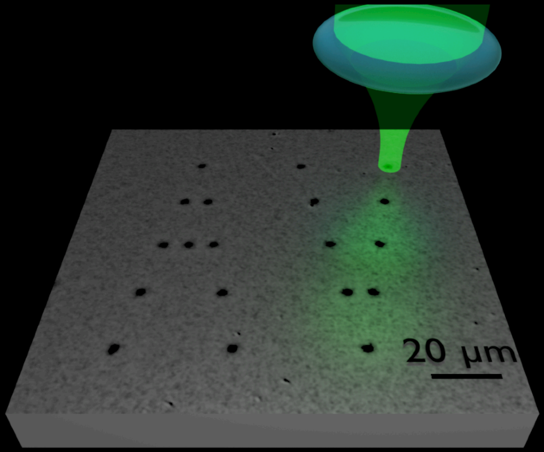
Optical Manipulation of Single Flux Quanta



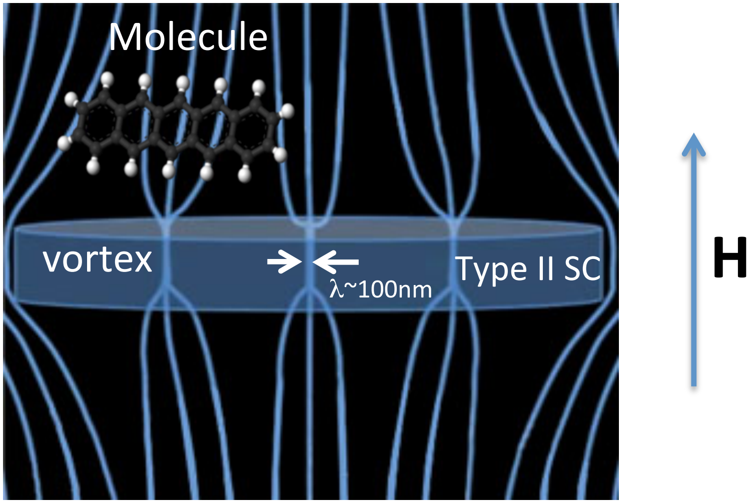
I. Veshchunov, W. Magrini, S. Mironov, A. Godin, J.-B. Trebbia,
A. Bouzdine, Philippe Tamarat & Brahim Lounis

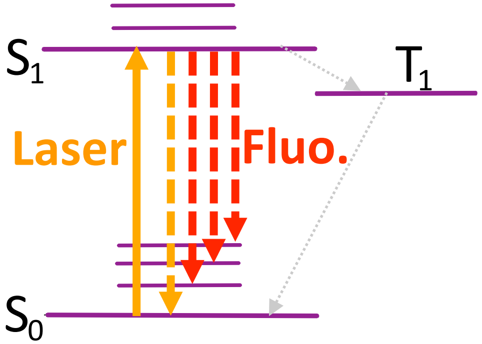
Initial motivation

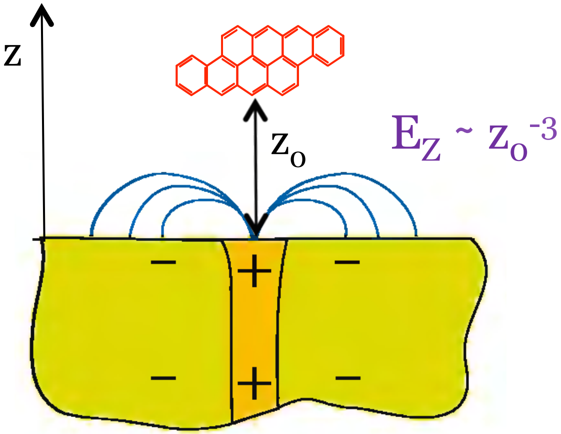
Bring a direct experimental proof of an electric charge accumulation in a vortex core, with single molecule optical spectroscopy/microscopy.

$\Phi_0 = h/2e$

$\sim 2.\ 10^{-15}$ Wb





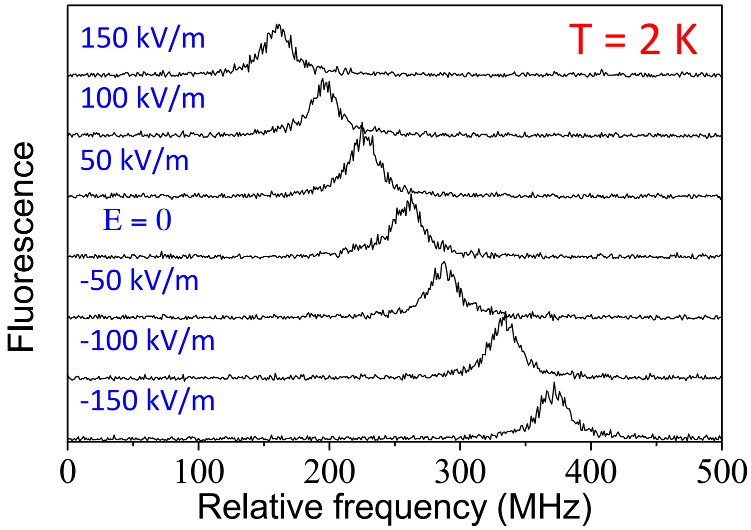


At $z_0 = 20$ nm, E ~ 10 kV/m

→ expected spectral shift by a linewidth ~20MHz

M. Fauré et al. EPL, 77 (2007) 17005

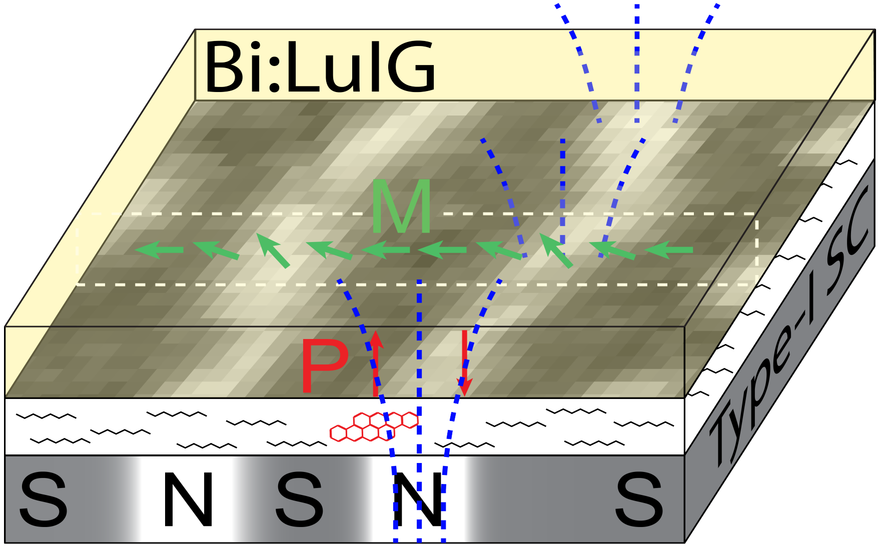
High quality factor, linear Stark effect



