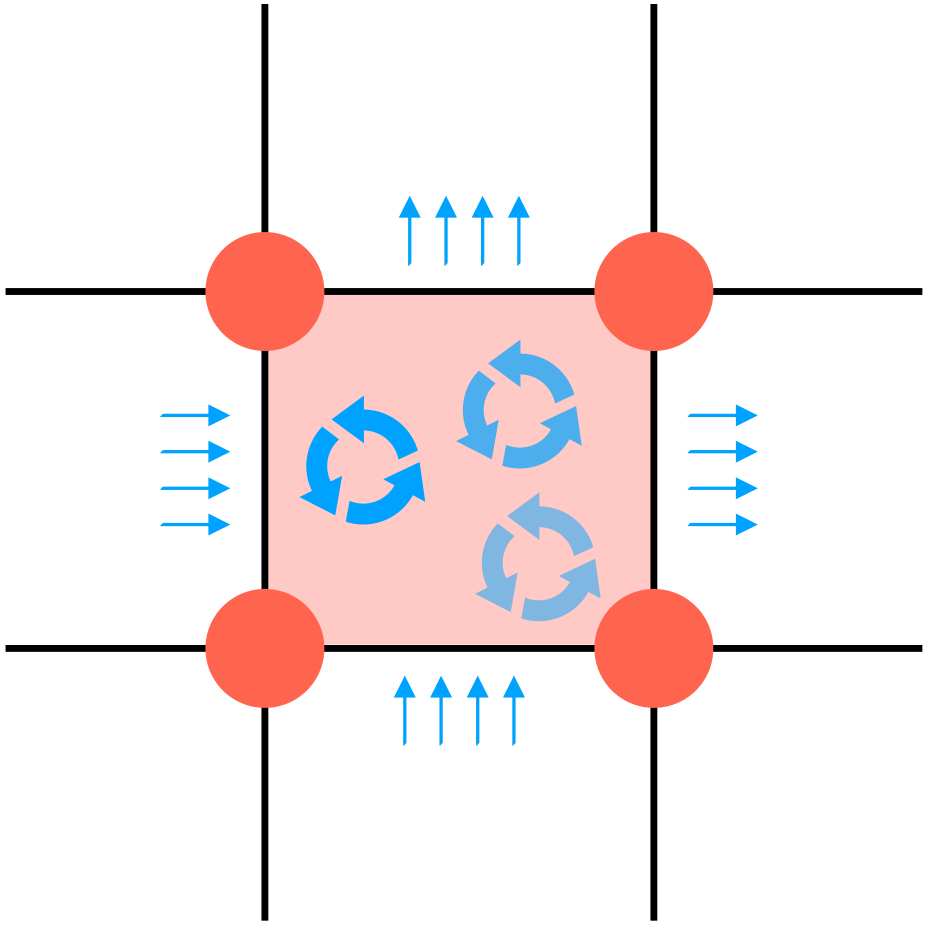
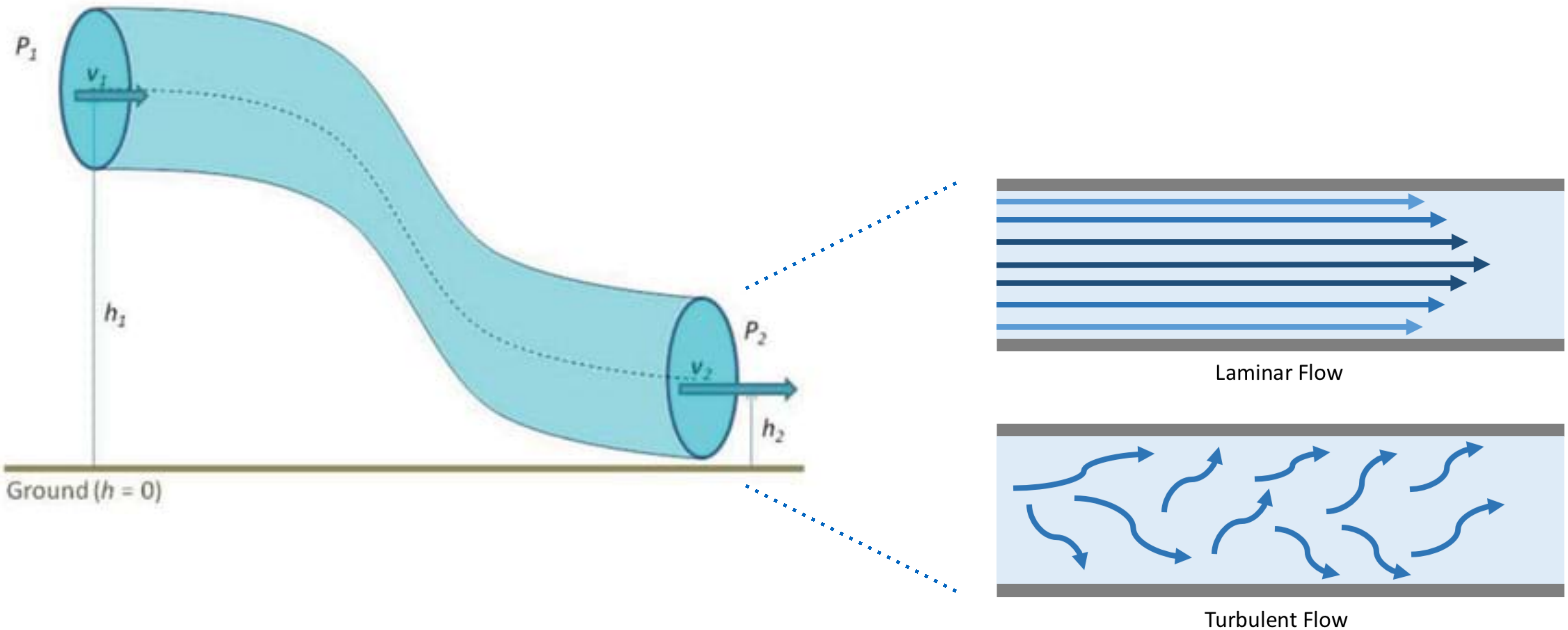
Putting magnetic vortices to work in spintronics

transport and energy storage based on topological textures



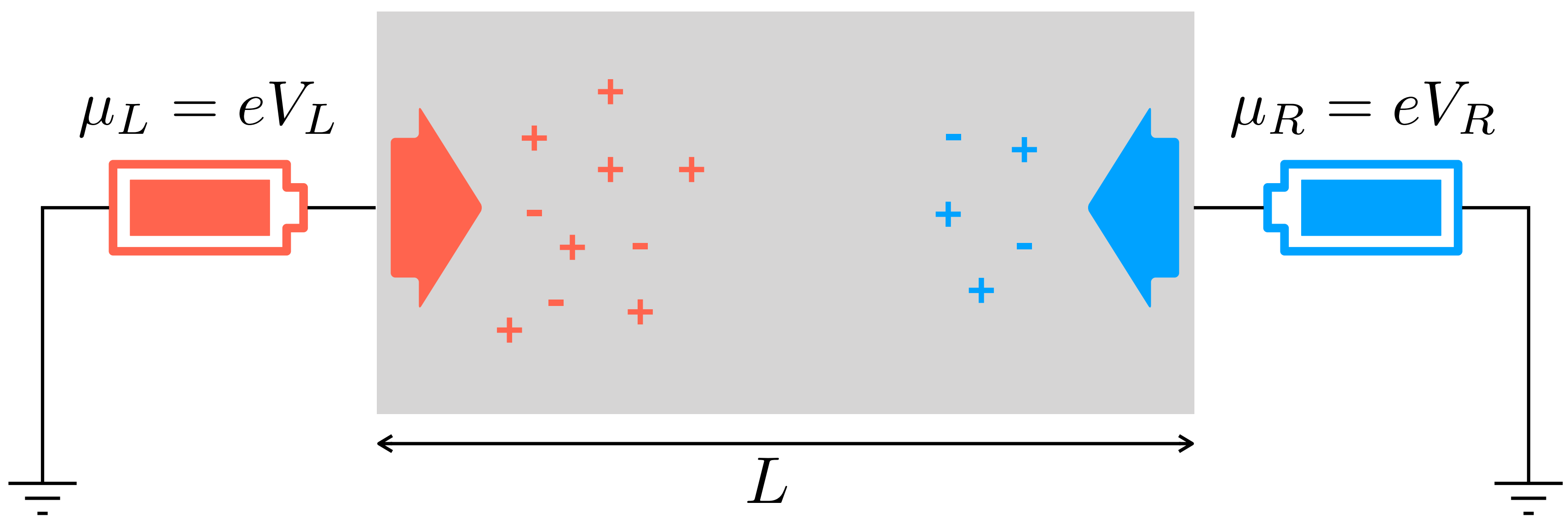
Yaroslav Tserkovnyak (*UCLA*)

