Closure structures around non-magnetic inclusions in an uniaxial magnetic thin film:

MFM characterization and theoretical analysis

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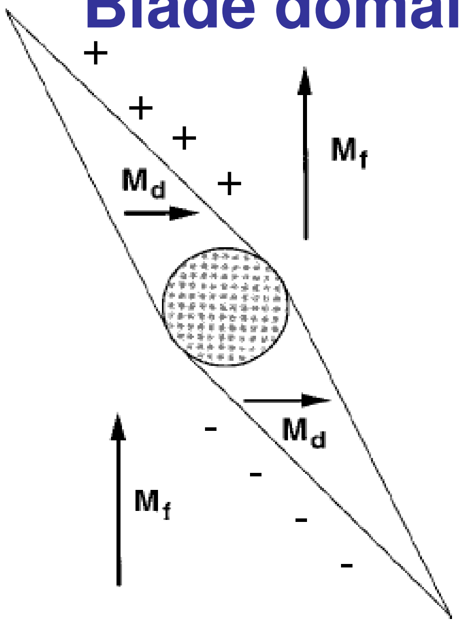
Closure structures around a non magnetic hole: 3D *vs.* 2D

- 3D Bulk material

Blade domains



L. Neel, Cah.Phys. 25 (1944) 21

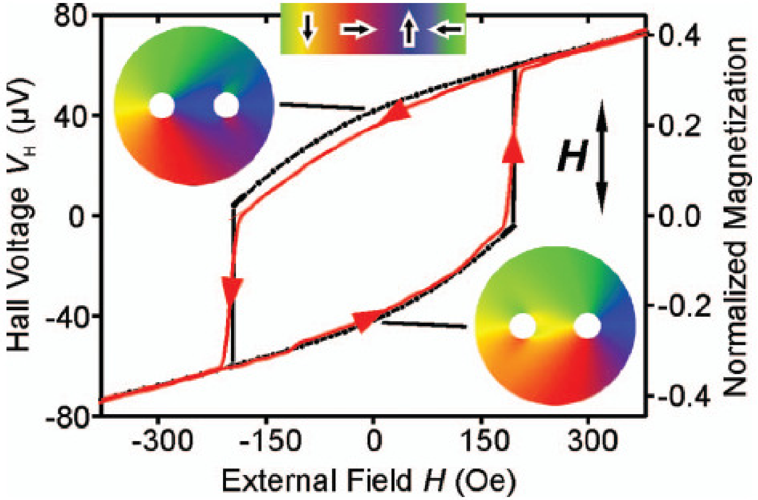
- 2D magnetic films ?
- 2D patterned nanostructures

- Domain wall pinning

-1/2 [illegible]

Nanorings

Memory elements



M. Rahm *et al* APL **87**, 182107 (2005)

F. J. Castaño *et al*, PRB **69**, 144421 (2004)

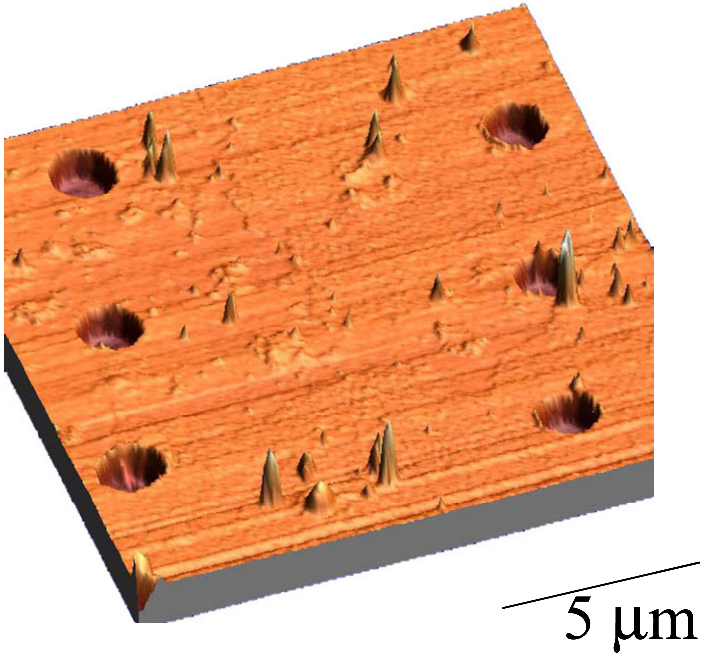
Tchernyshyov *et al* PRL **95,** 197204 (2005)

Closure structure around a hole in an extended 2D thin film?