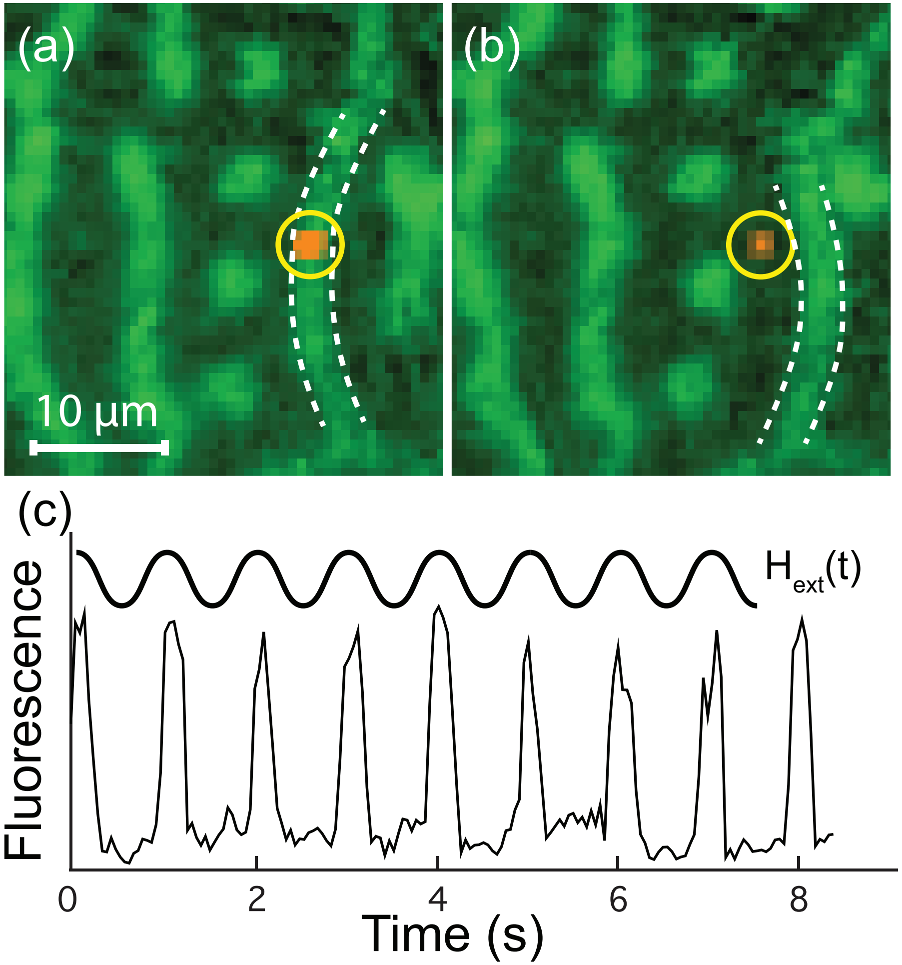
Evidence of the flexomagnetoelectric effect

In cycloid magnetic defects such as Néel domain walls:

$$\vec{P} = \gamma\chi_e\left[\left(\vec{M}\cdot\vec{\nabla}\right)\vec{M} - \vec{M}\left(\vec{\nabla}\cdot\vec{M}\right)\right]$$



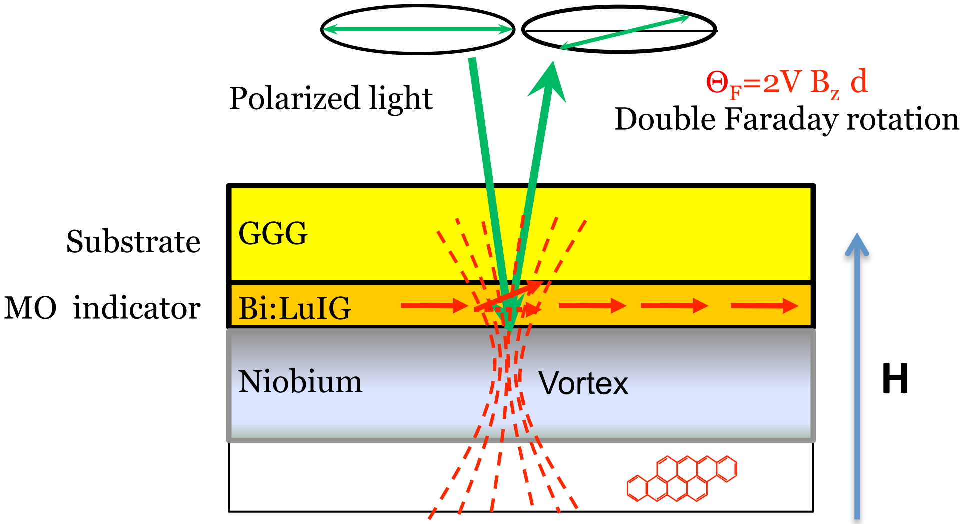
Single molecule fluorescence imaging +
Magneto-optical imaging of N, S domains