Hydrodynamic flows/circuits (Bernoulli)



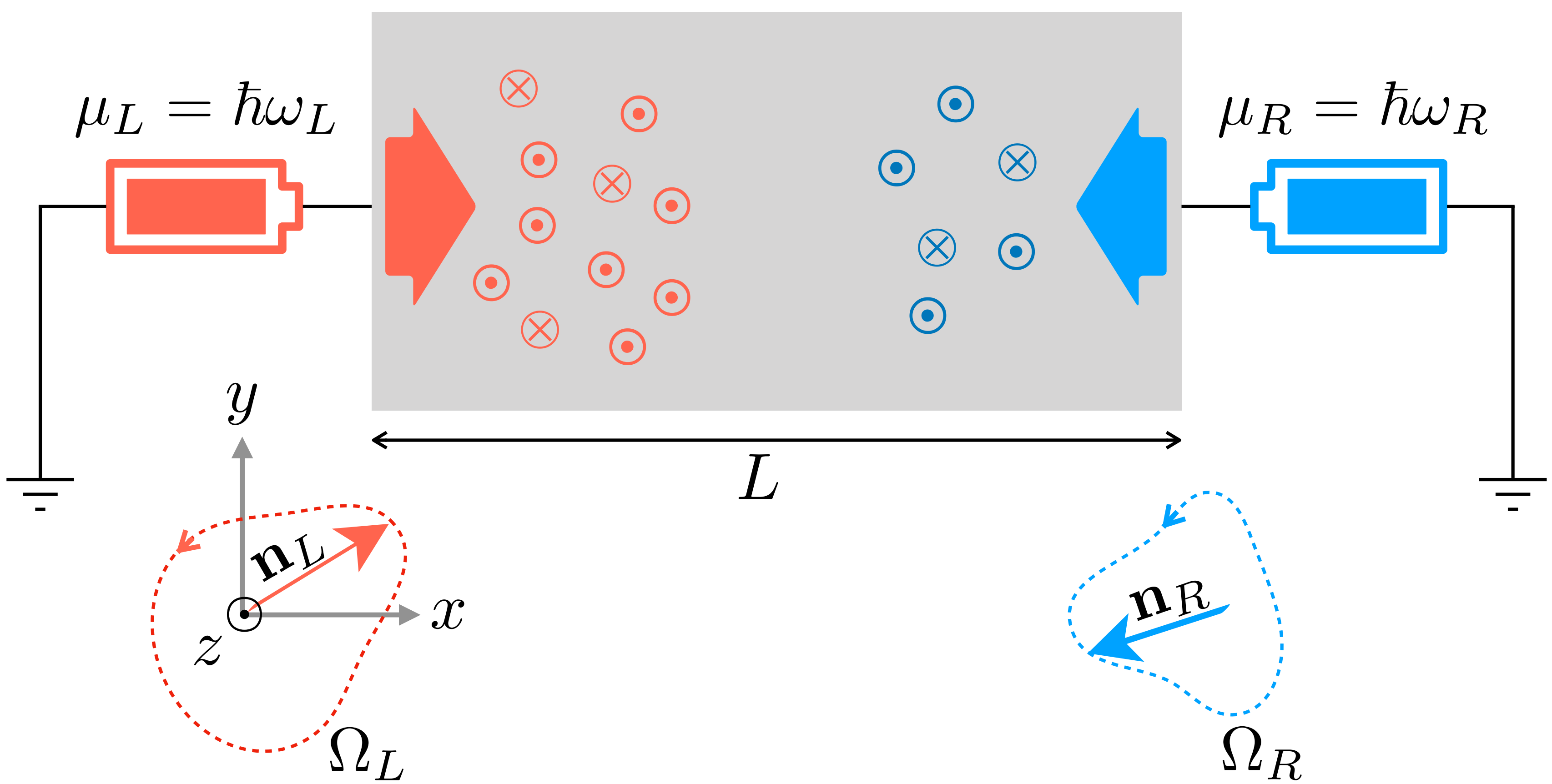
- Work by gravity (or external pressure) drives the flow
- *Conservation law for the fluid mass*
- *Different regimes of flow (constitutive relations, inertia, nonlinearities etc.)*

Electronic flows/circuits (Ohm)



- Work by electrochemical battery drives the current
- *Conservation law for the charge*
- *Different regimes of flow (constitutive relations, diffusion, nonlinearities etc.)*

Spintronics flows/circuits



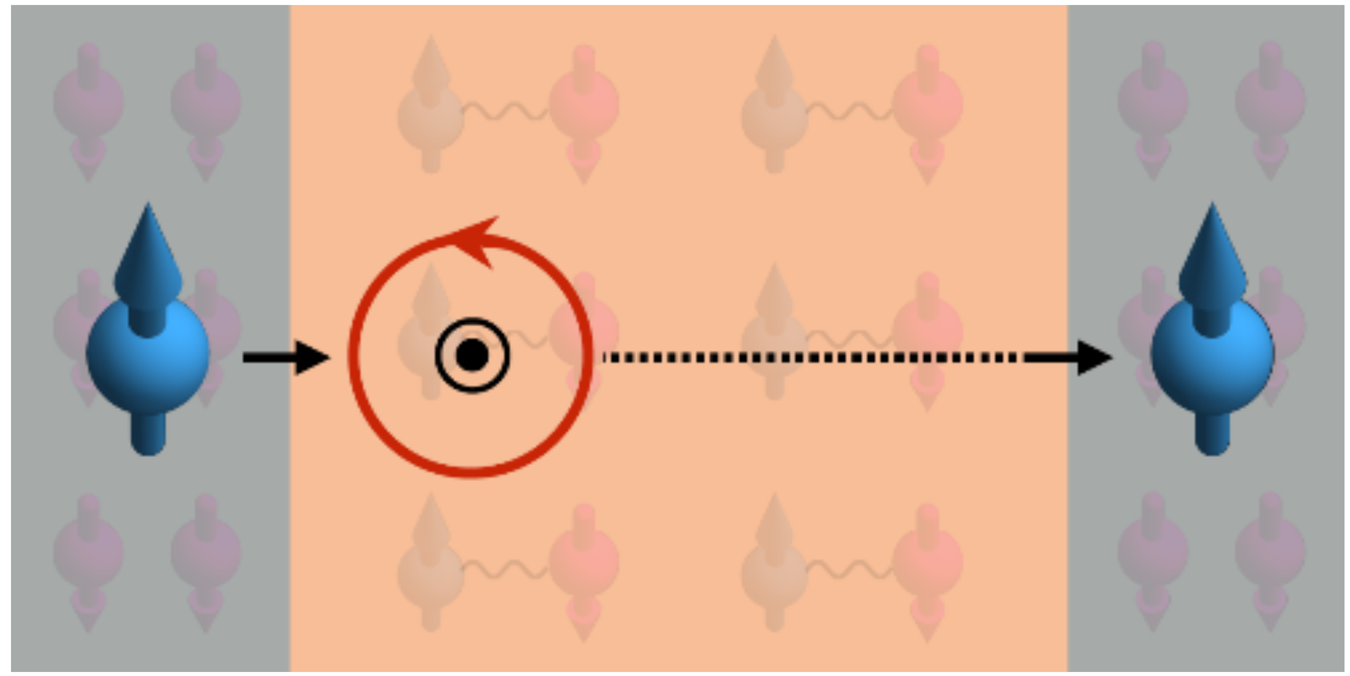
- Work by magnetic precession (spin pumping): Precessing magnet is a spin condensate at effective chemical potential of $\mu = \hbar\omega$

- *Approximate conservation law for the spin ⇒ spin diffusion length*

- *Different regimes of flow (constitutive relations, diffusion, spin superfluidity etc.)*

YT, Brataas, and Bauer *PRL* (2002)

Vorticity as a new mode of spintronic transport?



