PSEUDO-SPECTRAL APPROACHES TO VORTEX DYNAMICS IN NEMATIC SUPERCONDUCTORS

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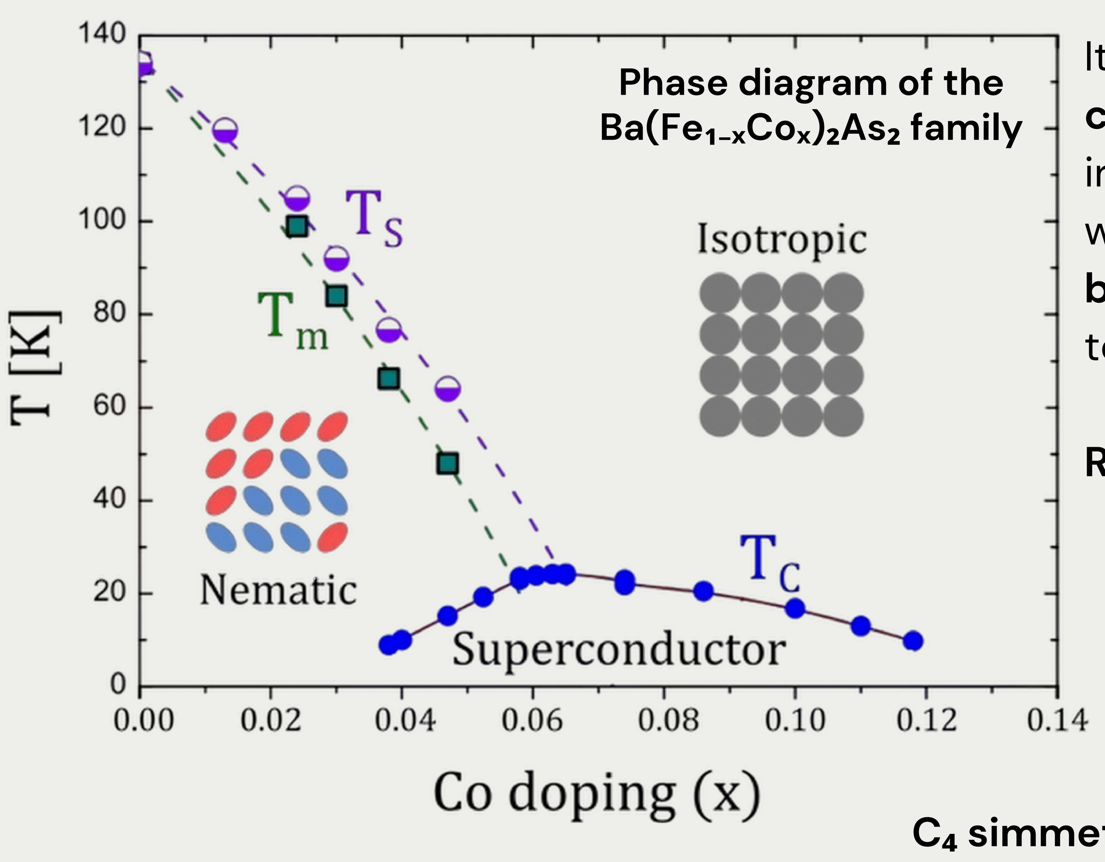
ABSTRACT

One of the most notable properties of iron-based superconductors (FeSc) is the emergence of pronounced anisotropies in both optical and transport properties, which have theoretically been linked to the existence of electronic nematic phases. In type-II superconductors, transport properties in the mixed state are primarily determined by the dynamics and configuration of the vortex system. If there is a coupling between the nematic and superconducting orders, both the morphology of the vortices and their dynamics and interaction with nematic domain walls should be reflected, among other things, in anisotropies in the magnetoresistance of the superconducting mixed state. Using numerical simulations based on pseudo-spectral methods [1–4] within the time-dependent Ginzburg–Landau (TDGL) framework, we compute the vortex viscosity in a model with an s-wave superconducting order parameter coupled to an Ising-type nematic order parameter [5].