Veshchunov et al., Phys. Rev. Lett. 115 (2015) 027601

Magneto-optical imaging of vortices

Following *Goa et al., Rev. Sci. Instrum. 74 (2003) 141.*



Polarized light

$\Theta_F=2V B_z d$

Double Faraday rotation

Substrate

GGG

MO indicator

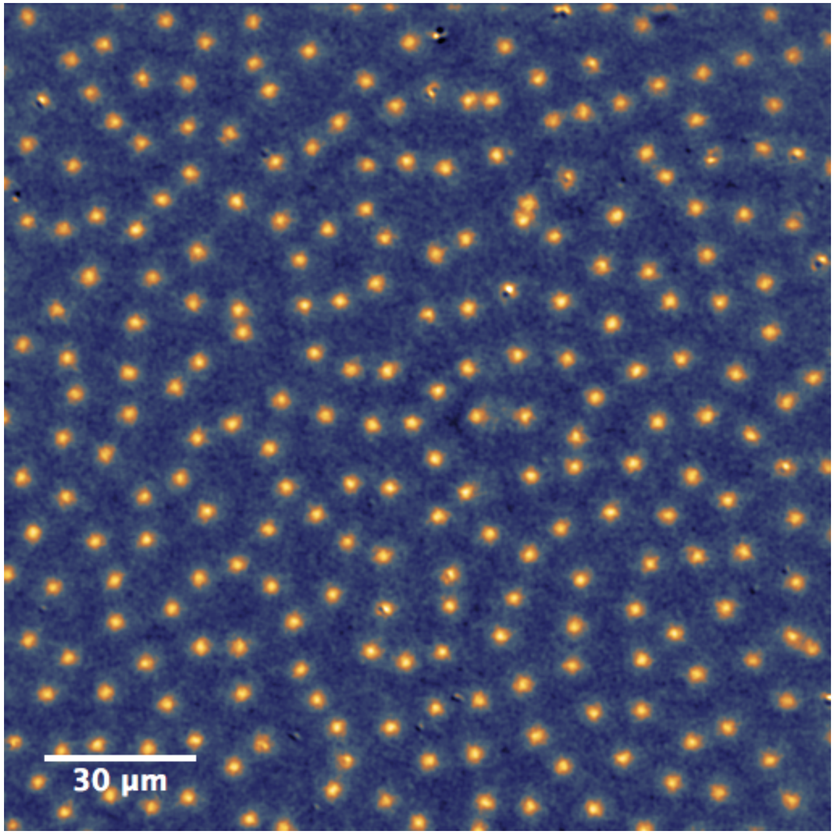
Bi:LuIG

Niobium

Vortex

H

Flux quantum $\phi_0=h/2e$



Niobium film, thickness 90 nm

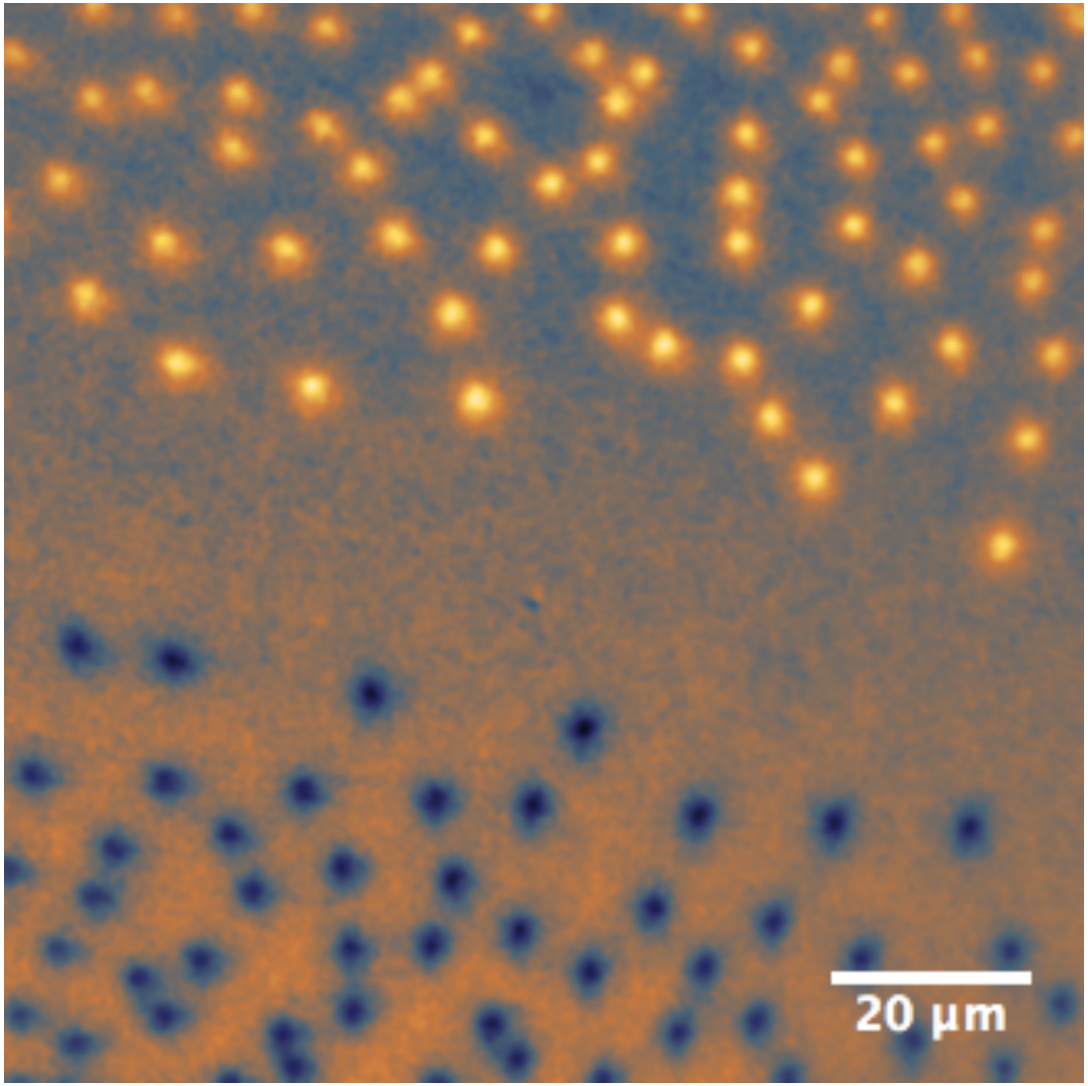
H_{ext} = 0.22 Oe, T = 4.6 K

Bi:LuIG, 2.5 µm thickness,

Verdet constant 0.06 °.mT^{-1}.μm^{-1}

Magnetic field control of the vortex density

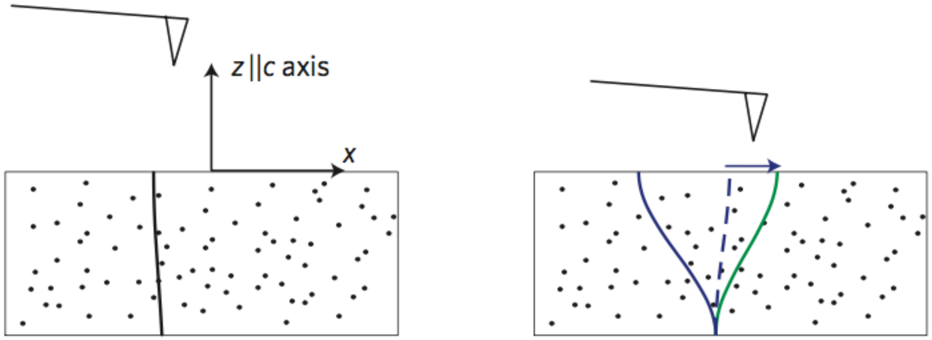
Niobium film cooled in an inhomogeneous magnetic field



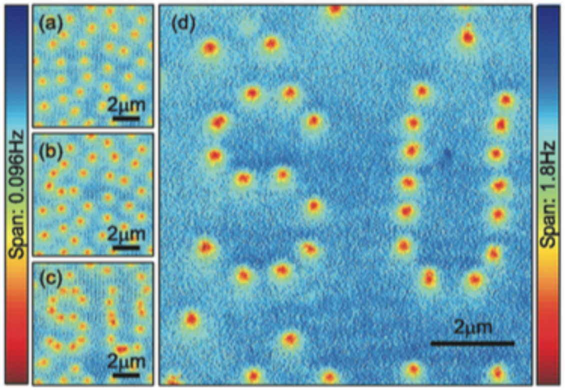
T = 4.6 K

Methods for single vortex manipulation

Magnetic force microscopy

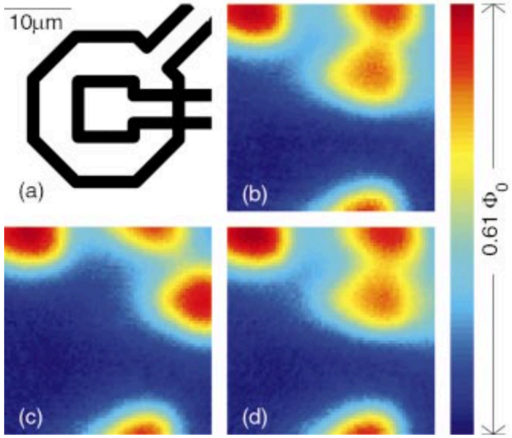


Auslaender et al. *Nat Phys 5 (2009) 35*



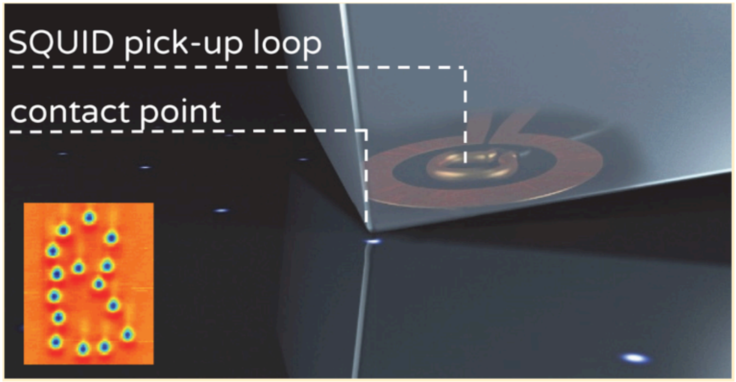
Straver et al., *Appl. Phys. Lett. 93 (2008) 172514*

SQUID microscopy



Gardner et al., *Appl. Phys. Lett. 80 (2002) 1010*
Kalisky et al, *Phys. Rev. B 83 (2011) 064511*