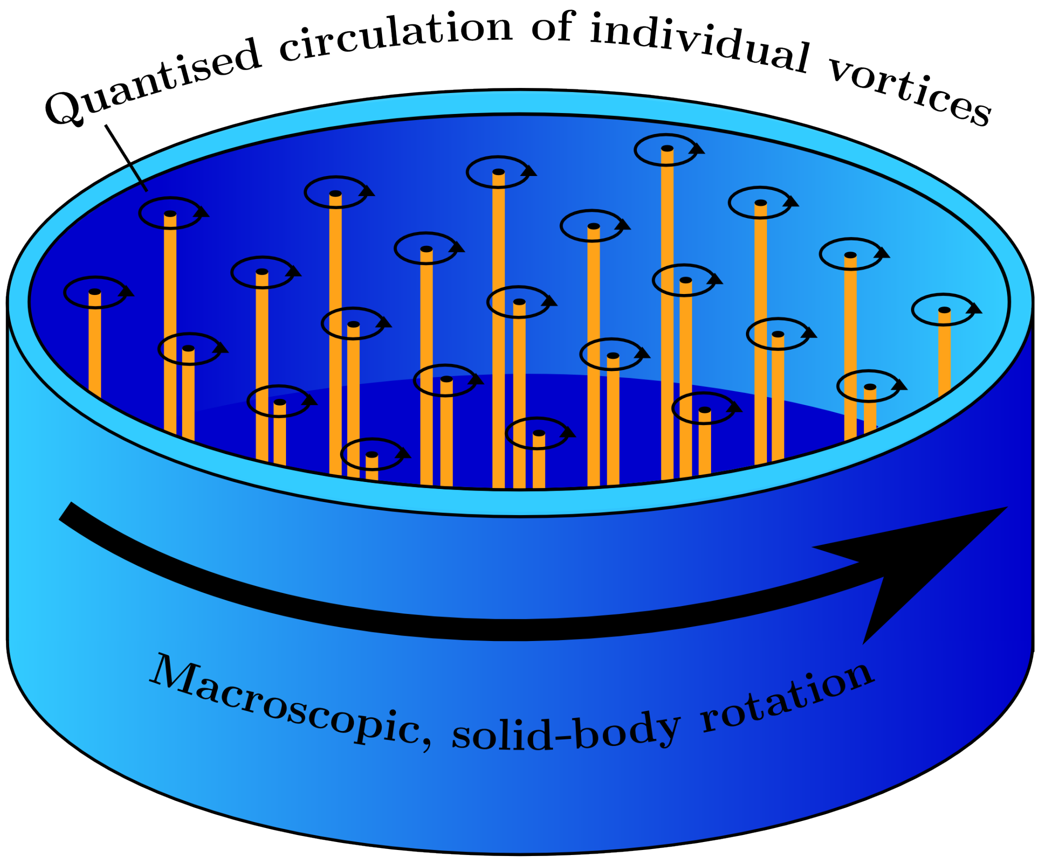
- We suggest vorticity—an archetypal topological texture—as a novel transport carrier (and a building block for functional circuitries)

- *Can vorticity flow in insulating magnetic films as a conserved hydrodynamic quantity?*

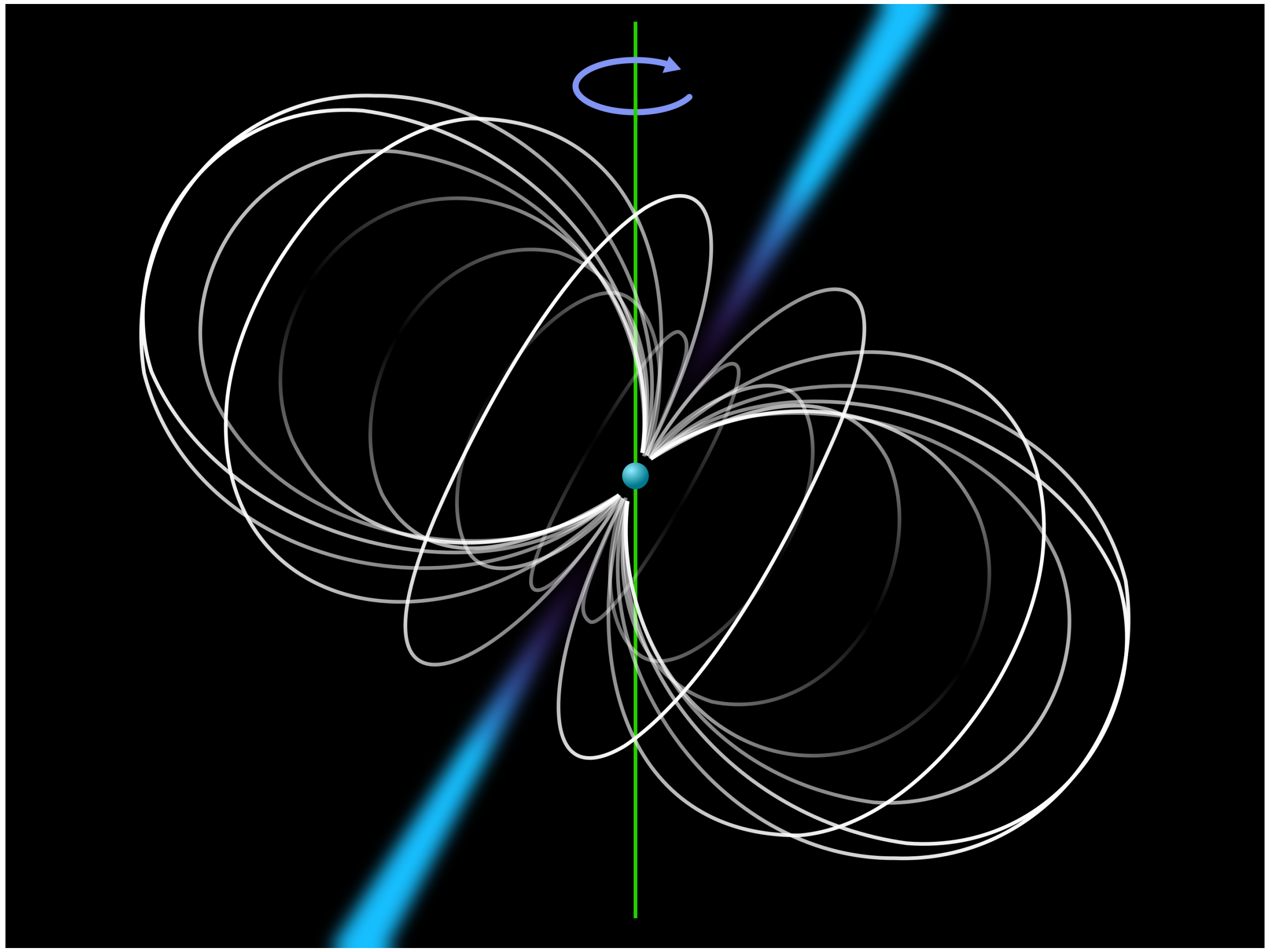
- *Can it be controlled electrically and are there obvious experimental signatures and possibly applications?*

Kim, Myers, and YT, *PRL* (2018)

How is vorticity normally controlled in a neutral system?