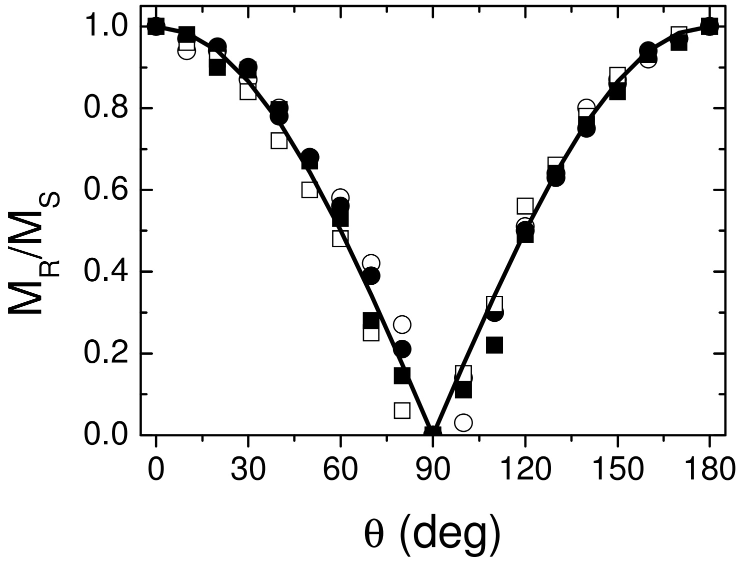
- Fabrication
- MFM characterization
- Micromagnetic simulations
- Analytical model
- Conclusions: ***Confinement distance***

Fabrication of non magnetic holes in uniaxial amorphous Co-Zr films

e-beam lithography+etching



Hole size ~ 1 μm

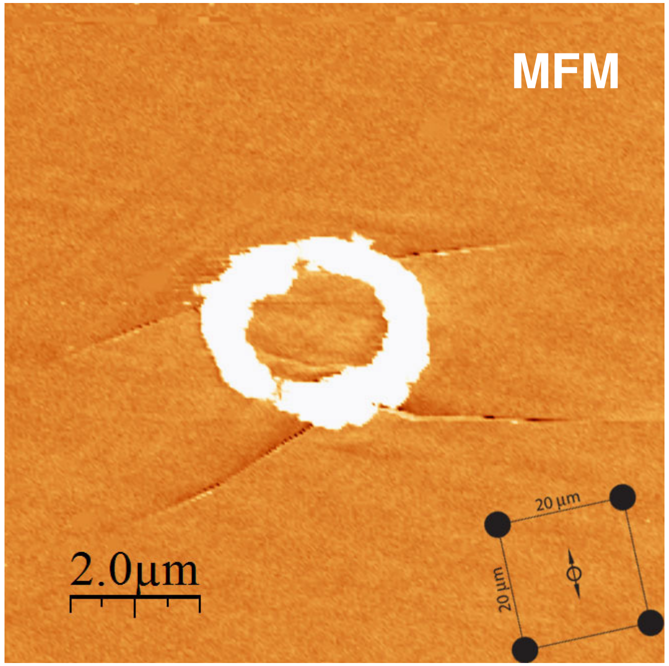


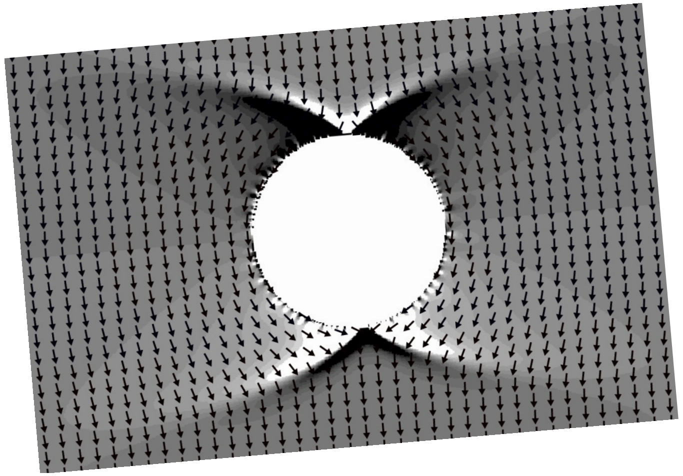
Diluted antidot array:

