Criteria for the validity of Amontons Coulomb's law; Study of friction using dynamics of driven vortices of superconductor

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Outline

1) Background:

Problems in physics of friction

Collective dynamics of quantum condensate

Dynamics of driven vortices in superconductors

2) Physics of friction by using dynamics of driven vortices

Model

Kinetic friction as a function of velocity

Broadened dynamical phase transition

A. Maeda *et al.*: Phys. Rev. Lett. 94 (2005) 077001.

Static friction as a function of waiting time

Criteria for the validity of Amontons-Coulomb friction

D. Nakamura *et al.*: arXiv 0906.3086.

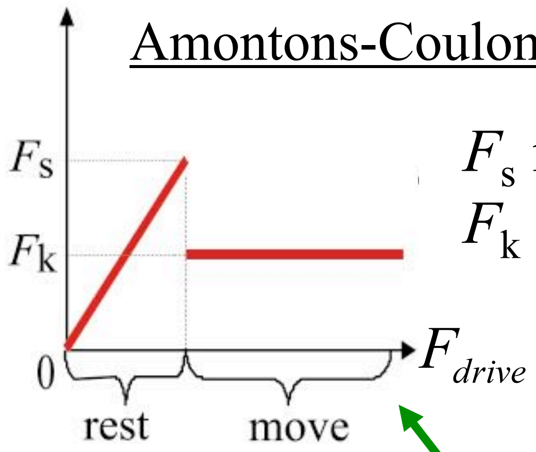
3) Response to ac (μ-wave) driving force

4) Conclusion, perspective

Microscopic friction *vs* Macroscopic friction

F_s : maximum static friction force
F_k : kinetic friction force

<u>Amontons-Coulomb's law (A-C law)</u>

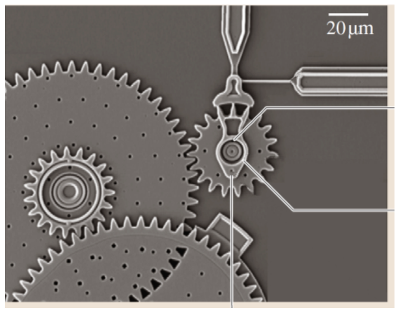


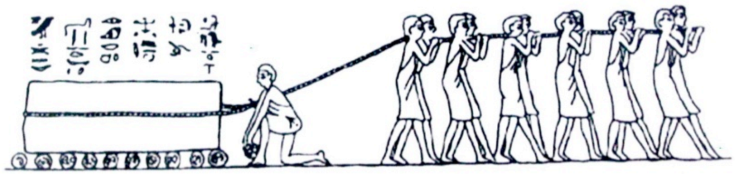
F_s is constant
F_k does not depend on v

microscopic friction

macroscopic friction

100μm



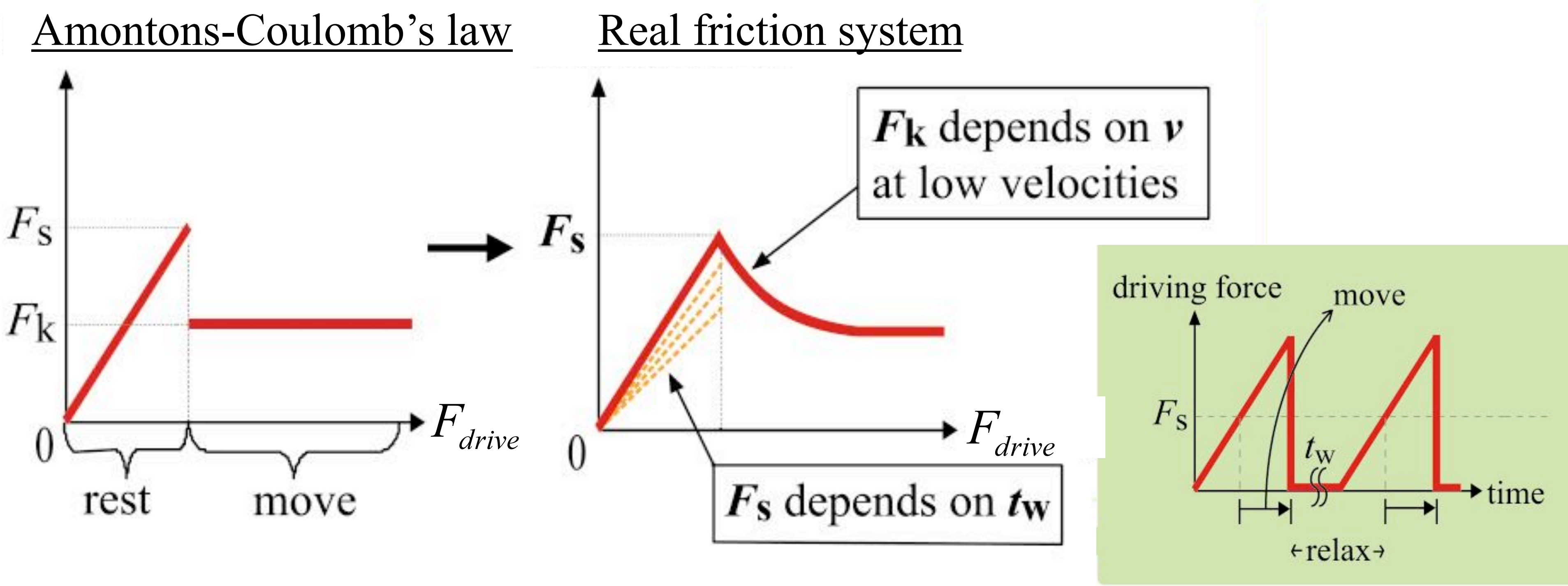


D. M. Tanner *et al.*, *MEMS Reliability : Infrastructure, Test Structures, Experiments, and Failure Modes* 2000-2091 (Sandia National Laboratories, 2000).

In some cases, even the macroscopic friction does not obey the A-C law

What is the limit of the validity of Amontons-Coulomb's law?

Amontons-Coulomb friction *vs* real friction

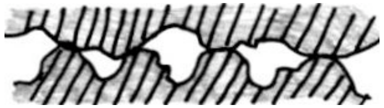


To understand friction from microscopic point of view_

Need model system with which systematic experiments are possible in a repeated manner (free from wear)

Microscopic formulation of friction

H. Matsukawa and H. Fukuyama: PRB 49, 17286 (1994)



$\leftarrow$**a** displacement of upper atom i $\mathbf{u}_i$, mass m_a

$\leftarrow$**b** displacement of lower atom i $\mathbf{v}_i$, mass m_b

$$m_a \ddot{\mathbf{u}}_i + m_a r_a (\dot{\mathbf{u}}_i - \langle \dot{\mathbf{u}}_i \rangle_i) = \sum_{j\in a} \mathbf{F}_a(\mathbf{u}_i - \mathbf{u}_j) + \sum_{j\in b} \mathbf{F}_I^{(i,j)}(\mathbf{u}_i - \mathbf{v}_j) + \mathbf{F}_{ex} + \mathbf{F}_G$$

eq. motion for an upper atom i

$$m_b \ddot{\mathbf{v}}_i + m_b r_b (\dot{\mathbf{v}}_i - \langle \dot{\mathbf{v}}_i \rangle_i) = \sum_{j\in b} \mathbf{F}_b(\mathbf{v}_i - \mathbf{v}_j) + \sum_{j\in a} \mathbf{F}_I^{(i,j)}(\mathbf{v}_i - \mathbf{u}_j) + \mathbf{F}_S(\mathbf{v}_i) + \mathbf{F}_G$$

eq. motion for a lower atom i

dissipation from a representative DF to others

steady state
summing up for all atoms
time averaged

$$-\sum_{i\in a}\sum_{j\in b} \left\langle F_{I//}(\mathbf{u}_i - \mathbf{v}_j)\right\rangle_t = N_a \left\langle F_{ex}\right\rangle_t$$

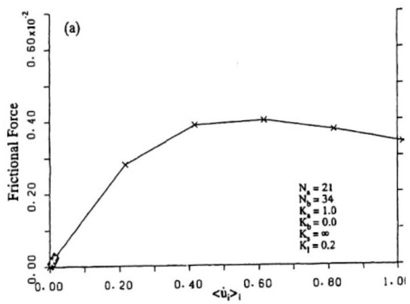
friction: sum of interatomic (pinning) forces

1 D model for clean surfaces

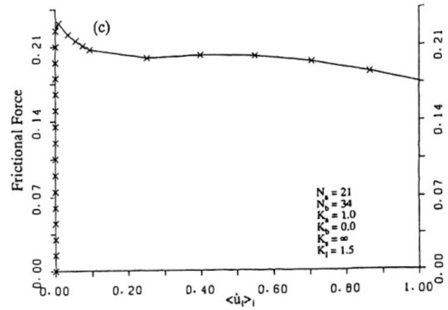
numerical solution for the above equation

- clean surface
  finite F_k even for zero F_s
- disordered surface
  less velocity dependent
  similar to Amontons-Coulomb's law

F_k as a function of velocity

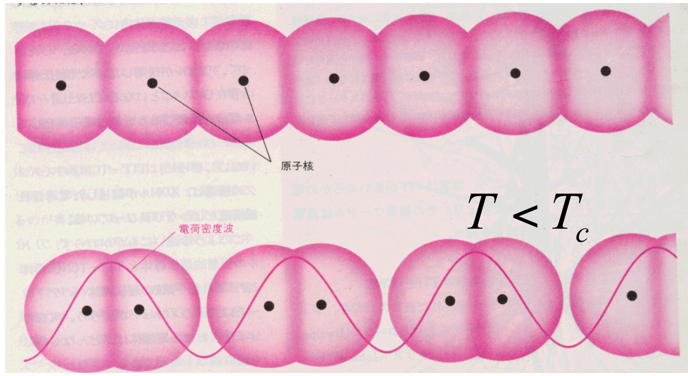


clean surface



(normal) dirty surface

Model systems for friction study in quantum condensate in solids



Charge-density wave (CDW)

1D

$$m\ddot{\mathbf{u}}_i + m\gamma\dot{\mathbf{u}}_i + \sum_{i,j}\mathbf{F}(\mathbf{u}_i - \mathbf{u}_j) + \sum_i \mathbf{F}_{\mathrm{p}}^{(i)}(\mathbf{u}_i) = \mathbf{F}_{\mathrm{ex}}$$

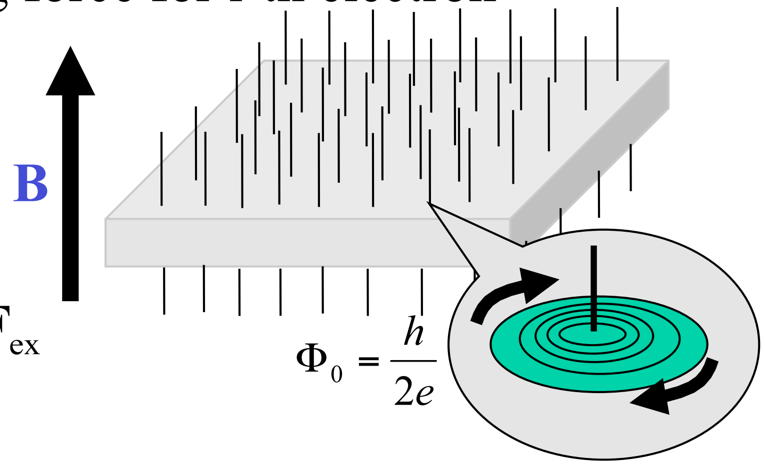
$$\mathbf{F}_{ex} = -e\mathbf{E}$$

$$\mathbf{j} = \sum_i -e\dot{\mathbf{u}}_i$$

$\mathbf{u}_i$: displacement of i-th electron in the CDW
m: mass of the i-th electron
F_p: pinning force for i-th electron

Vortex lattice of superconductor

2D



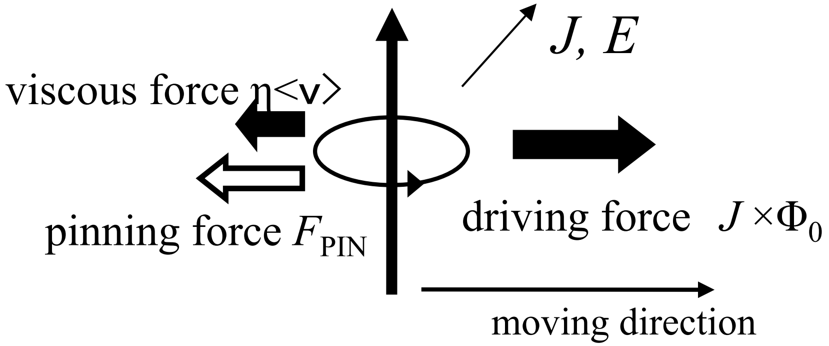
$$(m\ddot{\mathbf{u}}_i +)\gamma\dot{\mathbf{u}}_i + \sum_{i,j}\mathbf{F}(\mathbf{u}_i - \mathbf{u}_j) + \sum_i \mathbf{F}_{\mathrm{p}}^{(i)}(\mathbf{u}_i) = \mathbf{F}_{\mathrm{ex}}$$

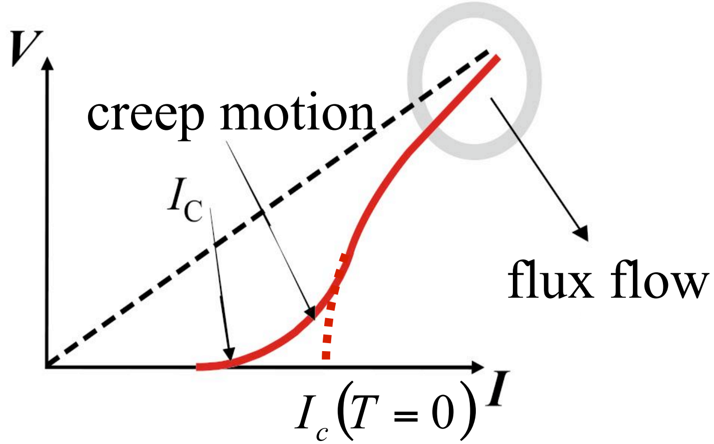
$$\mathbf{F}_{ex} = \Phi_0 \times \mathbf{j}$$

$$\mathbf{E} = \sum_i \Phi_0 \times \dot{\mathbf{u}}_i$$

$\mathbf{u}_i$: displacement of i-th votex in the lattice
m: mass of the i-th vortex in the lattice
F_p: pinning force for i-th votex