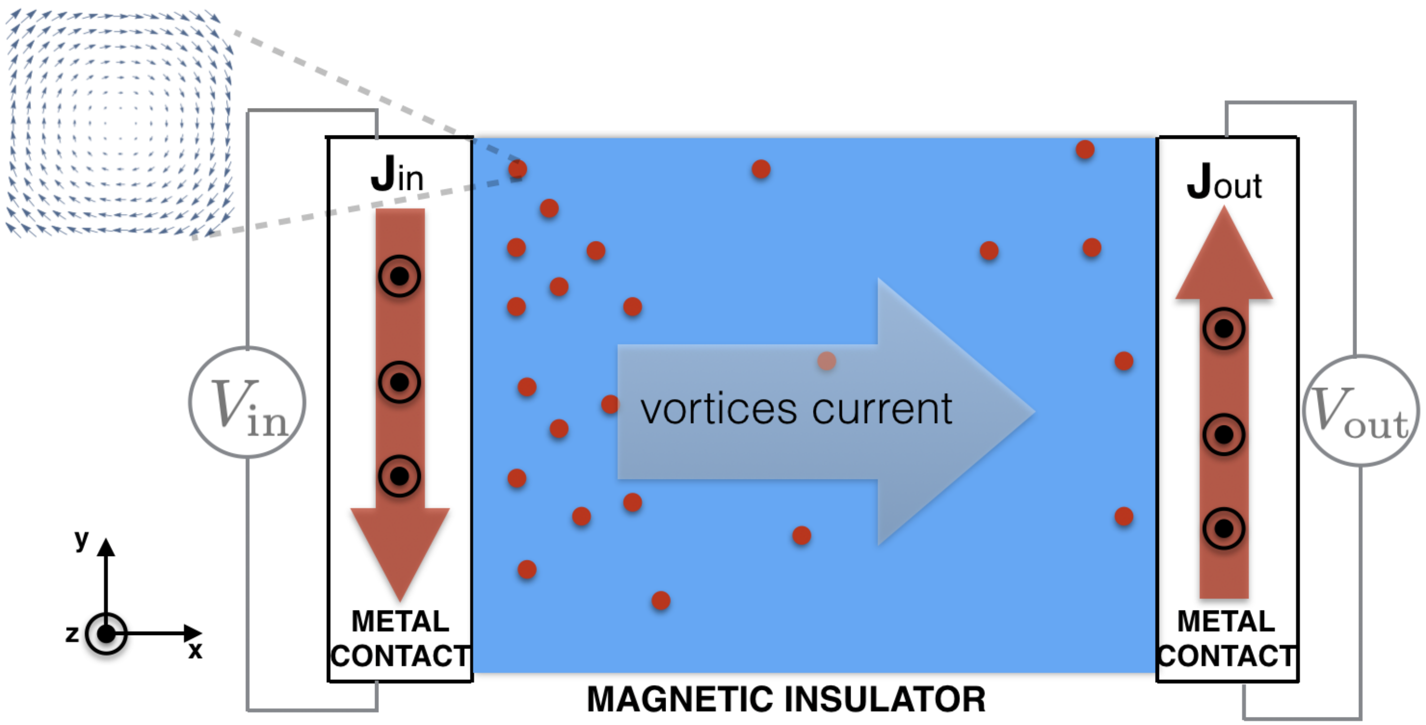
rotating superfluid container



similar physics is responsible for
neutron star pulsar glitches

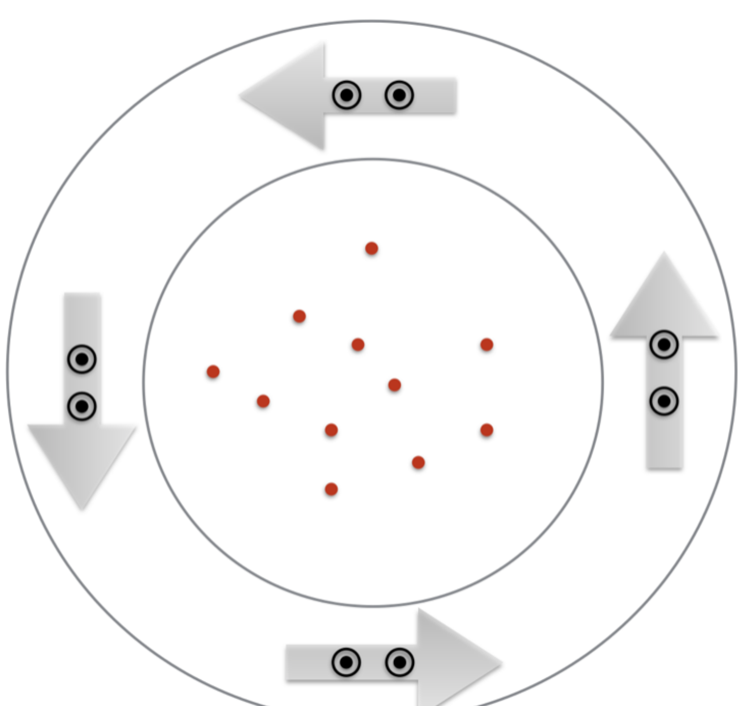
Vorticity transport in Heisenberg magnets

$$\rho = \frac{\mathbf{z}\cdot\partial_x\mathbf{m}\times\partial_y\mathbf{m}}{\pi} \qquad j_x = \frac{\mathbf{z}\cdot\partial_y\mathbf{m}\times\partial_t\mathbf{m}}{\pi} \qquad j_y = -\frac{\mathbf{z}\cdot\partial_x\mathbf{m}\times\partial_t\mathbf{m}}{\pi}$$



the two-component 2D vortex plasma provides a functional semiconductor-type medium

$$\partial_t\rho + \boldsymbol{\nabla}\cdot\mathbf{j} = 0$$



a circulating current around an (insulating) Heisenberg magnet controls the effective "chemical potential of the vorticity"

Zou, Kim, and YT, *PRB* (2019)

