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Theory of radiation-induced zero resistance states in 2D systems

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Microwave Induced Resistance Oscillations (MIRO) and Zero Resistance States (ZRS)

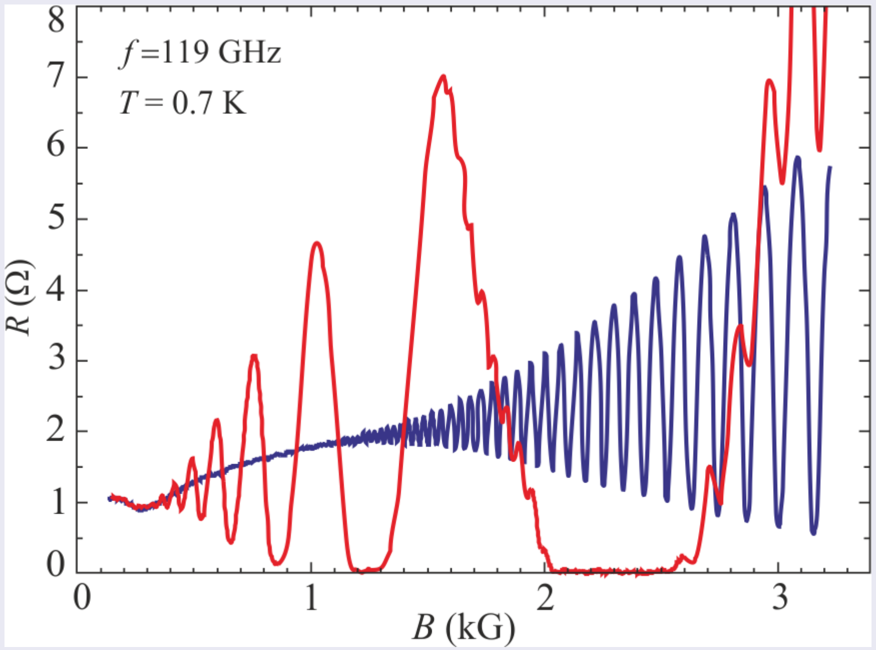
Nonequilibrium phenomena in high Landau levels

2001-Present:

- Integer and fractional MIRO and ZRS in semiconductor quantum Hall systems
- Zero Admittance States in 2D electron system on liquid He
- magnetooscillations induced by strong dc current
- magnetooscillations induced by resonant interaction with acoustic phonons
- photovoltaic effects. . .

Review:
Dmitriev, Mirlin, Polyakov, Zudov, *Rev. Mod. Phys. 84, 1709 (2012)*

Experiments: MIRO & ZRS



ZRS: Mani,Smet,von Klitzing, Narayanamurti,Johnson,Umansky'02, Zudov,Du,Pfeiffer,West'03, Dorozhkin'03, Willett,Pfeiffer,West'04 ..
MIRO: Zudov,Du,Simmons,Reno'01, Ye,Tsui,Simmons,Wendt,Vawter,Reno'01,..