Vortex dynamics - the ideal model system of friction





$$\kappa_P u + \eta\,\dot{u} = J\times\Phi_0 + f_{fluct}$$

elastic pinning

flux flow

creep motion

$$F_s = j_c\times\Phi_0$$
$$F_k = j\Phi_0 - \eta v$$

A. Maeda *et al.*, PRL 94, 077001 (2005).

Friction force on solid-solid interface

$$-\sum_{i\in a}\sum_{j\in b}\left\langle F_{I//}(\mathbf{u}_i-\mathbf{v}_j)\right\rangle_t = N_a\left\langle F_{ex}\right\rangle_t$$

H. Matsukawa and H. Fukuyama PRB 49, 17286 (1994).

Advantage

- scan *H*, *T* and *F* continuously
- intrinsically reproducible
  --- no wear, no debris

Common feature

- multi-internal-degrees of freedom
- non-equilibrium
- non-linearity

Purpose of study

Driven vortices as a model system of solid-solid friction

(1) **Measure kinetic friction as a function of velocity**

(2) **Static friction as a function of waiting time**

Change temperature, magnetic field, pinning, system size

(3) **Find the criteria for the validity of Amontons-Coulomb friction**

(4) **Ac dynamics (μ-wave to THz)**

Microscopic understanding of elementary excitation at the interface

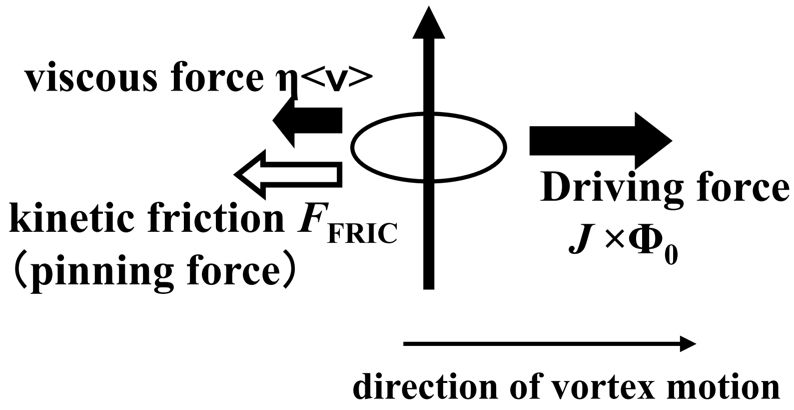
High-T_c cuprate superconductor : variety of H-T phase diagram

Expressing solid-solid friction in terms of vortex motion

necessary to make correspondence with theory

$$F_k = \kappa_P u = J \times \Phi_0 - \eta \dot{u}$$

$$= J \times \Phi_0 \left(1 - \frac{\rho}{\rho(\omega \to \infty)} \right)$$



Φ_0: flux quantum
J: current density
ρ: resistivity

$$\boxed{\rho(\omega \to \infty) = \frac{B\Phi_0}{\eta}}$$

Flux flow resistivity

***I -V* measurement and viscosity ,η , measurement can deduce kinetic friction**

Sample preparation

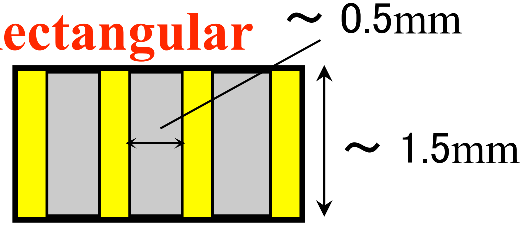
$La_{2-x}Sr_xCuO_4$ (LSCO)
(x = 0.12, 0.15)

thickness ～ 3000 Å

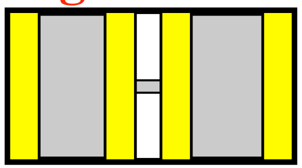
single crystal, thin film

Fabrication of samples

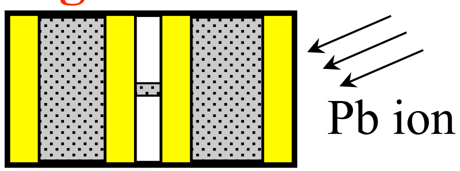
Rectangular



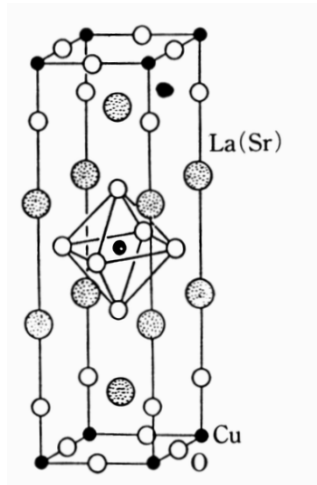
Bridge

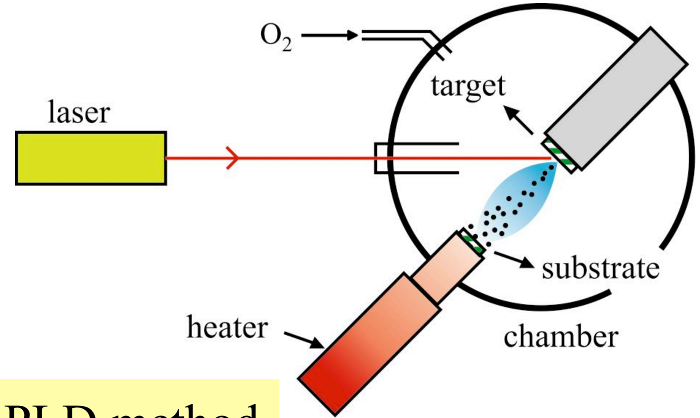


Bridge wih columnar defects



Crystal structure





PLD method

photolithography ＋ chemical etching

S. Komiyama (Univ. of Tokyo)

5.8 GeV Pb ion for the columnar defects
@ Grand Accelerateur National d'Ions Lourds(GANIL)

Ecole Polytechnique, M. Konczykowski and C. J. van der Beek

F_k (v)

$La_{2-x}Sr_xCuO_4$

(up to ∼1 km/s)

1) F_k changes with B and T
in a reproducible manner

good as a model system

2) very much different from
the Amontons-Coulomb behavior

similar to "clean surface"

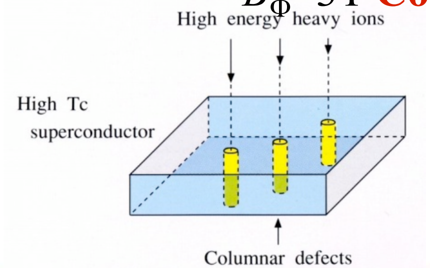
3) F_k saturates and decreases

existence of a peak in $F_k(v)$

4) smaller F_k in irradiated samples

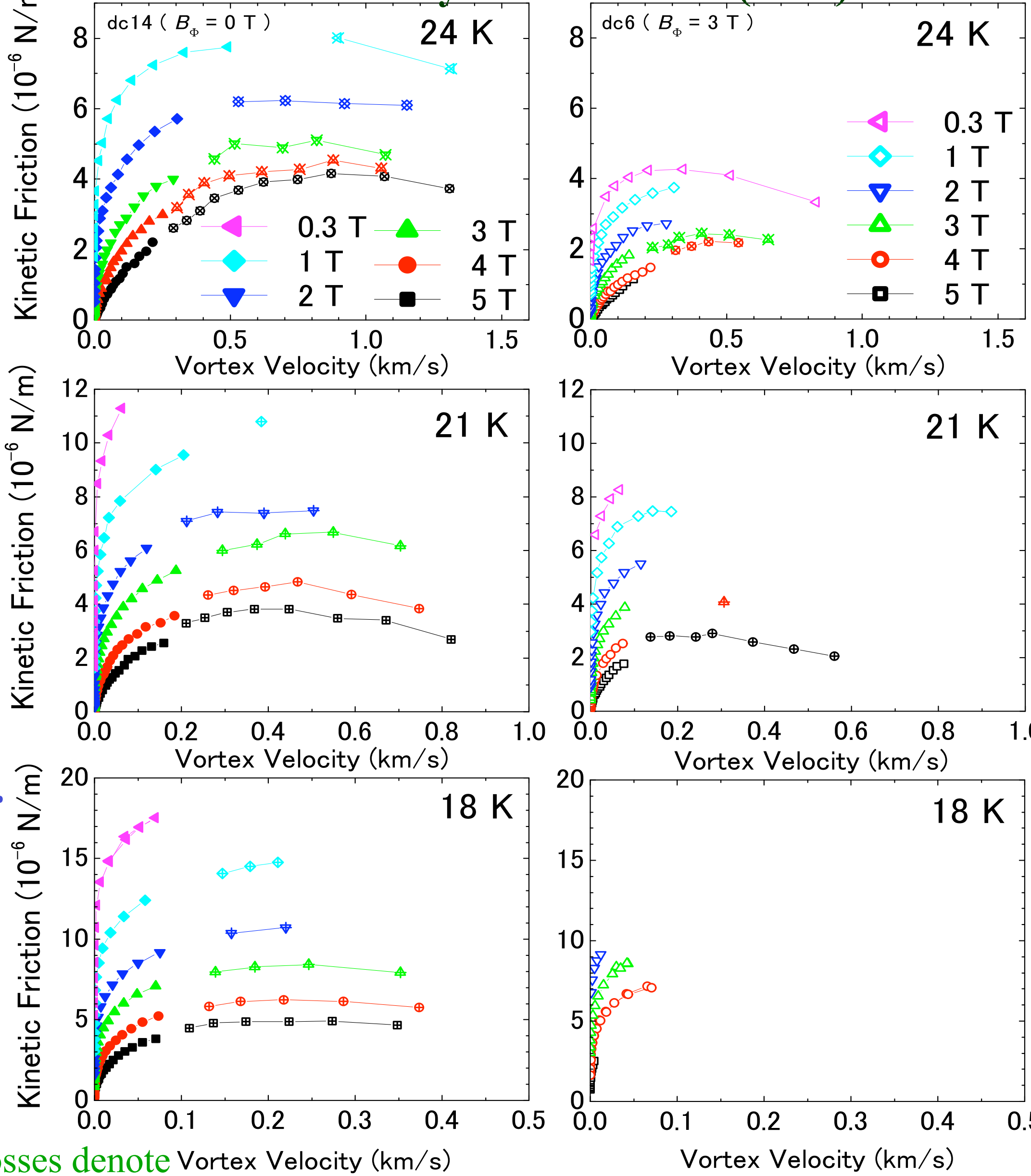
inconsistent with the behavior at low velocities ?

B_Φ=3T **Columnar defects**



200 MeV Iodine

A. Maeda *et al.*: Phys. Rev. Lett. 94 (2005) 077001.

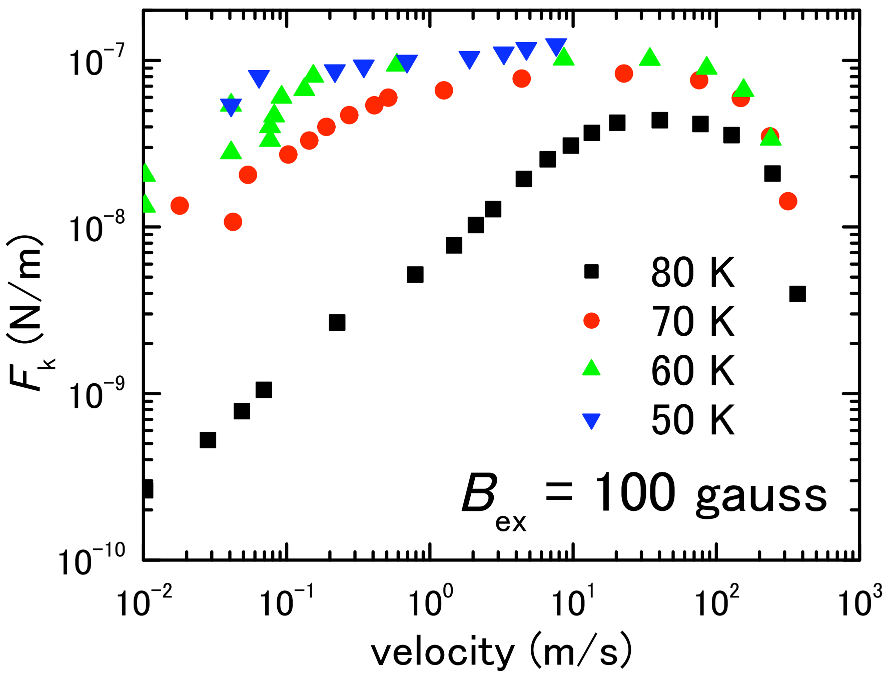


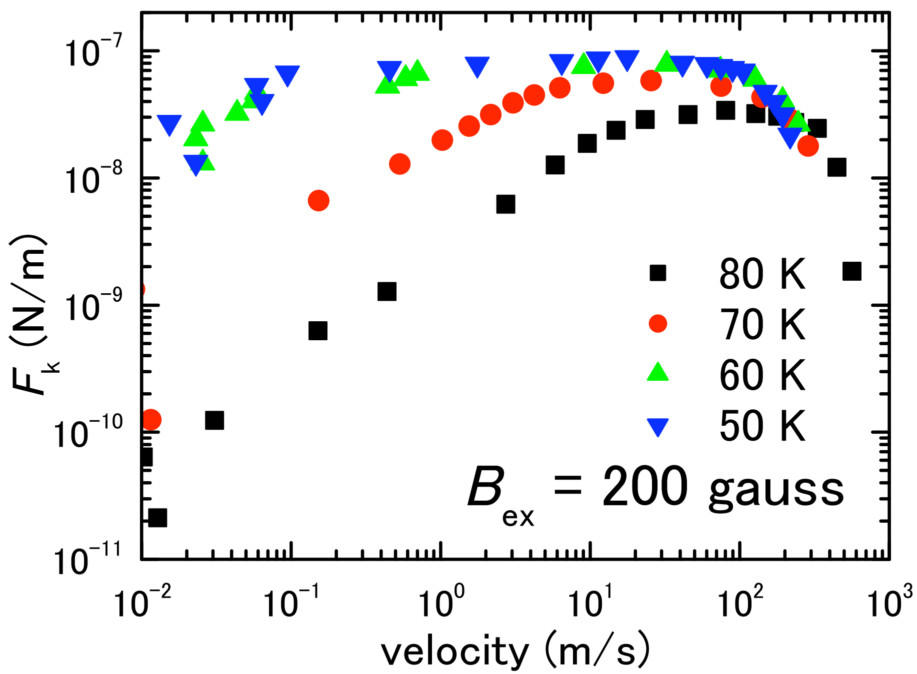
Data points with crosses denote pulsed measurements

pristine

3T irradiated

$Bi_2Sr_2CaCu_2O_y$ (bulk single crystals)





$$F_k = \phi_0 \times \left(j - \frac{\rho}{\rho_\infty} \right), \ \rho_\infty = \frac{B\phi_0}{\eta}$$