Strain induced microscopy



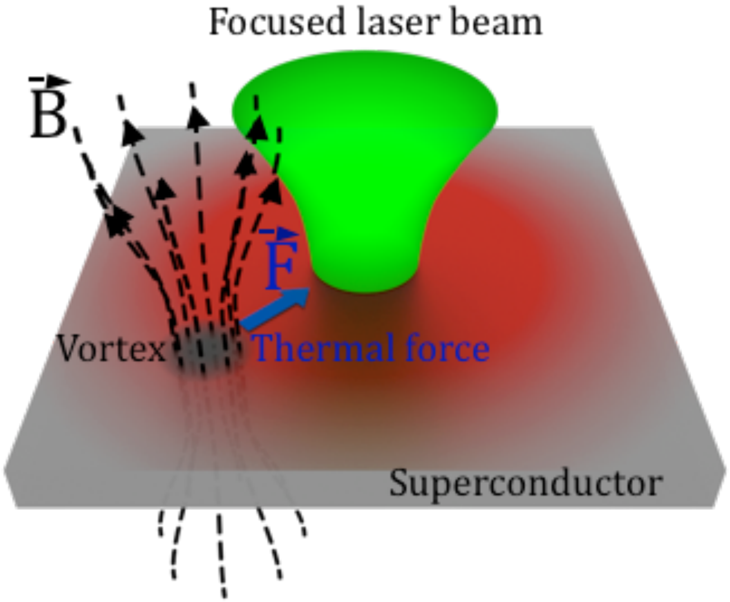
Kremen et al., *Appl. Phys. Nano Lett. 16 (2016) 1626*

Vortices in a thermal gradient

Global vortex flows induced by thermal gradients demonstrated 50 years ago.

Interpretation: vortex cores behave as entropy-carrying particles, in search for colder places.

Otter & Solomon, *Phys. Rev. Lett. 16 (1966) 681*;
Huebener & Seher, *Phys. Rev. 181 (1969) 701*.



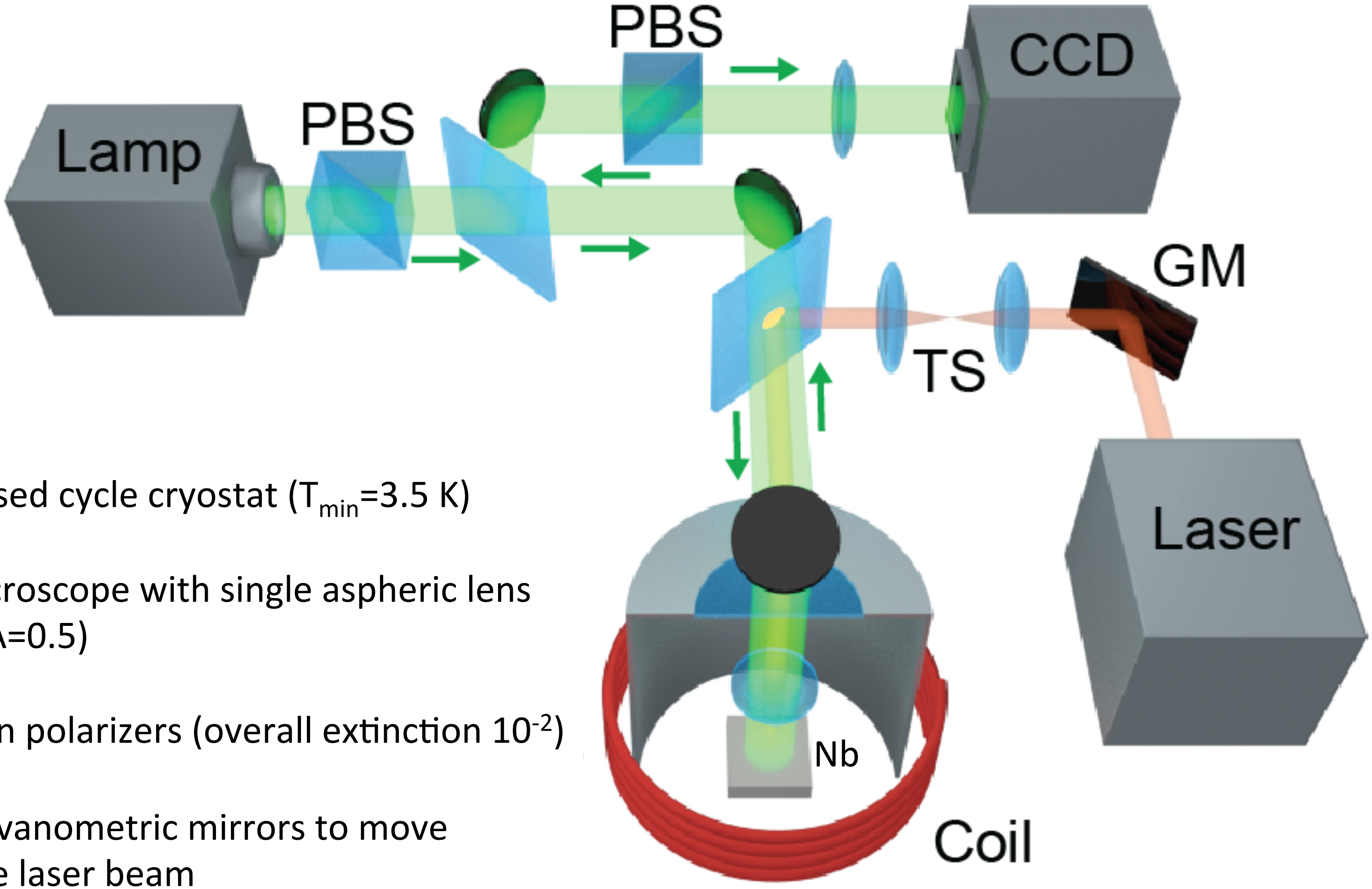
In the limit $\kappa = \lambda/\xi >> 1$, the contribution of the core to the free energy of a vortex is negligible.

Free energy of a vortex : $U = \frac{\Phi_0^2}{4\pi\mu_0\lambda^2}\ln(\kappa)$

where $\lambda = \lambda_0/\sqrt{1 - T/T_c}$ for T close to T_c.

The thermal force $\mathbf{F} = \frac{\Phi_0^2}{4\pi\mu_0\lambda_0^2}\ln(\kappa)\frac{\boldsymbol{\nabla}T}{T_c}$ drives the vortex towards hot regions.

