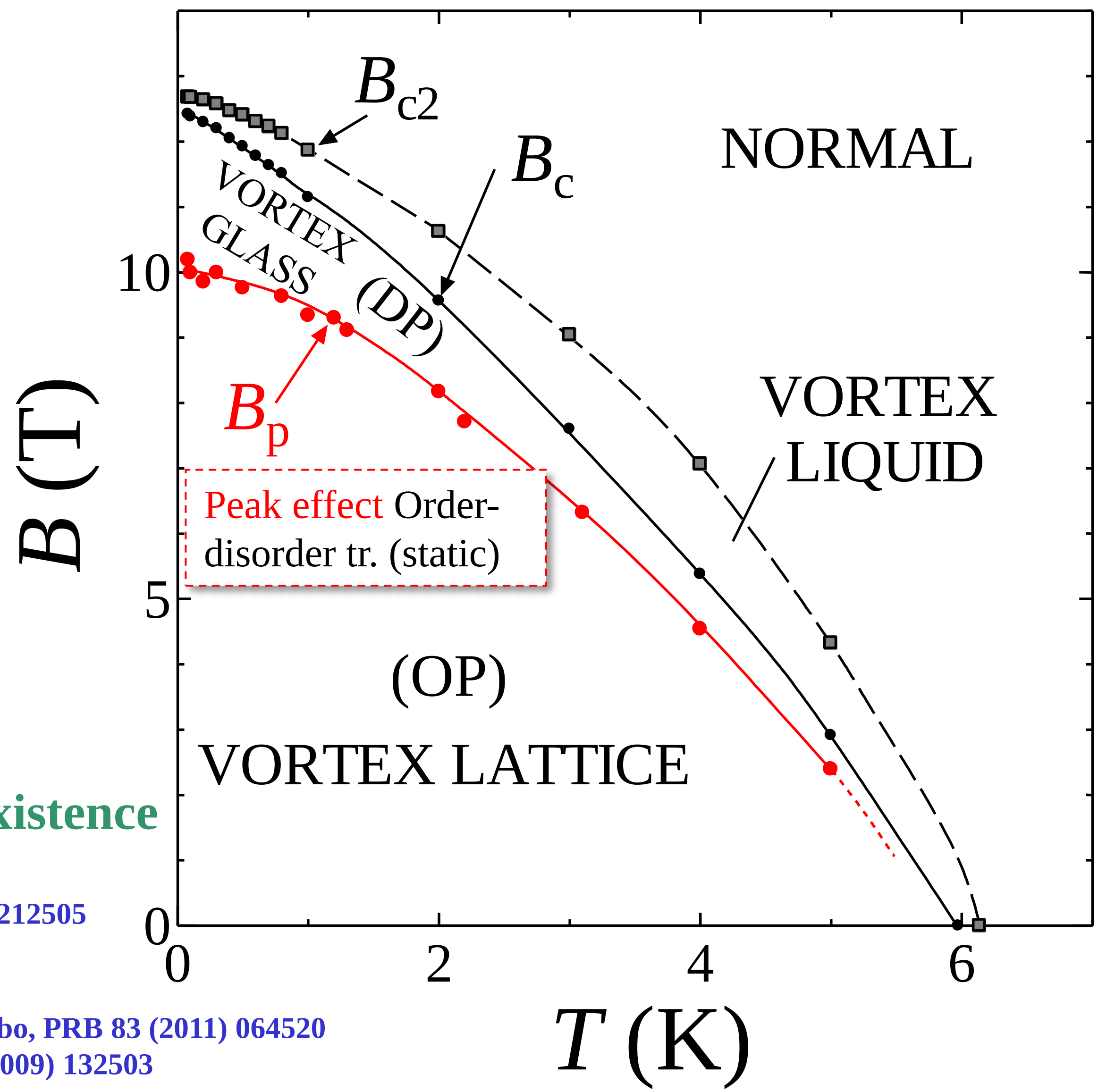
SO, H. Imaizumi, N. Kokubo, PRB 80 (2009) 132503

Order-disorder (OP-DP) transition at B_p



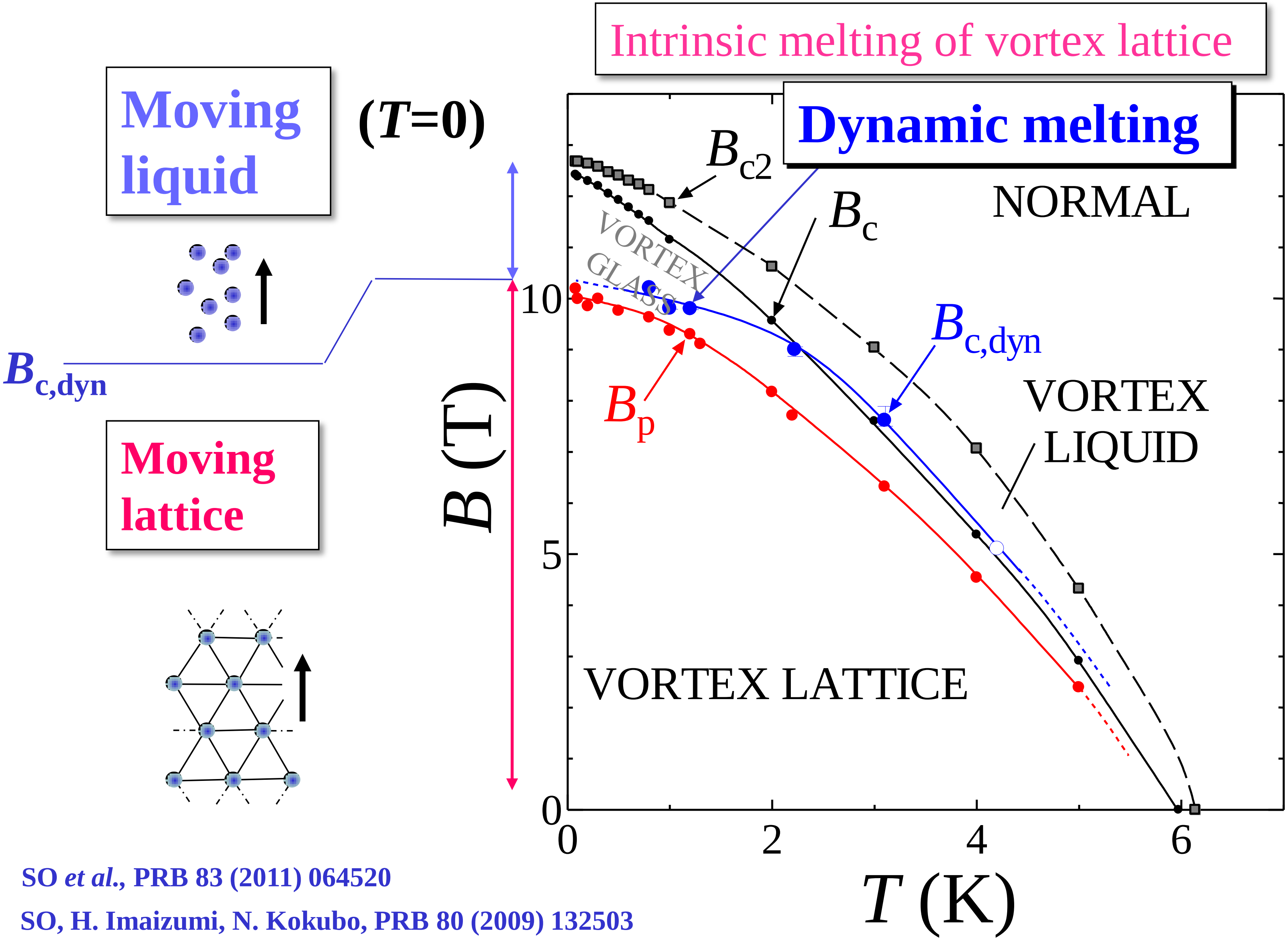
Largest noise at phase **coexistence**
OP+DP

SO, Y. Suzuki, N. Kokubo, PRB 77 (2008) 212505



SO, H. Imaizumi, D. Shimamoto, N. Kokubo, PRB 83 (2011) 064520
SO, H. Imamizumi, N. Kokubo, PRB 80 (2009) 132503

Dynamic melting $B_{c,dyn}$ decoupled from pinning vs static melting B_c



SO *et al.*, PRB 83 (2011) 064520

SO, H. Imaizumi, N. Kokubo, PRB 80 (2009) 132503

Suppression of $B_{c,dyn}$ by increased effective pinning (decreased v)

$v\downarrow$

⇩

Effective pinning↑

⇩

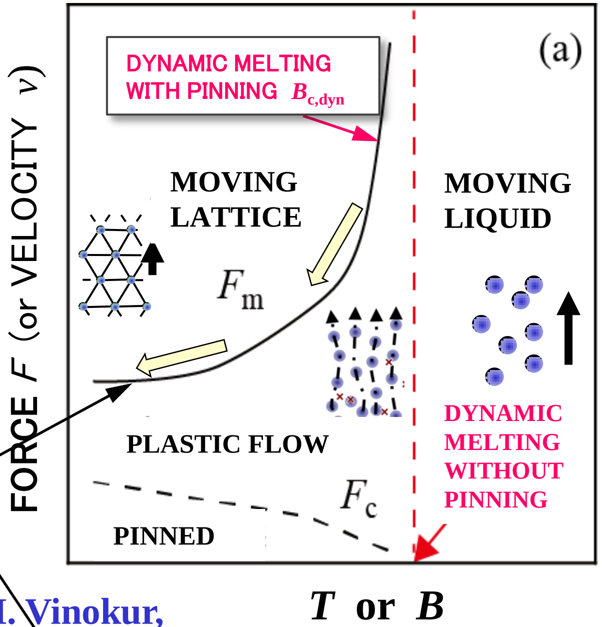
$T_{shaking}\uparrow$

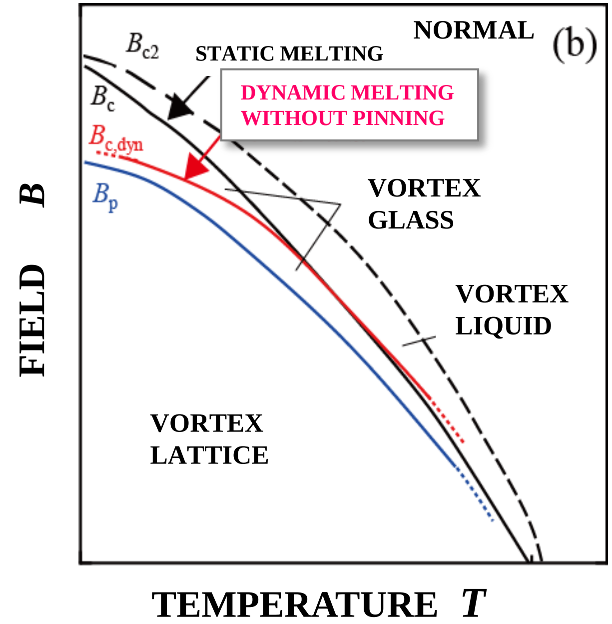
⇩

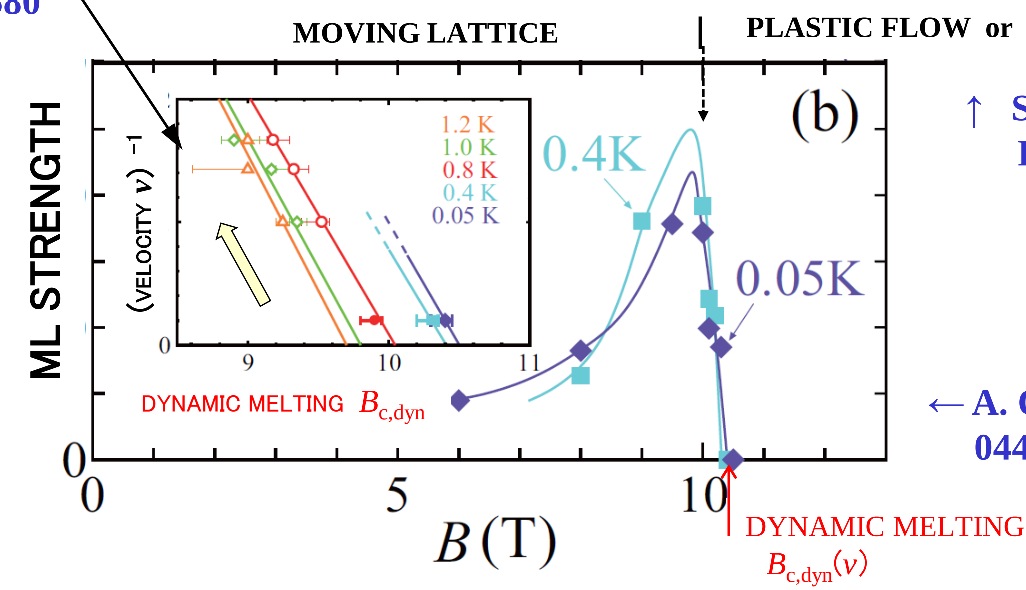
$T_m\downarrow$

$$T_{eff} = T + T_{shaking}$$

A.E. Koshelev, V.M. Vinokur, PRL 73 (1994) 3580





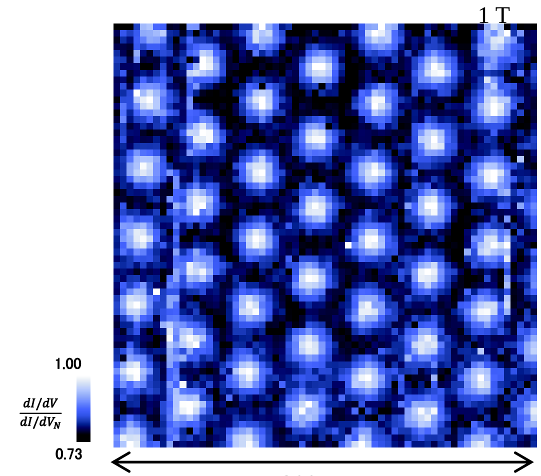


↑ SO, H. Imaizumi, N. Kokubo, PRB 80 (2009) 132503:

← A. Ochi *et al.*, JPSJ 85 (2016) 044701

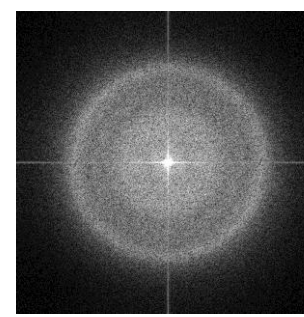
Vortex matter in type-II superconductors

- Exhibit **various phases** and **dynamic phase transitions** induced by motion, which are not largely dependent on materials



S. Kaneko, K. Kato, H. Sakata, SO

- ***a*-Mo$_x$Ge$_{1-x}$** films with **weak pinning**
  - very uniform
  - random point pinning ∼10 nm



Merits of vortex systems

1) We can conduct experiments **repeatedly** and **controllably**

2) readily **change** static vortex **structure**, *lattice*, *glass*, *liquid*, …
only by changing B and T

3) **drive** the system by **dc, ac,** and **dc+ac** currents (forces)

Uniqueness of this work

4) **global shear** (CD) as well as local shear (strip)

5) various non-equilibrium phenomena in **different *v* regimes**

-large v: **elastic to plastic** transformation **with *v* ↓ (pinning ↑)**

-small v: **non-equilibrium transitions** in interacting many particles **with *v* ↑ (pinning ↓)**

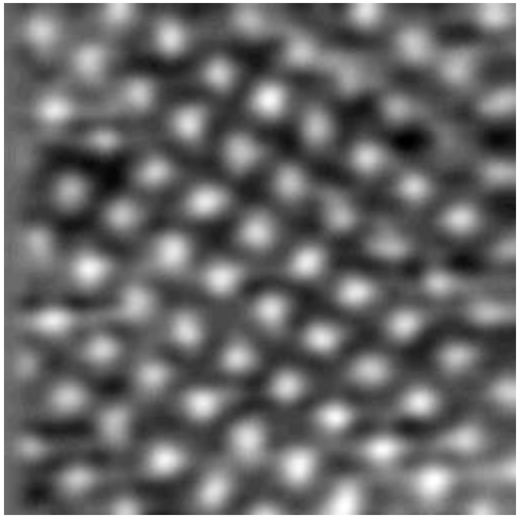
- **random organization** and reversible to irreversible transition (**RIT**)
- plastic **depinning** transition

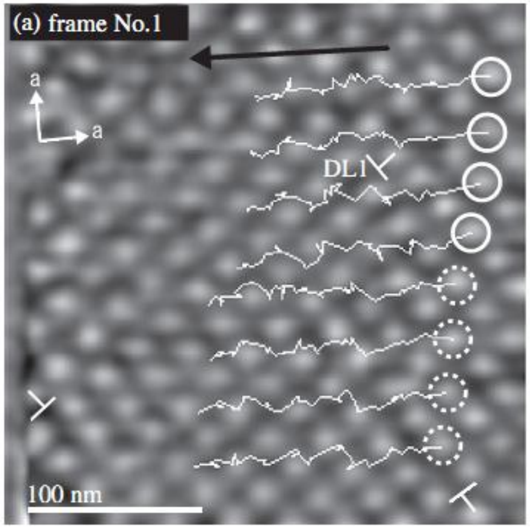
Vortex motion detected by STM/STS

Uchiyama, Kaneko, Sakata, Nishida *et al.*

STM/STS **High *B* (> 1 T)**

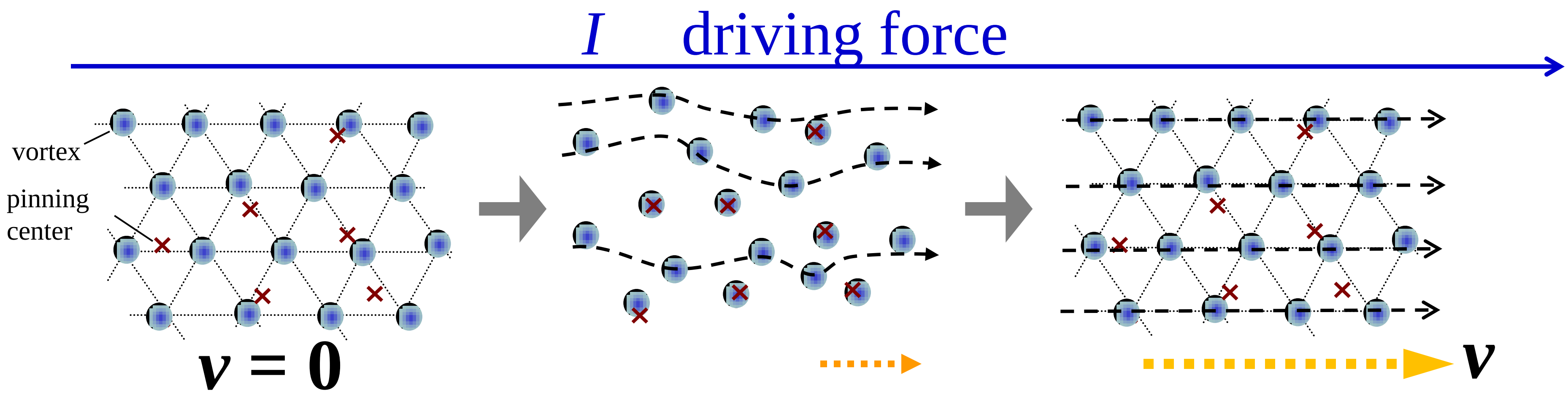
v_{STM}∼1 nm/s (too slow)





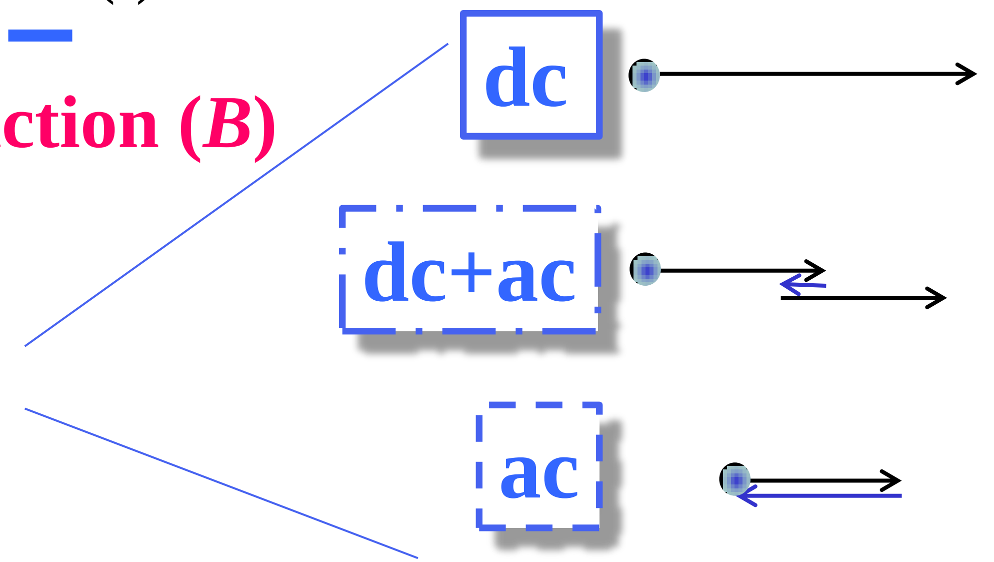
Driving force for the vortex motion

Forces acting on driven vortices

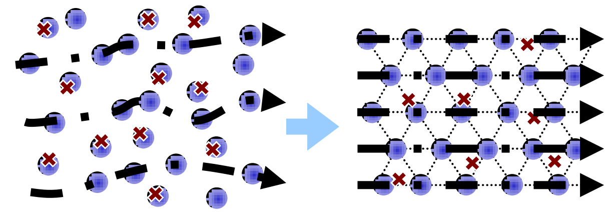


$$\eta \frac{d\mathbf{R}_i}{dt} = \mathbf{F}_i^{vv} + \mathbf{F}_i^{p} + \mathbf{F}^{ext}(t)$$

- **Vortex-vortex interaction (*B*)**
- **Pinning force (I_c)**
- **Lorentz force (*I*)**

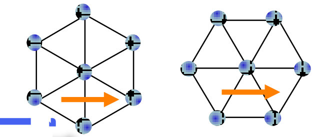


(1) *Dynamics of moving lattices*



➡ **Dynamic ordering of driven vortices**

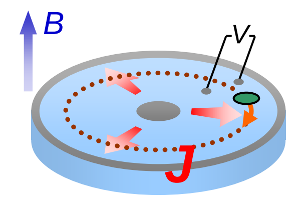
- lattice orientation, non-equilibrium SC



dc+ac

Dynamic melting of driven lattices

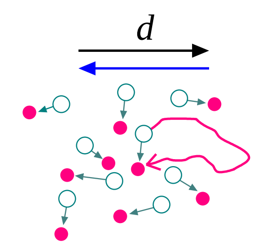
- intrinsic (quantum) melting



Plastic flow of solids

Fast

(2) *Dynamics of non-equilibrium many particles*



Novel dynamic transitions

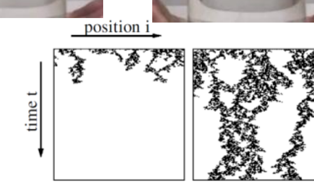
ac

- **rev-irreversible tr.** and random organization

- absorbing tr.