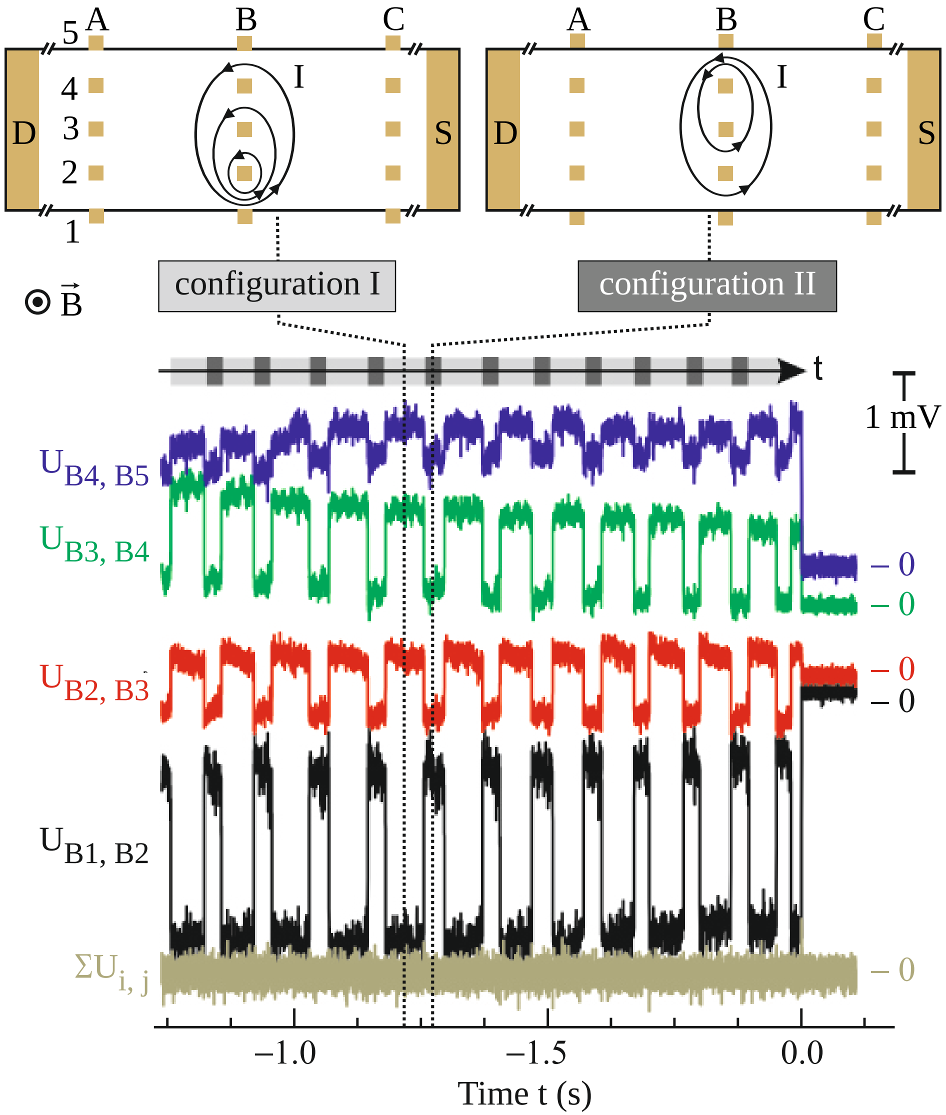
Direct evidence for static domains in ZRS?

Time-resolved measurement of photovoltage signals between internal probes under continuous illumination

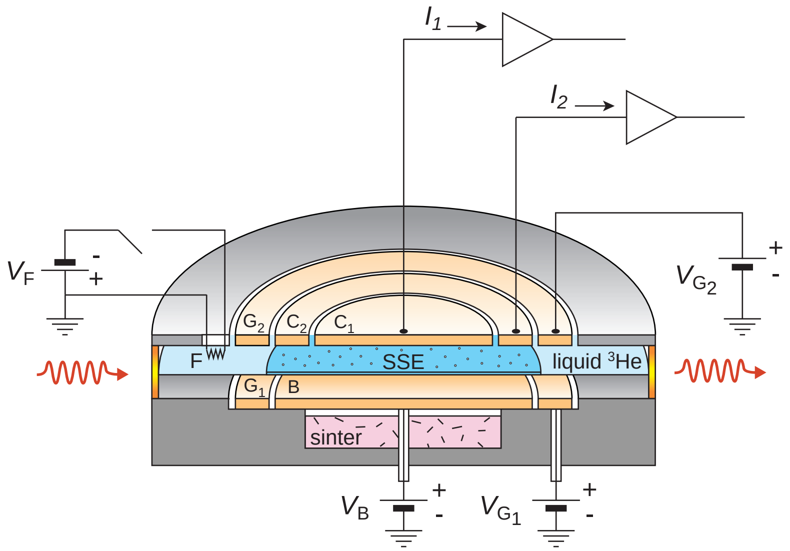
Random telegraph signals for Hall voltages