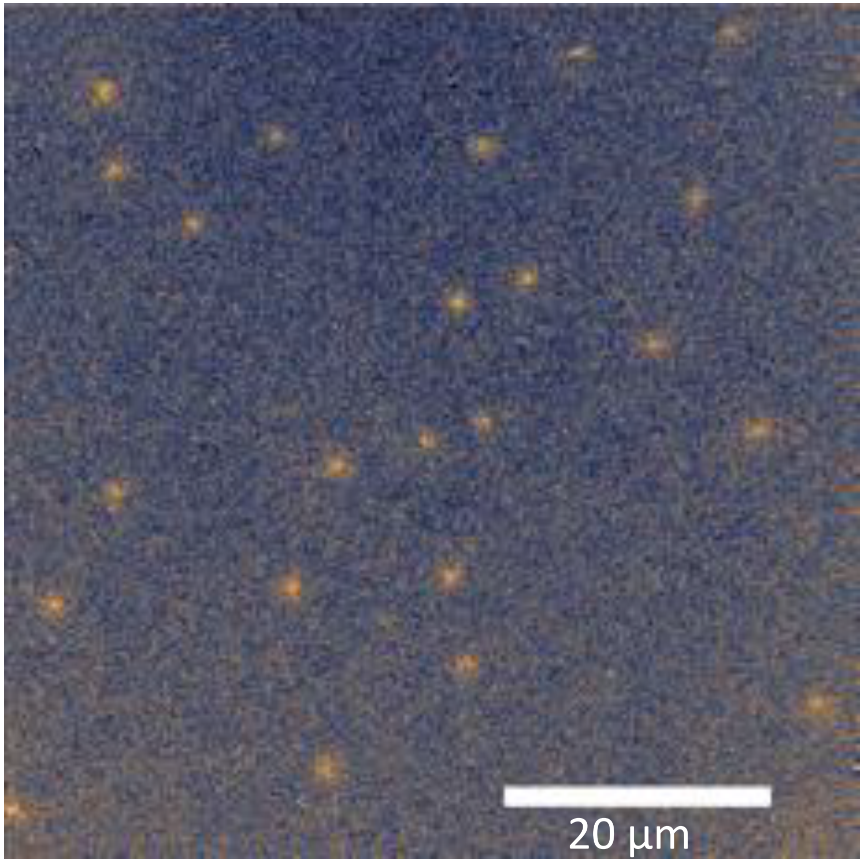
Experimental setup



- Closed cycle cryostat (T_{min}=3.5 K)
- Microscope with single aspheric lens (NA=0.5)
- Glan polarizers (overall extinction 10^{-2})
- Galvanometric mirrors to move the laser beam

Single vortex repositionning

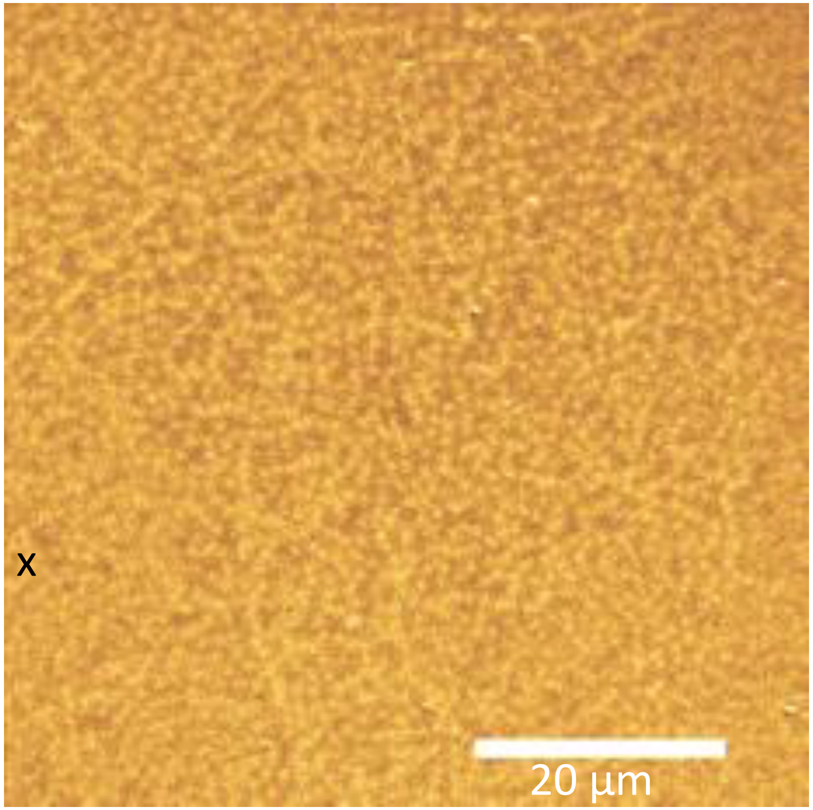
90 nm thick Nb film + Bi:LuIG indicator (2.5 µm thick)
H_{ext}=0.02 Oe, T = 4.6 K
Absorbed laser power P = 17 µW, focused on a FWHM-diameter of 1.1 µm
(Thermal gradient up to 1 $K.\mu m^{-1}$)



Veshchunov, Magrini et al.
Nature Comm.
7, 12801 (2016)

Vortex broom

H_{ext}=1.6 Oe, T = 4.6 K, P_{laser} = 17 µW focused on a FWHM-diameter of 1.1 µm

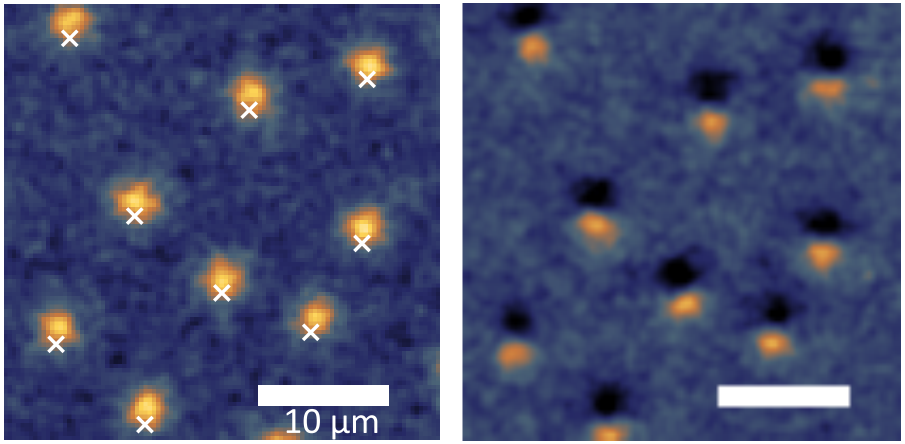


Cleaning time 420 s
Minimal cleaning time 350 ms, average vortex drive speed 8 mm.s^{-1}

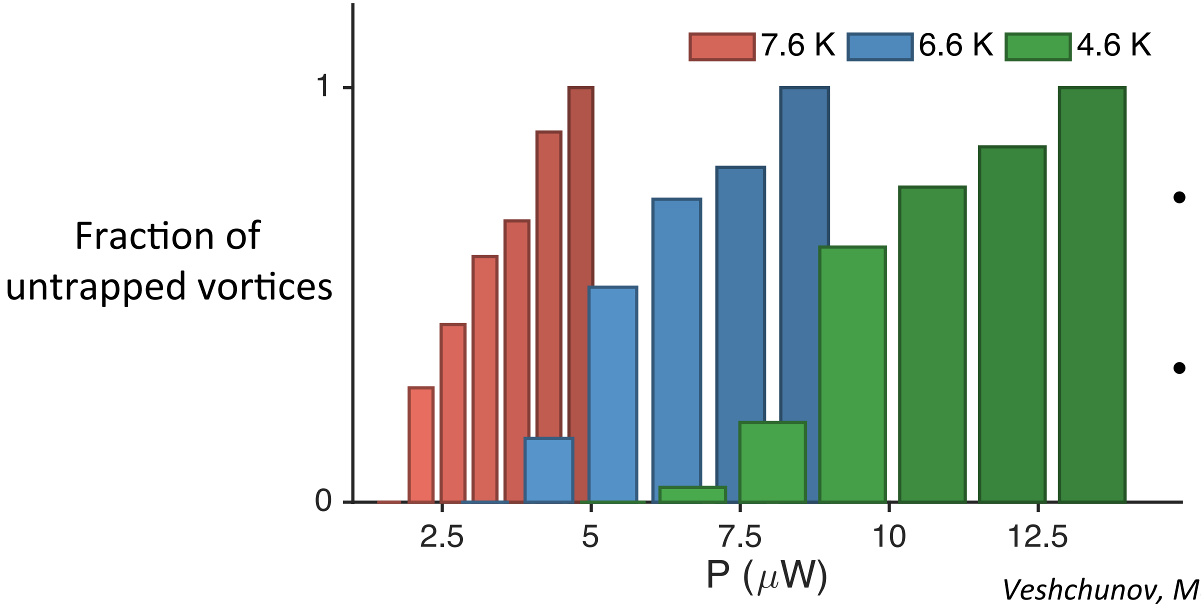
Veshchunov, Magrini et al. Nature Comm. 7, 12801 (2016)