- **depinning tr.**

dc



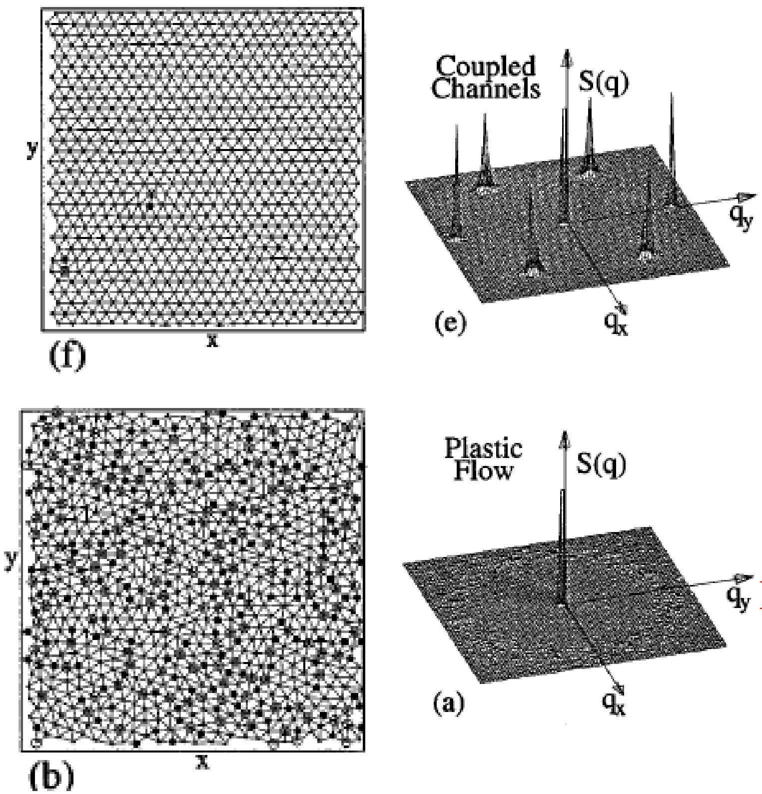
Slow

Dynamic ordering of driven vortices

Vortex configurations for *flux flow* and *plastic flow*

simulation

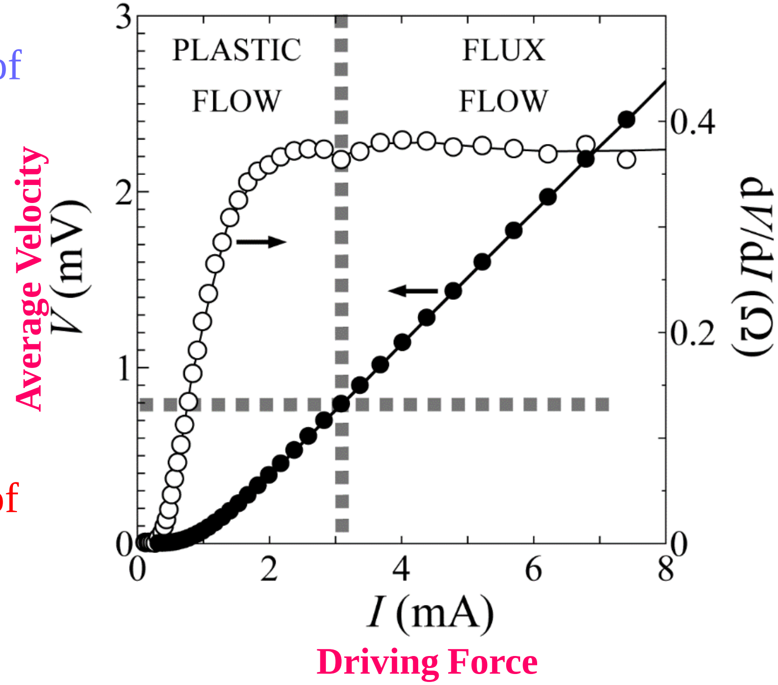
experiment



Flux flow
Small number of dislocation

Plastic flow
Large number of dislocation

Plastic flow ***Flux flow***

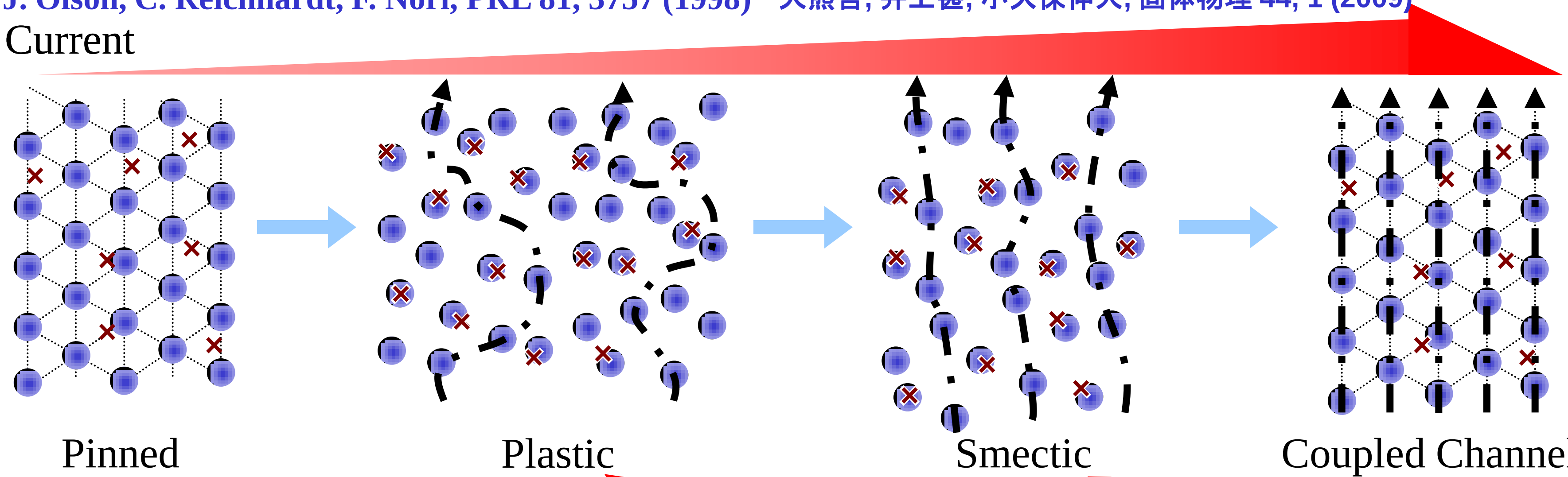


C. J. Olson, C. Reichhardt, F. Nori, PRL 81, 3757 (1998)

SO, Y. Kawamura, Y. Tsugawa, JPSJ 81, 114718 (2012)

Vortex flow states and dynamic ordering

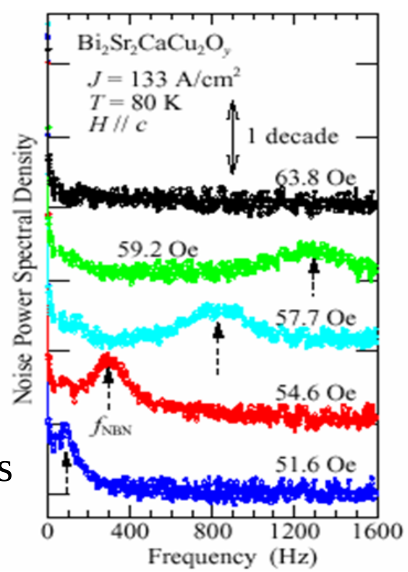
C. J. Olson, C. Reichhardt, F. Nori, PRL 81, 3757 (1998)　大熊哲, 井上甚, 小久保伸人, 固体物理 44, 1 (2009)



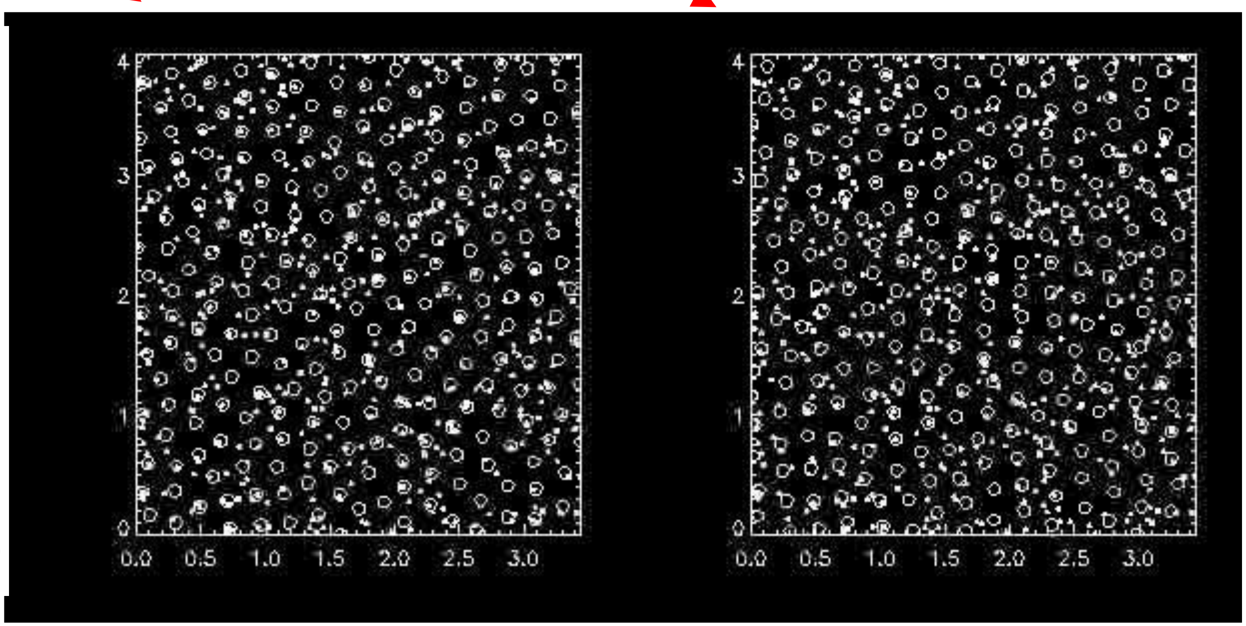
Vortex
× Pinning

Narrow band noise $S_V(f)$

v ∼0.1 mm/s



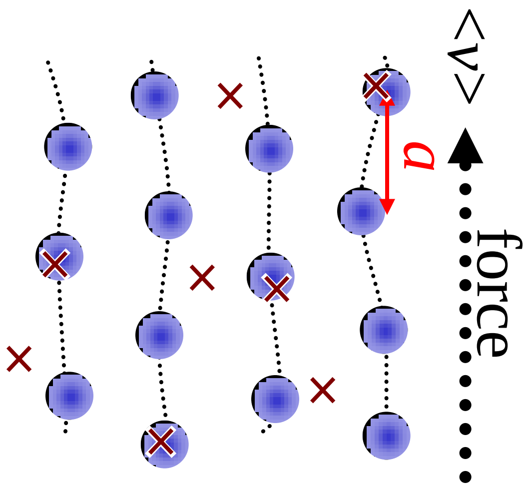
Y. Togawa, R. Abiru, K. Iwaya, H. Kitano, A. Maeda, PRL **85** (2000) 3716



A. B. Kolton, D. Domínguez, N. G. Jensen

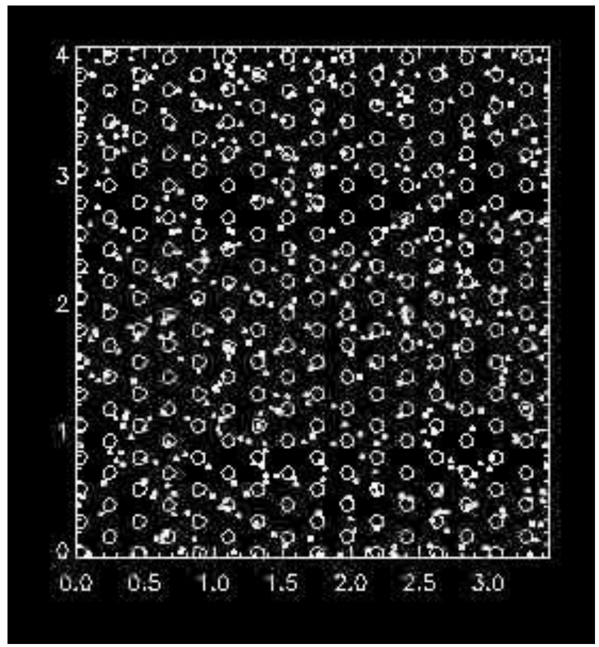
ML in uniform films with random pinning

Random pinning; dc + superimposed ac forces

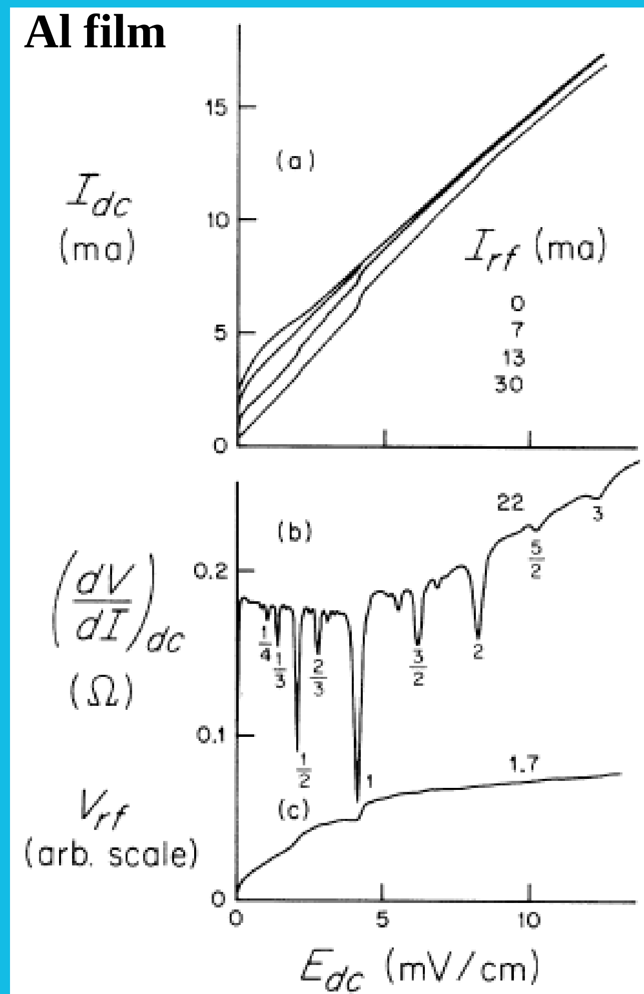


$$f_{int} = \frac{\langle v \rangle}{a}$$

$$p f_{ext} = q f_{int} \quad (p, q : \text{integer})$$



A. B. Kolton, D. Domínguez, N. G. Jensen

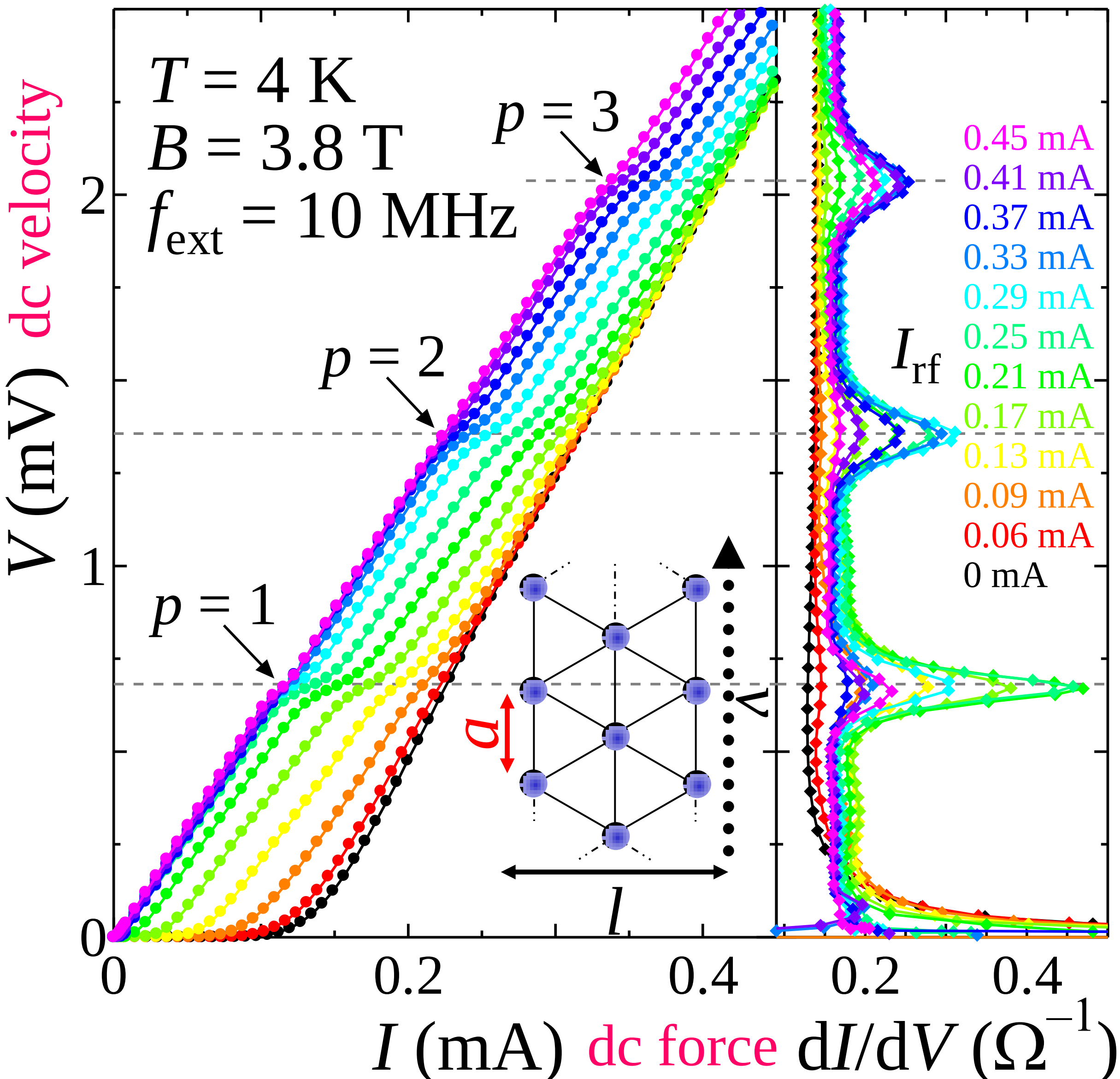


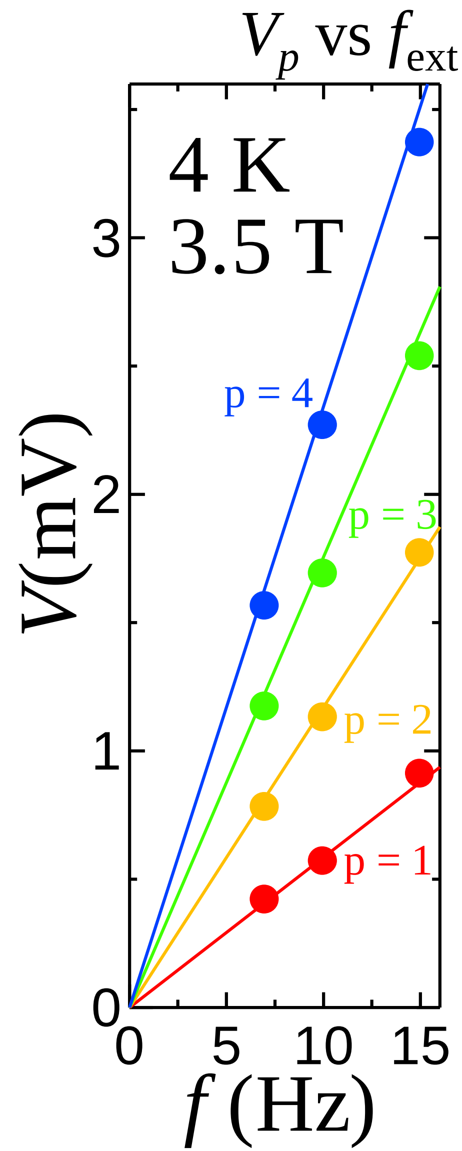
T = 1.36 K, H = 80 G, f = 96 MHz

A. T. Fiory, PRL 27, 501 (1971)

- Coherent motion of a vortex lattice → Periodicity can be induced dynamically
- At ML, the step-like structure analogous to Shapiro steps appears in the *I*-*V* curves.