Universal to many SCs

A. Maeda *et al.*: Phys. Rev. Lett. 94 (2005) 077001.

Minimal model to explain the data : overdamped equation of motion

S. Savel'ev and F. Nori

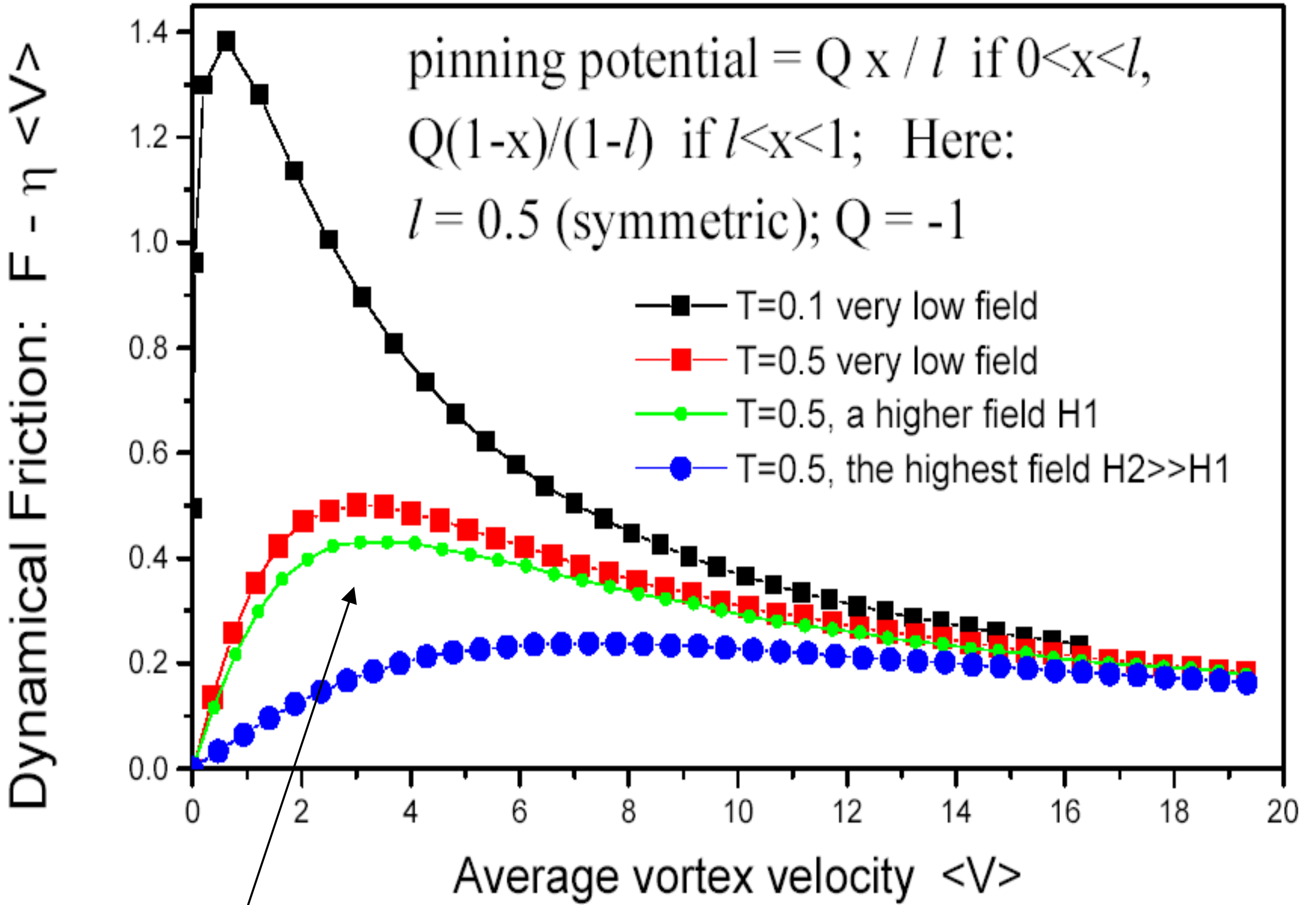
$$\boxed{\eta \dot{x}_i = -\frac{\partial}{\partial x_i}\left(U(x_i) + \sum_i W(x_i - x_j) \right) + F_d + \sqrt{2k_B T}\,\xi(t)}$$

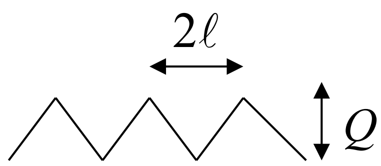
x_i	: position of vortices
η	: viscosity of vortices
$U(x_i)$	: substrate pinning potential
$W(x_i - x_j)$	: inter-vortex interaction
F_d	: driving force
$\xi(t)$	: thermal random force
T	: temperature

A. Maeda *et al.*: Phys. Rev. Lett. 94 (2005) 077001.

Numerical simulation for 1D vortex array at finite temperatures

S. Savel'ev and F. Nori





$$F_{viscous} \approx F_{pin}$$

a peak $\therefore \eta v \approx j_c \Phi_0$

A peak in the kinetic friction $F_{\mathrm{k}}(v)$

velocity at the peak $v_p \approx \dfrac{j_c \Phi_0}{\eta}$ **S. Savel'ev and F. Nori**

$$j_c \approx 10^6\ \mathrm{A/cm^2}$$

$$\Phi_0 = 2.07 \times 10^{-7}\ \mathrm{gauss \bullet cm^2}$$

$$\eta \approx 10^{-7}\ \mathrm{Ns/m}$$

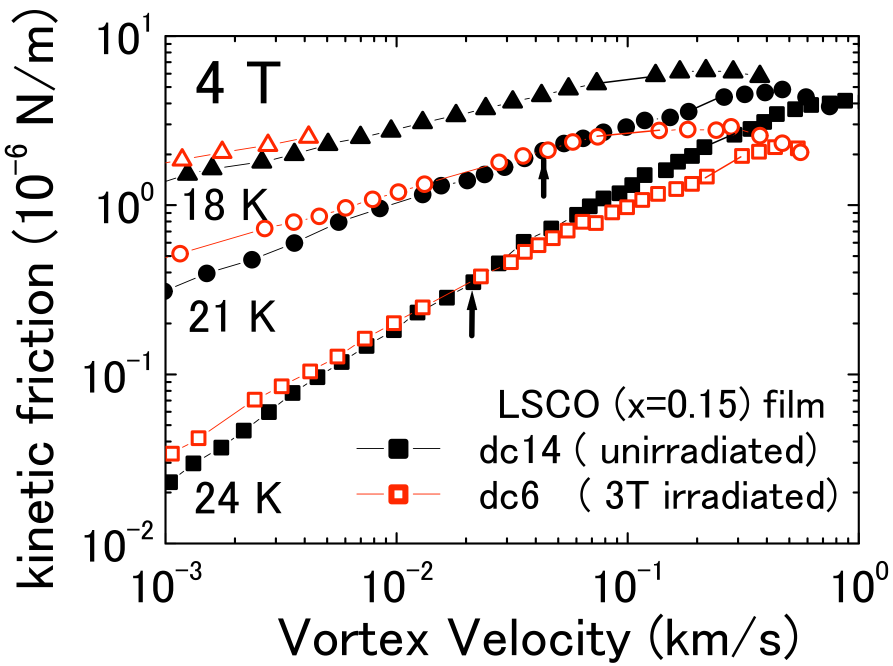
$$\boxed{v_p \approx 2 \times 10^2\ \mathrm{m/s}}$$

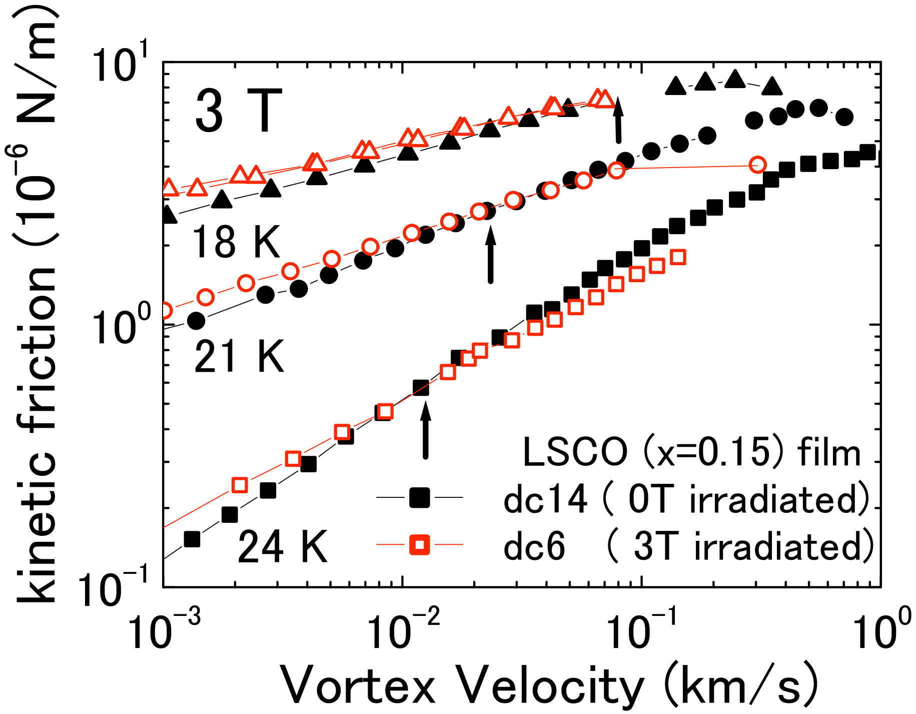
in good agreement with experiment

Potential energy plays an important role for $F_{\mathrm{k}}(v)$.

A. Maeda *et al.*: Phys. Rev. Lett. 94 (2005) 077001.

"Inversion" of kinetic friction at intermediate velocities !