ELECTRONIC NEMATICITY

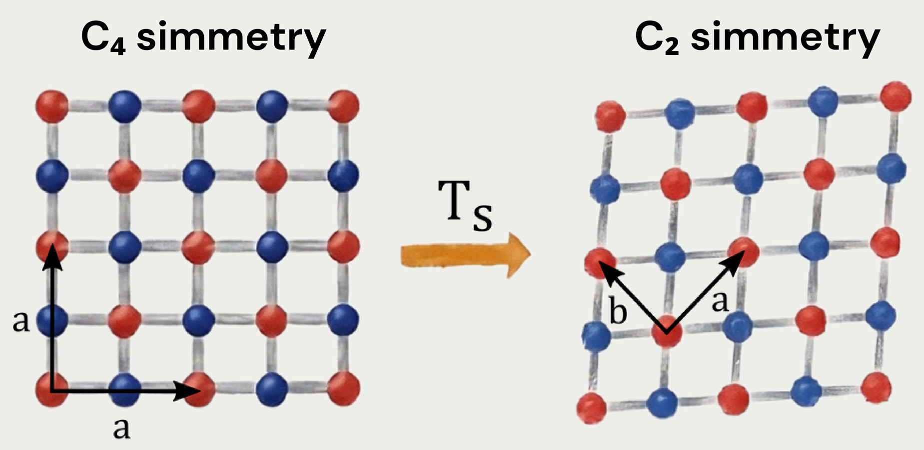


It emerges in materials with **strongly correlated electronic states**, such as iron-based superconductors (FeSCs), where **electrons spontaneously break** a crystalline symmetry, leading to so-called electronic **nematic** order

Relevant examples:

- FeSe
- $Ba(Fe_{1-x}Co_x)_2As_2$

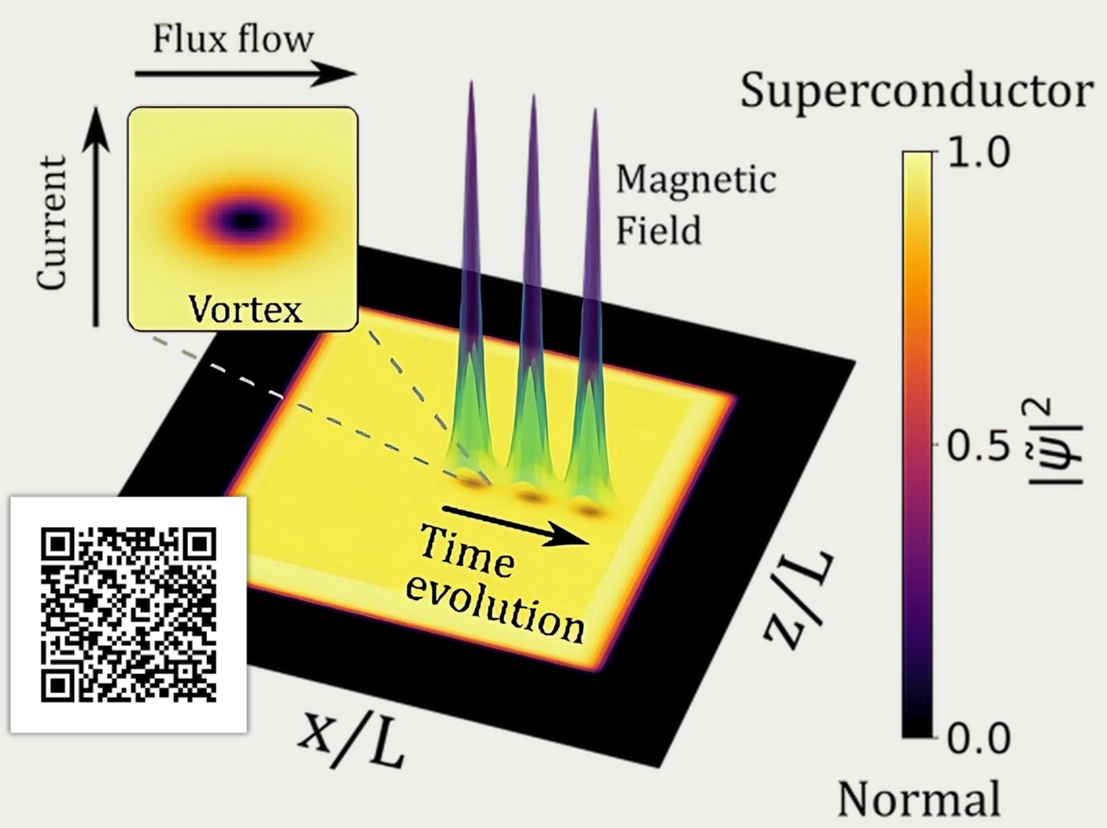
As the temperature is lowered, the **tetragonal** unit cell undergoes a distortion that gives rise to an **orthorhombic** structure. When the structural transition occurs in single crystals, **domains** alternating the crystallographic axes naturally form