ML steps in $I-V$ curves





S. Okuma, J. Inoue, N. Kokubo, PRB 76 (2007) 172503

Voltage steps $V_p = (l f_{ext} a B) p$

Plastic flow of solids
-Rotating vortex matter in CD

CD
Strong shear

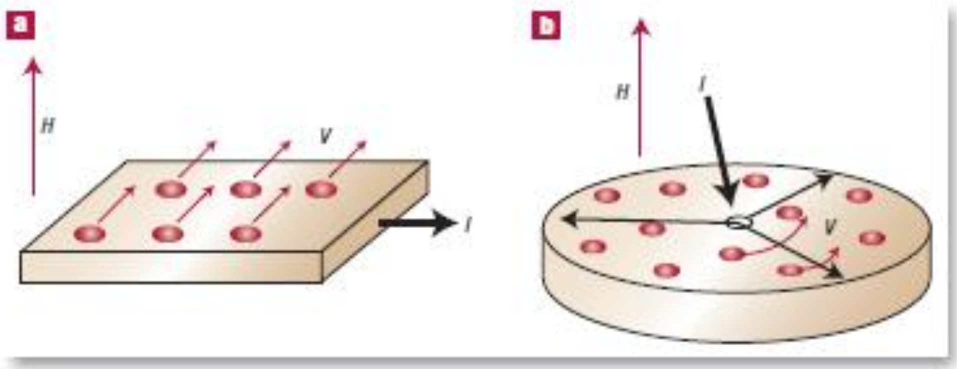
SUPERCONDUCTORS

The mysteries of plastic motion

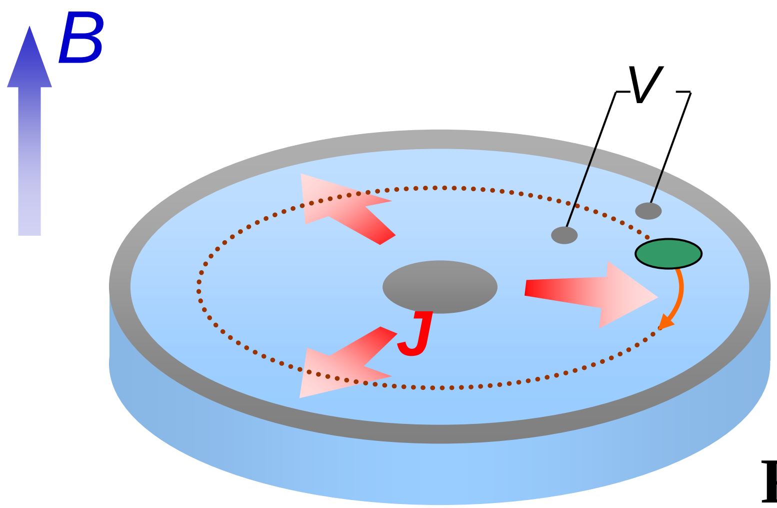
Understanding plastic motion of solids — in which atoms change their neighbours as they move — is complicated because it is discontinuous and does not conserve energy. An elegant study of vortex dynamics in superconductors provides new insights.

GEORGE W. CRABTREE is at the Materials Science Division, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439, USA.
e-mail: crabtree@anl.gov

Plastic motion of solids governs many processes in our physical world. On geological timescales, plastic motion is responsible for the topography of the landmasses of the Earth, for the drift of the continents, and for the regeneration of the Earth's crust from sources at the mid-ocean ridges. On shorter time scales, plastic motion produces cataclysmic events such



r dependence of velocity *v* (or *V*) in CD



$$J = \frac{I}{2\pi t}\frac{1}{r}$$

Frustrated Lorentz force inversely proportional to *r*

SO, S. Morishima, M. Kamada, PRB 76, 224521 (2007)

$v \propto r$ (ω = const)

Elastic (rigid-disk-like) rotation

$v \propto 1/r$

Liquid-like rotation

Experiment

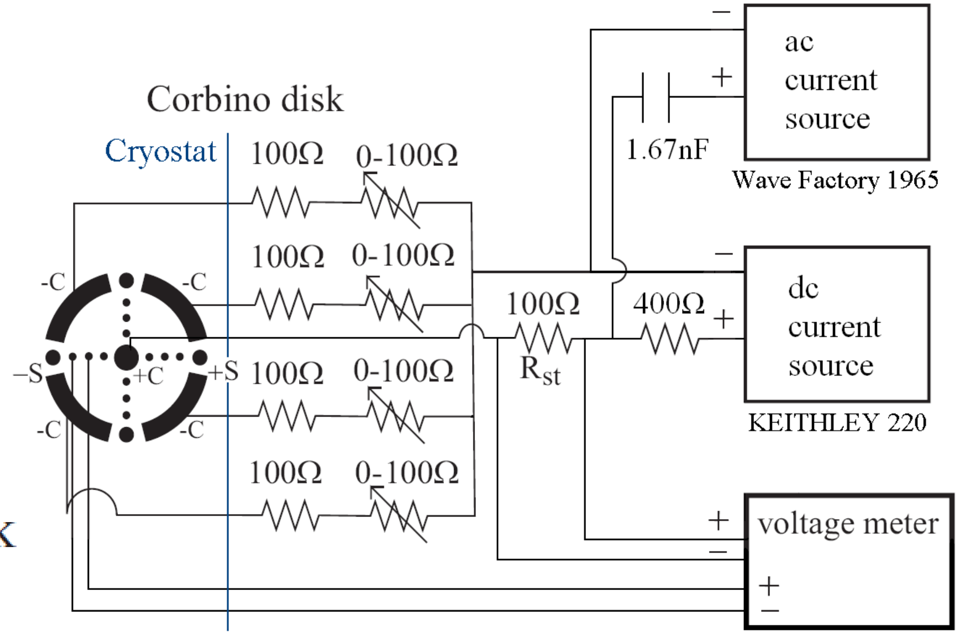
◆Sample

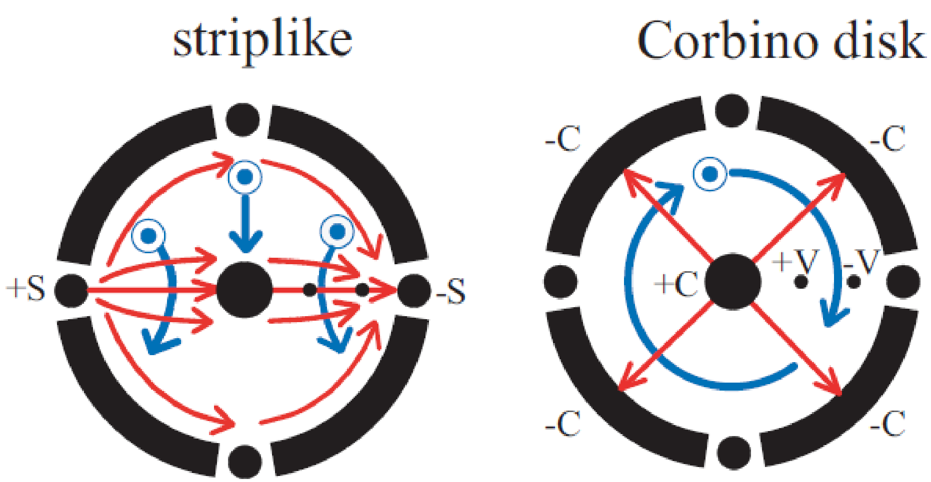
a-Mo$_x$Ge$_{1-x}$ film (CD)

- Thickness 330 nm
- x 0.78
- T_{c0} 6.3 K
- ρ_n 2.2 μΩm
- Inner radius 0.8 mm

◆Measurement

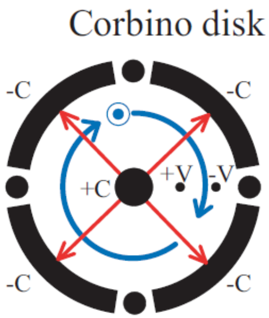
dc I-V with four-terminal method

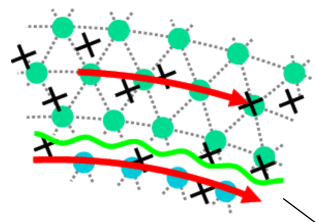


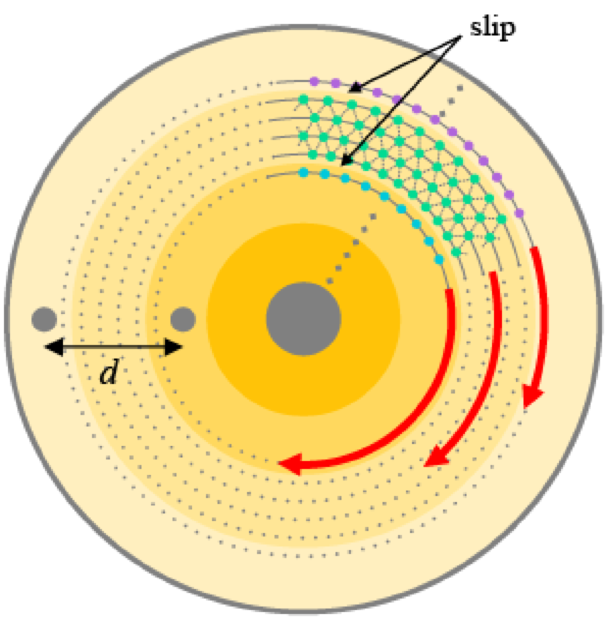


Paltiel, Zeldov *et al.*

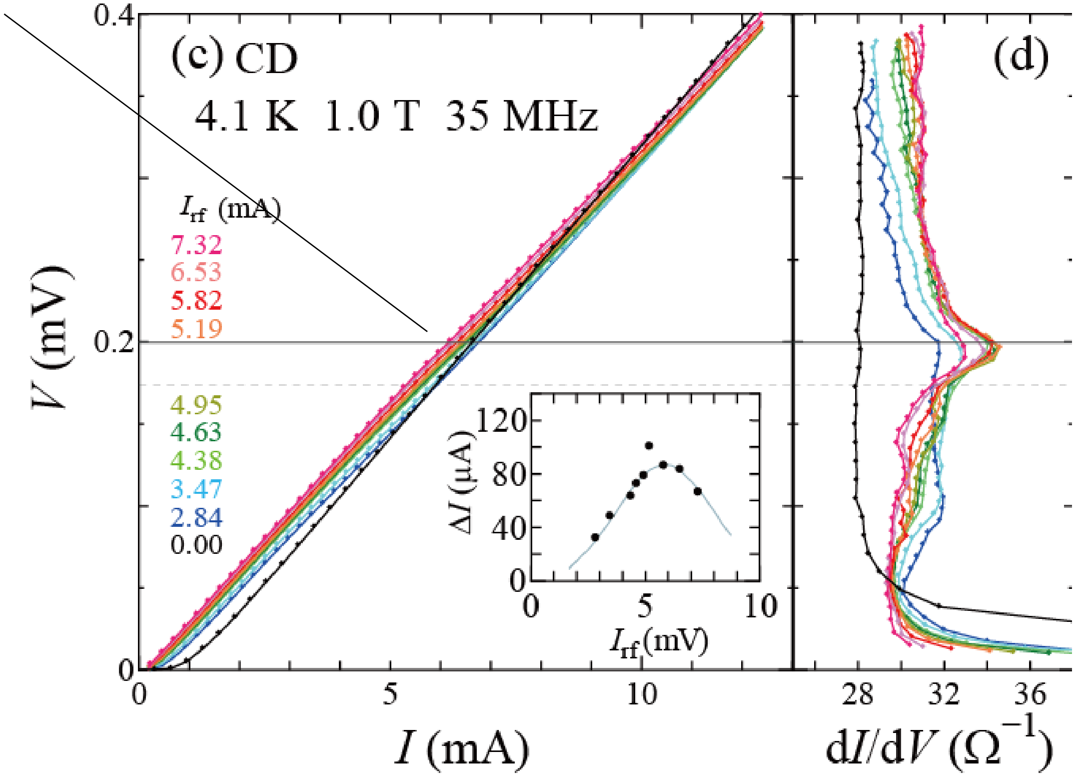
Observation of rotating lattice rings





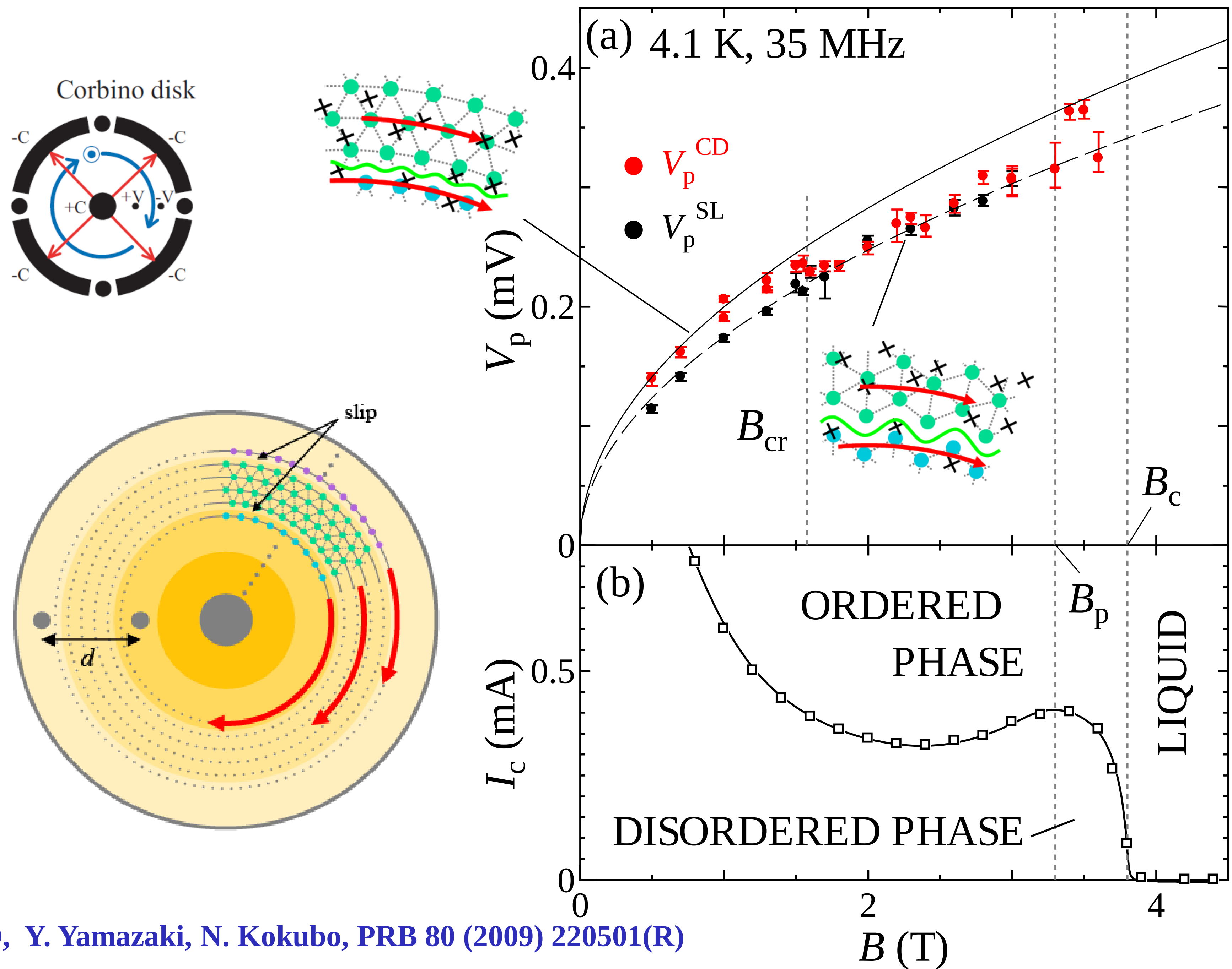


ML resonance



SO, Y. Yamazaki, N. Kokubo, PRB 80 (2009) 220501(R)

Y. Matsumura, SO, N. Kokubo, Physica E 43 (2011) 707



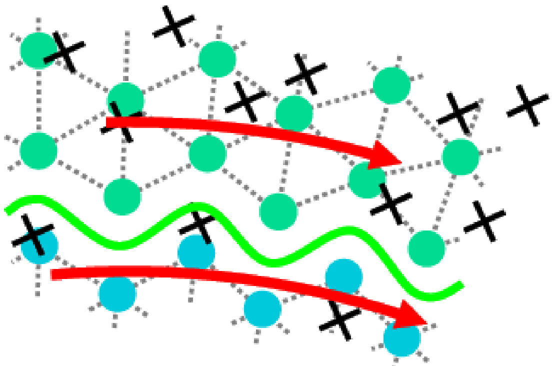
SO, Y. Yamazaki, N. Kokubo, PRB 80 (2009) 220501(R)

Y. Matsumura, SO, N. Kokubo, Physica E 43 (2011) 707

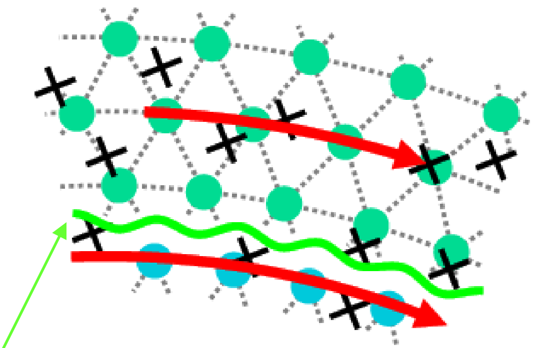
Change in lattice orientation of rotating rings at low *B*

Slip between adjacent rings

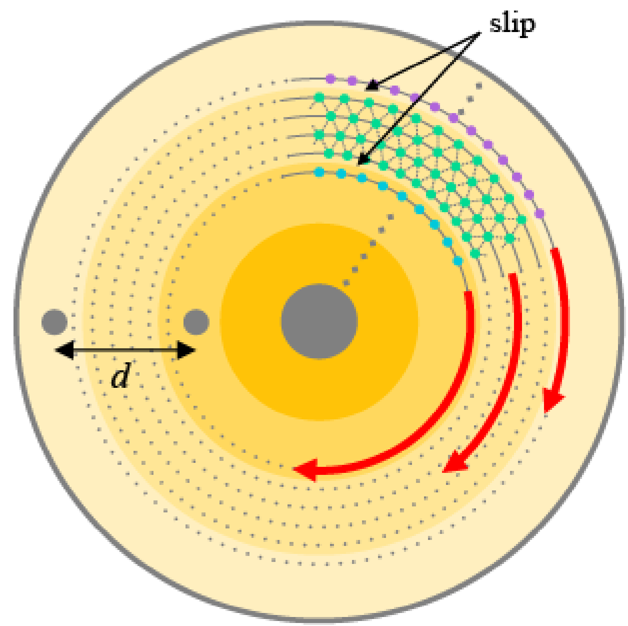
High *B* (perp.)