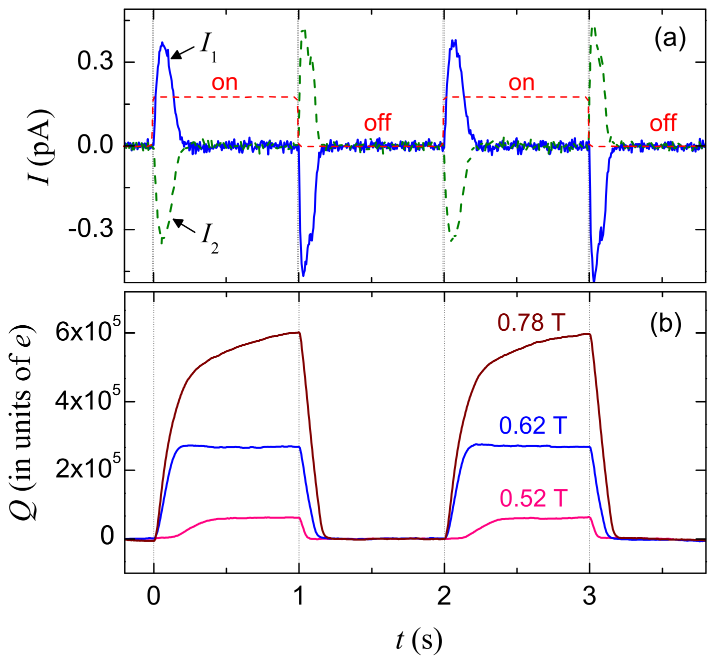
Spontaneous switching between two nearly degenerate configurations of domains