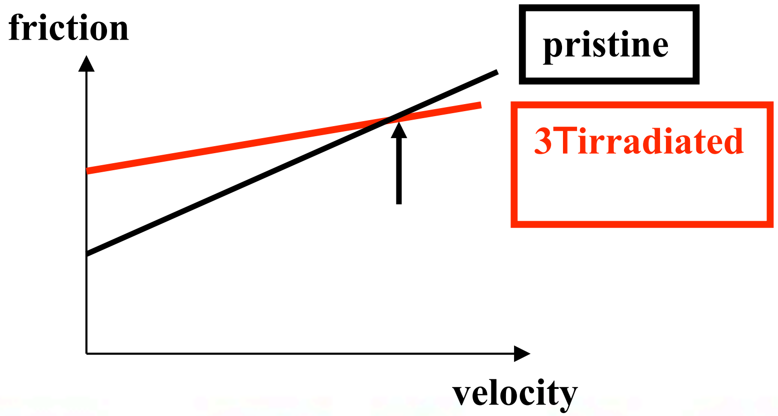


sample with strong pinning

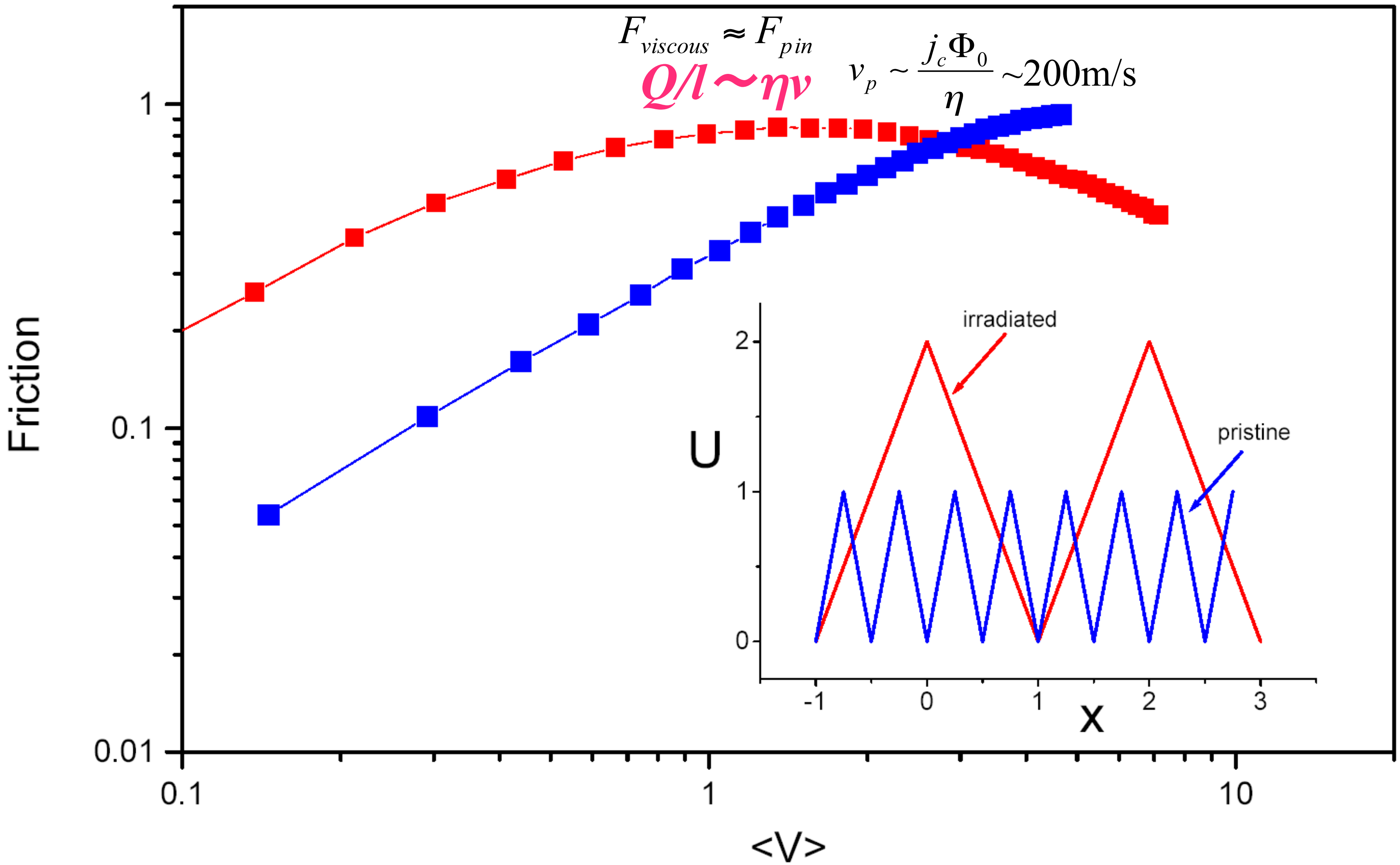
higher static friction

lower kinetic friction

more gradual dependence on **v**

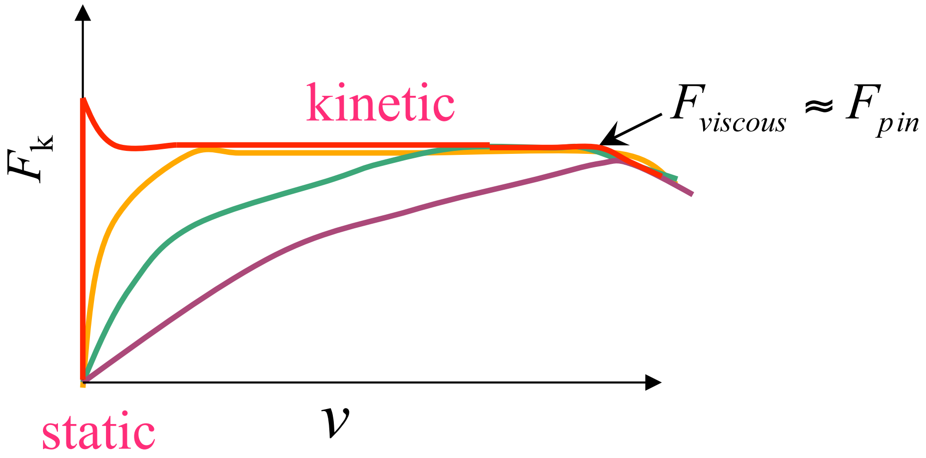


S. Savel'ev and F. Nori



A. Maeda *et al.*: Phys. Rev. Lett. 94 (2005) 077001.

Physical origin of the peak



changing parameters

change transition between
static and kinetic regime

broaden the transition

increasing magnetic field
increasing temperature
decreasing system size (macro to micro)

N strongly coupled system

collective coordinate $$x_{macro} = \sum_i \frac{x_i}{N}$$

new stochastic variable $$\xi_{macro} = \sum_i \frac{\xi_i}{N}$$

effective temperature $$T_{eff} = \frac{T}{N}$$

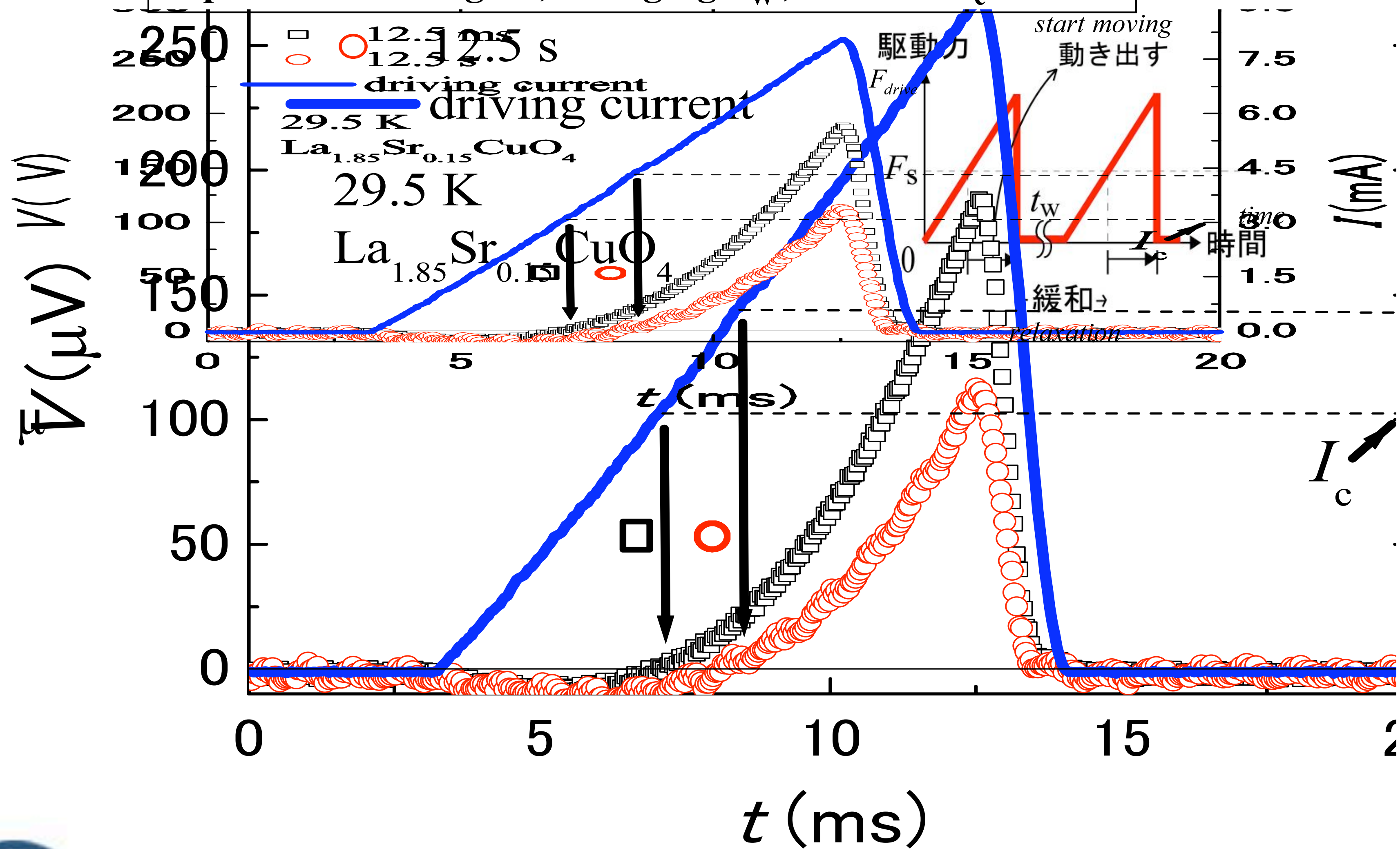
$$\boxed{T_{eff} \propto \frac{T}{L^3}}$$ (L : system size)

Suggesting the importance of thermal fluctuation in microscopic friction

Time domain response for various t_w

D. Nakamura *et al.*: arXiv 0906.3086.

Input sawtooth signal, changing t_w, measure I_c

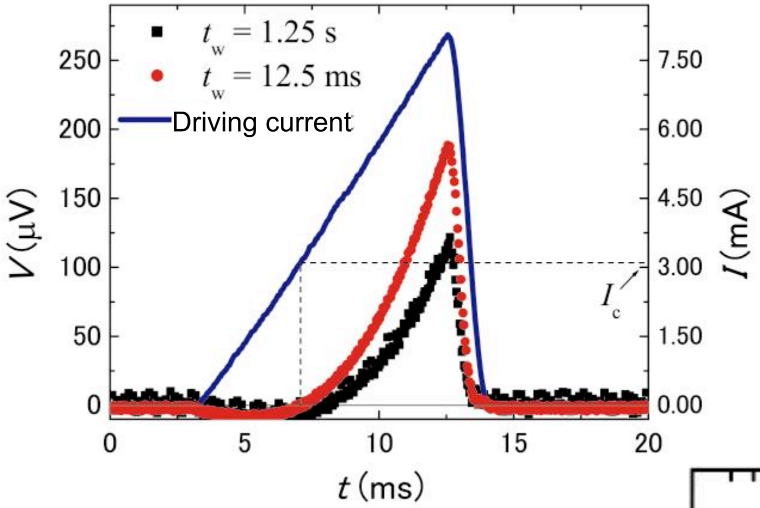


Measurement of $F_s(t_w)$

D. Nakamura *et al.*: arXiv 0906.3086.

	x	T_c (K)
# rectangular A	0.12	35.20
# rectangular B	0.15	35.06

Rectangular-type thin film

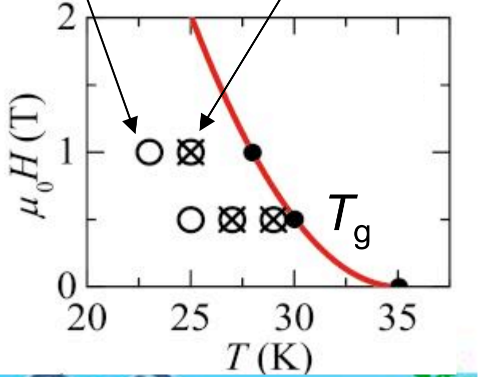


Waveforms become different with t_W

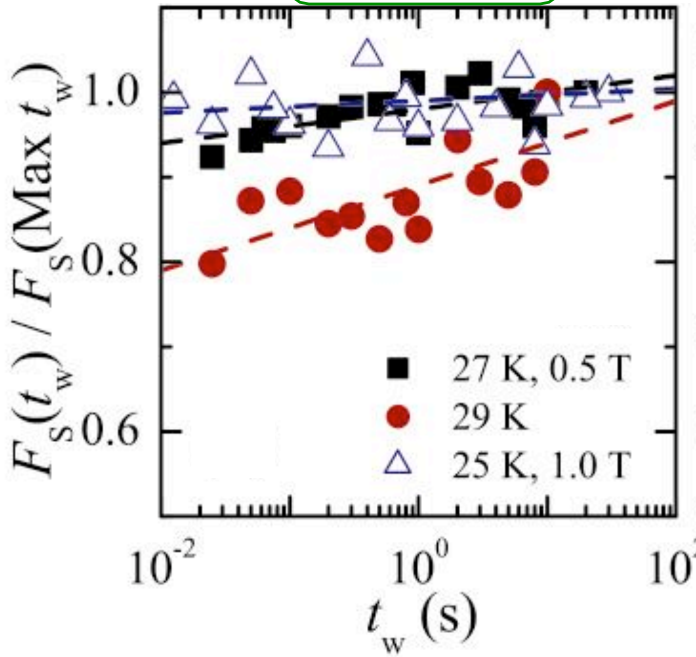
I_c depends on T → normalize by I_c(max t_W)

characteristic timescale

log t_w

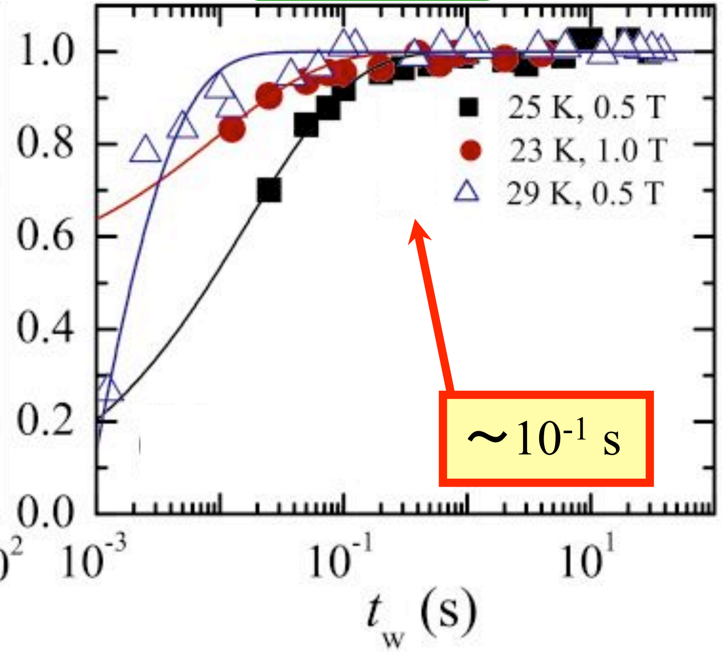


High *T*



Logarithmic

Low *T*

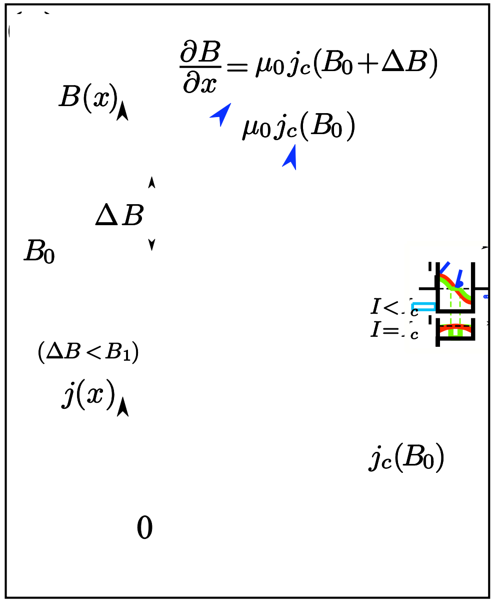


Characteristic timescale

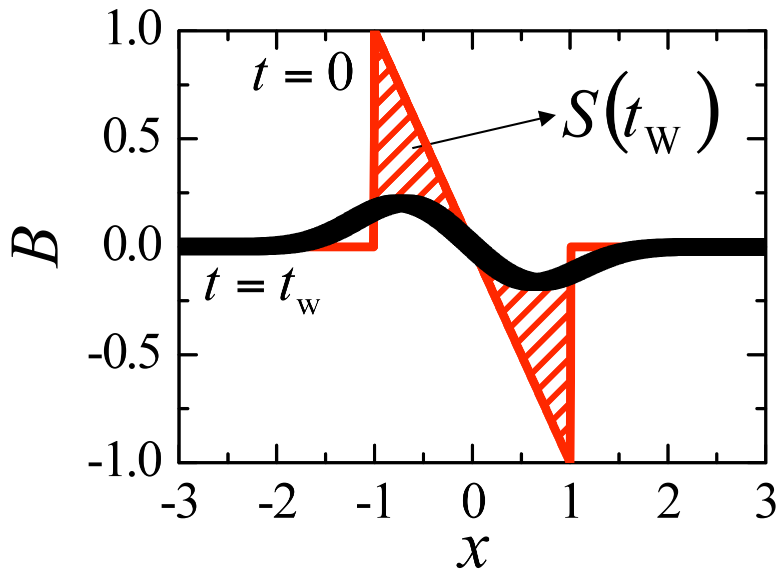
The origin of logarithmic dependence near T_g