Rate of success in vortex manipulation

90 nm thick Nb film
$T_c = 8.6$ K


Before laser
Difference After-Before laser

T = 4.6 K
P = 13µW
All vortices untrapped

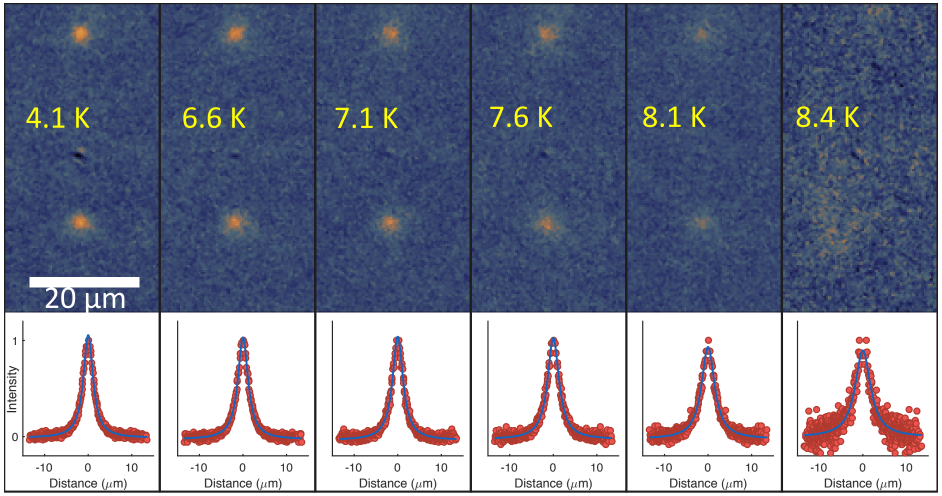


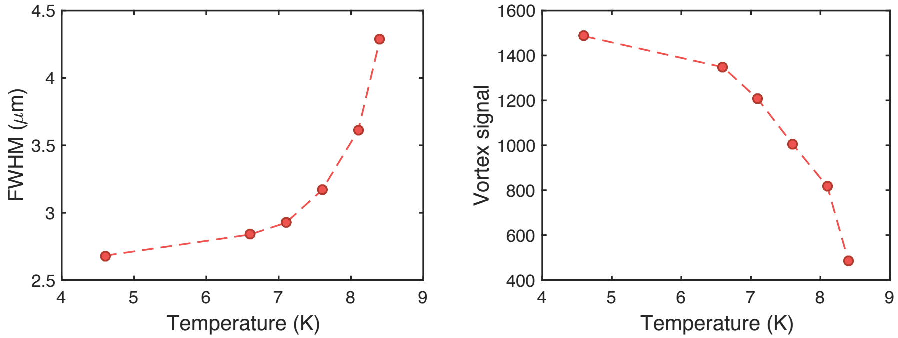
- Pinning is higher at lower temperatures
- Rate of success 100% for high enough laser powers

Veshchunov, Magrini et al. Nature Comm. 7, 12801 (2016)

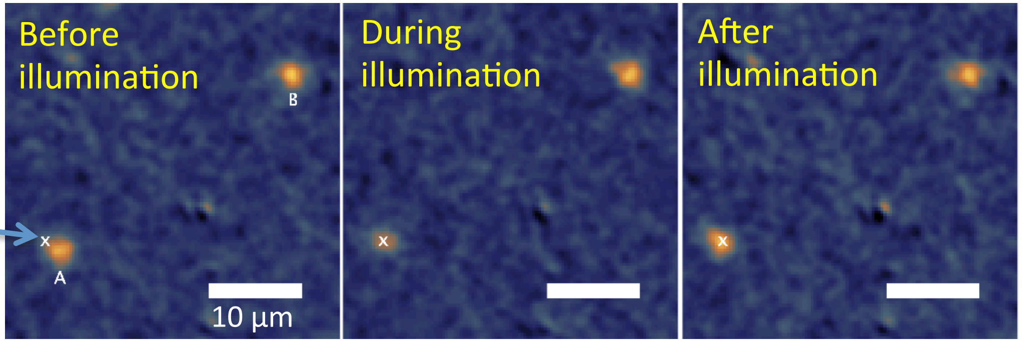
Vortex survival under laser illumination

Temperature dependence
of vortex images
without laser



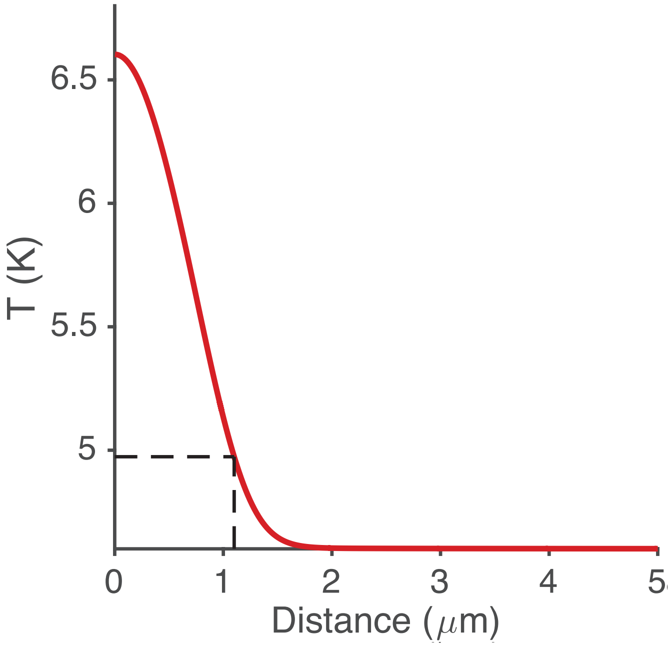


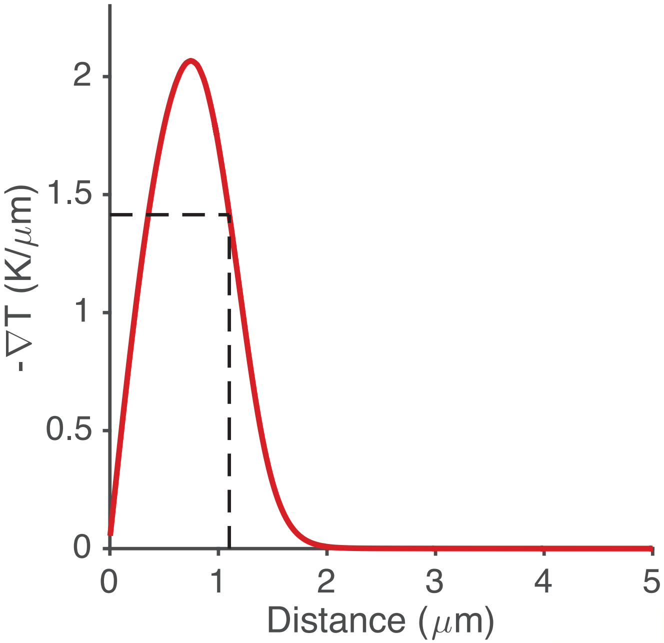
Laser
Position
(17 µW)