Low *B* (para.)

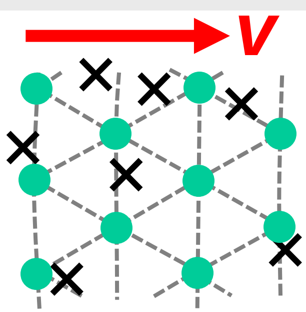


smoother



cf. Strip(like)

Any *B* measured (perp.)



Change in lattice orientation at B^* ($\sim 0.3 B_{c2}$) may be due to the **change in elasticity** of vortex arrays

SO, Y. Yamazaki, N. Kokubo, PRB 80 (2009) 220501(R)

Simulation: Unusual vortex dynamics in Meso-CD

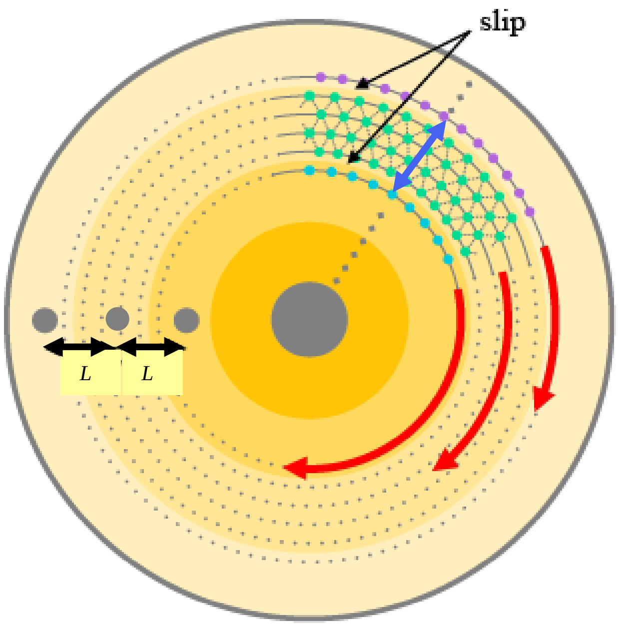
N.S. Lin, V.R. Misko, F.M. Peeters, PRL 102, 197003 (2009)

ML in CD can detect

→ coherence in the flow direction ○

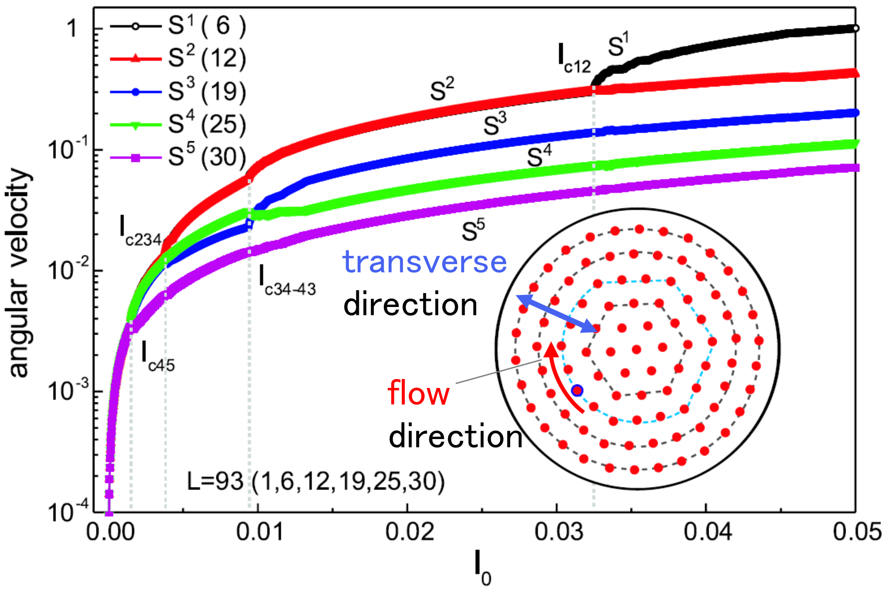
but cannot detect

coherence in the transverse (radial) direction ×



Unconventional vortex dynamics in meso-size CD

simulation

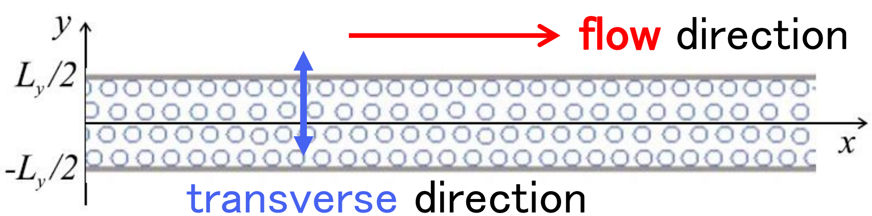


Inversion of shell velocities with respect to gradient driving force and angular melting propagating from shear minimum to center

N.S. Lin, V.R. Misko, F.M. Peeters, PRL 102, 197003 (2009)

Dynamics of colloids in a narrow channel driven by nonuniform force

simulation



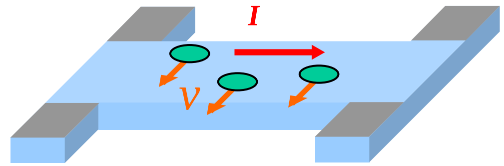
Shear-induced melting and **onset of plasticity near the boundaries.**

D. V. Tkachenko, V. R. Misko, and F. M. Peeters, PRB 80, 051401 (2009)

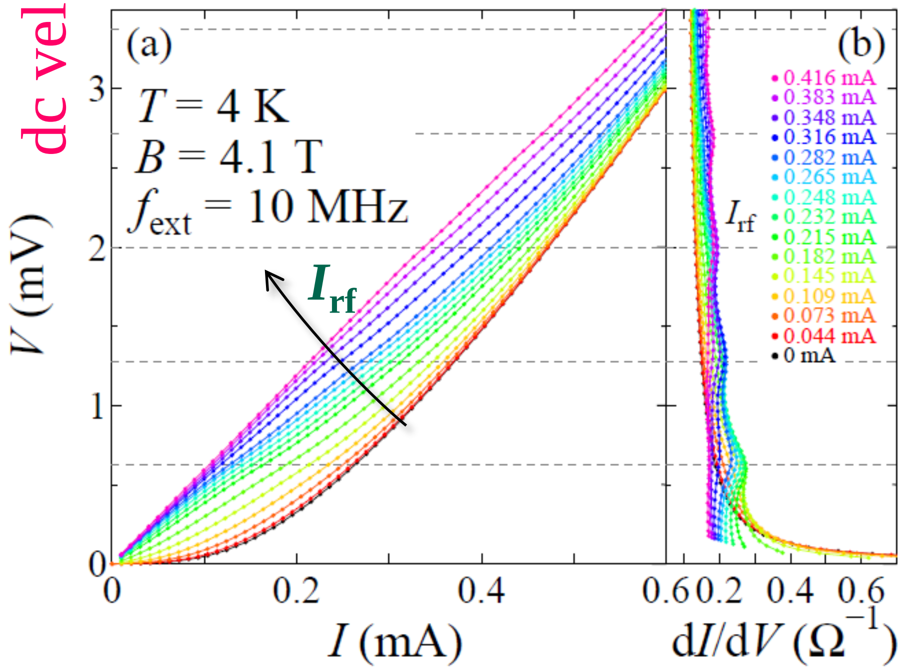
Unusual dc $I-V$ characteristics superimposed with ac I_{rf} in CD

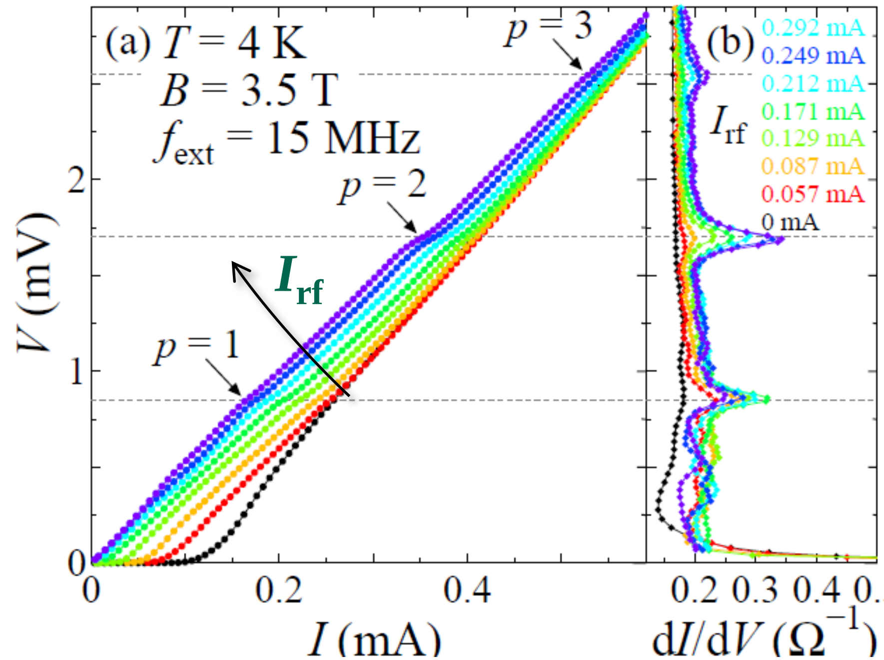
Dc I-V superimposed with I_{rf} in strip samples

Strip



dc velocity





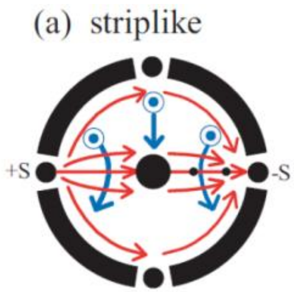
I_{rf}-induced increase in $V(I)$ → **Reduced pinning** effects by **increased I_{rf}**, leading to an **increase in dc velocity** (V).

→ **cf. D. Perez Daroca *et al.*, PRB 81, 184520 (2010)**

SO, J. Inoue, N. Kokubo, Phys. Rev. B **76**, 172503 (2007)

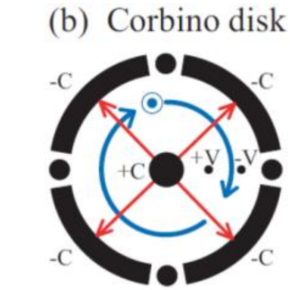
Unusual I-V superimposed with I_{rf} in CD

f_{rf} = 35 MHz, B = 1 T



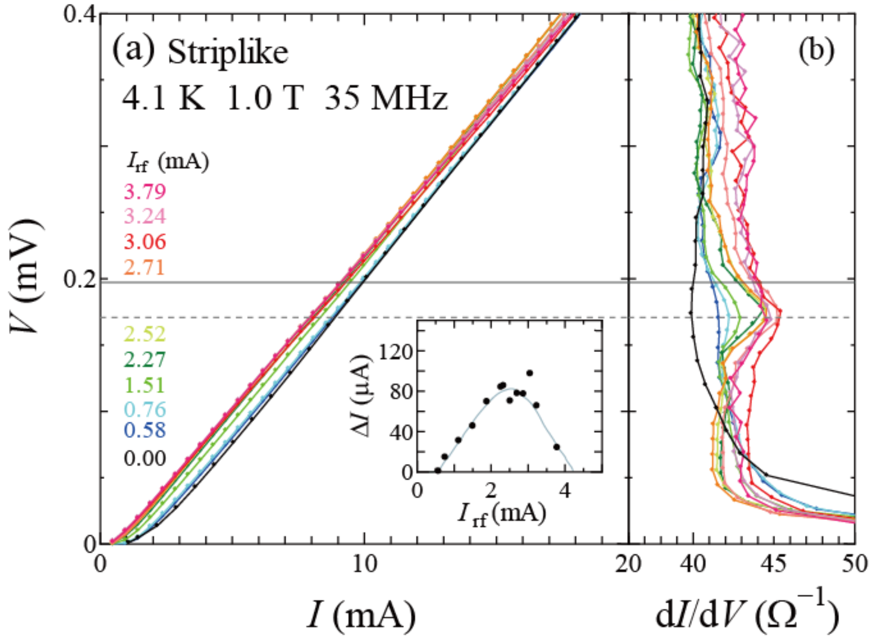
Striplike

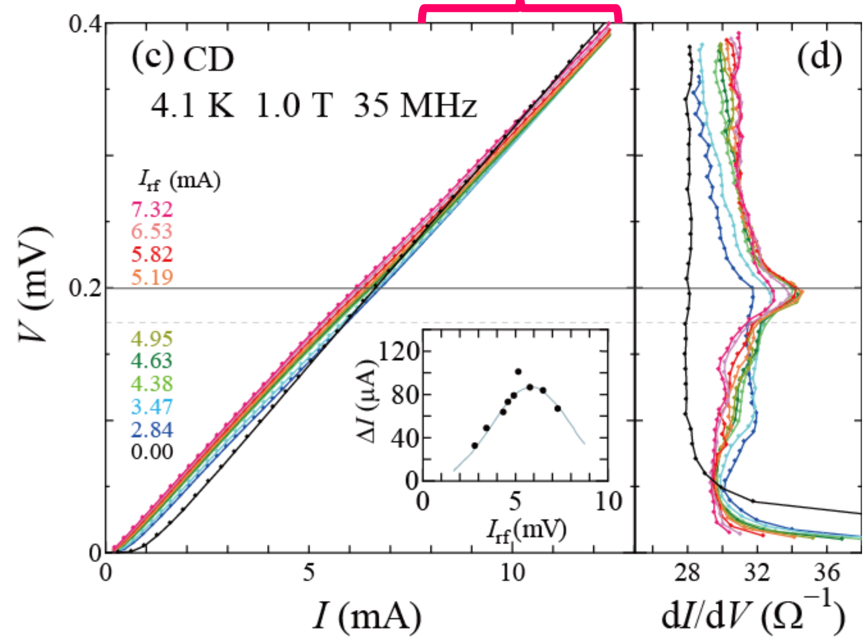
I_{rf}-induced increase in $V(I)$



CD

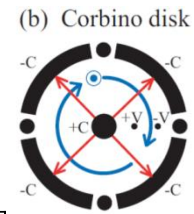
Unusual decrease of $V(I)$ with increasing I_{rf} for large I.

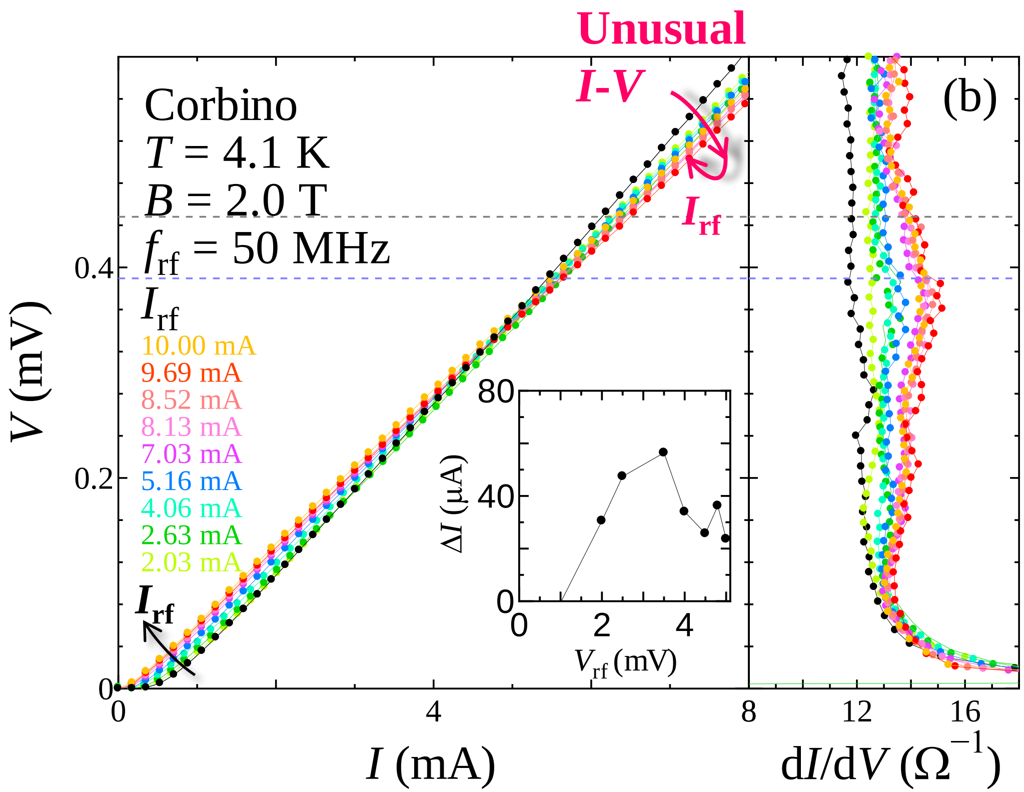


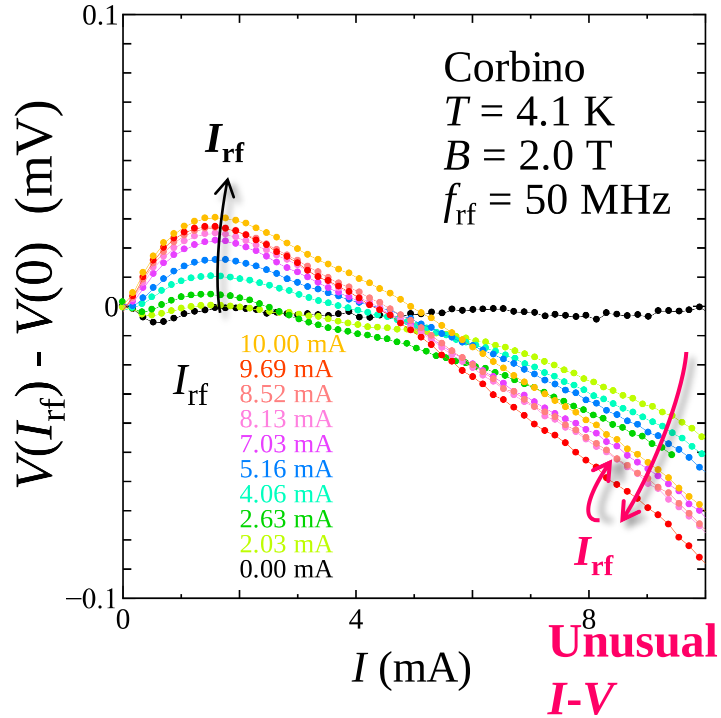


→ cf. D. Perez Daroca *et al.*, PRB 81, 184520 (2010)

f_{rf} = 50 MHz, B = 2 T

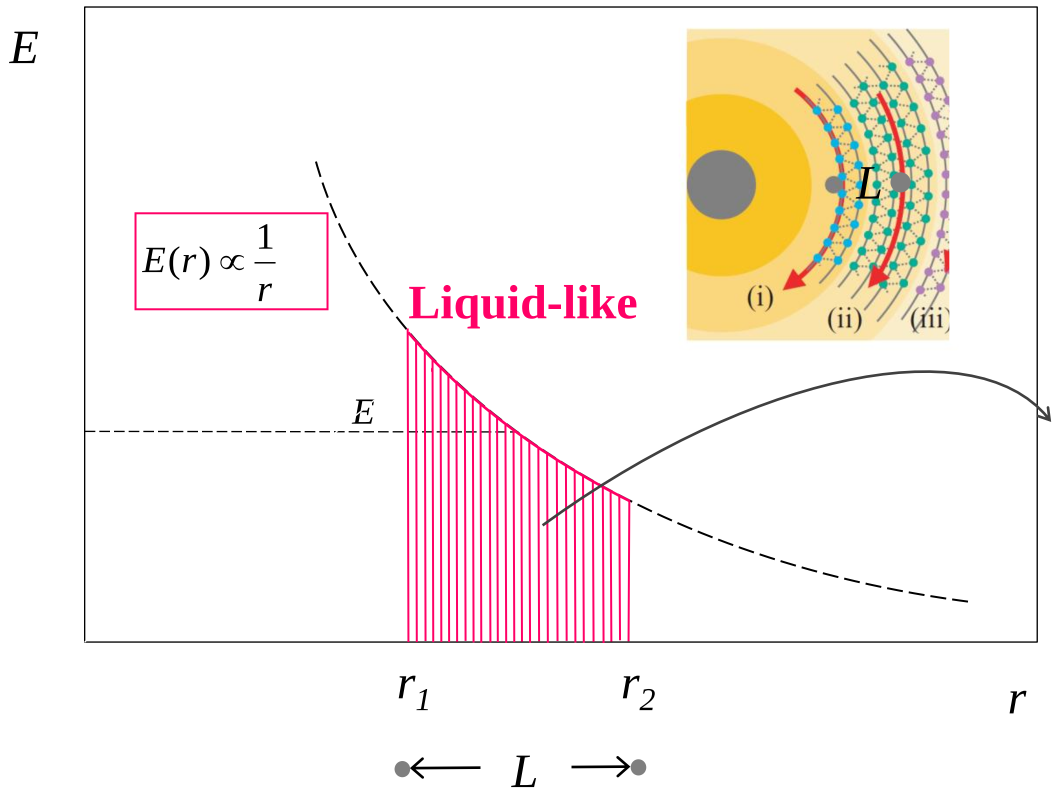






Unusual decrease of *I*-*V* curves with increasing I_{rf} is also observed at higher f_{rf} and more pronounced.