Induced anisotropy << Film uniaxial anisotropy

Closure structures 2D

- 2D extended thin film: **Confined singularities**

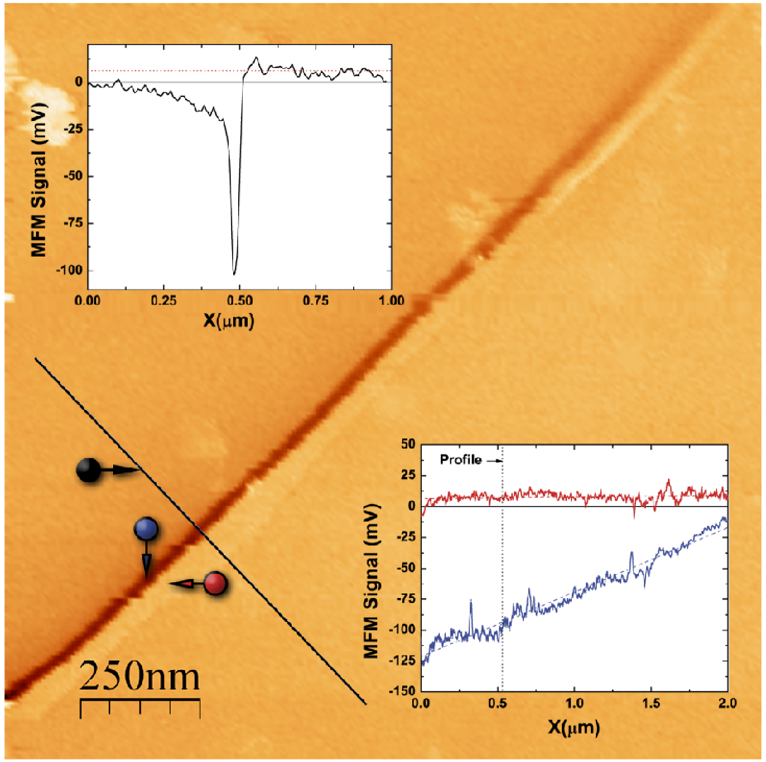




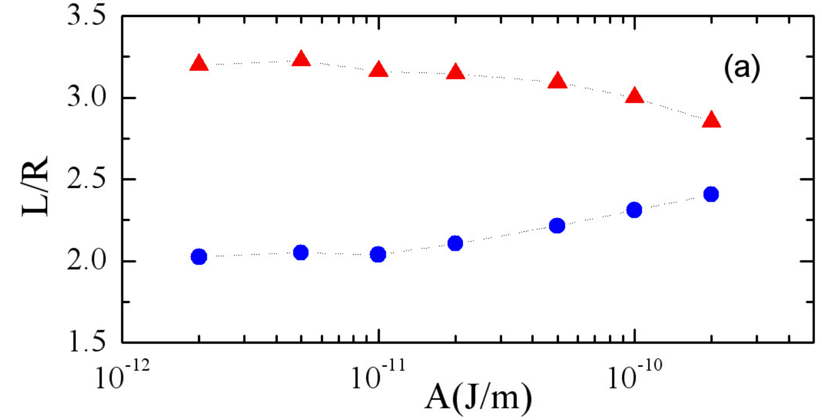
OOMMF simulation

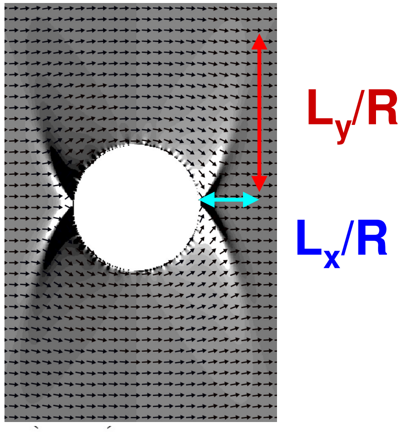
Charged Neel Walls

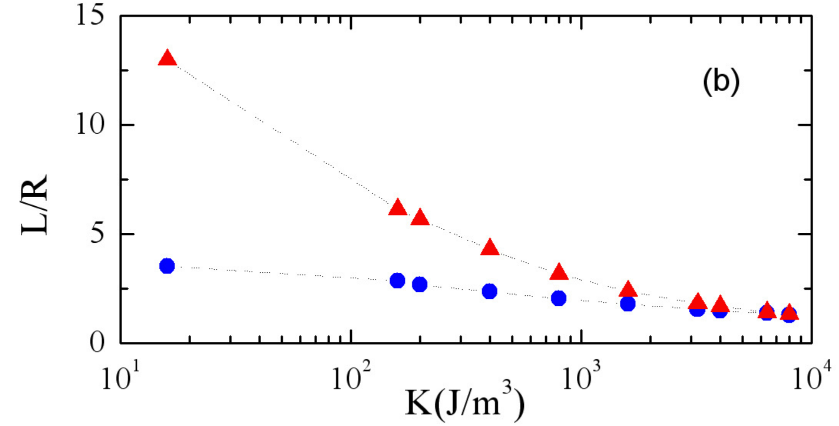