A: Test vortex
B: Reference vortex

Estimation of the pinning force





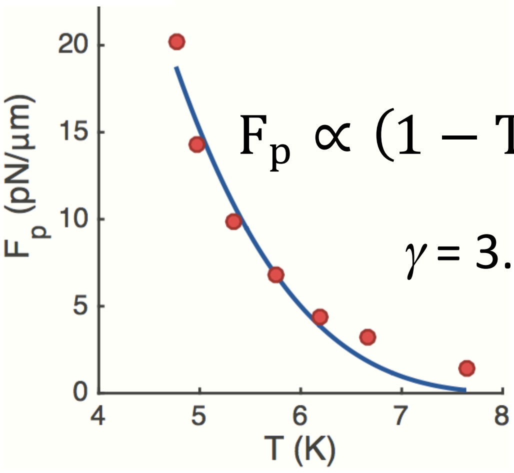
COMSOL program

$$Q(r) = \frac{P}{2\pi r_0^2} \exp\left[\frac{-r^2}{2r_0^2}\right]$$

r_0 = 0.5 µm
P = 13 µW
κ_{Nb} = 0.05 $W.m^{-1}.K^{-1}$
κ_{Si} = 450 $W.m^{-1}.K^{-1}$
Base temperature 4.6 K

Taking λ_0 = 90 nm and λ_0/ξ_0 = 9 :

$$F_p = \frac{\Phi_0^2}{4\pi\mu_0\lambda_0^2} \ln\left(\frac{\lambda_0}{\xi_0}\right)\frac{\nabla T}{T_c} = 14\ \mathrm{pN.\mu m^{-1}}$$



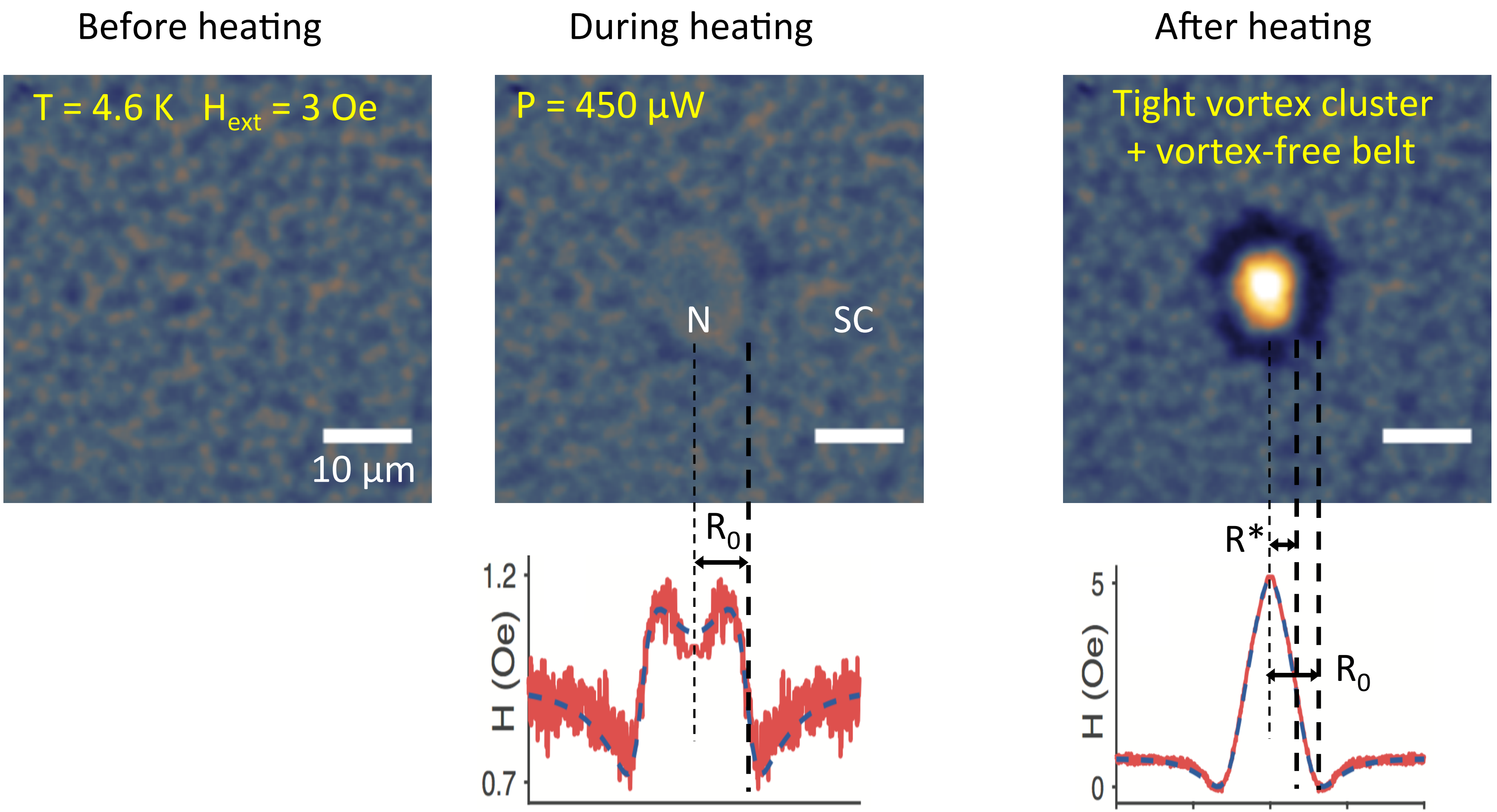
$$F_p \propto (1 - T/T_c)^{\gamma}$$

γ = 3.4

γ in agreement with ensemble measurements:

Allen& Claassen Phys. Rev. B 39 (1989) 2054 ; Goldstein & Moulton, Phys. Rev. B 40 (1989) 8714

Shaping the magnetic flux with light

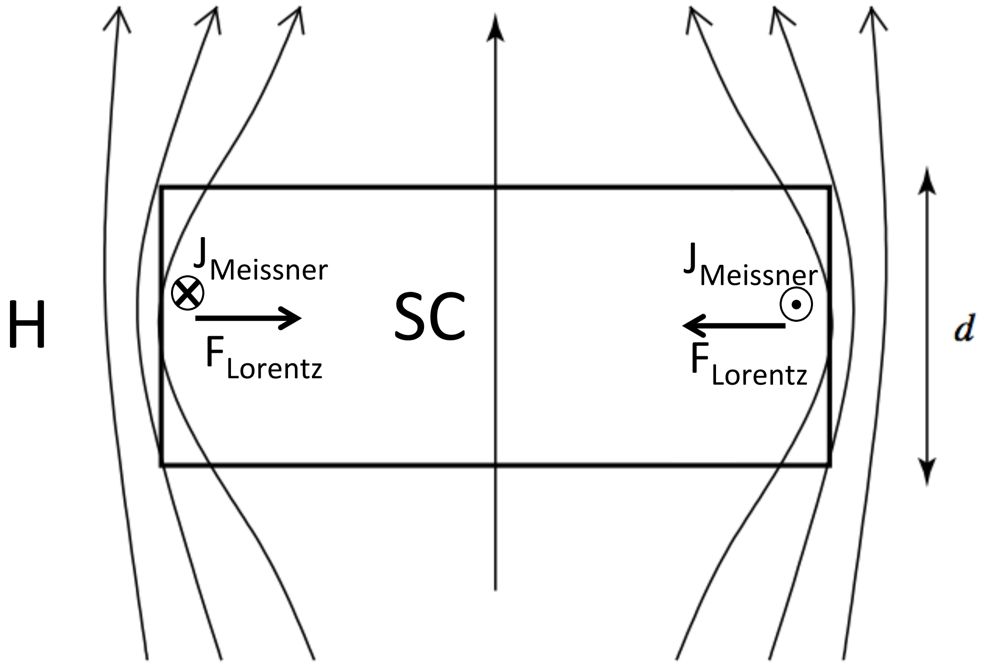


Normal region, $T > T_c$
Traps the flux $\Phi = \pi R_0^2 H_{ext}$
Supercurrent loop of radius R_0