Explanation: *V* generated by rotating lattice rings with different width

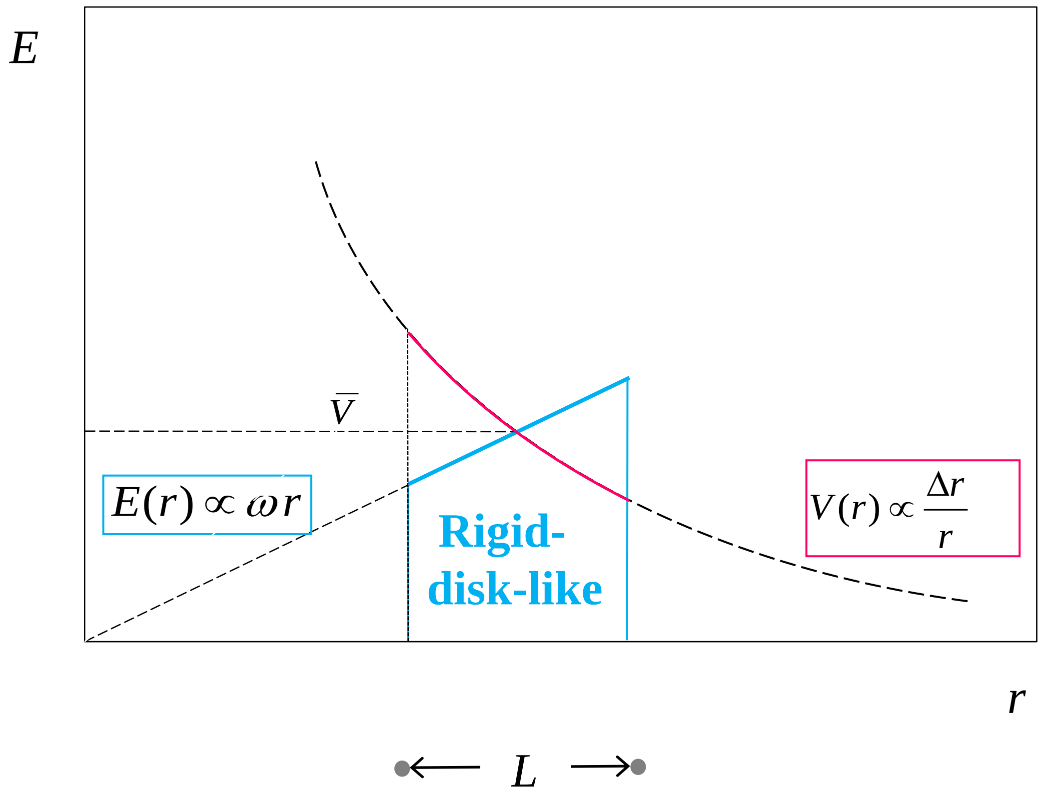


$$V(r) \propto \ln\left(1+\frac{\Delta r}{r}\right)$$

$$\approx \frac{\Delta r}{r} \qquad r >> \Delta r$$

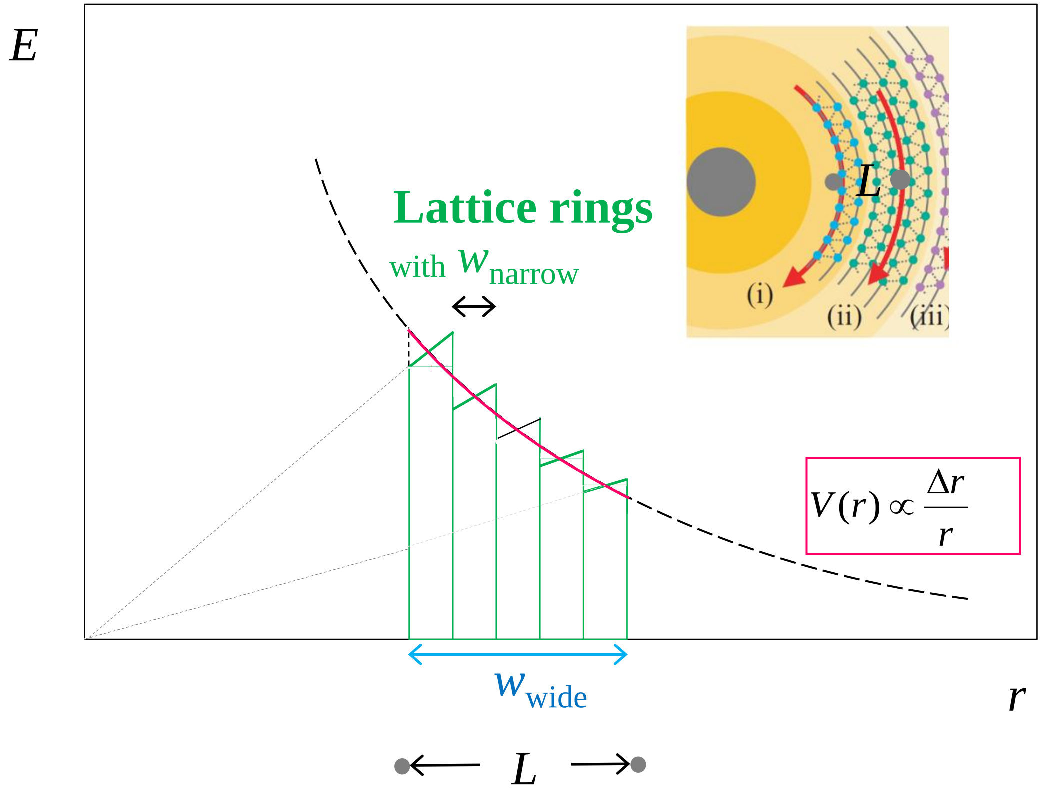
For liquid-like rotation, $E \propto 1/r$

Explanation: *V* generated by rotating lattice rings with different width



$V_{\mathrm{liq}} > V_{\mathrm{rd}}$

Explanation: *V* generated by rotating lattice rings with different width



$V_{liq} > V_{nar} > V_{wide}$

Wider rings generate smaller *V* →

***I*$_{rf}$-induced decrease of *I*-*V* curves is attributed to growth of *w*, which occurs associated with enhanced ML**

Y. Kawamura *et al.*, SUST 28, 045002 (2015)

I_{rf} -induced growth in lattice-ring width

As ac force (I_{rf}) *increases*:

- effective **pinning** (i.e., local shear) and
- **dislocation** number

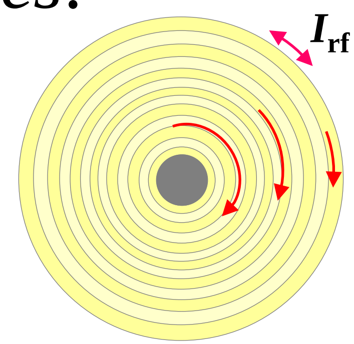
decrease

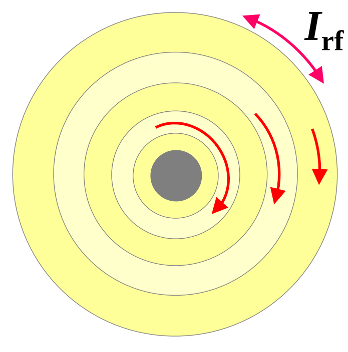
⇒
- **healing** of lattice
- enhanced ML

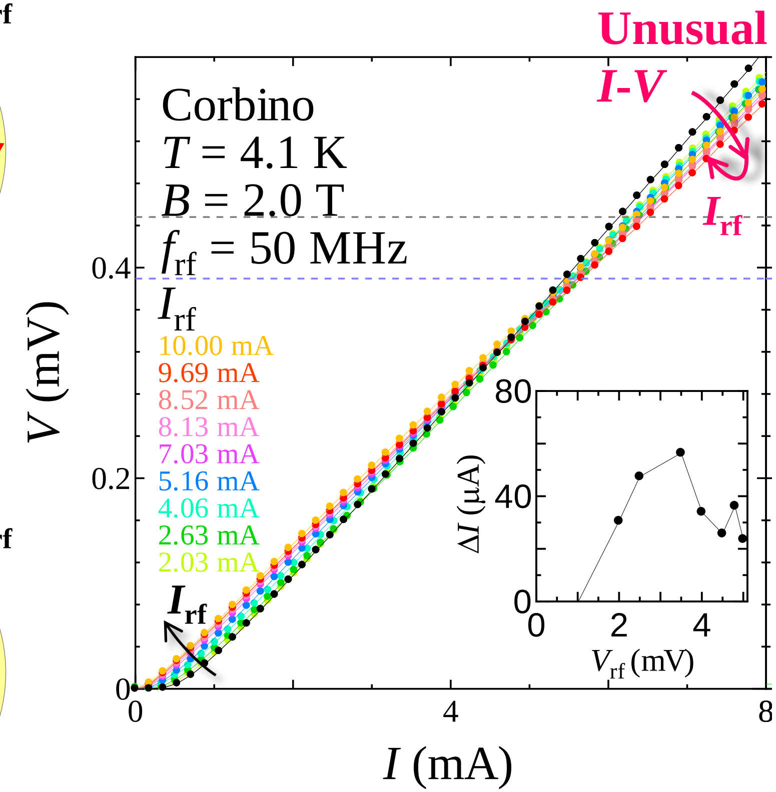
⇓

increase in:

- **transverse correlation**
- **width** of lattice rings







Y. Kawamura *et al.*, SUST 28, 045002 (2015)

Summary 1

▪We measure I -V and ML for vortex-lattice rings rotated by dc I superimposed with ac I_{rf} of different amplitudes in CD.

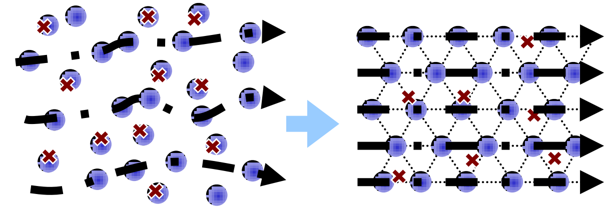
▪**As I_{rf} is increased from zero, ML becomes more pronounced and the I –V curve in the large I region *decreases*.**

▪**This is opposite to the usual behavior of vortex flow, in which I_{rf}-induced depinning leads to an increase in the flow voltage.**

▪**The result is explained in terms of the I_{rf} -induced growth in the width of the rotating lattice rings**

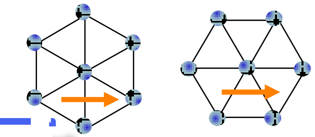
Y. Kawamura *et al*., SUST 28, 045002 (2015)

(1) *Dynamics of moving lattices*



Dynamic ordering of driven vortices

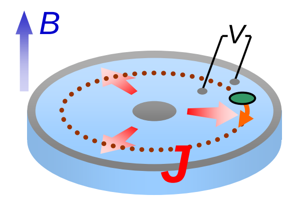
- lattice orientation, non-equilibrium SC



dc+ac

Dynamic melting of driven lattices

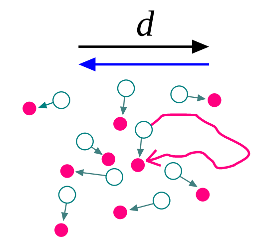
- intrinsic (quantum) melting



Plastic flow of solids

Fast

(2) *Dynamics of non-equilibrium many particles*



Novel dynamic transitions

ac

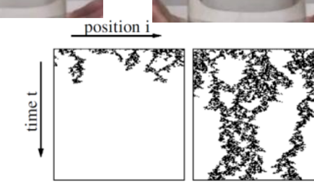
- **rev-irreversible tr.** and random organization

- absorbing tr.

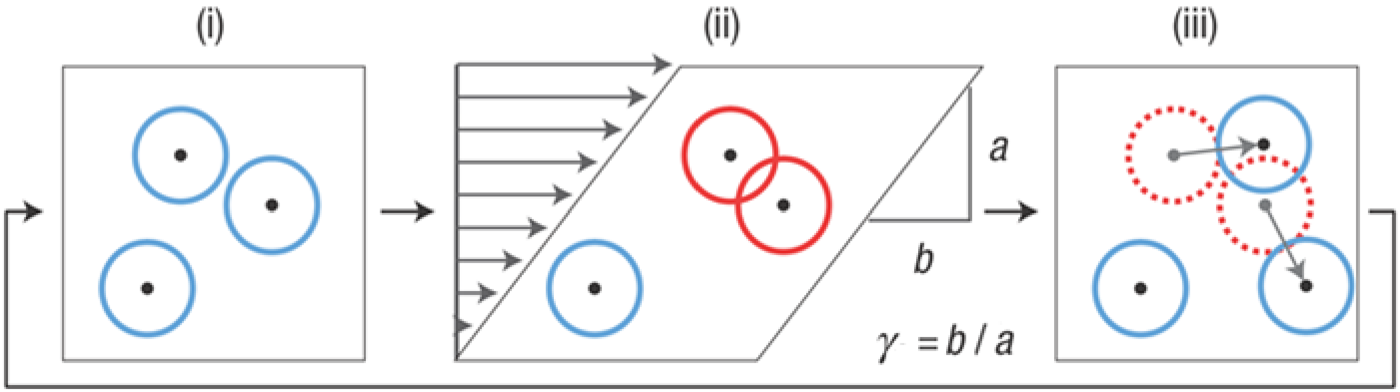
- **depinning tr.**

dc

Slow



Dynamics of many particles subject to periodic shear



γ: shear amplitude

Application of periodic shear

↓

Collided particles move in the random direction with small distance

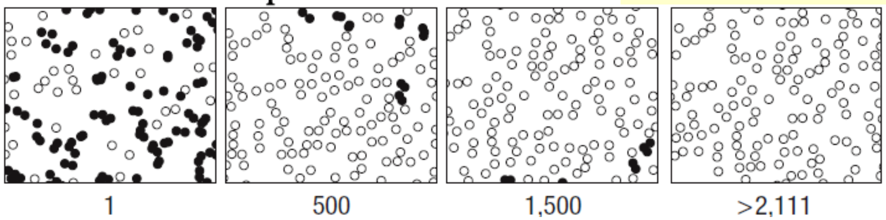
L. Corte *et al*., Nat. Phys. **4**, 420 (2008)

Random organization and Reversible-Irreversible Transition

simulation

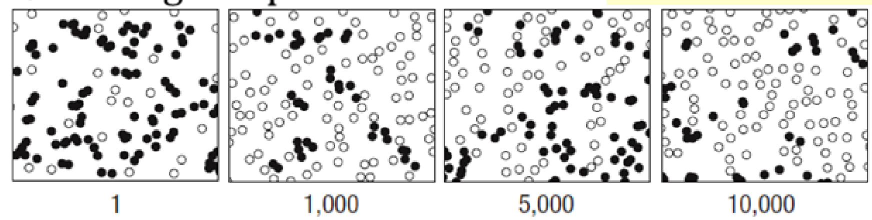
Random organization (transient state)

$\gamma_0 = 2$ small displacement d "Absorbing" state



$\rightarrow t$

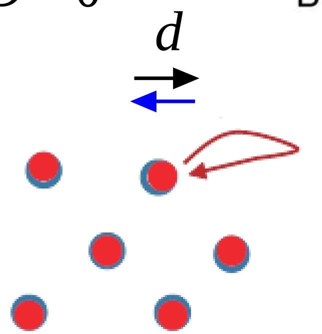
$\gamma_0 = 3$ large displacement d "Fluctuating" state

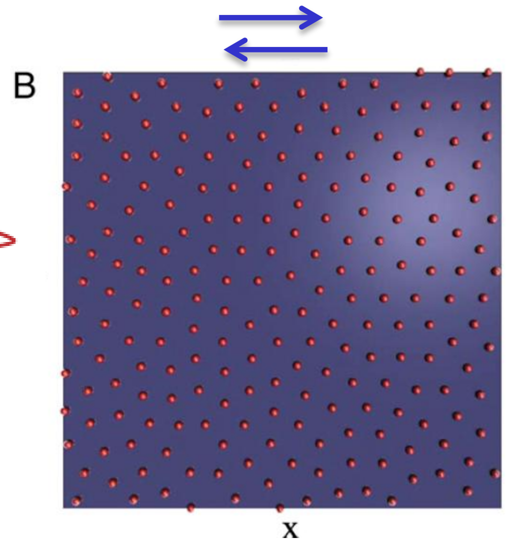


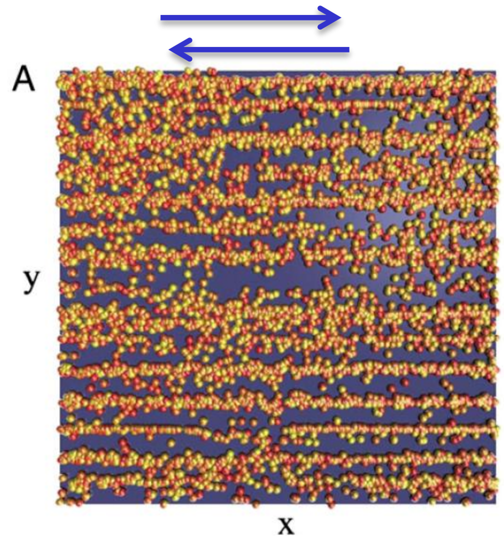
D.J. Pine *et al.*, Nature 438, 997 (2005) $\rightarrow t$