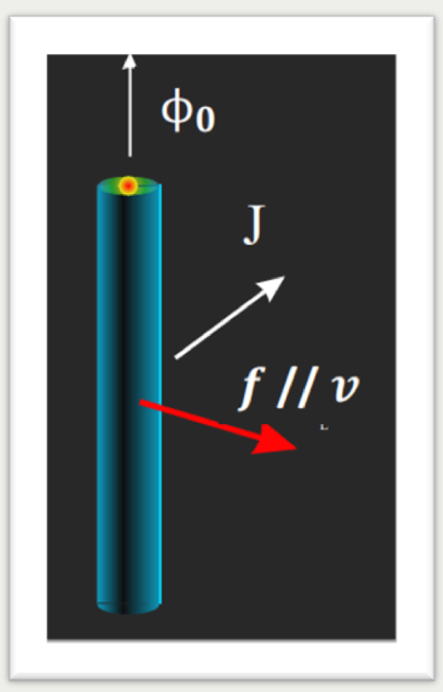


Nematic fluctuations have been proposed as a potential candidate responsible for the **effective pairing** between **electrons**, although the question remains open

VORTEX DYNAMICS

In the superconducting mixed state, resistivity originates from the **dissipative motion of vortices** that, under the action of an average current density, experience a Lorentz-type force. When pinning is weak relative to the driving force, vortices reach a terminal velocity governed by **viscous drag**, corresponding to the **flux-flow regime**





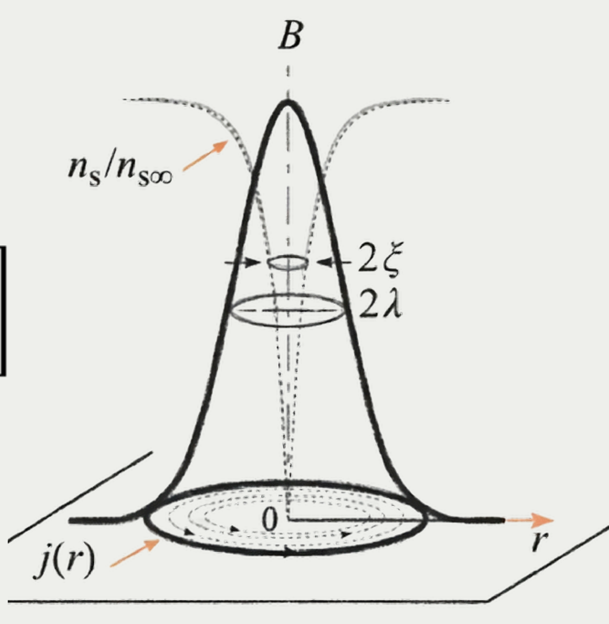
$$f = J \times \frac{\Phi_0}{c} = \nu V$$

$$\rho_f = \frac{E}{J} = \frac{\Phi_0 B}{c^2 \nu}$$

We investigate **vortex-flow anisotropy** in **nematic superconductors**, with emphasis on the effects of the coupling between nematic and superconducting order parameters on **vortex dynamics**

PHENOMENOLOGICAL MODEL

- The **Ginzburg–Landau** (GL) theory has proven to be a highly successful framework for describing the **phenomenology** observed in **superconducting materials**