$R_0^2 H_{ext} = R^{*2} H_p$
Vortex distribution set by
$F_p = j_c \Phi_0$ (Bean critical state model)

Geometrical barrier

Zeldov et al., Phys. Rev.73 (1994) 1428



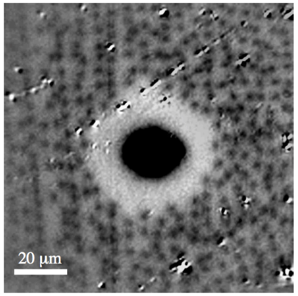
Vortex penetration when the Lorentz force induced by the supercurrent density reaches the vortex line energy per unit length

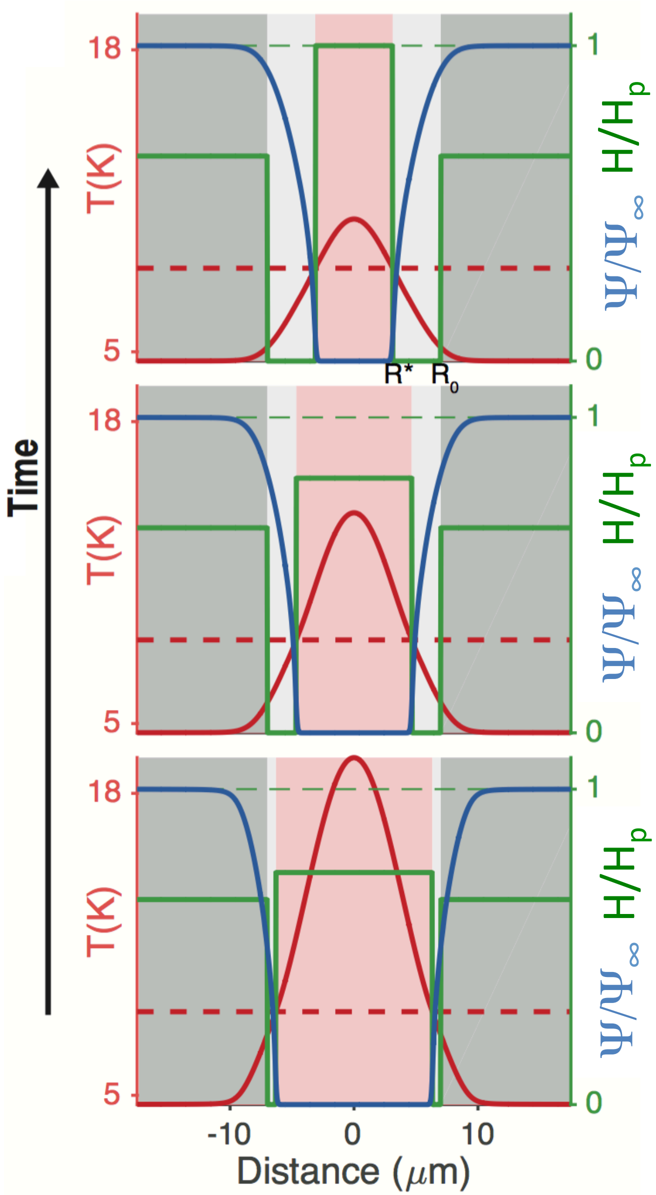
$$\frac{J\phi_0}{c} = \frac{2\phi_0 H_{c1}^0}{4\pi L_T}$$

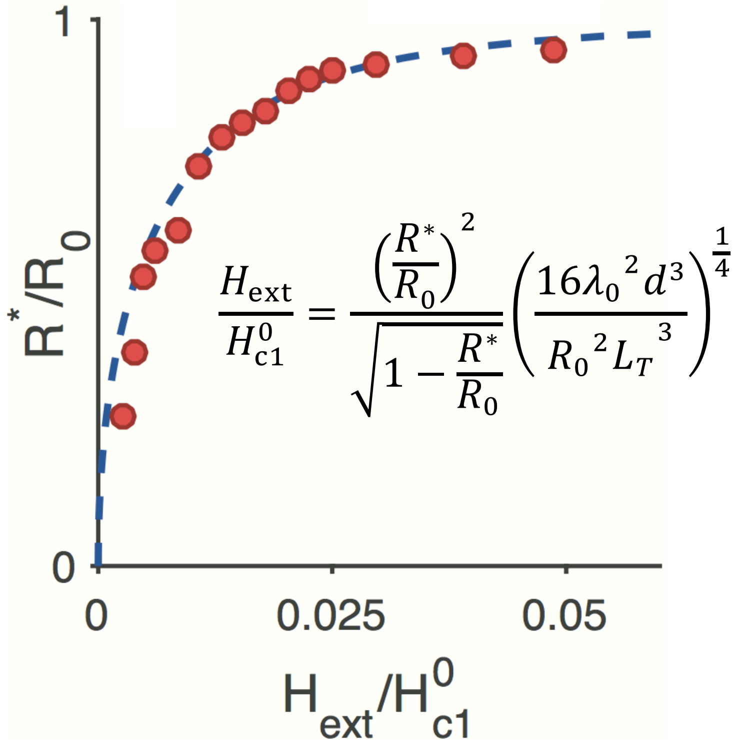
H_{c1}^0 : critical field at T=0

$L_T = T_c/\nabla T$: thermal length

Geometrical barrier







$$\frac{H_{\text{ext}}}{H_{c1}^{0}} = \frac{\left(\frac{R^*}{R_0}\right)^2}{\sqrt{1-\frac{R^*}{R_0}}}\left(\frac{16{\lambda_0}^2 d^3}{{R_0}^2 {L_T}^3}\right)^{\frac{1}{4}}$$

Agreement without fitting parameter

Conclusion & outlook

- Far-field optical method to manipulate single vortices as with optical tweezers
- Fast, safe manipulation with 100% rate of success

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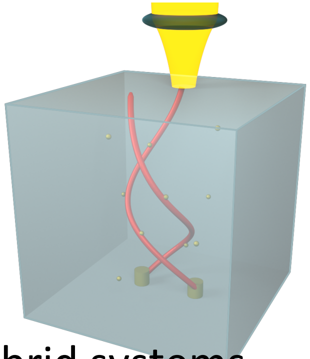
Nature Comm. 7, 12801 (2016)

- Various regimes of vortex manipulation (single vortices, vortex bunches, vortex-broom…)
- New concept of attractive thermal force => further theoretical investigations needed
- Maximal vortex driving speed should be given by:
  hotspot size (≈1µm) / thermal response time (≈1ns) = 1 km.s^{-1}
- Versatility of the method will fuel fondamental investigations of the vortex matter:
  inter-vortex interactions, vortex entanglement…



- Open up new research directions in quantum computation:
  Optical operation of Josephson transport, …
- Applications beyond superconducting electronics:
  Control of spin textures in diluted magnetic semiconductor in hybrid systems
  Trapping and manipulation of ultra-cold atoms