Direct detection of vortex transport in superconductors

VOLUME 92, NUMBER 23 PHYSICAL REVIEW LETTERS week ending 11 JUNE 2004

Long-Range Nonlocal Flow of Vortices in Narrow Superconducting Channels

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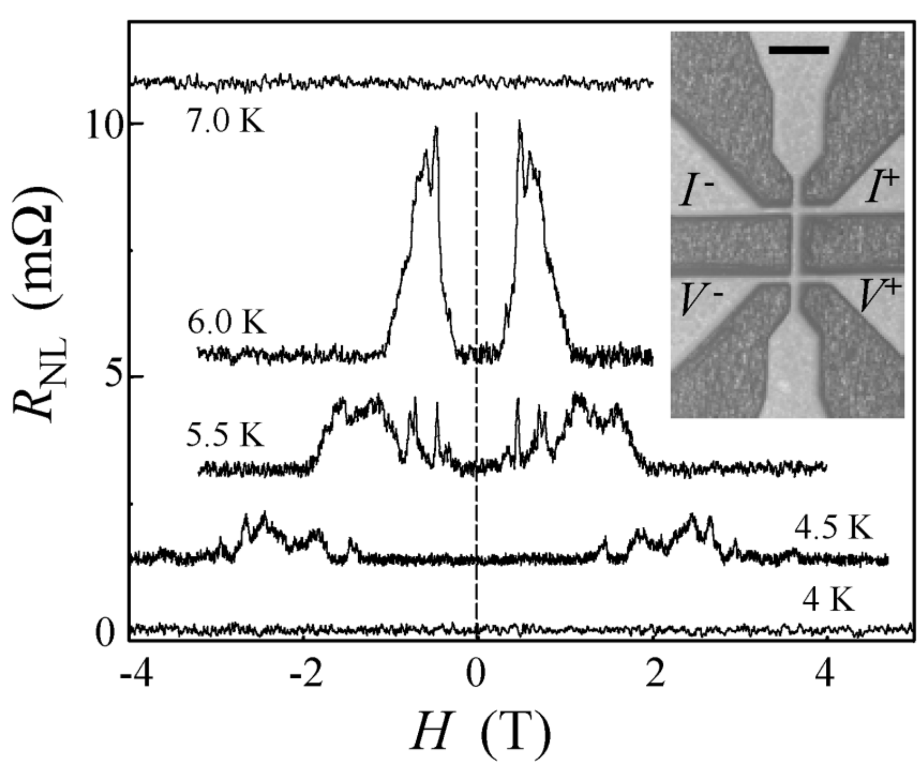
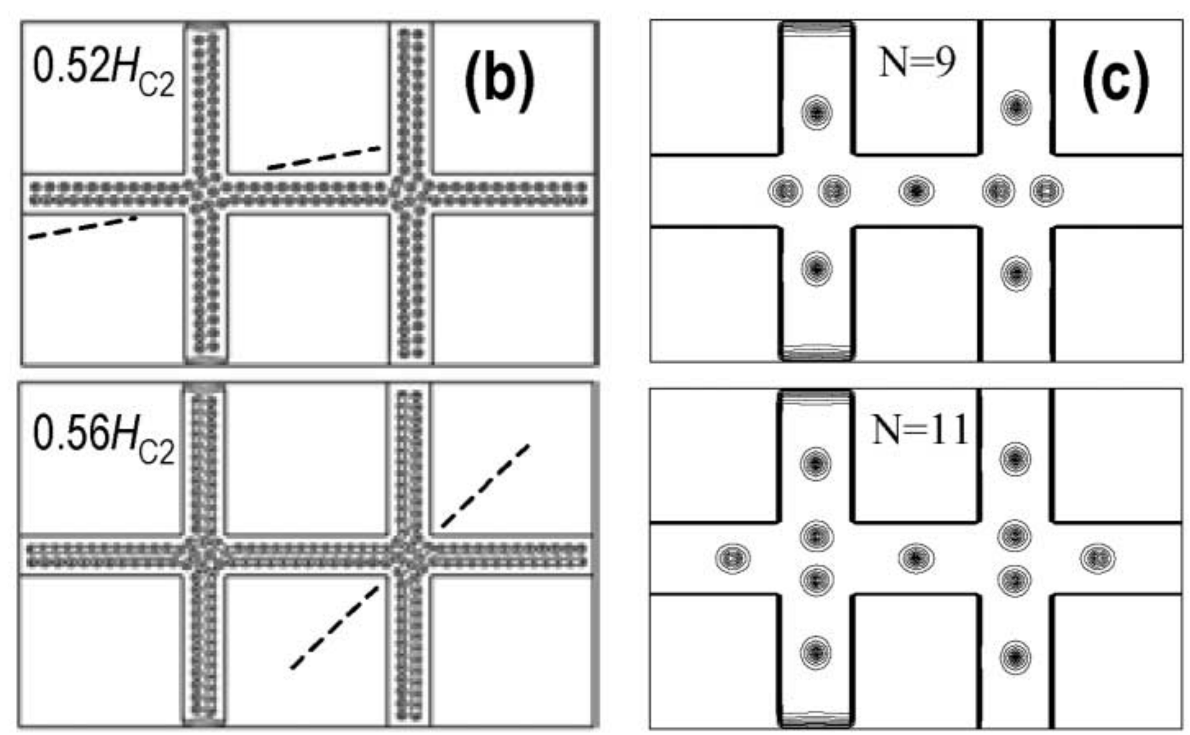
(Received 1 December 2003; published 8 June 2004)

We report a new nonlocal effect in vortex matter, where an electric current confined to a small region of a long and sufficiently narrow superconducting wire causes vortex flow at distances hundreds of intervortex separations away. The observed remote traffic of vortices is attributed to a very efficient transfer of a local strain through the one-dimensional vortex lattice (VL), even in the presence of disorder. We also observe mesoscopic fluctuations in the nonlocal vortex flow, which arise due to ‘‘traffic jams’’ when vortex arrangements do not match a local geometry of a superconducting channel.

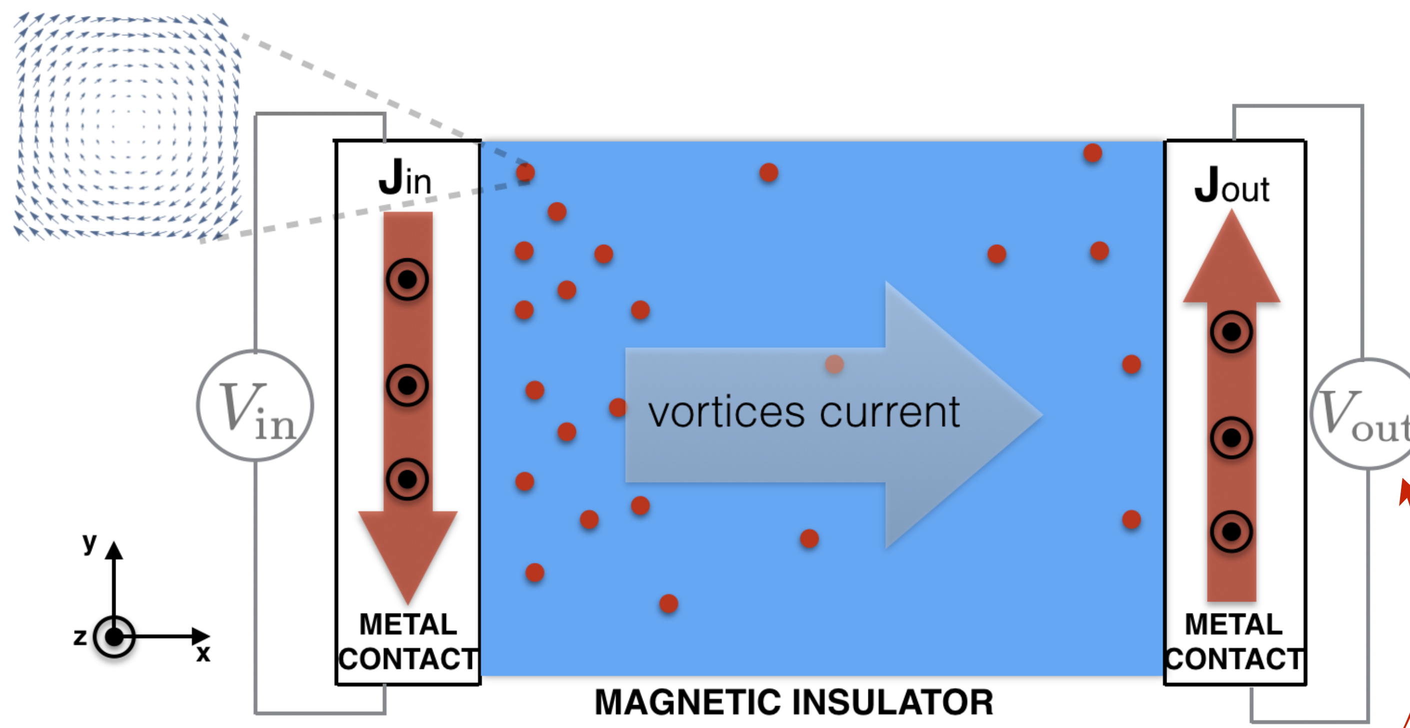




A little bit of "microscopics"

spin torque by the input current at the left interface:

$$\boldsymbol{\tau} = \eta \mathbf{M} \cdot \mathbf{m} (\mathbf{J} \cdot \boldsymbol{\nabla}) \mathbf{m}$$