Thermally Assisted Flux Flow

P. W. Anderson and Y. B. Kim, Rev. Mod. Phys. 36, 39(1964).
P. H. Kes *et al.*, Supercond. Sci. Technol. 1, 242(1989).



At $I < I_c$,
Critical state



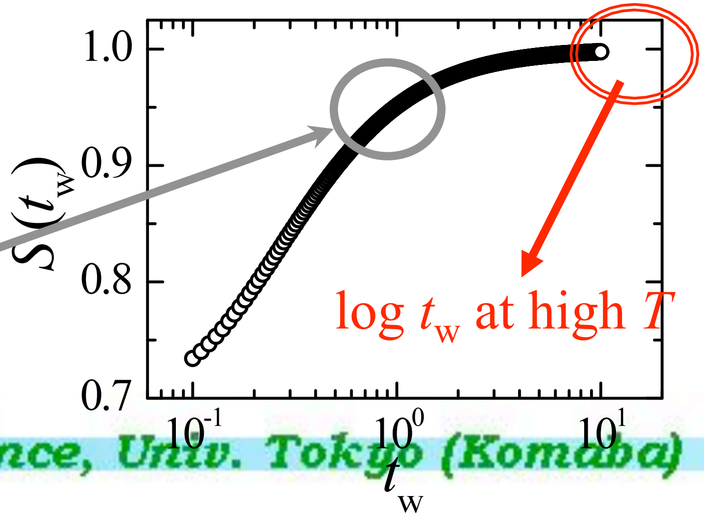
In TAFF region, spatial magnetic profile obeys diffusion equation of motion

$$\frac{\partial B}{\partial t} \approx \frac{c^2}{4\pi}\rho\Delta B$$

Blatter *et al.* RMP (94).

This timescale can be estimated as

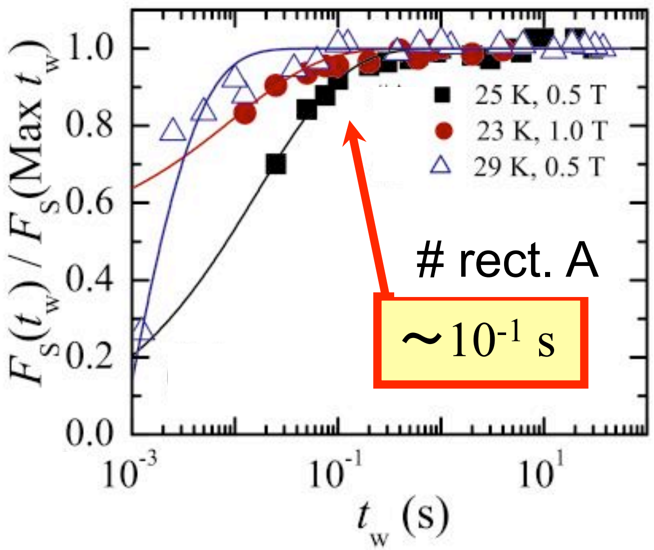
$$A_{sample}D^{-1} = A_{sample}\left(\frac{c^2}{4\pi}\rho\right)^{-1} \approx 5\times10^{-1}\ \mathrm{s}$$



D. Nakamura *et al.*: arXiv 0906.3086.

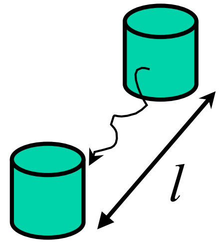
Rapid relaxation at low T with characteristic timescale

Low temp. Slow t_w^* cannot be explanined by the motion of a single vortex



Bundle relaxation

h : thickness, η: viscous coefficient
ξ: coherence length



$$E_{diffusion} \approx E_{depinning}$$

$$\boxed{h \cdot \eta \frac{l}{t_w^*} \cdot l} = \boxed{j_c \Phi_0 \cdot h \cdot \xi^*} \rightarrow l \approx \sqrt{\frac{j_c \Phi_0 t_w^* \xi^*}{\eta}}$$

energy loss by the viscous motion

depinning energy

$$\left.\begin{array}{l} t_w^* \approx 0.1\,\mathrm{s} \\ \eta \approx 5 \times 10^{-8}\ \mathrm{Ns/m^2} \\ j_c \Phi_0 \approx 3.62 \times 10^{-8}\ \mathrm{N/m} \\ \xi^* \approx 20\ \mathring{\mathrm{A}} \end{array}\right\} \rightarrow l \approx 12\ \mu\mathrm{m}$$

Length scale of coherent relaxation
(cf. vortex-vortex pacing : ~ 50nm)

Dynamic coherence length : 30μm

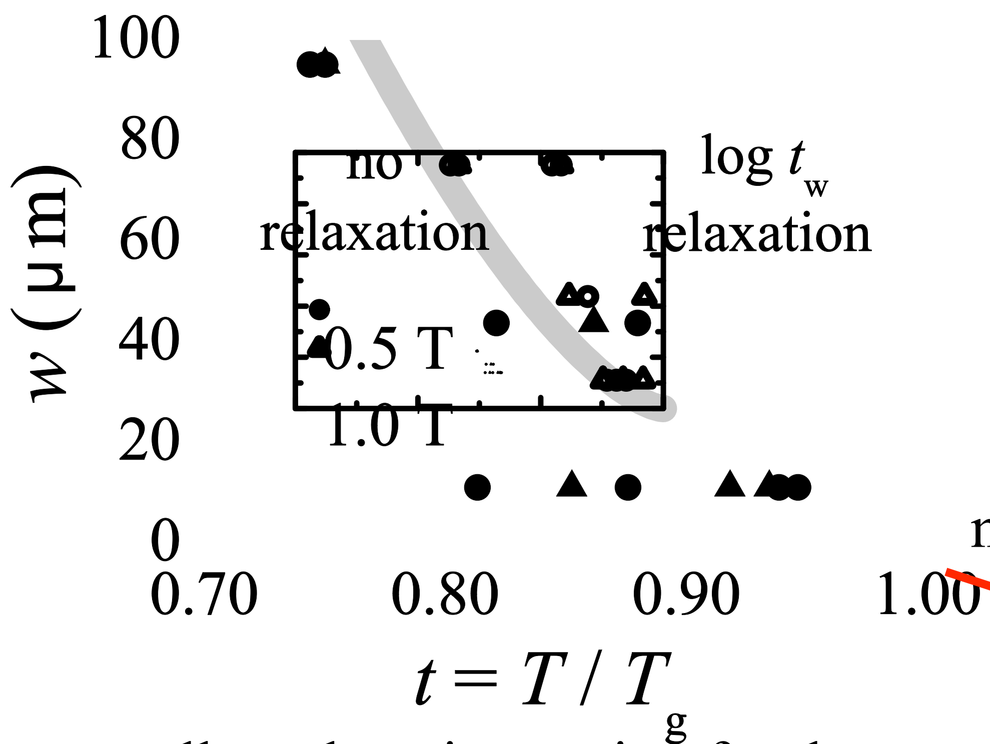
(from noise study in Bi-2212)
A. Maeda *et al.*, Phys. Rev. B 65, 054506 (2002).

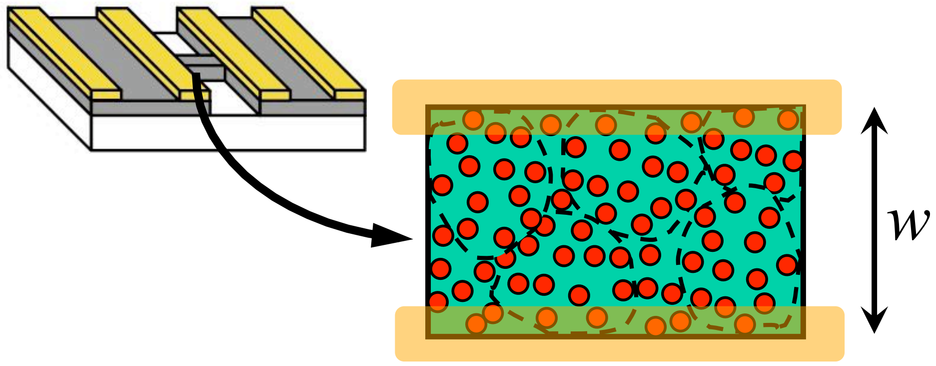
Bundle relaxation picture confirmed

D. Nakamura *et al.*: arXiv 0906.3086.

Size effect of the relaxation

crossover line of the relaxation





no relaxation by the edge pinning effect

$w_c \propto t^{1.5}$

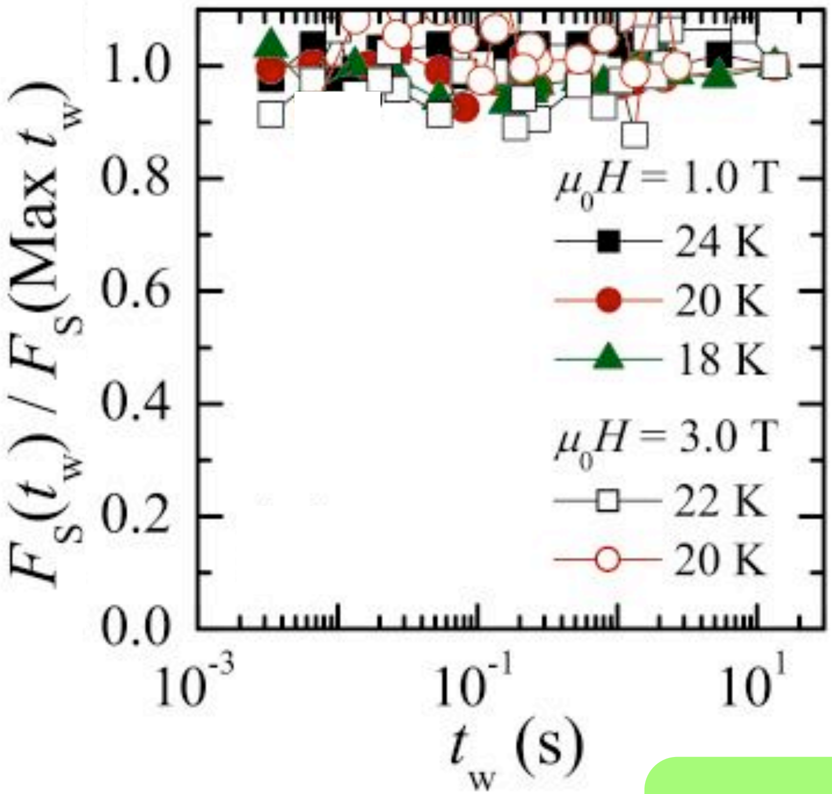
smaller relaxation region for the narrower bridge sample

Interplay between the size of coherent bundle and the system size crucially affects the validity of Amontons-Coulomb's law

D. Nakamura *et al.*: arXiv 0906.3086.

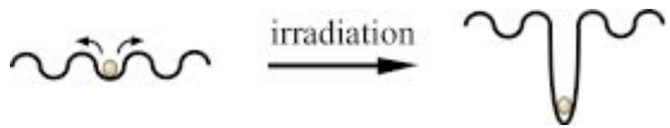
Bridge sample with columnar defects

	x	T_c (K)	B_Φ (T)
# Columnar	0.15	35.11	2.0



Dramatic changing for the relaxation

Sample with columnar defects → no relaxation at all



Strong pinning force also leads to the Amontons-Coulomb's type friction

D. Nakamura *et al.*: arXiv 0906.3086.

Summary of $F_s(t_w)$ experiments

The size of vortex bundle →

	high T	low T
Rectangular film	**log t_w**	**characteristic timescale**
Bridge film	**log t_w**	**no relaxation**
Bridge film with columnar defects	**no relaxation**	**no relaxation**

size effect

columnar pin effect

The origin of the relaxation phenomena

Thermally Assisted Flux Flow of vortex bundle

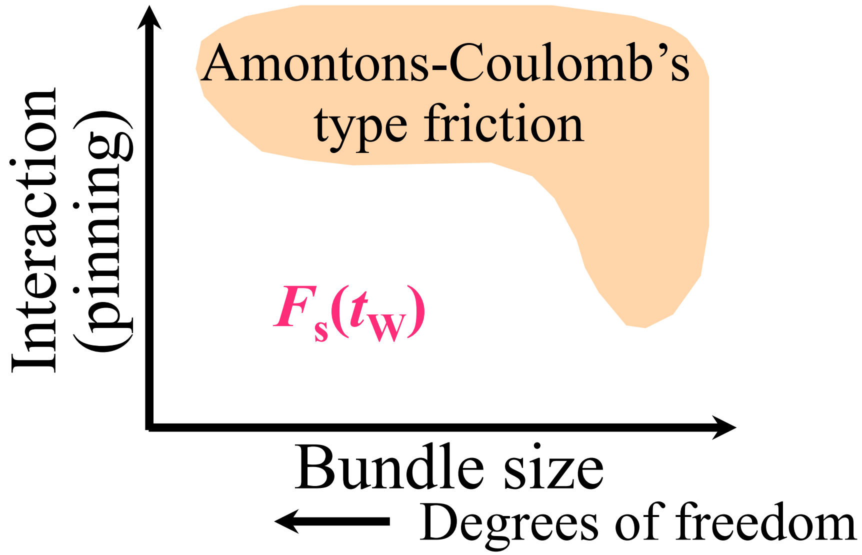
Bundle size determines the characteristic timescale