Superconducting vortex

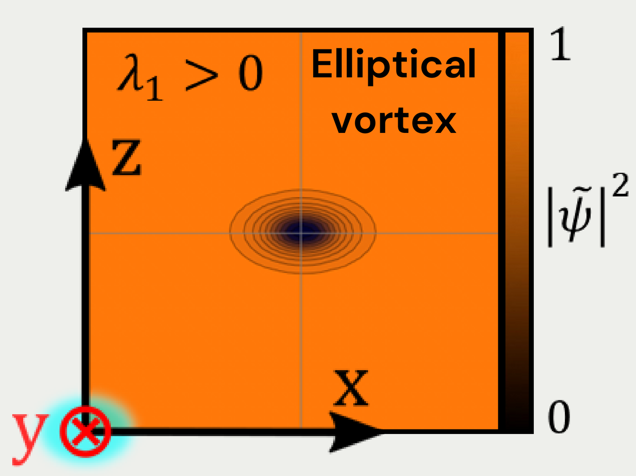
$$F_S = \int dV \left[\alpha_{GL}|\psi|^2 + \frac{\beta_{GL}}{2}|\psi|^4 + \frac{\hbar^2}{2m}|\boldsymbol{D}\psi|^2 + \frac{(\nabla \times \boldsymbol{A})^2}{8\pi} \right]$$

- We include **nematicity** in the form of a real order parameter (**Ising**-type) that couples with superconductivity and with the magnetic field

$$|\psi|^2 = n_s \qquad \alpha_{GL} = \alpha_0 (T - T_C) \qquad \boldsymbol{D} = -i\nabla - \frac{e}{\hbar c}\boldsymbol{A}$$

$$F_N + F_{SN} = \int dV \left[\gamma_2 (\nabla\eta)^2 + \gamma_3 \eta^2 + \frac{\gamma_4}{2}\eta^4 + \frac{\hbar}{2m}\lambda_1 \eta (|D_x\psi|^2 - |D_z\psi|^2) + \lambda_2 \eta^2 |\psi|^2 \right]$$

Nematic free energy with spontaneous symmetry breaking; Symmetry-allowed trilinear coupling; Biquadratic coupling



$\lambda_2 > 0$ **Competition:** the nematic order is **enhanced** in the vortex core (BaFeCoAs)

$\lambda_2 < 0$ **Cooperation:** the nematic order is **suppressed** in the vortex core (FeSe)

- A standard approach to describe **nonequilibrium** evolutions is to introduce a **dissipative dynamics**

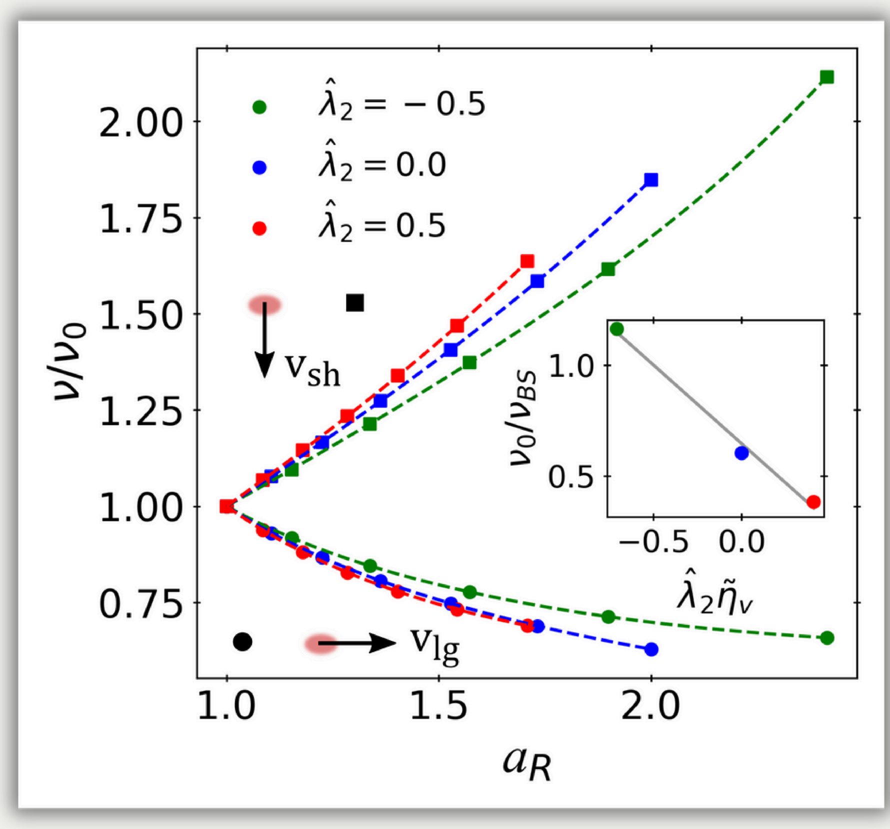
$$\frac{\hbar^2}{2mD}\partial_t \psi = -\frac{\delta F}{\delta \psi^*}$$
$$\frac{\boldsymbol{\rho}^{-1}}{c}\partial_t \boldsymbol{A} = -c\frac{\delta F}{\delta \boldsymbol{A}}$$
$$\frac{\hbar^2}{2mD_n}\partial_t \eta = -\frac{\delta F}{\delta \eta}$$