Final steady state

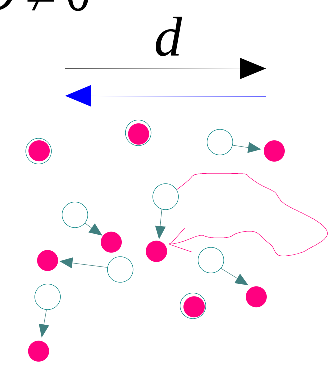
$D = 0$







$D \neq 0$



Dynamically frozen state

Reversible flow

d_c

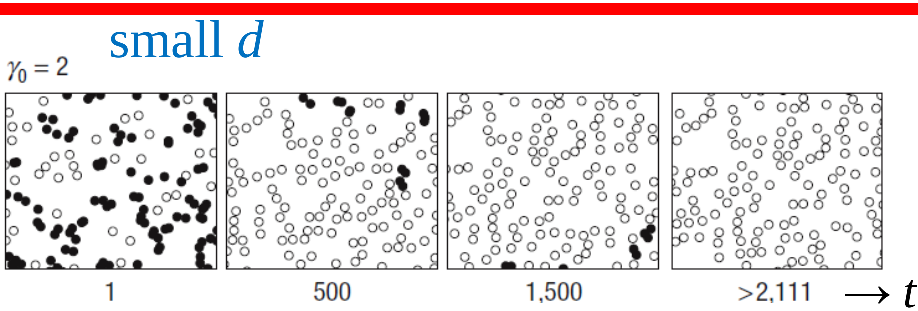
Fluctuating dynamical state

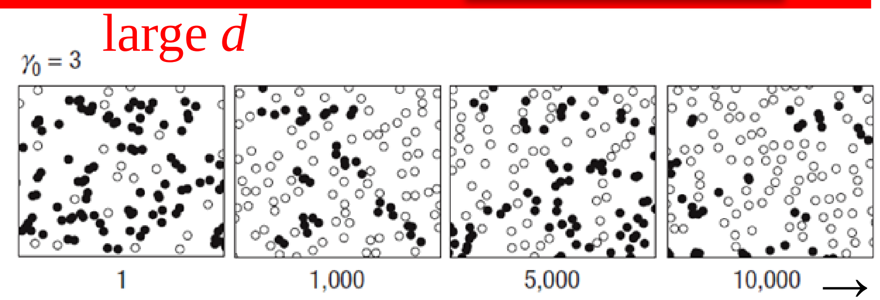
Irreversible flow

C. Reichhardt, C.J.O. Reichhardt, PNAS 108, 19099 (2011)

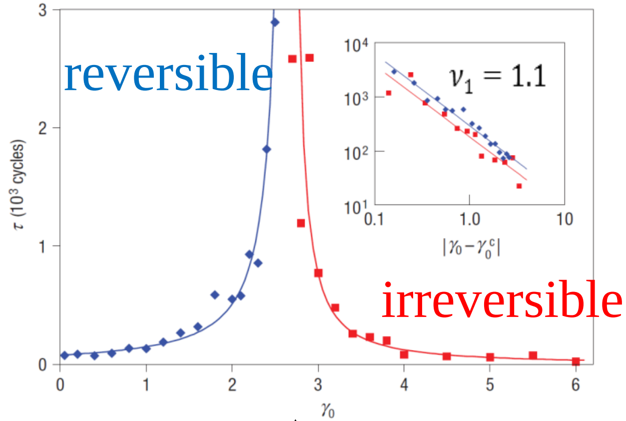
Critical behavior of RIT

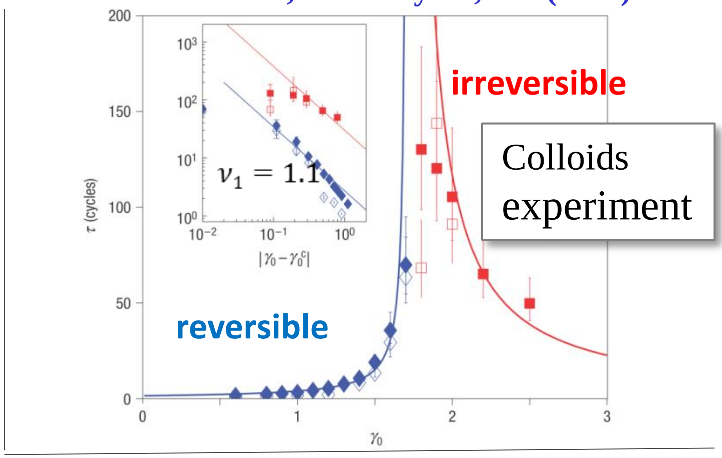
simulation

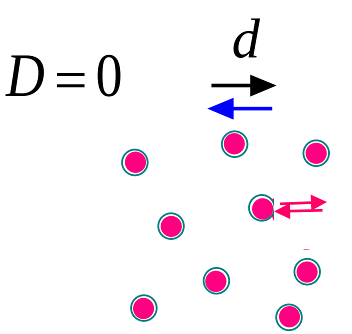


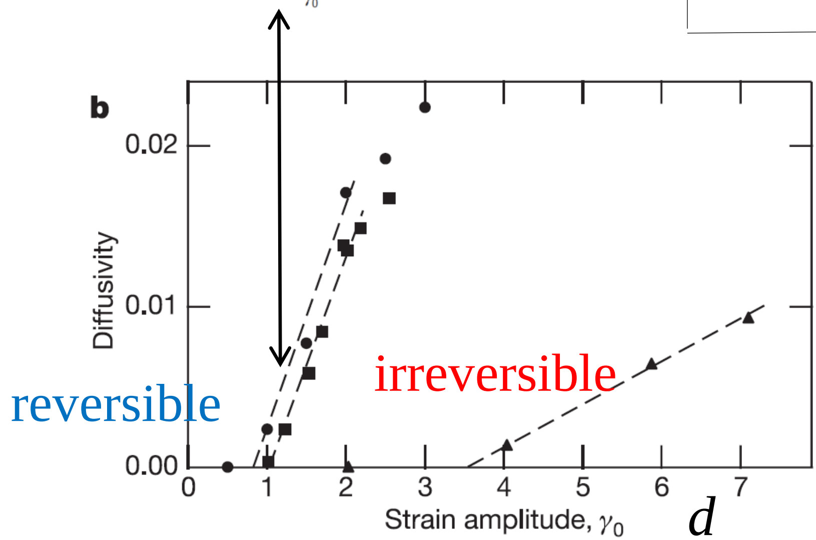


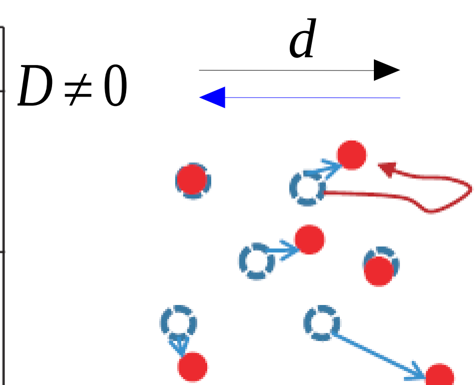
L. Corte *et al*., Nat. Phys. 4, 420 (2008)





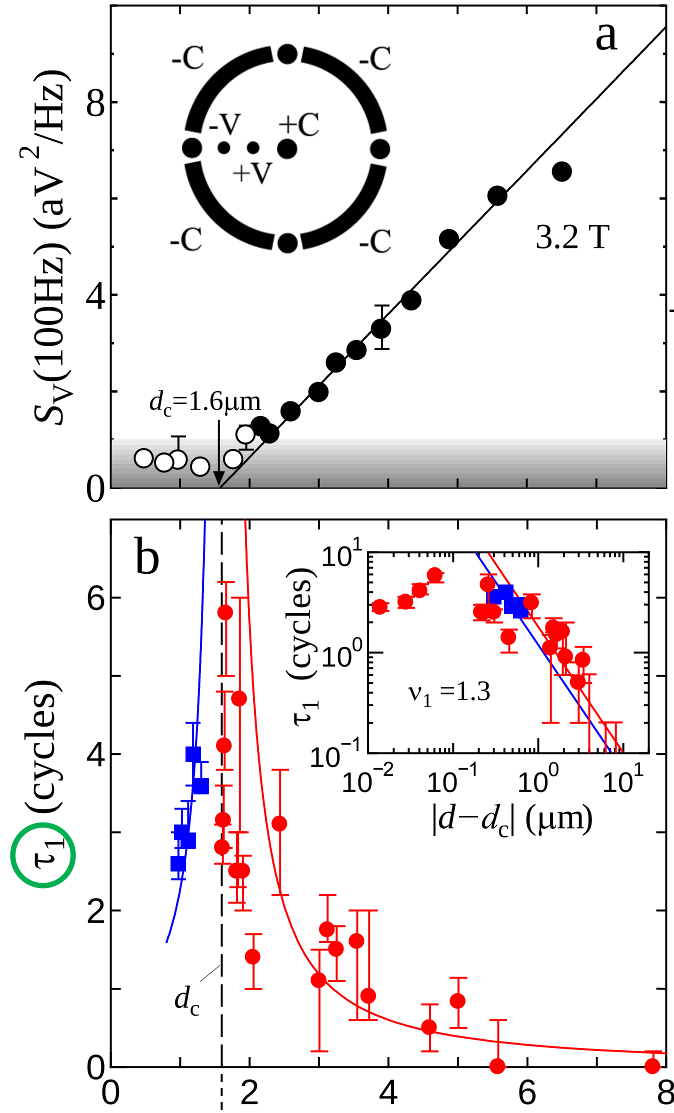


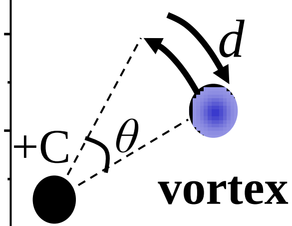




Random organization and RIT: Vortices CD experiment

SO, Y. Tsugawa, A. Motohashi, PRB 83 (2011) 012503

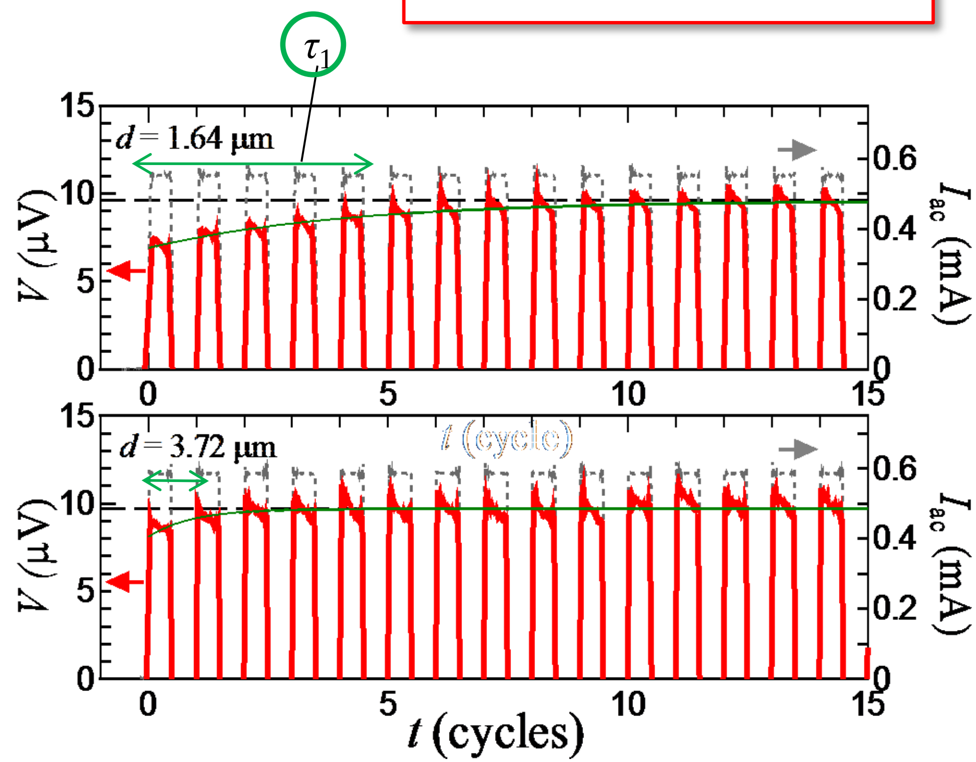




τ_1 diverges at critical displacement d_c

⇩

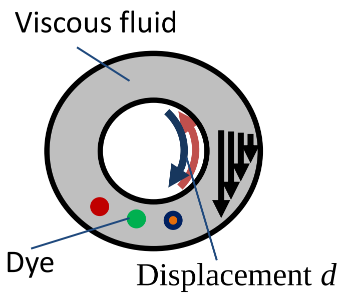
Evidence for RIT



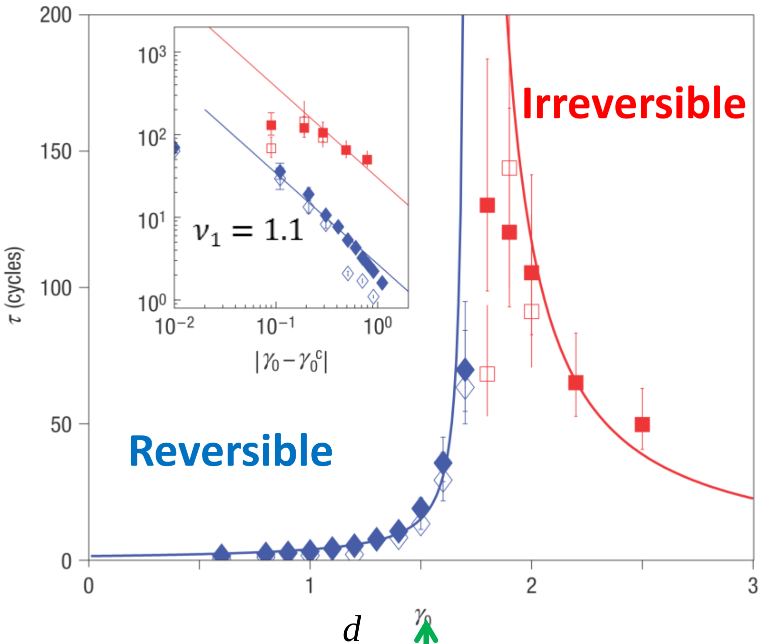
Reversible (Absorbing)

Irreversible (Fluctuating)

Colloids experiment

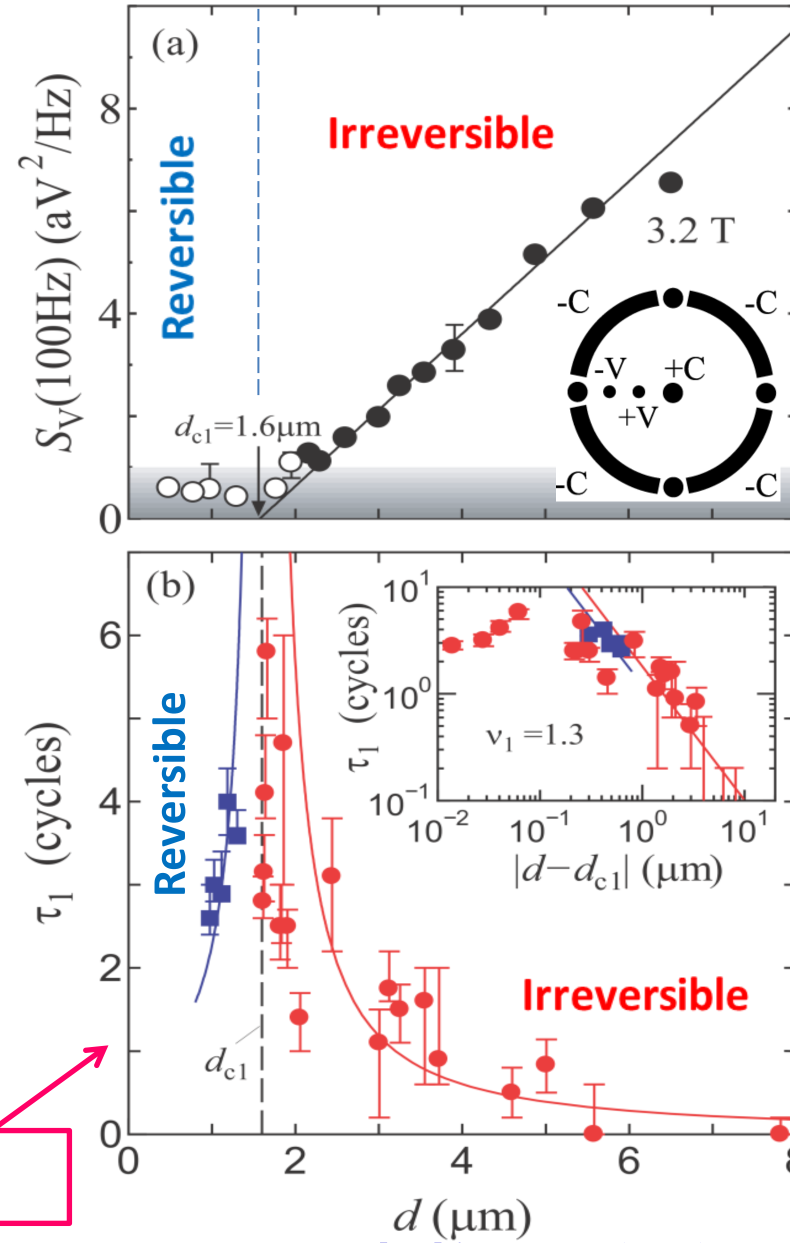


L. Corte *et al.*, Nat. Phys. 4, 420 (2008)



$\nu_1 = 1.1$ (3D)

Vortices experiment



$\nu_1 = 1.3$ (2D)

SO, Y. Tsugawa, A. Motohashi, PRB 83 (2011) 012503

Absorbing tr.
Experiment

Random Fields at a Nonequilibrium Phase Transition

Hatem Barghathi and Thomas Vojta
Department of Physics, Missouri University of Science and Technology, Rolla, Missouri 65409, USA
(Received 19 June 2012; published 26 October 2012)

Finally, we turn to experiments. Although clear-cut realizations of absorbing state transitions were lacking for a long time [34], beautiful examples were recently found in turbulent liquid crystals [35], driven suspensions [36,37], and superconducting vortices [38].

[35] K. A. Takeuchi, M. Kuroda, H. Chate, and M. Sano, Phys. Rev. Lett. **99**, 234503 (2007).
[36] L. Corte, P. M. Chaikin, J. P. Gollub, and D. J. Pine, Nat. Phys. **4**, 420 (2008).
[37] A. Franceschini, E. Filippidi, E. Guazzelli, and D. J. Pine, Phys. Rev. Lett. **107**, 250603 (2011).
[38] S. Okuma, Y. Tsugawa, and A. Motohashi, Phys. Rev. B **83**, 012503 (2011).

liquid crystal

colloid

vortex

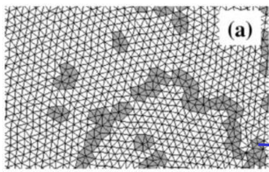
Vortex configurations in **rev.** and **irrev.** states

All reversible

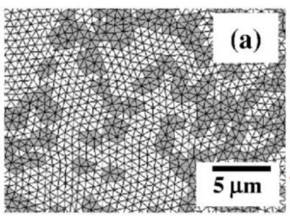
Reversible + Irreversible

All irreversible

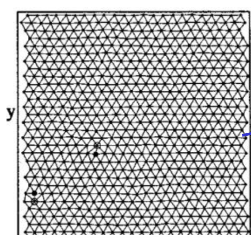
ZFC
A **small** number of defects



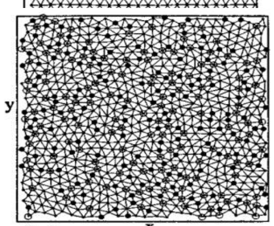
FC
A **large** number of defects

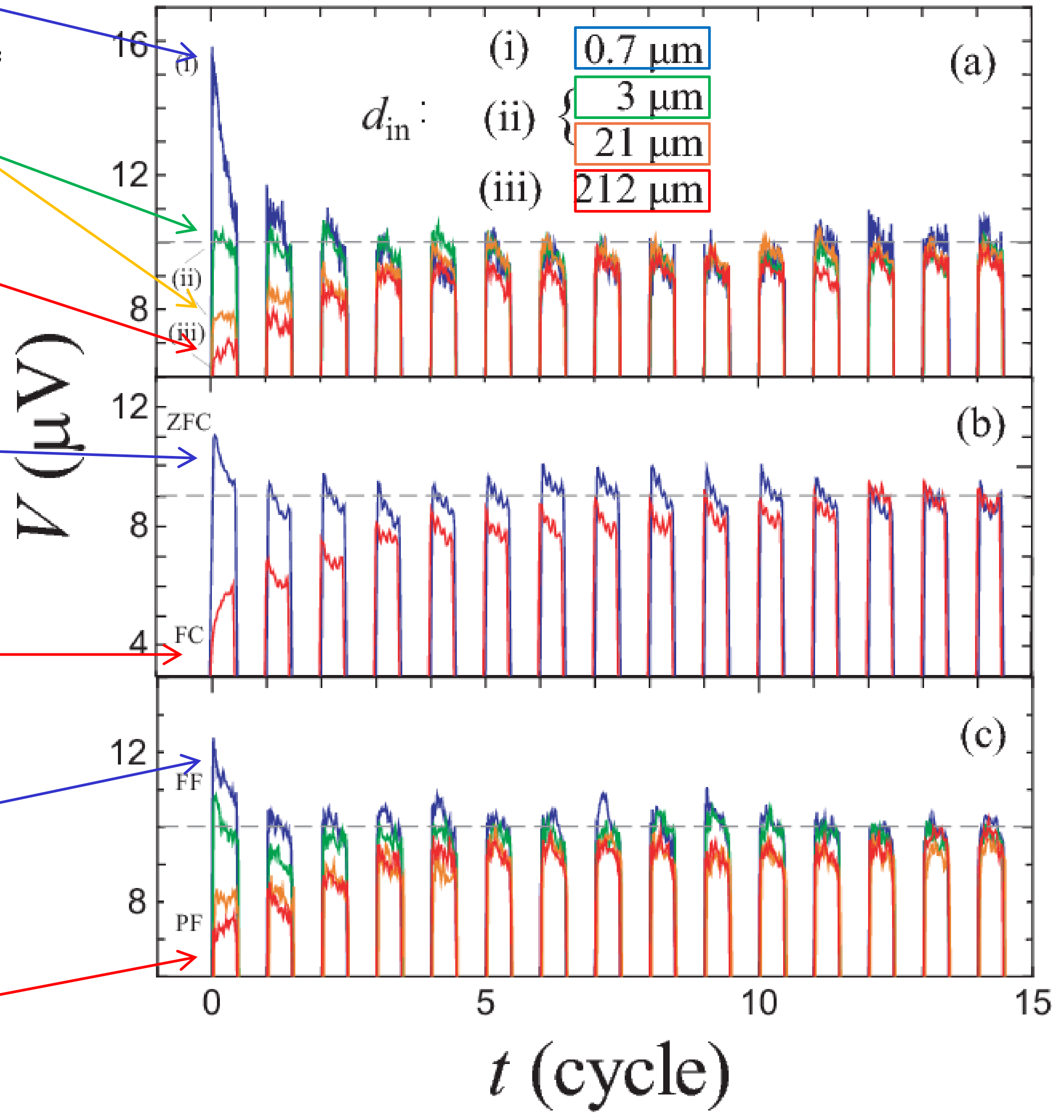


Flux flow
A **small** number of defects



Plastic flow
A **large** number of defects





Y. Fasano *et al.*, PRB **66** , 020512 (2002)
C. J. Olson, C. Reichhardt, F. Nori, PRL **81**, 3757 (1998)

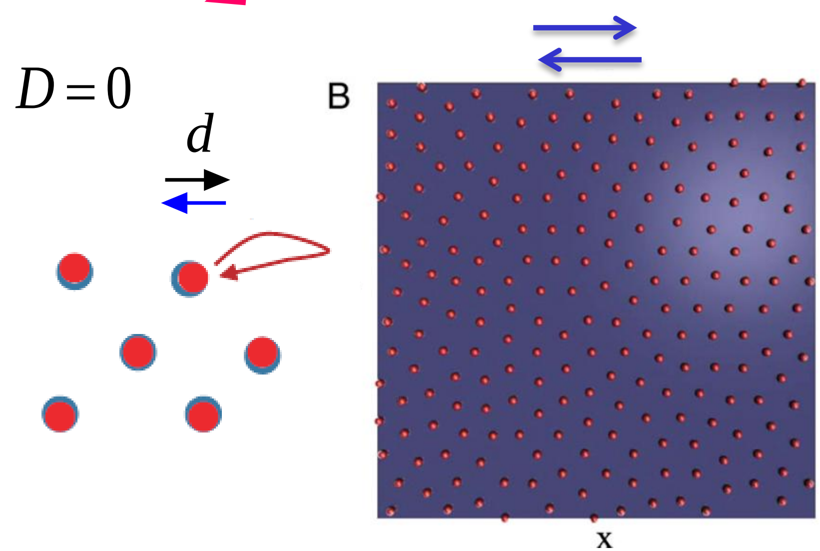
SO, Y. Kawamura, Y. Tsugawa, JPSJ 81, 114718 (2012)
Y. Kawamura, SO, JPS Conf. Proc. 4 (2015) 011007.