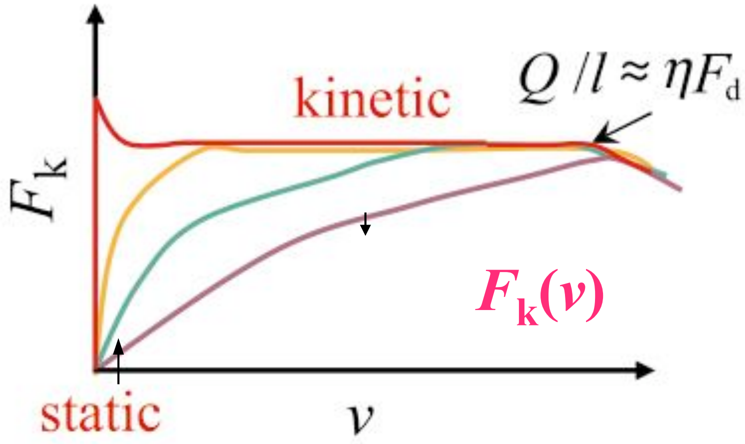
no relaxation ⟺ very strong pinning center

(Amontons-Coulomb like)

D. Nakamura *et al.*: arXiv 0906.3086.

Our achievements on this model approach





Key parameters of the validity of Amontons-Coulomb's law

- pinning strength and thermal fluctuation
- size of the coherently moving object and system size

a universal parameter : $C \equiv \frac{L}{R_c} \exp\left[-U/k_B T_{\mathrm{eff}}\right] \quad T_{\mathrm{eff}} \propto T/L^3$

a criteria of the validity of A-C law : $C << C_{cr}, \quad C_{cr}$: critical value

Friction *vs* ac dynamics

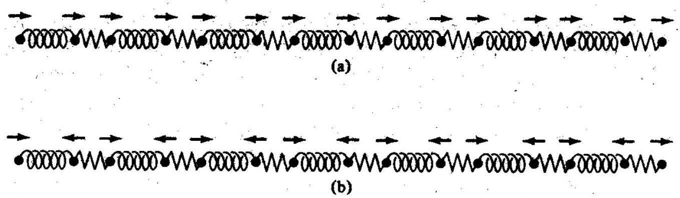
Friction at the interface ⟺ Dissipation by elementary excitation at the interface

Ac dynamics at the interface
***vs* microscopic understanding of friction**

1) Importance of lattice dynamics
   - Phonons
   - Phonons in disordered systems
   - Corresponding excitations in CDWs and vortices in SC

2) data at μ-waves for vortices

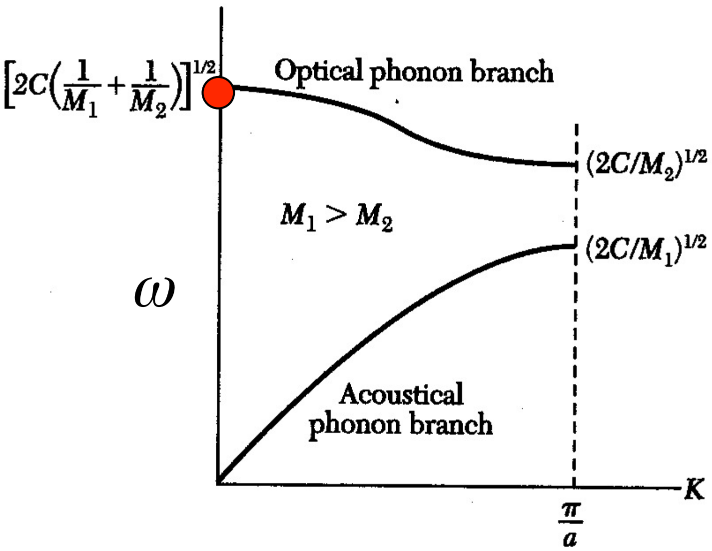
Normal modes by periodic array of atoms: Phonon

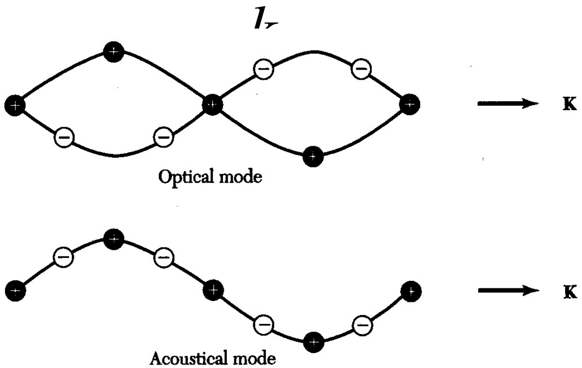


$\omega = \omega(k)$ Dispersion relation

ω Angular frequency

k Wave number (well defined)





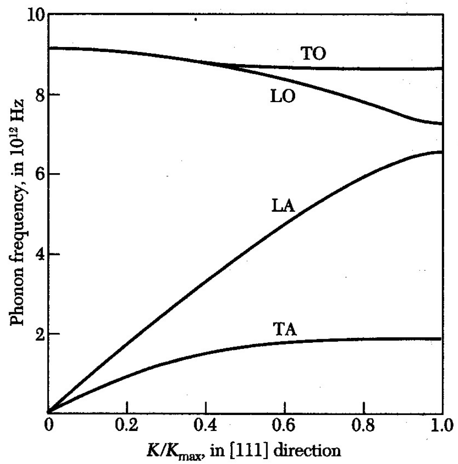


Figure 8a Phonon dispersion relations in the [111] direction in germanium at 80 K. The two TA phonon branches are horizontal at the zone boundary position, $K_{max} = (2\pi/a)(\frac{1}{2}\frac{1}{2}\frac{1}{2})$. The LO and TO branches coincide at $K = 0$; this also is a consequence of the crystal symmetry of Ge. The results were obtained with neutron inelastic scattering by G. Nilsson and G. Nelin.

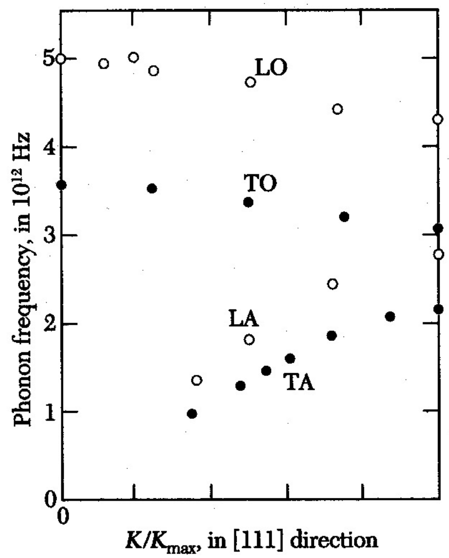


Figure 8b Dispersion curves in the [111] direction in KBr at 90 K, after A. D. B. Woods, B. N. Brockhouse, R. A. Cowley, and W. Cochran. The extrapolation to $K = 0$ of the TO, LO branches are called ω_T, ω_L.

(C. Kittel : "Introduction to Solid State Physics")

Optical response by a bound mode: Lorentz oscillator

$$\boxed{m\ddot{x} + m\Gamma\dot{x} + m\omega_0{}^2 x = -eEe^{i\omega t}}$$

$$\boxed{\tilde{\varepsilon} = 1 + \frac{Ne^2}{\varepsilon_0 m}\frac{1}{(\omega_0{}^2 - \omega^2) - i\Gamma\omega}}$$

$$\tilde{\varepsilon} \equiv \varepsilon_1 + i\varepsilon_2$$

$$\varepsilon_1 = 1 + \frac{Ne^2}{\varepsilon_0 m}\frac{(\omega_0{}^2 - \omega^2)}{(\omega_0{}^2 - \omega^2)^2 + (\Gamma\omega)^2}$$

$$\varepsilon_2 = \frac{Ne^2}{\varepsilon_0 m}\frac{\Gamma\omega}{(\omega_0{}^2 - \omega^2)^2 + (\Gamma\omega)^2}$$

$$\sigma_1(\omega) = \omega\varepsilon_2(\omega) \propto \omega^2$$

for small ω

(F. Wooten : "Optical Properties of Solids")

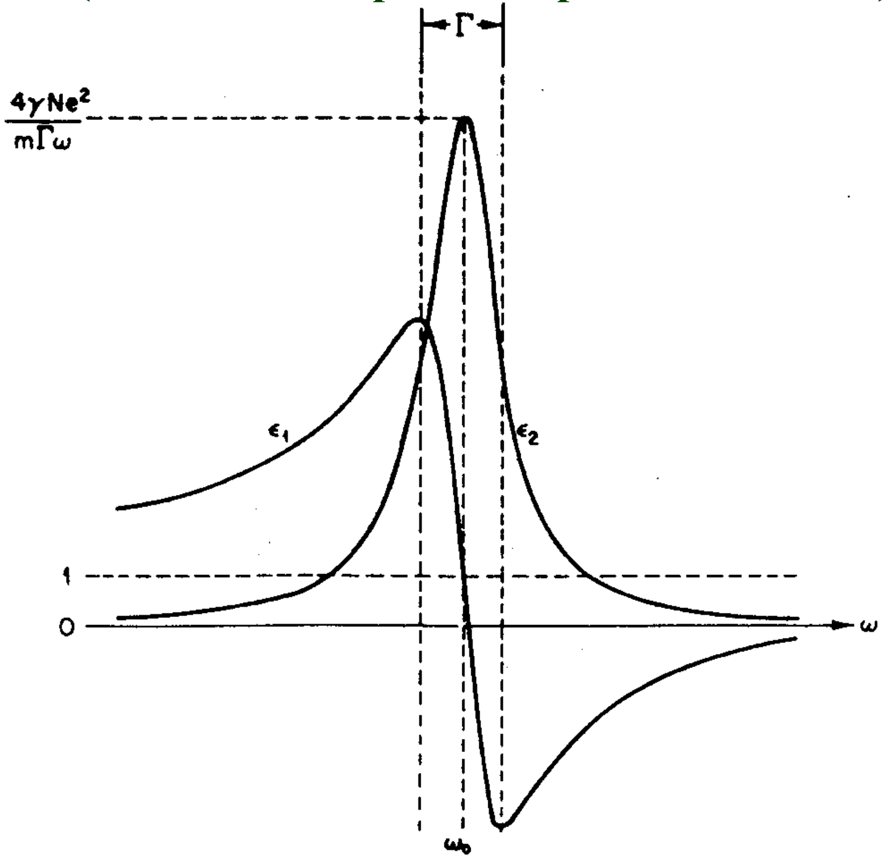


Fig. 3.1 Frequency dependence of ε_1 and ε_2.

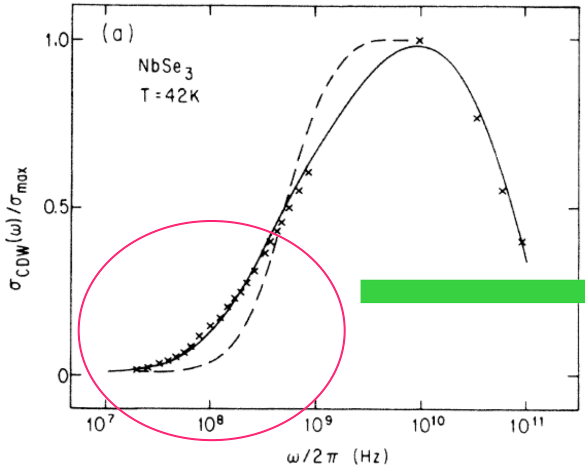
For pinned CDW

H. Fukuyama and P. A. Lee : Phys. Rev. B17 (1978) 535.

P. A. Lee, T. M. Rice and P. W. Anderson: SSC 14 (1974) 703.

Experiments in CDWs

(D. Reagor *et al.*: Phys. Rev. B34 (1986) 2212.)



(W. Wu *et al.*: Phys. Rev. Lett. 52 (1984) 2382.)

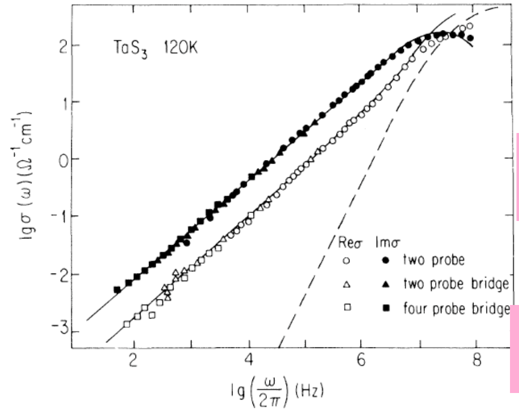


FIG. 1. Re$\sigma(\omega)$ and Im$\sigma(\omega)$ vs frequency at $T=120$ K. The dc conductivity has been subtracted from Reσ. The full lines represent the Cole-Cole-like expression, Eq. (7), with $\alpha=0.87$ and $\tau^{-1}/2\pi=25$ MHz. The dashed line gives the low-frequency limit of the harmonic oscillator response, Re$\sigma \propto \omega^2$.