Onsager-reciprocal motive force

$\mathbf{M} \propto \mathbf{z}$ - magnetization of the metal contact

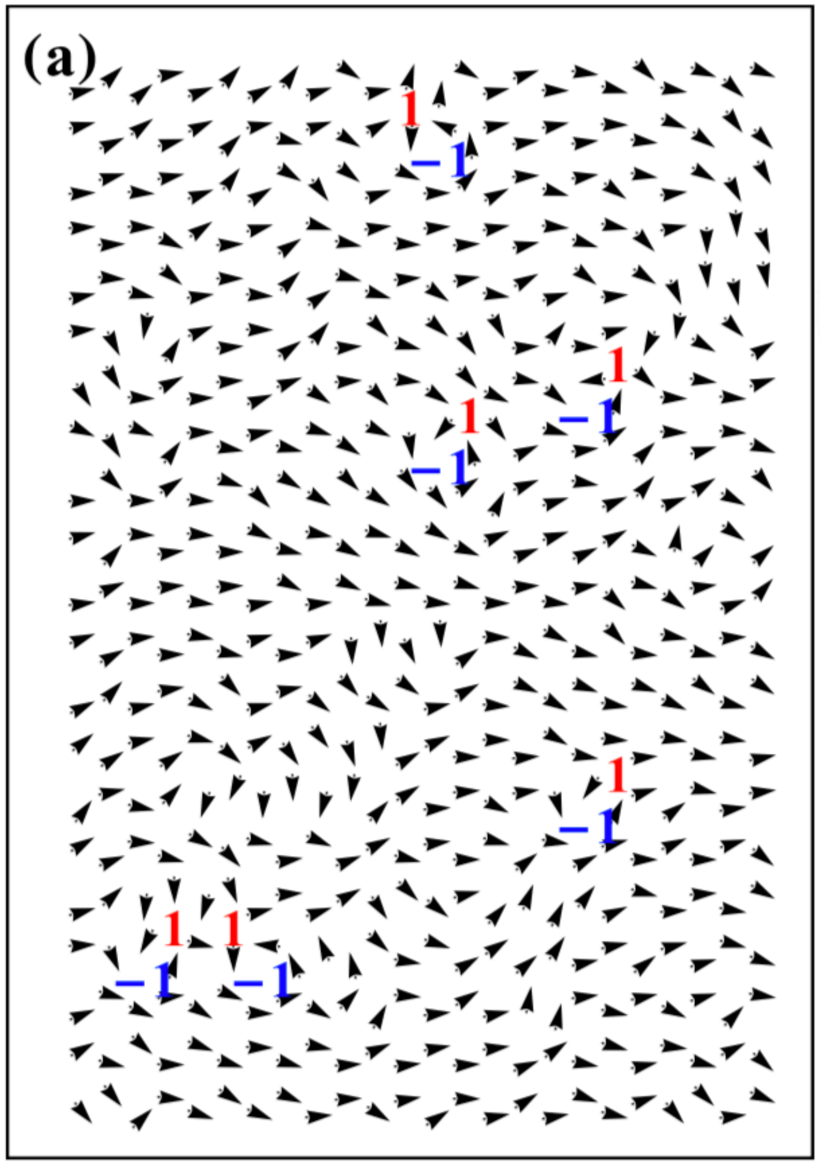
$\mathbf{m}(x, y, t)$ - magnetic texture of the insulator

$$\dot{W} = \int dt dy \, \boldsymbol{\tau} \cdot (\mathbf{m} \times \partial_t \mathbf{m}) = \eta \, \mathbf{z} \cdot \mathbf{J} \times \mathbf{j}$$