- *Fading contrast:* confinement of singularities in extended films within a distance ***L***

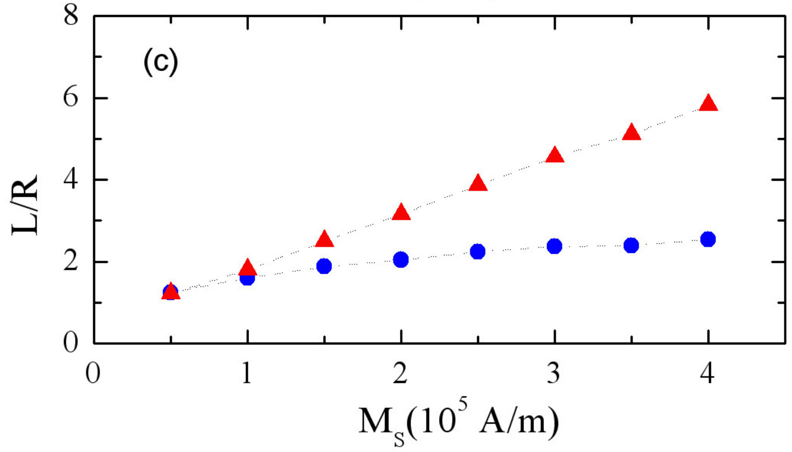


OOMMF Simulations









Analytical Model:

Magnetostatic and anisotropy energies

- *Pole avoidance in 2D*

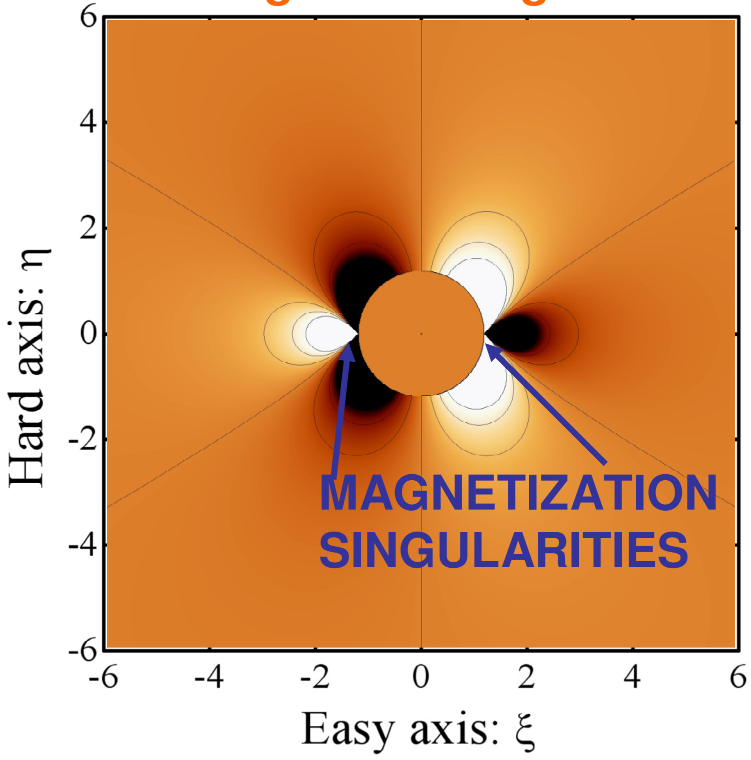
$\mathbf{M} = \nabla \times \mathbf{A} \quad \mathbf{A} = (0,0,\Psi)$