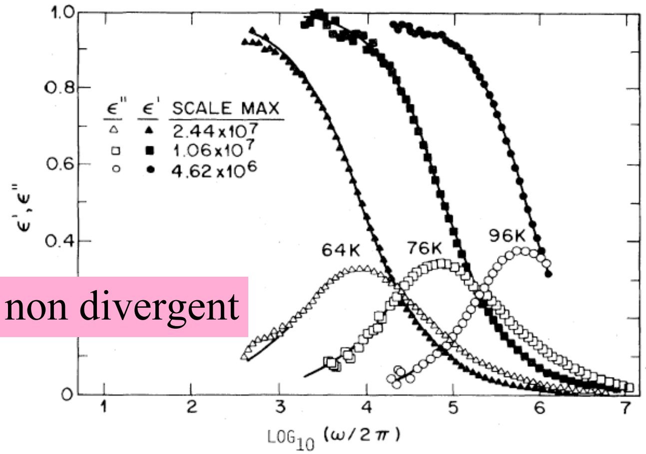
$$\sigma_1(\omega) \propto \omega^{\alpha}$$

$$\alpha \cong 0.8$$

$$\varepsilon_2(\omega) \propto \omega^{-(1-\alpha)}$$

divergent

(R. J. Cava *et al.*: Phys. Rev. B30 (1984) 3228.)



ε_2 non divergent

FIG. 6. Frequency dependence (log scale) of the real and imaginary parts of the dielectric constants for the pinned CDW in $K_{0.3}MoO_3$ for three representative temperatures. Solid lines are from the fits of Eq. (2) to the data.

(R. J. Cava *et al.*: Phys. Rev. B31 (1985) 8325.)

strongly amplitude dependent

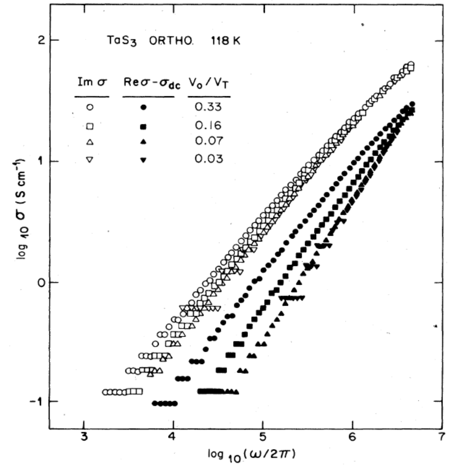


FIG. 1. Low-frequency conductivity of orthorhombic TaS$_3$ at 118 K as a function of ac signal level (rms). Open symbols imaginary σ; closed symbols real $\sigma-\sigma_{dc}$.

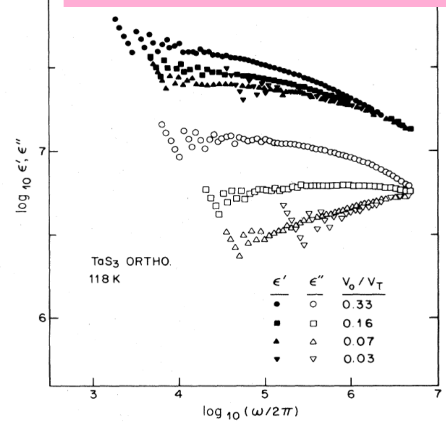


FIG. 2. Low-frequency dielectric response of orthorhombic TaS$_3$ at 118 K as a function of ac signal level (rms). Open symbols: $\epsilon''(\omega)$, closed symbols: $\epsilon'(\omega)$.

(also J. P. Stokes *et al.*: Phys. Rev. B32 (1985) 6939.)

Mean-field model of vortex motion

P. Martinoli *et al*. Physica B 165&166, 1163 (1990),
M. W. Coffey and J. R. Clem: PRL 67 (1991) 386, PRB 45 (1992) 9872.

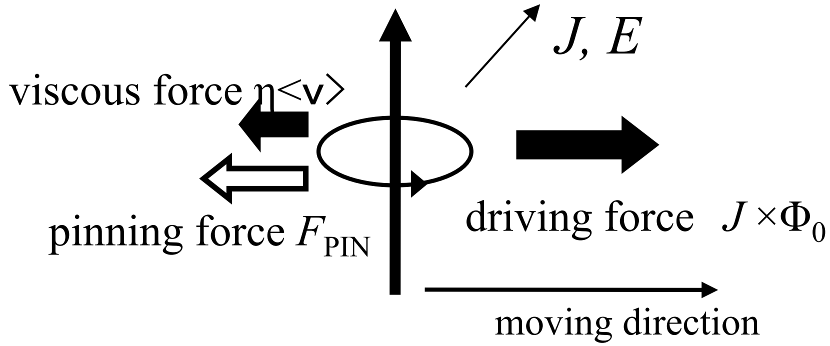
$$\boxed{\eta \dot{\mathbf{u}}(\mathbf{r},t) + \kappa_p \mathbf{u}(\mathbf{r},t) = \mathbf{j}(\mathbf{r},t) \times \Phi_0 \hat{\mathbf{a}} + f_T(t)}$$

massless
overdamped

$$\mathbf{j} = \mathbf{j}_\mathrm{n} + \mathbf{j}_\mathrm{s}$$

$$\mathbf{j}_n = \sigma_{nf}\mathbf{E}$$

$$\mathbf{j}_\mathrm{s} = -\frac{1}{\mu_0 \lambda_l^2}\mathbf{A} + C_o \nabla \varphi$$



$$C_0 = \frac{\Phi_0}{2\pi\mu_0\lambda^2}$$

remarks

(a) Magnus force, vortex-vortex interaction are not considered.

(b) Vortex mass is considered to be zero.

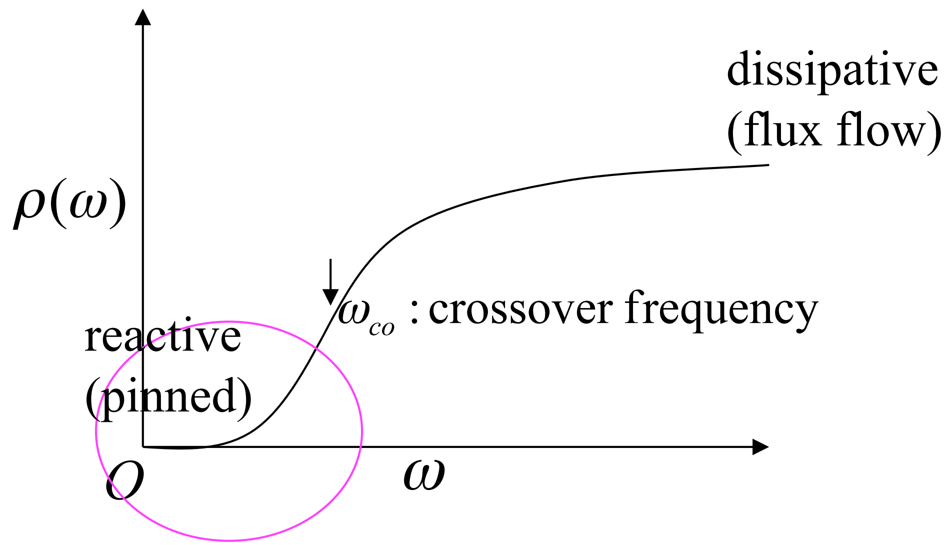
(c) Condensate wave function is considered to be *s*-wave.

(d) From microscopic point of view, the two-fluid picture is not a good approximation.
(Eschrig-Rainer-Sauls)

Ac resistivity by the vortex motion

$$E(\omega) = \rho(\omega)\, j(\omega)$$

$\rho(\omega)$: resistivity



ω^2 ?

ω^α ? (ε_2 divergent)

strongly nonlinear (amplitude dependent)?

Our expectation

Non AC like

$\rho(\omega)$

Weaker pinning

Smaller bundle size

Digergent $\varepsilon(\omega)$

Remarkable nonlinearity

Stronger pinning

Larger bundle size

Lorentz-oscillator like $\varepsilon(\omega)$

no nonlinearity

AC like

Experiments in vortices in superconductors (THz)

overdamped

B. Parks *et al.* Phys. Rev. Lett. 74 (1995) 3265.

YBCO

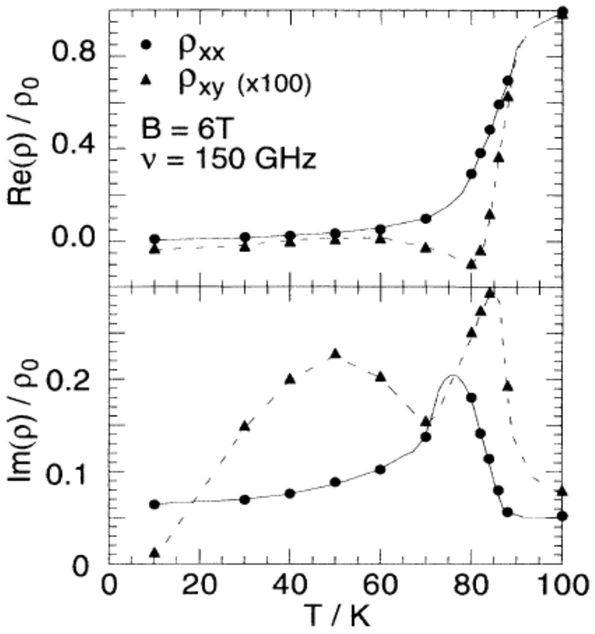


FIG. 1. Real and imaginary parts of ρ_{xx} and ρ_{xy}. Despite scaling by 10^2, the sign changes in ρ_{xy} from negative to positive near 70 K and back to negative near 20 K are barely discernable. All resistivities are normalized to ρ_0, the dc resistivity at 100 K. The data shown correspond to the 40 nm film on $LaAlO_3$. The lines are guides to the eye.

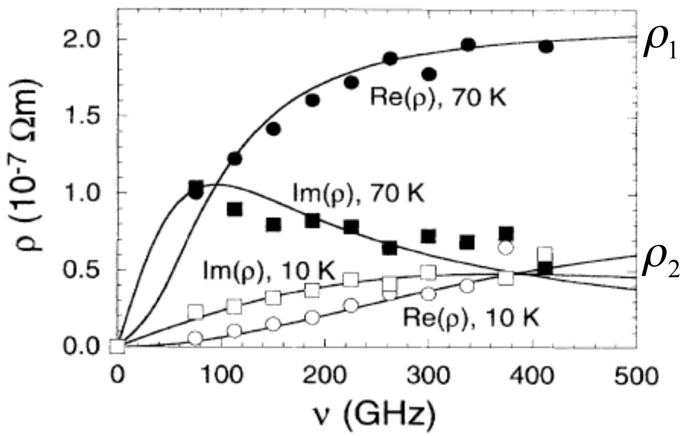


FIG. 2. The vortex contribution to the resistivity plotted vs frequency at 10 and 70 K for $B = 6$ T. The lines are fits to the data using Eq. (3a). The data shown were taken on the 70 nm film on CeO_2/Al_2O_3.

$$X_v = \omega \phi_0 B / \kappa$$

$$\Gamma \equiv \kappa / \eta$$

$$\rho_v^{xx} = i X_v \frac{(1 + i\omega/\Gamma)}{(1 + i\omega/\Gamma)^2 - (\alpha\omega/\kappa)^2},$$

$$\rho_v^{xy} = X_v \frac{\alpha\omega/\kappa}{(1 + i\omega/\Gamma)^2 - (\alpha\omega/\kappa)^2},$$

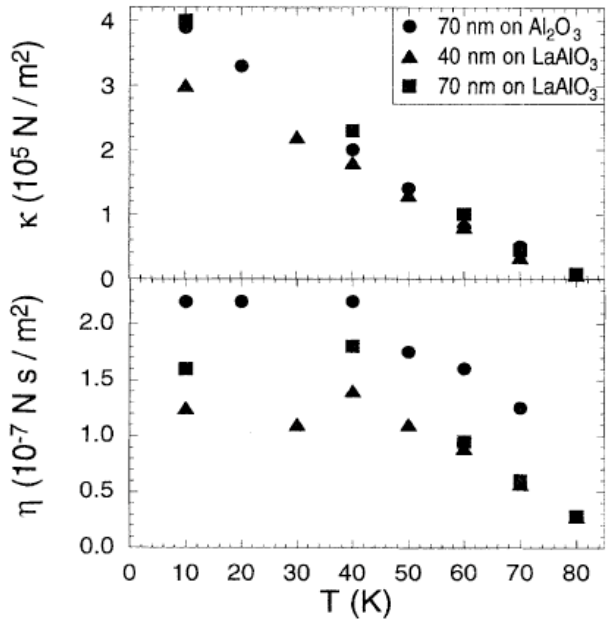


FIG. 3. The vortex pinning and damping parameters κ and η plotted as functions of temperature for all three samples.

Experiments in vortices in superconductors (μ-wave)

overdamped

Conventional superconductor

Pb-In, Nb-Ta

(J. C. Gittleman and B. Rosenblum: Phys. Rev. Lett. 16 (1968) 734.)