Possible vortex configurations of the reversible flow state

Our experiment

Abrikosov lattice

Reversible flow



Dynamically frozen state

Reversible flow

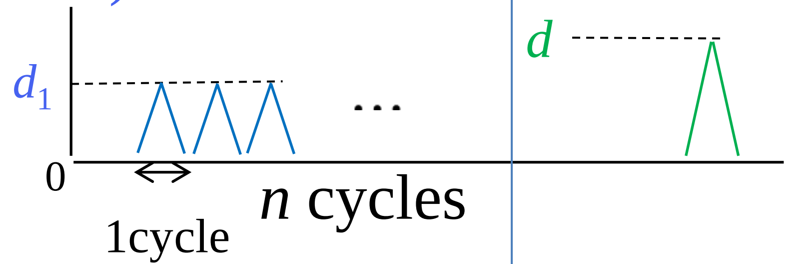
Simulation:

C. Reichhardt, C.J.O. Reichhardt, PNAS 108, 19099 (2011)

Memory effect of ac drive *d* in particle configurations (simulation)

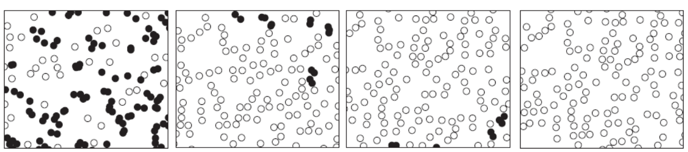
Trial amplitude
d_1 (=fixed)

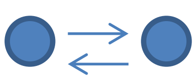
Readout amplitude ***d***



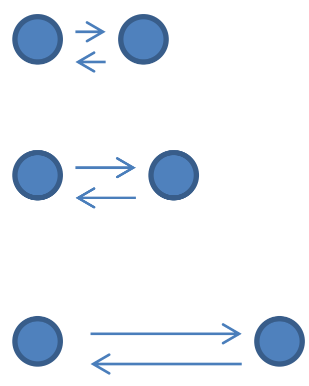
Number of cycles

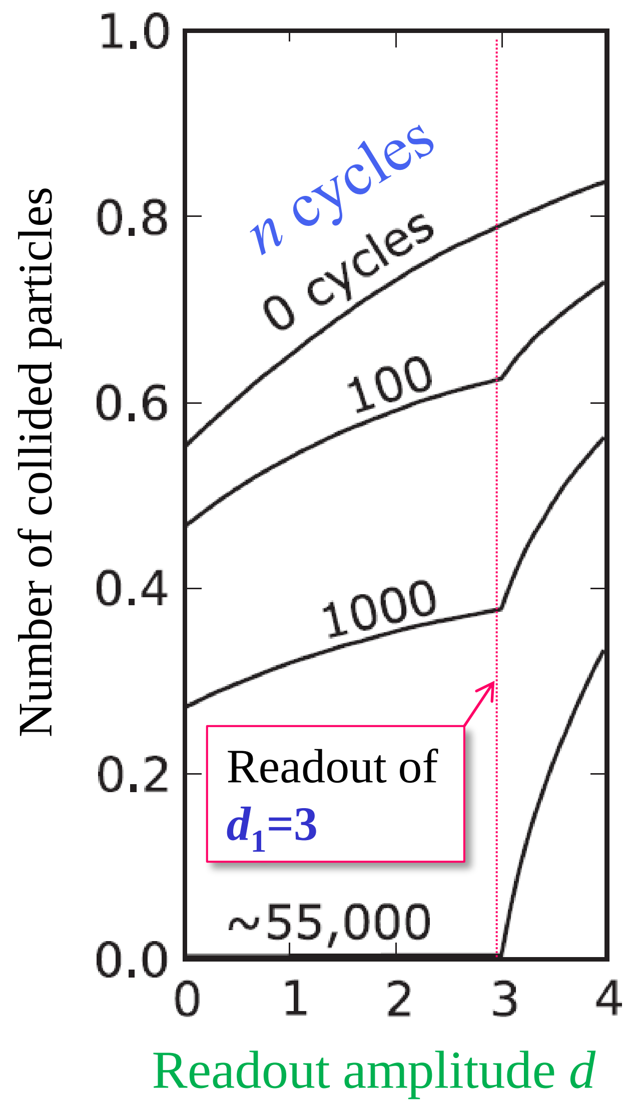
n=1, 100, 1000, 55,000





$\boldsymbol{d_1=3}$=fixed





N. C. Keim and S. R. Nagel, PRL 107, 010603 (2011)

Memory effect of ac drive in the vortex configuration

(experiment)

Sorry, unpublished data

Readout of d_1=3 μm

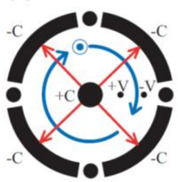
d (μm)

RIT under local shear

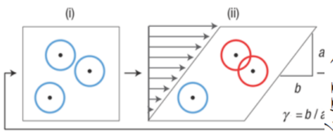
and

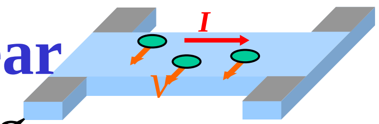
RIT in the moving frame with a constant velocity?

Vortices experiment on RIT (ac drive)



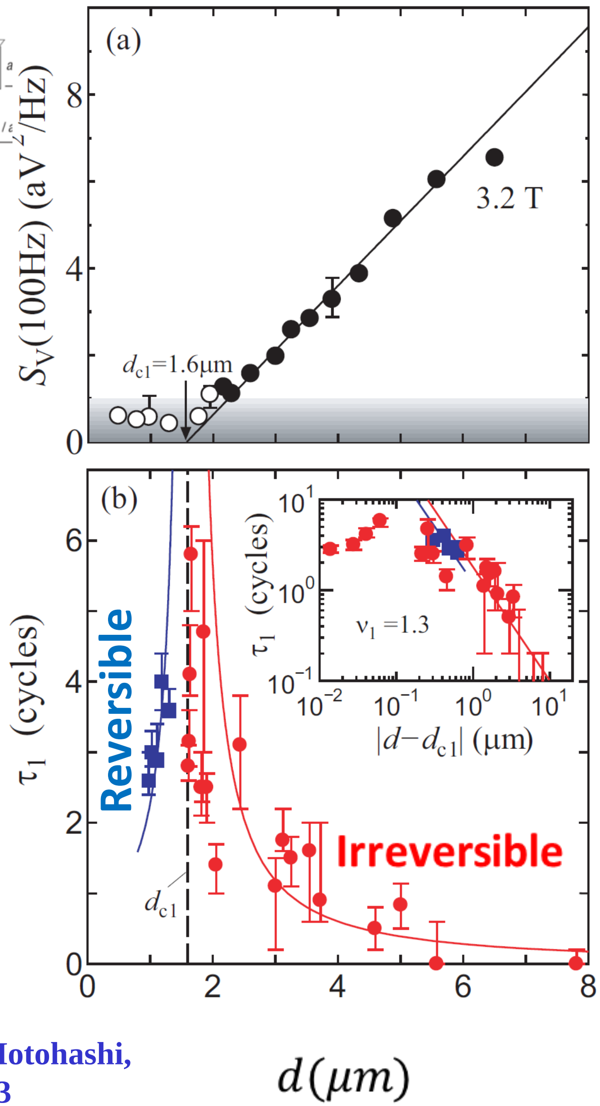
CD: strong ***global*** **shear**
weak pinning





Strip: weak ***local*** **shear**
stronger pinning

$\nu_1 = 1.3$



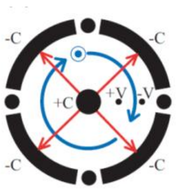
Simulation → RIT Yes

N. Mangan, C. Reichhardt, C. J. Olson Reichhardt, PRL 100, 187002 (2008)

Sorry, unpublished data

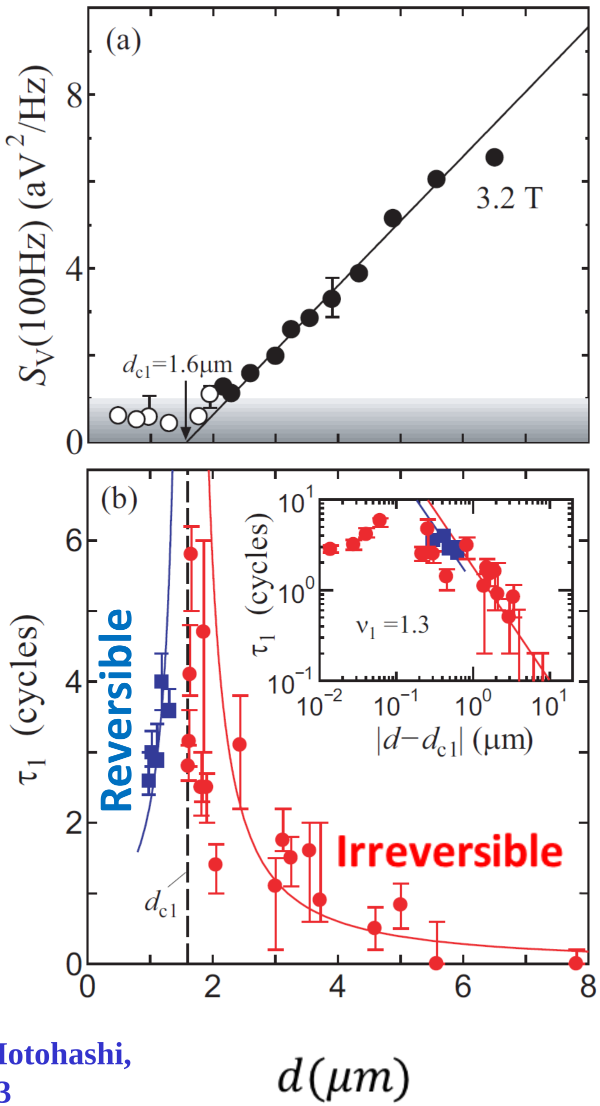
SO, Y. Tsugawa, A. Motohashi, PRB 83 (2011) 012503

Vortices experiment on RIT (ac drive)

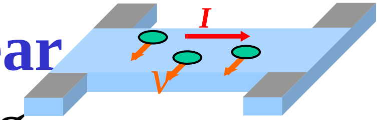


CD: strong ***global*** **shear**
weak pinning

$\nu_1 = 1.3$



Strip: weak ***local*** **shear**
stronger pinning



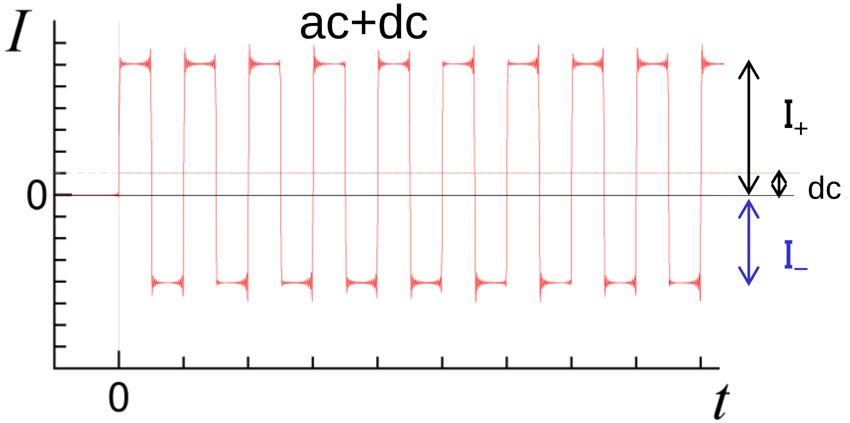
Sorry, unpublished data

Phys. Procedia (2015), in press.

SO, Y. Tsugawa, A. Motohashi,
PRB 83 (2011) 012503

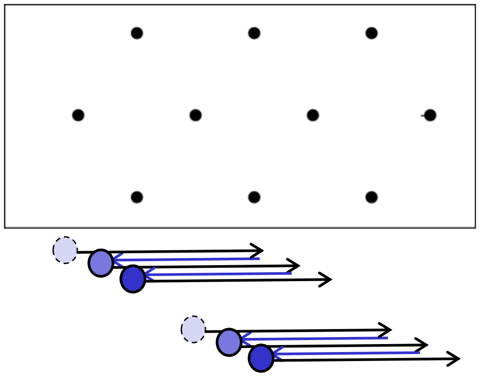
Observation of “RIT” in the moving frame with v_{dc}

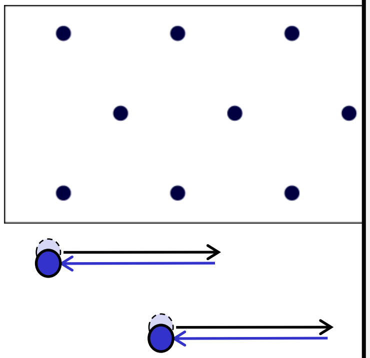
Our idea: Reduction of pinning forces
by driving the vortex system with v_{dc}
→ RIT in the moving frame?



Oscillation viewed from:
rest (lab) frame

moving frame





Sorry, unpublished data

Vortex matter in conventional type-II SC

— *a*-Mo_xGe_{1-x} films with weak pinning —

(1) Field-driven quantum phase transition

(2) Dynamics of moving lattices

-Dynamic ordering

-Plastic flow of solids -Strong shear: Corbino disk

dc + ac

(3) **Dynamics of non-equilibrium many particles and novel dynamic transitions**

- rev-irreversible tr. and random organization
- absorbing tr.

ac

- **depinning tr.**

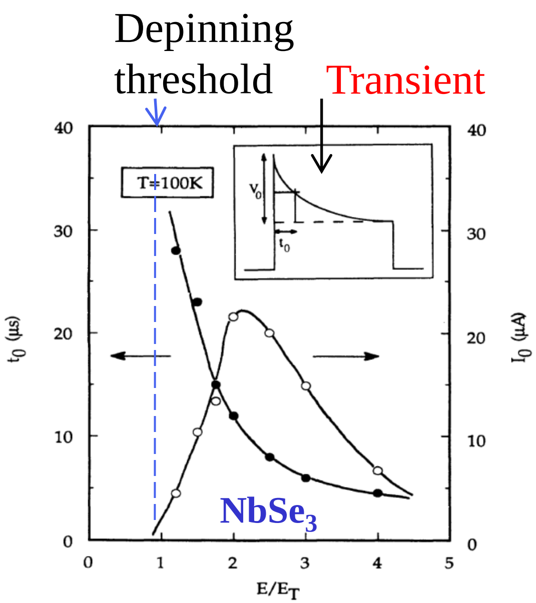
Exploring further dynamic transitions

dc

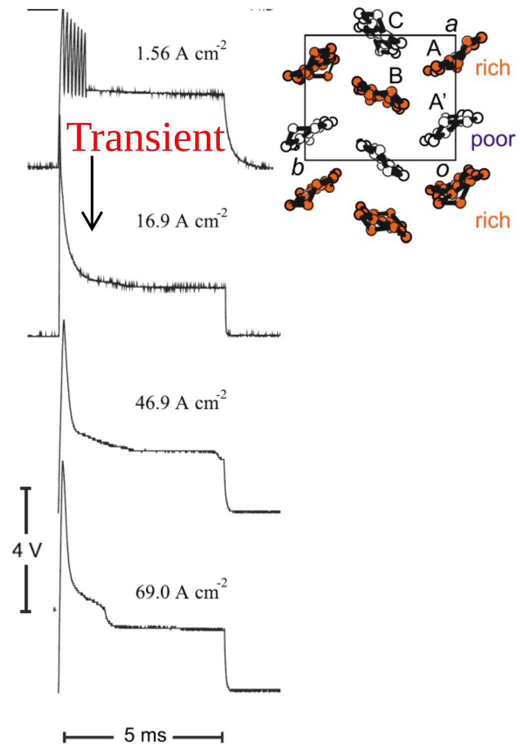
Depinning phenomena in various physical systems

Colloids, Electron crystals, SC vortices, … ,

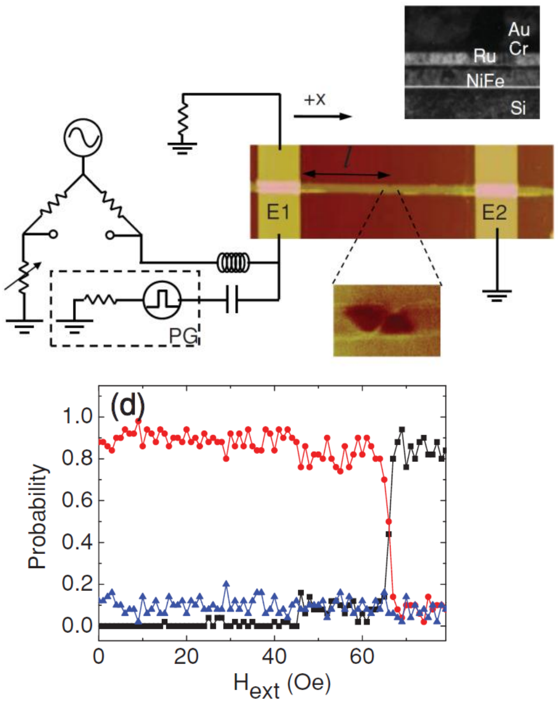
CDW   Charge-ordered org. cond.   Magnetic domain walls



I.D. Parker, A. Zettl, PRB 45, 3260 (1992)



K. Tamura, T. Mori *et al.*, JAP 107, 103716 (2010)



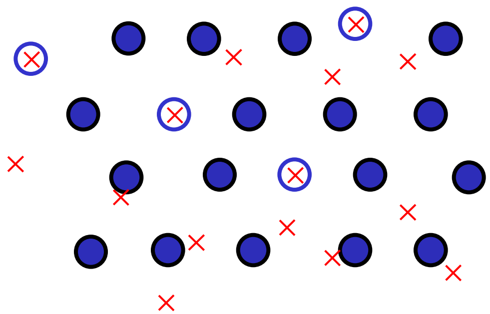
U.H. Pi *et al.*, PRB 84, 024426 (2011)

Importance of the depinning transition

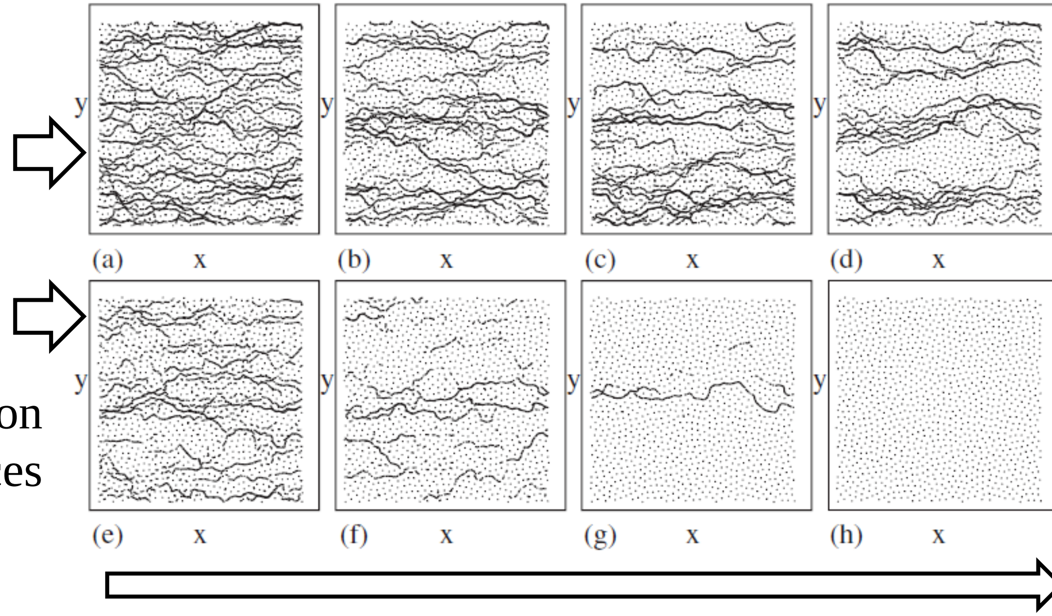
- **Practical application of logic and memory devices in spintronic and flux-based SC circuits**
- **Fundamentally, a new dynamic (nonequilibrium) phase transition**