charge current

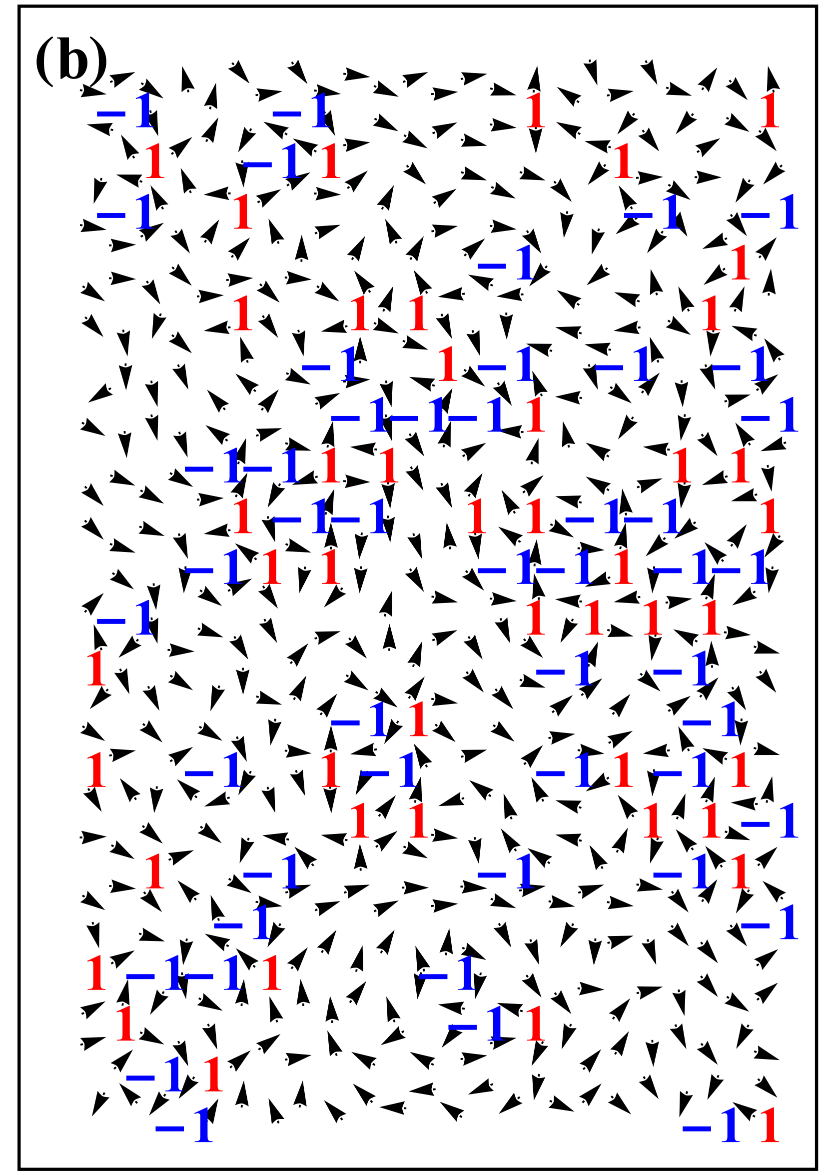
vortex flux

A useful conceptual example: Kosterlitz-Thouless transition



$T < T_{KT}$

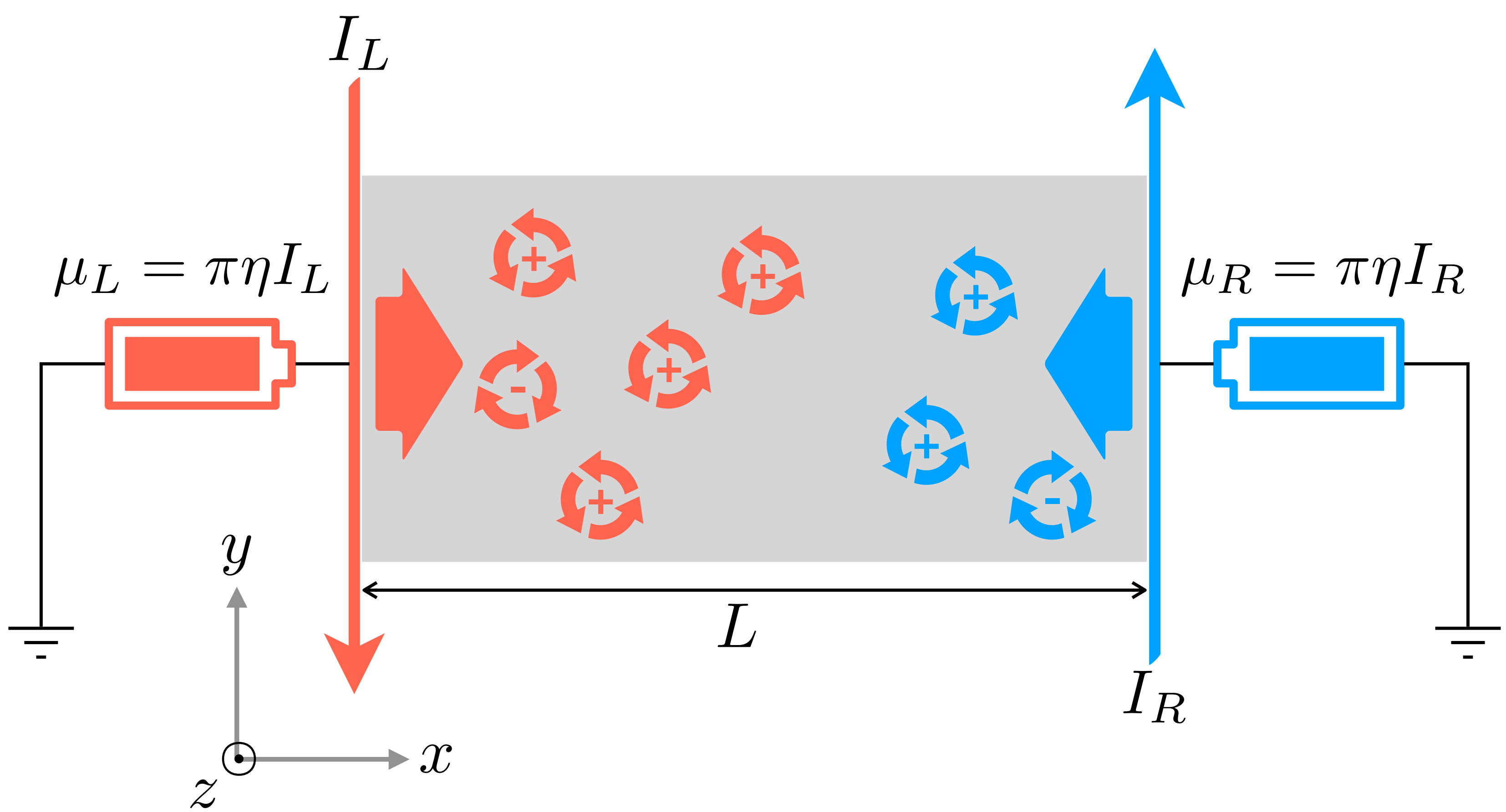
vortices bind with antivortices:
vorticity insulator



$T > T_{KT}$

(anti)vortices unbind and proliferate:
vorticity metal (two-component plasma)

Why magnetic vortices could be interesting?



- Robust conservation law ⇒ long-ranged transport
- Intricate relation to winding ⇒ topological energy storage
- Wealth of insulating room-temperature magnetic materials, particularly antiferromagnets

A proposal for magnetic energy storage

PHYSICAL REVIEW LETTERS **121,** 127701 (2018)

Editors' Suggestion

Energy Storage via Topological Spin Textures

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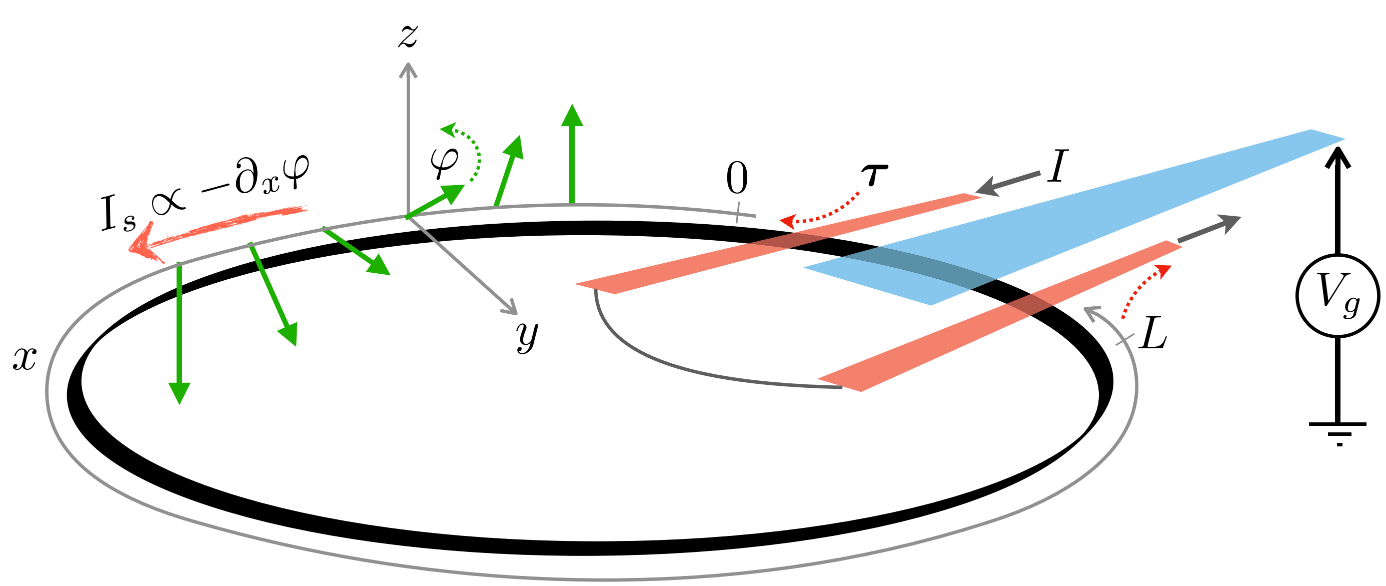
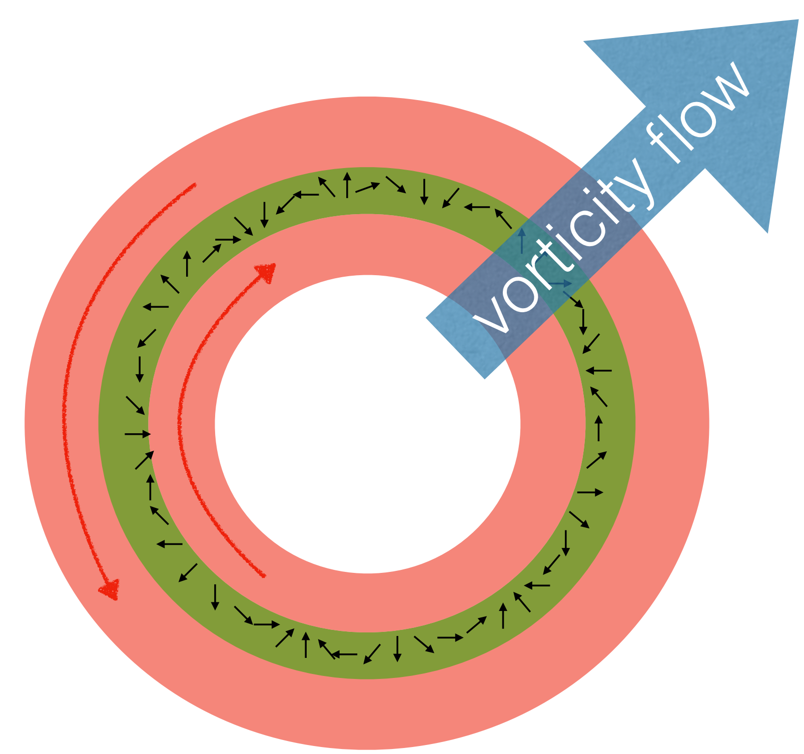
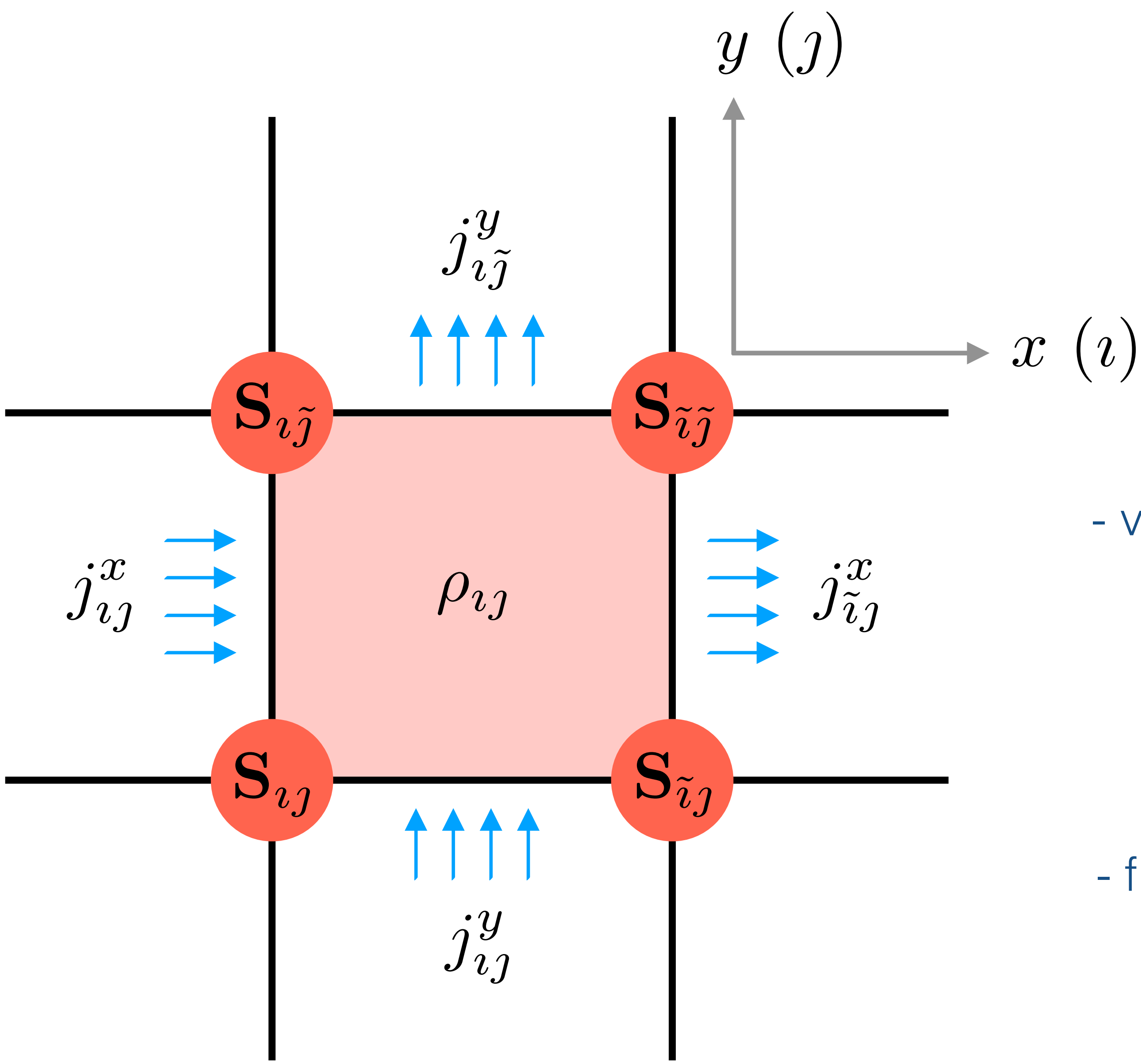
We formulate an energy-storage concept based on the free energy associated with metastable magnetic configurations. Despite the active magnetic region of the battery being electrically insulating, it can sustain effective hydrodynamics of spin textures, whose conservation law is governed by topology. To illustrate the key physics and potential functionality, we focus here on the simplest quasi-one-dimensional case of planar winding of the magnetic order parameter. The energy is stored in the metastable winding number, which can be injected electrically by an appropriately tailored spin torque. Because of the nonvolatility and the endurance of magnetic systems, the injected energy can be stored essentially indefinitely, with the topological charge cycles that do not degrade over time.