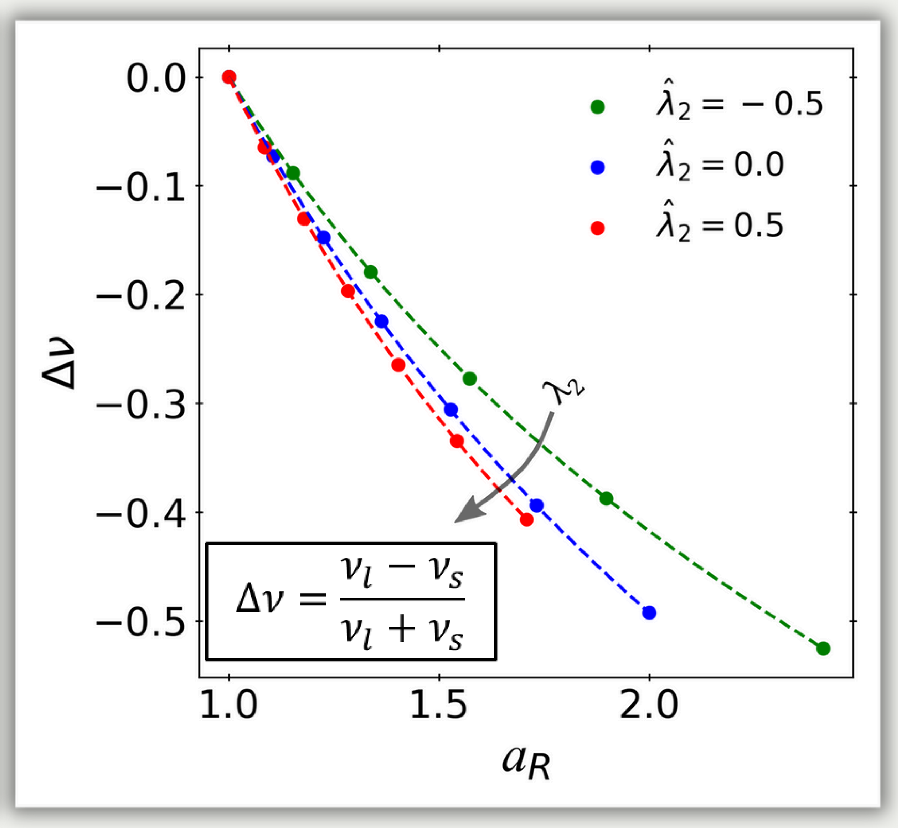
The numerical solution of the dynamical equations using **pseudo-spectral** methods with the ***Geophysical High-Order Suite for Turbulence*** (GHOST) package is based on expanding the dynamical variables in Fourier modes and integrating the time evolution of their coefficients with an adaptive **Runge–Kutta** method

RESULTS

F. CASTILLO MENEGOTTO ET AL, PHYS. REV. B 112 (13), 134506 (2025)

- The method allows us to **compute** the **viscous drag coefficient** for vortex motion along both directions —*l* (long axis) and *s* (short axis)— as well as the corresponding **anisotropy**, as a function of the vortex-core **aspect ratio**





REFERENCES

- [1] P. D. Mininni *et al*, Parallel Computing 37(6), 316-326 (2011)
- [2] D. Rosenberg *et al*, Atmosphere 11(2), 178 (2020)
- [3] R. S. Severino *et al*, Phys. Rev. B 106, 094512 (2022)
- [4] R. S. Severino *et al*, Phys. Rev. B 109, 094513 (2024)
- [5] **F. Castillo Menegotto** *et al*, Phys. Rev. B 112 (13), 134506 (2025)

CONCLUSIONS

Our results show that **nematicity** gives rise to a pronounced **anisotropy** in the **flux-flow resistivity**, determined by both the anisotropy of the **vortex-core morphology** and the resistive anisotropy of the normal state, and strongly affected by the **competitive–cooperative coupling** between the two order parameters [5].