$\nabla^2 \Psi = 0$

$$\Psi = M_S(\rho - 1/\rho)\sin\theta$$

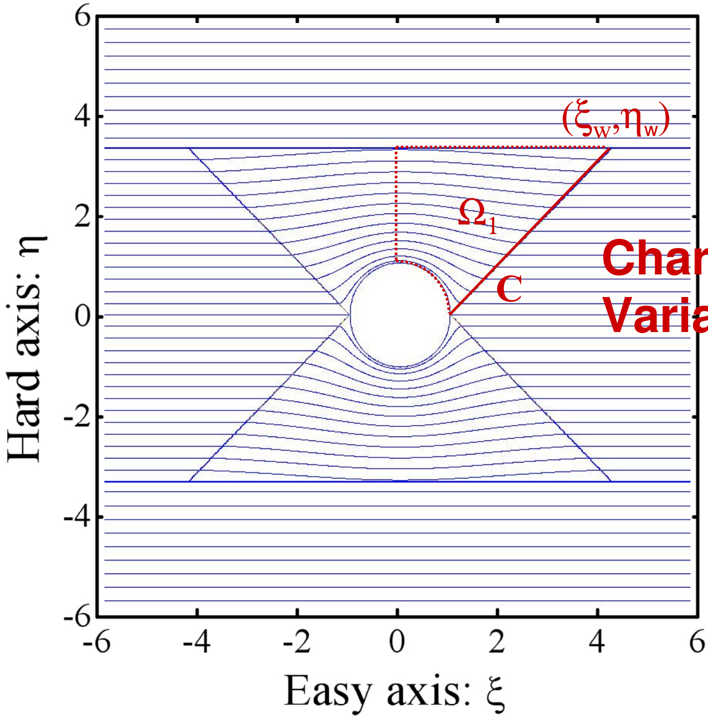
- *$|M| = M_S$*

→ magnetic charges around hole



Magnetic charges

Confinement distance: *Gauss theorem*



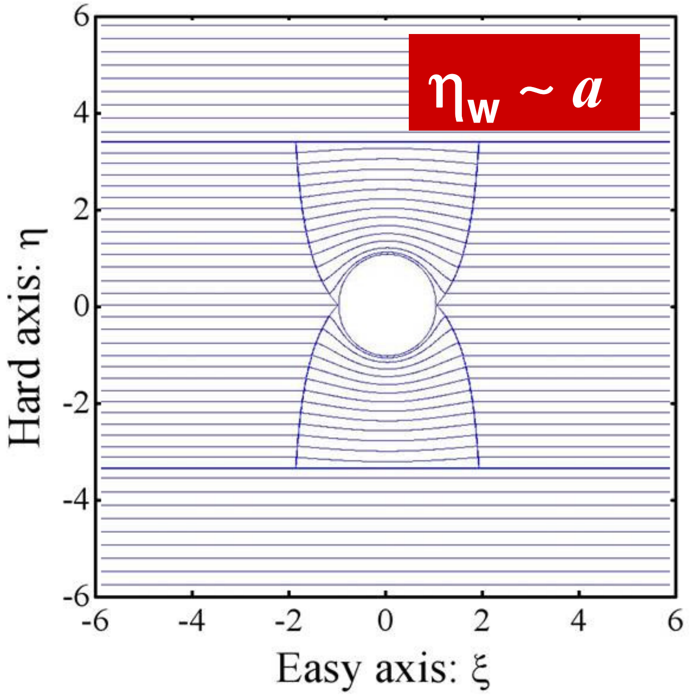
Charged Neel wall
Variable angle

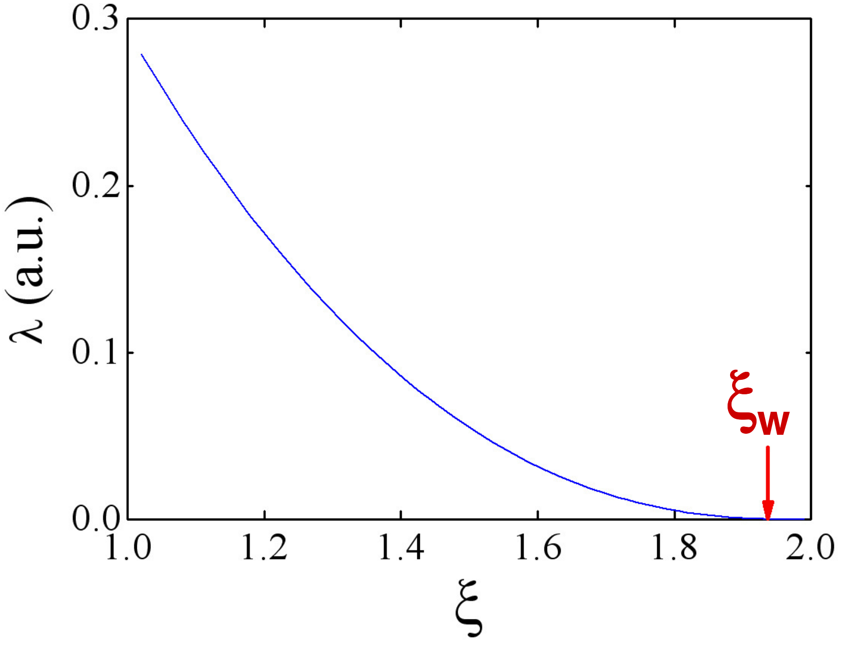
$$\int_{\Omega_1} \nabla \cdot \mathbf{M}\, d\boldsymbol{\rho} + \int_C M_s(\mathbf{m_1} - \mathbf{m_2}) \cdot \mathbf{n_C}\, dl = -M_s R$$

Gauss theorem: *confinement distance*

- DW Trial function:

$$\eta^2 = (\xi - 1)^2 \left(\frac{a + \xi - 1}{a - \xi + 1} \right)$$





Magnetostatic and anisotropy energies

Magnetostatic energy

Surface charges around non-magnetic hole

$$E_s = -\frac{\mu_o M_s^2}{4\,\pi} \int_\Omega \int_\Omega [\nabla \cdot \mathbf{m}(\boldsymbol{\rho})]\ [\nabla \cdot \mathbf{m}(\boldsymbol{\rho}')]\ \ln(|\boldsymbol{\rho} - \boldsymbol{\rho}'|)\, d^2\rho\, d^2\rho'$$

Surface charges – charged Neel walls

$$E_{is} = -\frac{\mu_o M_s^2}{2\,\pi} \int_\Omega \int_C [\nabla \cdot \mathbf{m}(\boldsymbol{\rho})]\,[(\mathbf{m}_1(\boldsymbol{\rho}') - \mathbf{m}_2(\boldsymbol{\rho}')) \cdot \mathbf{n}_\mathrm{C}(\boldsymbol{\rho}')]\ \ln(|\boldsymbol{\rho} - \boldsymbol{\rho}'|)\, d^2\rho\, dl'$$