Quantum hydrodynamics of vorticity



$$\partial_t \rho_{\imath\jmath} + \frac{j^x_{\tilde\imath\jmath} - j^x_{\imath\jmath} + j^y_{\imath\tilde\jmath} - j^y_{\imath\jmath}}{a} = 0$$

- vorticity per plaquette:

$$\rho_{\imath\jmath} = \frac{\mathbf{z}\cdot(\mathbf{S}_{\tilde\imath\jmath} - \mathbf{S}_{\imath\tilde\jmath}) \times (\mathbf{S}_{\tilde\imath\tilde\jmath} - \mathbf{S}_{\imath\jmath})}{2\pi(aS)^2}$$

- flux per link:

$$j^x_{\imath\jmath} = \frac{\mathbf{z}\cdot(\mathbf{S}_{\imath\tilde\jmath} - \mathbf{S}_{\imath\jmath}) \times \partial_t(\mathbf{S}_{\imath\tilde\jmath} + \mathbf{S}_{\imath\jmath})}{4\pi a S^2} + \text{H.c.}$$

- *Experimental (transport) signatures of the quantum statistics of vortices?*
- *A direct transport probe of the superfluidity of vorticity?*

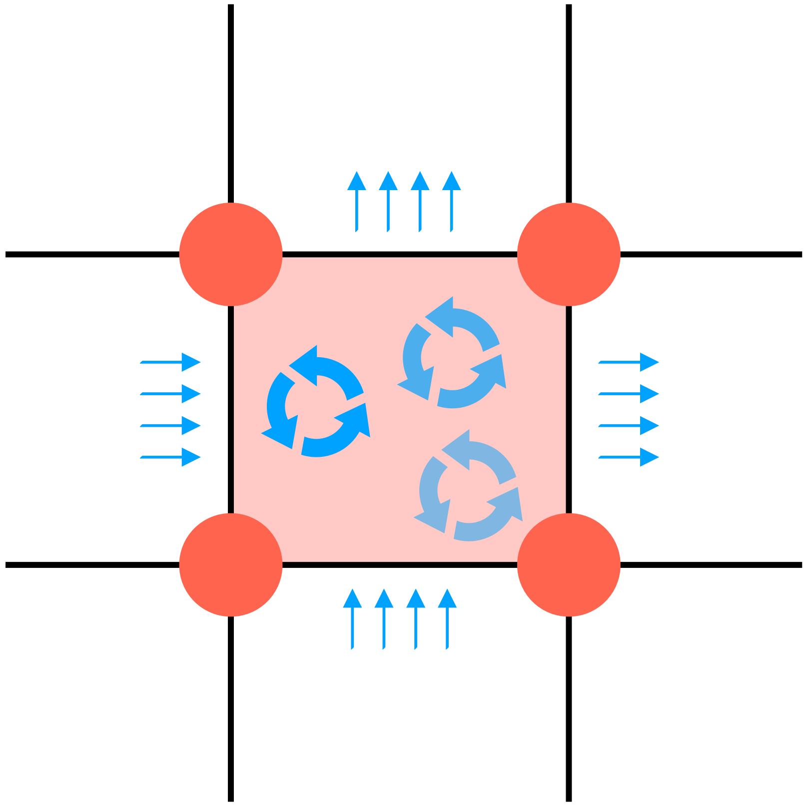
YT and Zou, *PRR* (2019)

Some take-home messages

- *Hydrodynamic* properties of vorticity in magnets and superfluids may yield robust long-ranged signal flows

- Magneto-(thermo)-electric tools allow us to access this versatile physics utilizing (interfacial) spin torques

- Our practical outlook is towards insulator-based integrated circuits, where smooth topological textures and topological solitons engender both active device elements, transport interconnects, as well as energy storage



Thank you!