C. Reichhardt, C.J. Olson Reichhardt, PRL 103, 168301 (2009)

Non-equilibrium depinning transition (simulation)



Ordered initial configuration with many **depinned** vortices



t

$F > F_c$

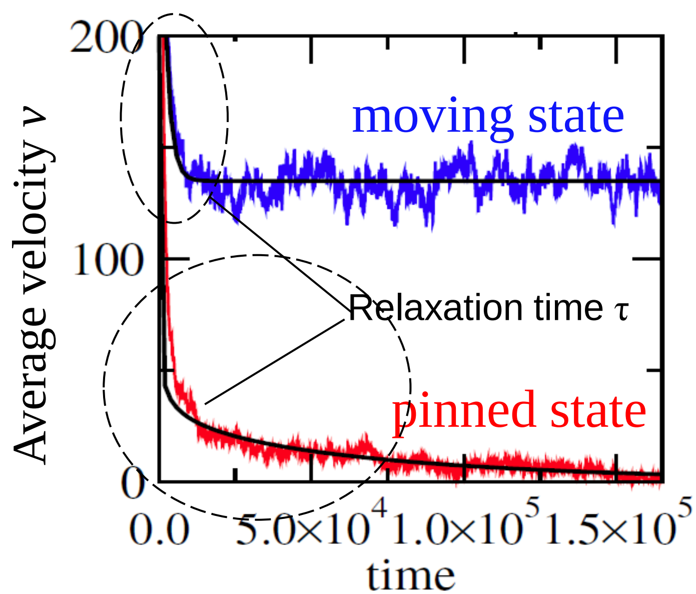
moving state

fluctuating state

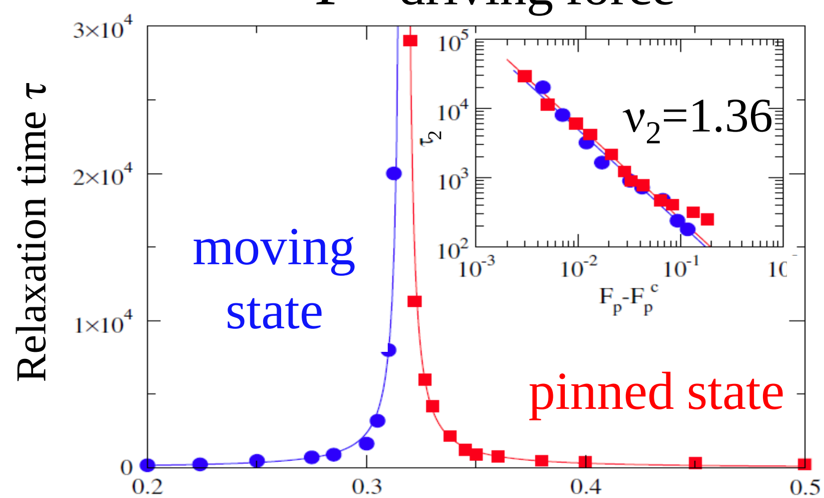
$F < F_c$

pinned state

absorbing state

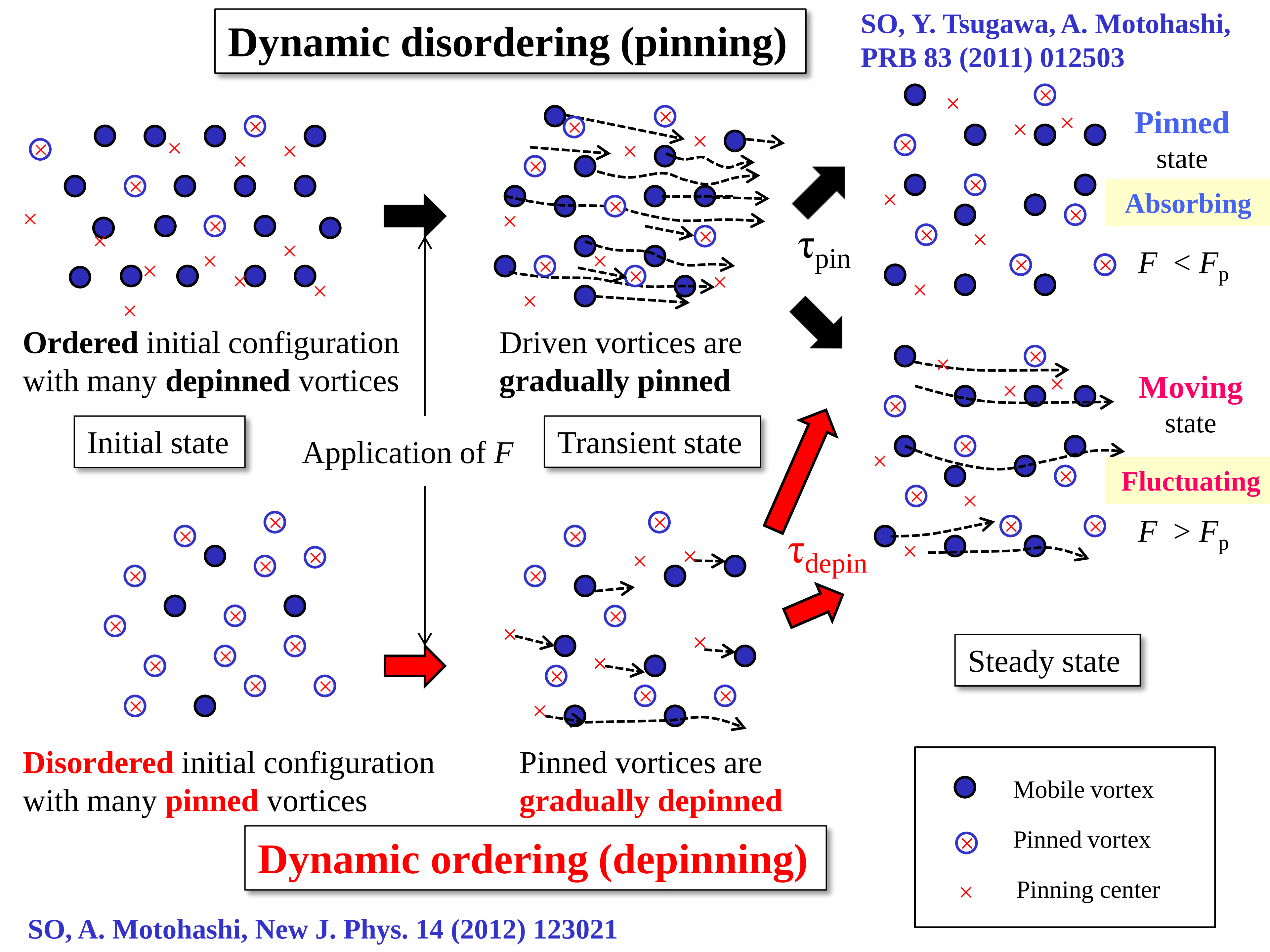


← F driving force



F_p pinning force →

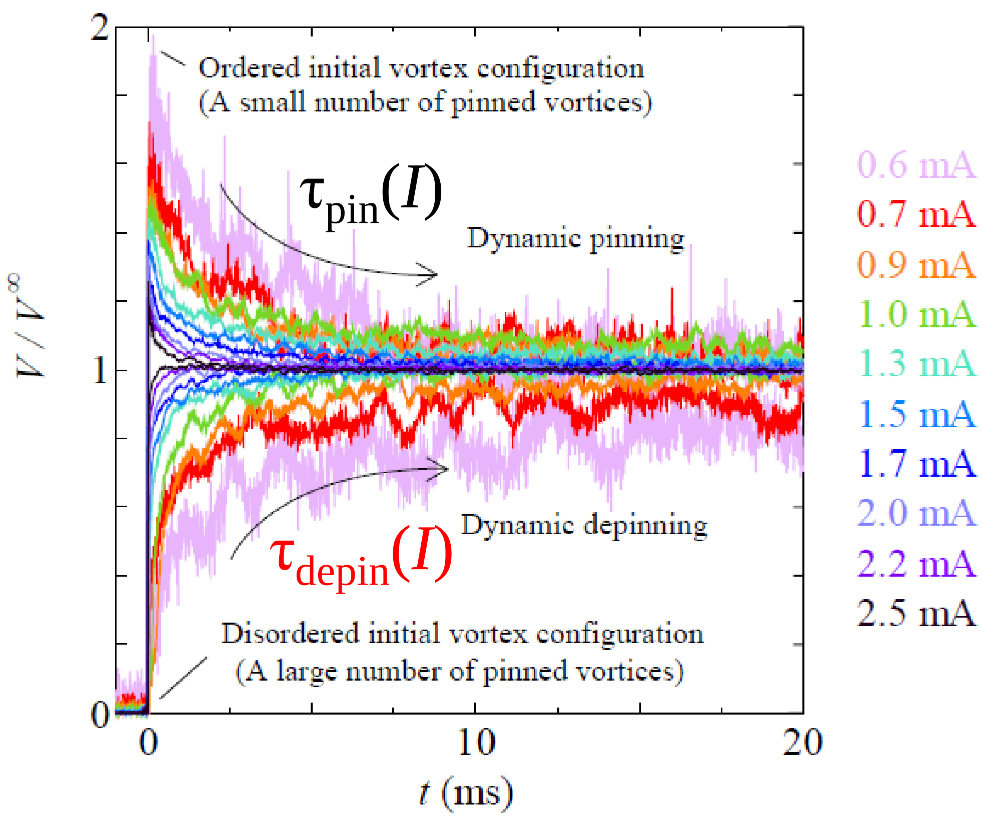
C. Reichhardt *et al.* , PRL **103**, 168301 (2009)

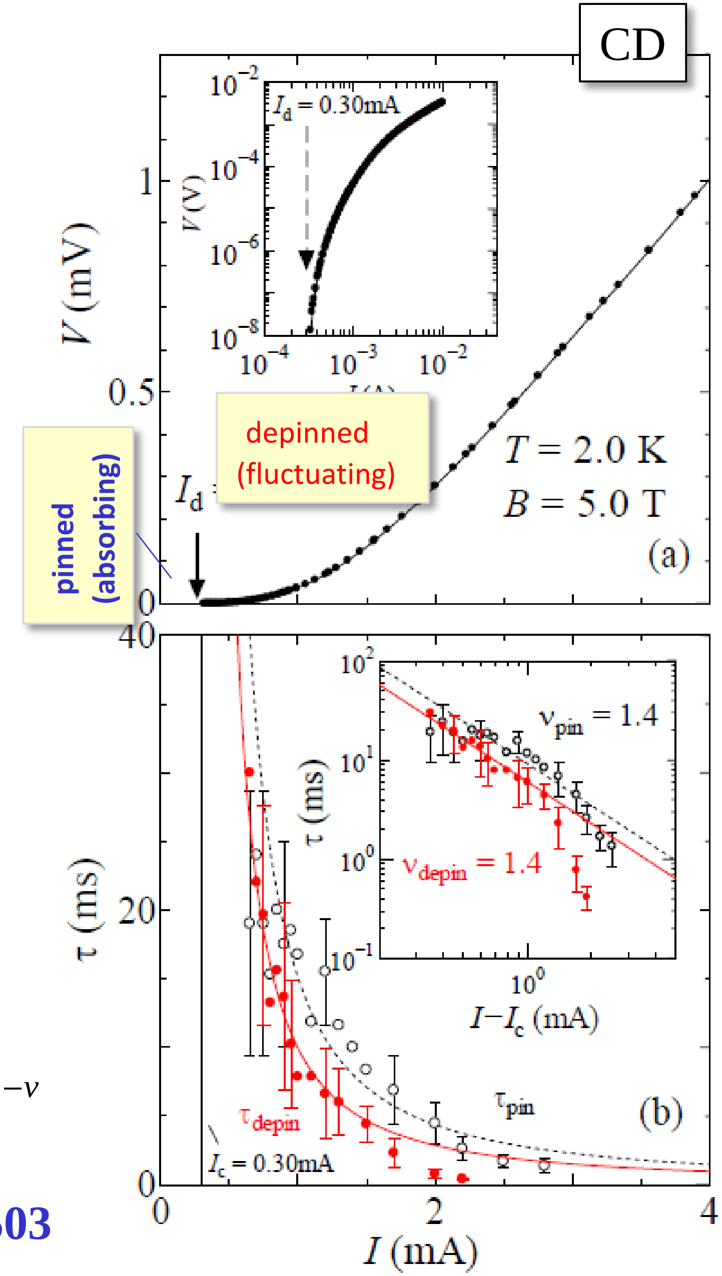


Dynamic disordering (pinning)
SO, Y. Tsugawa, A. Motohashi, PRB 83 (2011) 012503
Ordered initial configuration with many depinned vortices
Driven vortices are gradually pinned
Initial state
Application of F
Transient state
τ_pin
Pinned state
Absorbing
F < F_p
Moving state
Fluctuating
F > F_p
τ_depin
Steady state
Disordered initial configuration with many pinned vortices
Pinned vortices are gradually depinned
Dynamic ordering (depinning)
Mobile vortex
Pinned vortex
Pinning center
SO, A. Motohashi, New J. Phys. 14 (2012) 123021

Evidence of plastic depinning transition: dynamic transition

SO, A. Motohashi, New J. Phys. 14 (2012) 123021



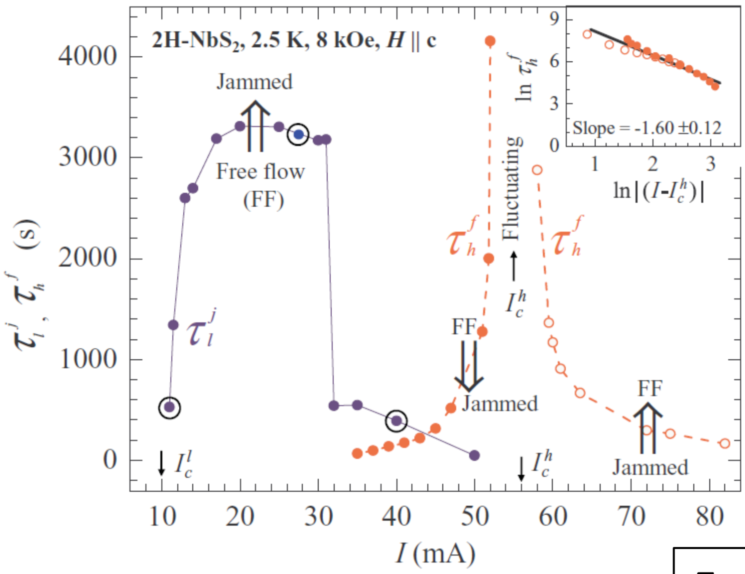


$$V(t) = \frac{(V^0 - V^\infty)\exp(-t/\tau)}{t^\alpha} + V^\infty \qquad \tau \sim |I - I_c|^{-\nu}$$

SO, Y. Tsugawa, A. Motohashi, PRB 83 (2011) 012503

Phys. Rev. Lett. 103, 168301 (2009).

Jammed(?)-FF in NbS_2



G. Shaw *et al.*, PRB **85**, 174517 (2012)

Critical behavior in pinned phase for *a*-Mo_xGe_{1-x}

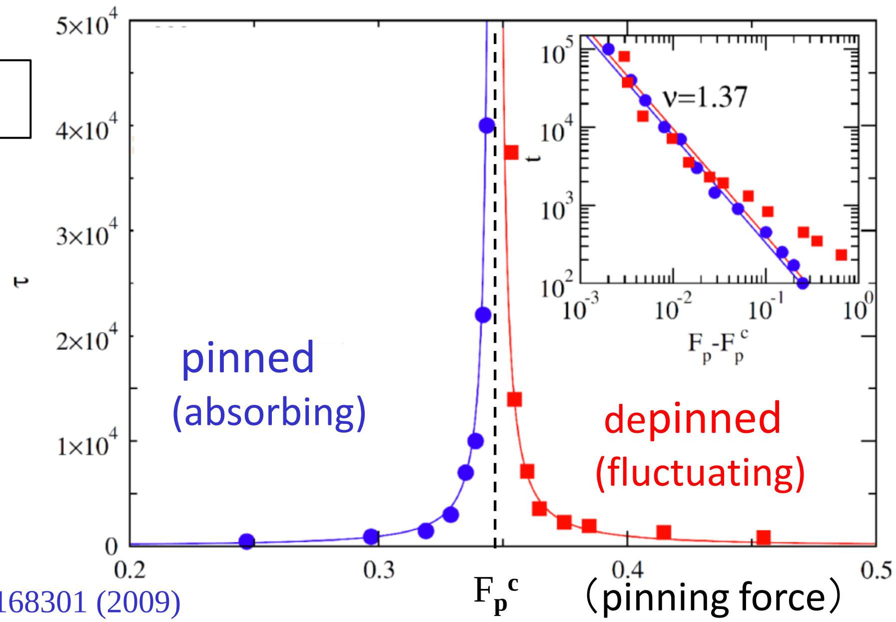
T. Kaj
(2015)

Experime

SO e

Sorry, unpublished data

Simulation



C. Reichhardt, C.J. Olson Reichhardt, PRL **103**, 168301 (2009)

Summary 2

Non-equilibrium phenomena and phase transitions in a vortex system

(1) *Reversible-irreversible transition (RIT)*

- **Rev.** state is a **weakly disordered** (but not perfect) lattice
  → **Memory effect** of the input amplitude and its readout
- **RIT** occurs under **local** shear as well as global shear
- "**RIT**" occurs in the **moving frame,** but **ν (=0.7) is smaller**

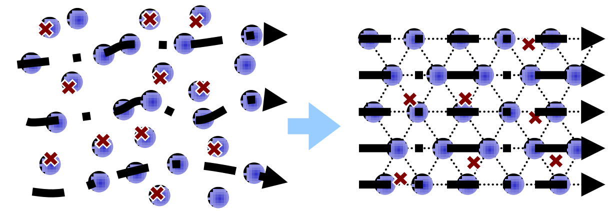
(2) *Dynamic depinning transitions for …*

DC drive:

- Critical dynamics similar to that in the depinned phase is observed in the **pinned** phase
- In **coexistence** phase **ν** =1.0, which **is smaller** than ν =1.3 in OP

Plastic flow and dynamic transitions of vortex matter

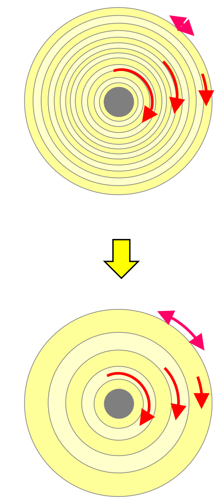
(1) *Dynamics of moving lattices*



Dynamic ordering of driven vortices

- *B* and *v*-induced lattice reorientation

SO, H. Imaizumi, D. Shimamoto, N. Kokubo, PRB 83 (2011) 064520
SO, D. Shimamoto, N. Kokubo, PRB 85 (2012) 064508
D. Shimamoto, SO, N. Kokubo, JPCS 302 (2011) 012027



Dynamic melting of driven lattices

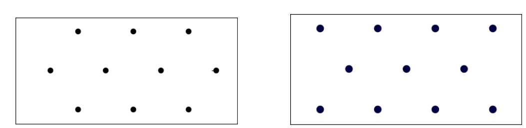
SO, H. Imaizumi, N. Kokubo, PRB 80 (2009) 132503
A. Ochi *et al.*, JPSJ 85 (2016) 044701: JPSJ 85 (2016) 034712

Rotating lattice rings in CD: roles of effective pinning

SO, Y. Yamazaki, N. Kokubo, PRB 80 (2009) 220501(R)
Y. Kawamura *et al.*, SUST 28 (2015) 045002

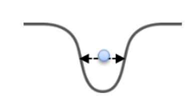
(2) *Dynamics of non-equilibrium many particles*

Novel dynamic transitions



- RIT and random organization
- depinning tr.

SO, Y. Tsugawa, A. Motohashi, PRB 83 (2011) 012503
Y. Kawamura, SO, JPS 4 (2015) 011007: 81 (2012) 114718



SO, A. Motohashi, NJP 14 (2012) 123021
SO, Y. Kawamura, Y. Tsugawa, SUST 26 (2013) 025013