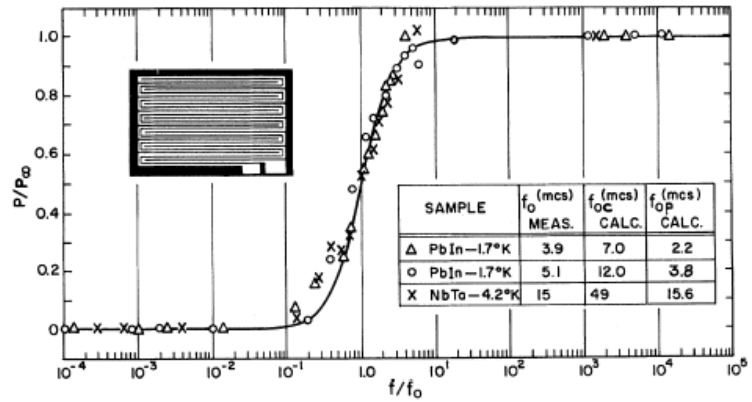
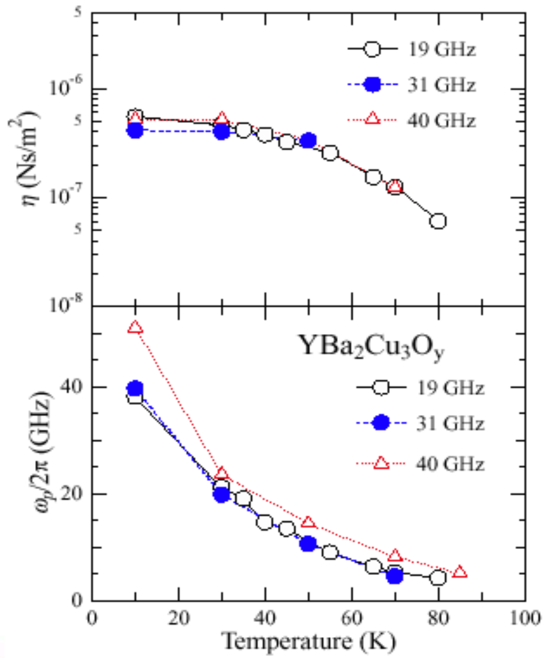


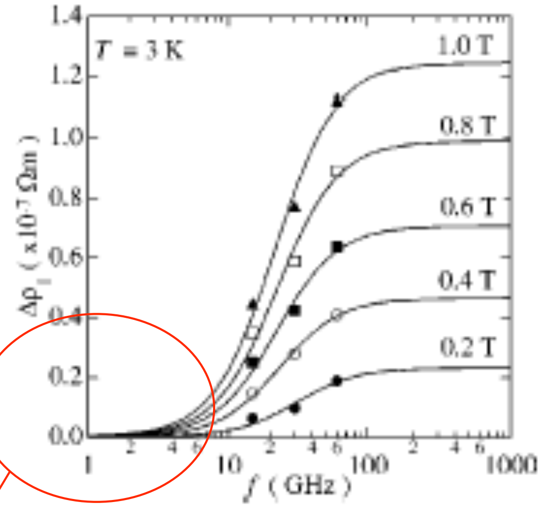
FIG. 1. Power absorption in the mixed state for subcritical currents as a function of frequency. Points at very high frequencies are microwave data taken on other samples of the same materials.

High-T_c superconductor

(Y. Tsuchiya *et al.*: Phys. Rev. B63 (2001) 184517-1.) **(Y. Matsuda *et al.*: PRB66(2002)014527.)**



YBCO TBCO



Well described by the mean-field model with field independent ω_{co}

Seems to exhibit no apparent nonlinearity at present

Need to be investigated systematically in more detail

Ac impedance of SC: vortex motion plus superfluid

M. W. Coffey and J. R. Clem, PRL 67, 386 (1991).

$$\rho(\omega) = \frac{\rho_{\text{vortex}}(\omega) + i\mu_0\omega\lambda^2}{1 + 2i\boxed{\lambda^2 / \delta_{\text{nf}}(\omega)^2}}$$

$\boldsymbol{\delta}_{\text{nf}}$: normal-fluid skin depth
$\boldsymbol{\lambda}$: penetration depth

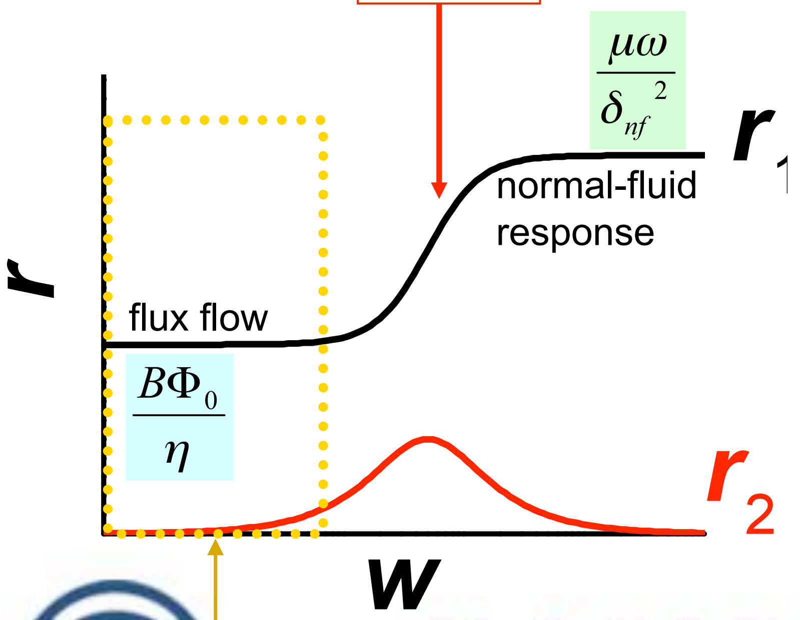
$$\rho_{\text{vortex}}(\omega) = \frac{B\Phi_0}{\eta}\left[\frac{\varepsilon(\omega) + (\omega\tau_p)^2 + i(1-\varepsilon(\omega))\omega\tau_p}{1+(\omega\tau_p)^2}\right] \approx \frac{B\Phi_0}{\eta}$$

Parameters

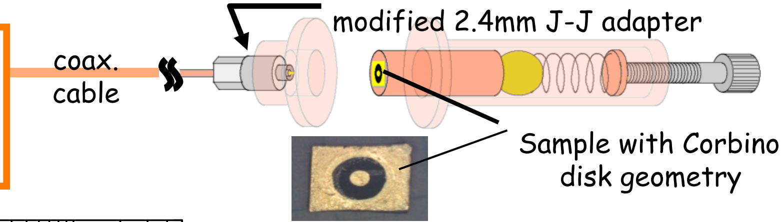
$\boldsymbol{\eta}$: viscous drag coeff.
$\boldsymbol{\tau}_p^{-1}$: pinning frequency
$\boldsymbol{\varepsilon}$: flux-creep factor
(from $\boldsymbol{\rho}_1$)

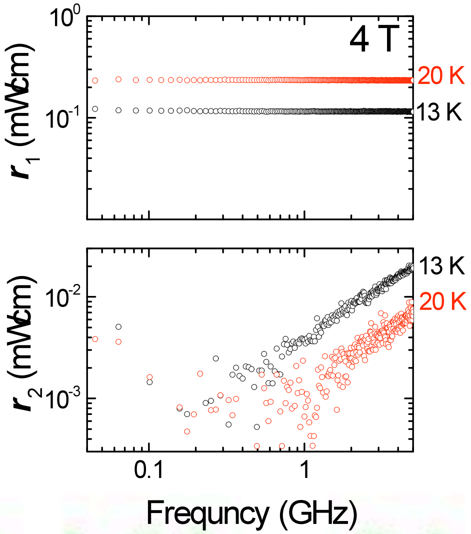
$\boldsymbol{\lambda}$: penetration depth — from $\boldsymbol{\rho}_2$

$\lambda < \delta_{\text{nf}}$ ← $\lambda \approx \delta_{\text{nf}}$ → $\lambda > \delta_{\text{nf}}$



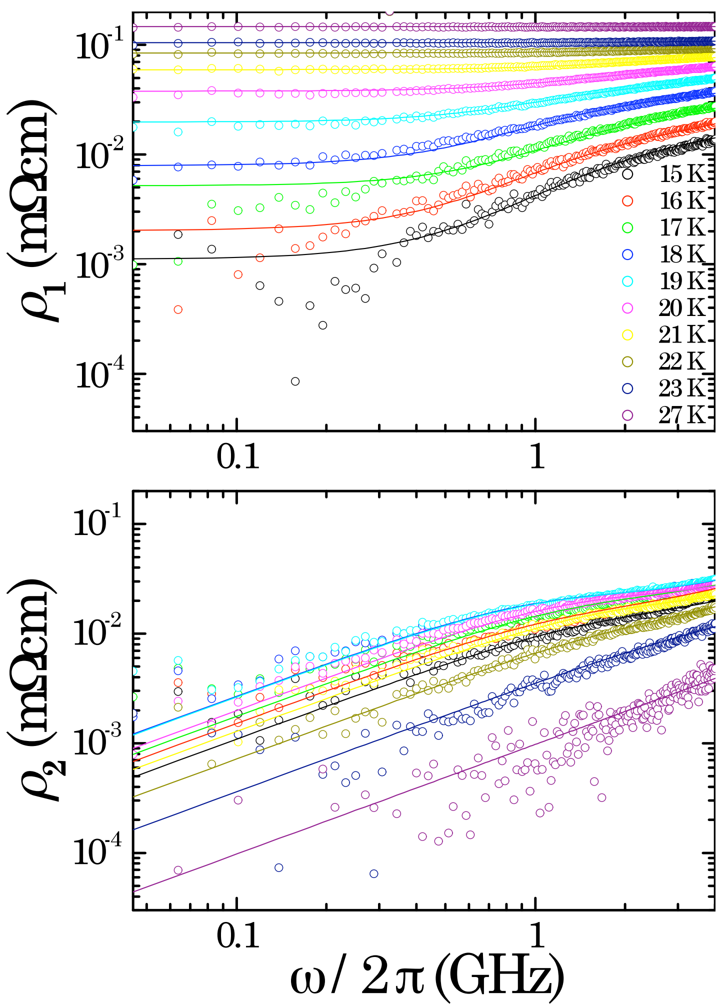
Measurement of $S_{11}(\omega)$
by
Vector Network
Analyzer



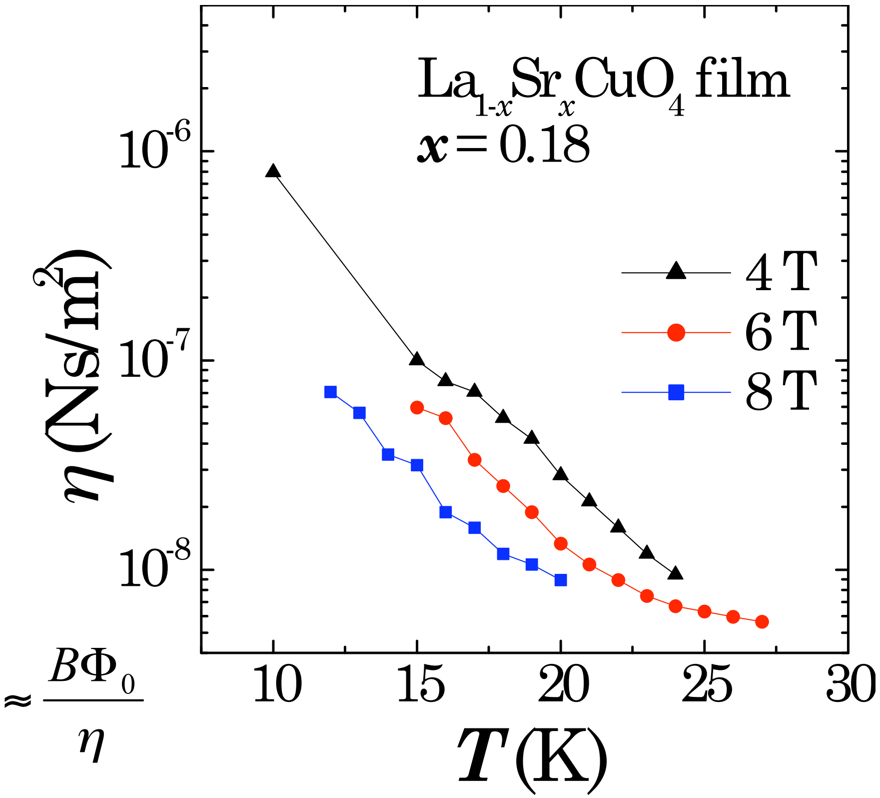


$$d\rho_1 / dT \sim 0$$
$$d\rho_2 / dT > 0$$
$$\downarrow$$
$$\lambda << \delta_{\text{nf}}$$

LSCO: viscous drag η



$$\rho_{vortex} \approx \frac{B\Phi_0}{\eta}$$



$$\rho = \frac{\rho_{\mathrm{vortex}} + i\mu_0\omega\lambda^2}{1 + 2i\left(\lambda/\delta_{\mathrm{nf}}\right)}$$

Dissipation: similar to other cuprates (YBCO, BSCCO *etc.*)

$$\boxed{\ell_{core} \approx \xi_{GL} << \ell}$$

Y. Tsuchiya *et al.*: PRB 63 (2001) 184517.

A. Maeda *et al.*: JPSJ 76 (2007) 094708.

A. Maeda *et al.*: Physica C 460-562 (2007) 1201.

η depends on B.

Conclusion

（1）**Discuss dynamics of driven vortices and physics of friction utilizing driven vortices of superconductor**

（2）**Kinetic friction as a function of velocity:**

understood in terms of simple overdamped oscillator model

Broadened transition of dynamic phase transition (Amontons-Coulomb behavior)

suggesting the importance of thermal fluctuation for microscopic friction

（3）**Static friction as a function of waiting time: relaxation of vortex bundle**

stronger pinning, large bundle size ⇔ Amontons-Coulomb like behavior

（4）**Criteria for the validity of Amontons-Coulomb friction**

Presence of a universal parameter : $C \equiv \frac{L}{R_c} \exp\left[-U/k_B T_{\mathrm{eff}}\right] \quad T_{\mathrm{eff}} \propto T/L^3$

$$\boxed{C << C_{cr}, \quad C_{cr} : \text{critical value}}$$

（5）**Ac dynamics (μ-wave to THz) of vortices**

no remarkable anomaly nor nonlinearity such as CDW system at present

Future perspective

（1）Change pinning, system size more systematically

introduce stick-slip motion in driven vortices

change velocity dependence of kinetic friction largely

Feedback to physics of friction

ー Basic step for understanding friction, control of friction ー

（2）Need to investigate

correspondence between ac dynamics and other friction properties

ー comparative studies of $F_k(v)$, $F_s(t_w)$ and $\sigma(\omega)$ ー