Charged Neel walls

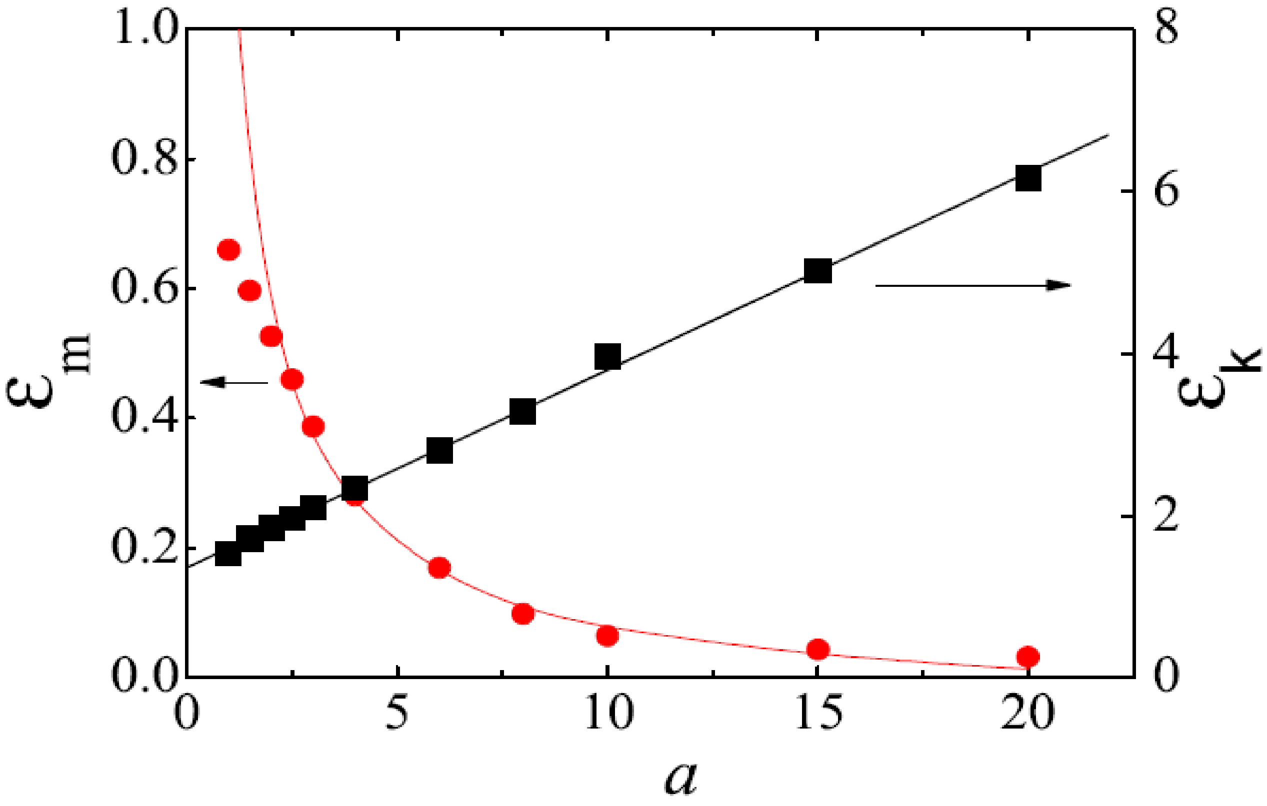
$$E_{ij} = -\frac{\mu_o M_s^2}{2\,\pi} \int_C \int_{C'} [(\mathbf{m}_1(\boldsymbol{\rho}) - \mathbf{m}_2(\boldsymbol{\rho})) \cdot \mathbf{n}_\mathrm{C}(\boldsymbol{\rho})]\ \times$$

$$[(\mathbf{m}_1(\boldsymbol{\rho}') - \mathbf{m}_2(\boldsymbol{\rho}')) \cdot \mathbf{n}_{\mathrm{C}'}(\boldsymbol{\rho}')]\ \ln(|\boldsymbol{\rho} - \boldsymbol{\rho}'|)\, dl\, dl'$$

Anisotropy Energy

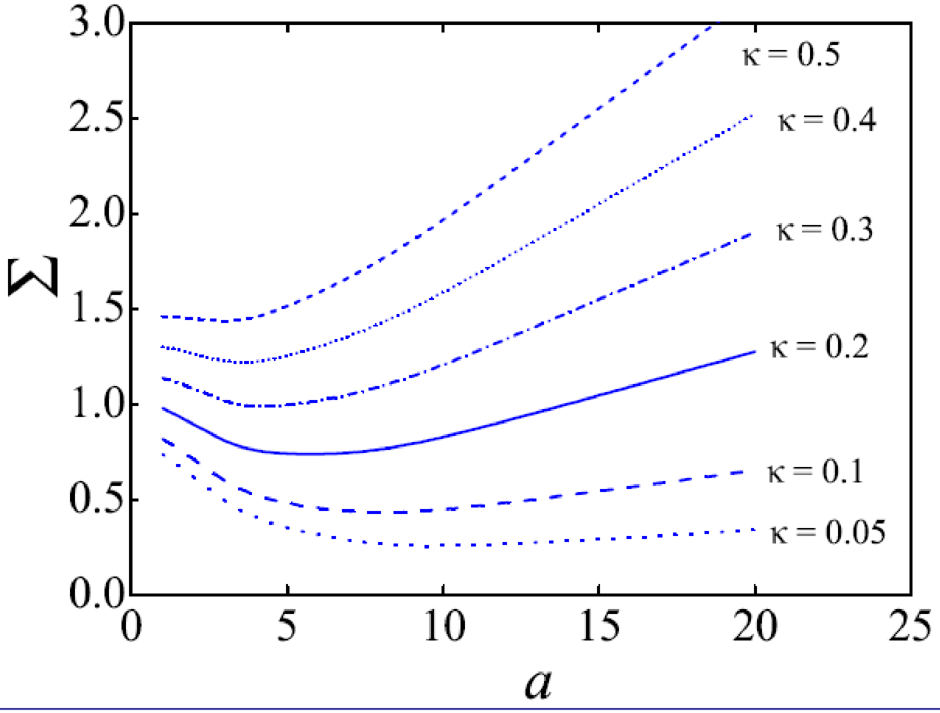
$$E_K = -K \int_\Omega [\mathbf{m}(\boldsymbol{\rho}) \cdot \mathrm{e}]^2\ d^2\rho$$

Magnetostatic and anisotropy energies



Total energy minimization

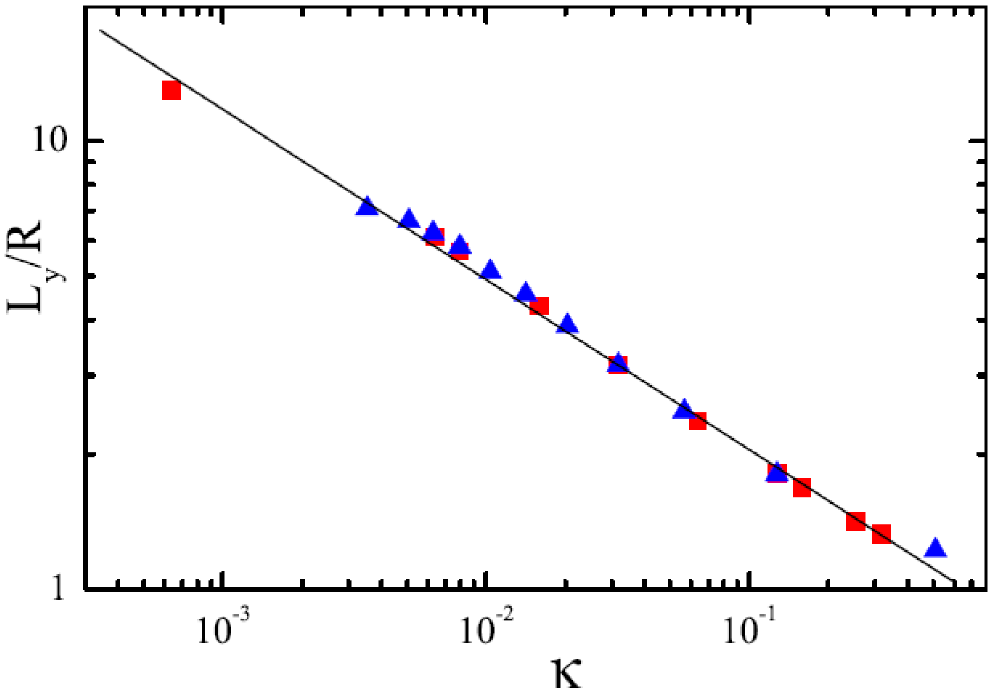
$$\Sigma \equiv \frac{2\,E}{\mu_o\,M_s^2} = -\frac{1}{\pi}\left[\frac{1}{2}\varepsilon_s + \sum_i \varepsilon_{is} + \sum_{ij}\varepsilon_{ij}\right] - \boxed{\kappa}\,\varepsilon_k$$



$$\boxed{\kappa \equiv 2K/\mu_0 M_s^2}$$

$$\boxed{a \sim \kappa^{-0.5}}$$

Confinement distance



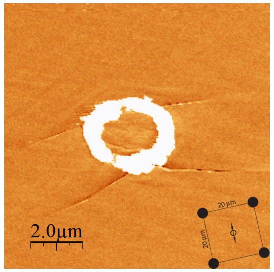
Analytical model

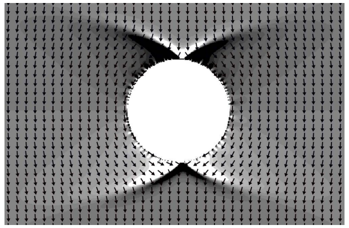
$$\boxed{a \sim \kappa^{-0.5}}$$

OOMMF simulations

$$\boxed{L_y \sim \kappa^{-0.4}}$$

Conclusions





- Closure domain structures around holes in extended 2D film: **Confined -1/2 vortices**
- Confinement distance determined by magnetic **charge conservation** (Gauss theorem) and **energy minimization**
- Closure structure size scales as **L/R** $\sim \kappa^{-0.5}$