Dorozhkin,Pfeiffer, West, von Klitzing, Smet'11



Wigner electron liquid on surface of liquid He



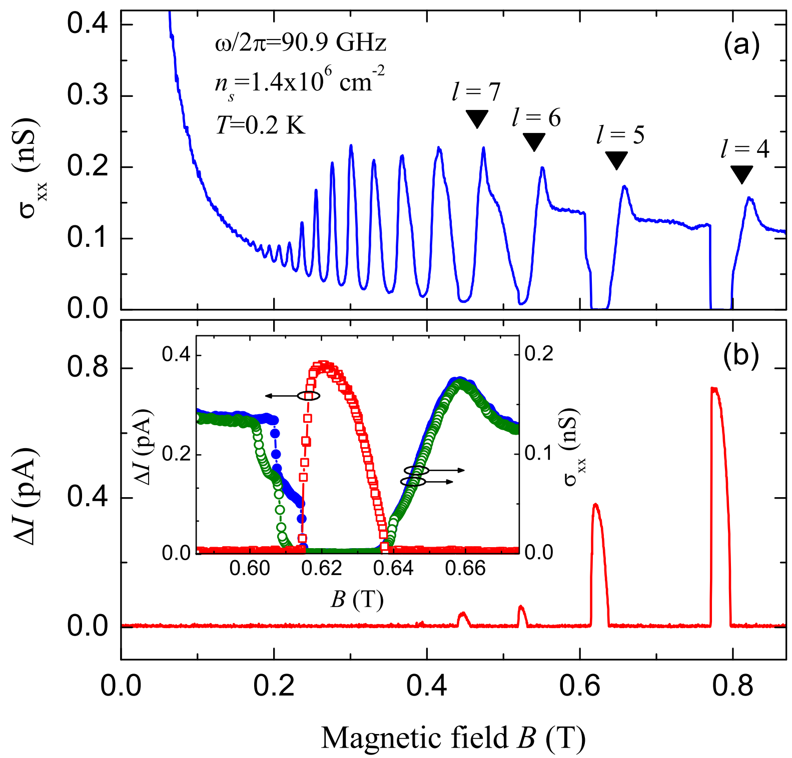


Konstantinov and Kono'09,10,
Konstantinov,Chepelianskii,Kono'12

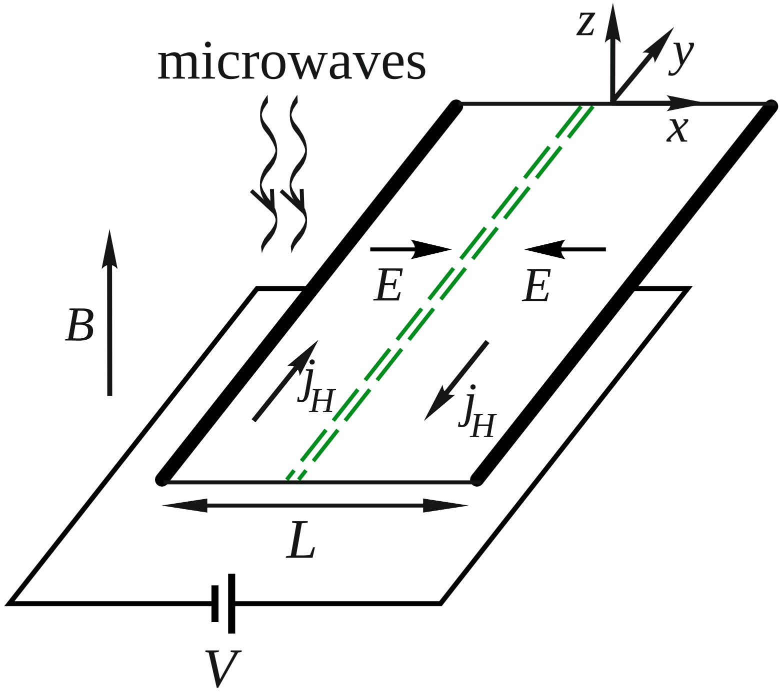
- Magnetooscillations and zero dissipation in the minima under microwave illumination

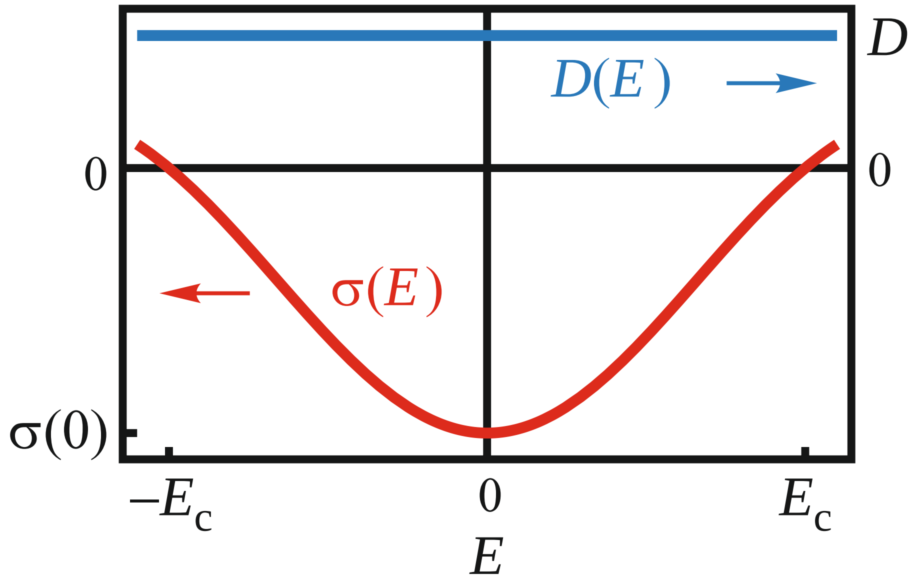
- Time-resolved capacitive measurement for radiation switched on and off:

Charge transfer due to domain formation!



Domain state in ZRS: Stripe geometry





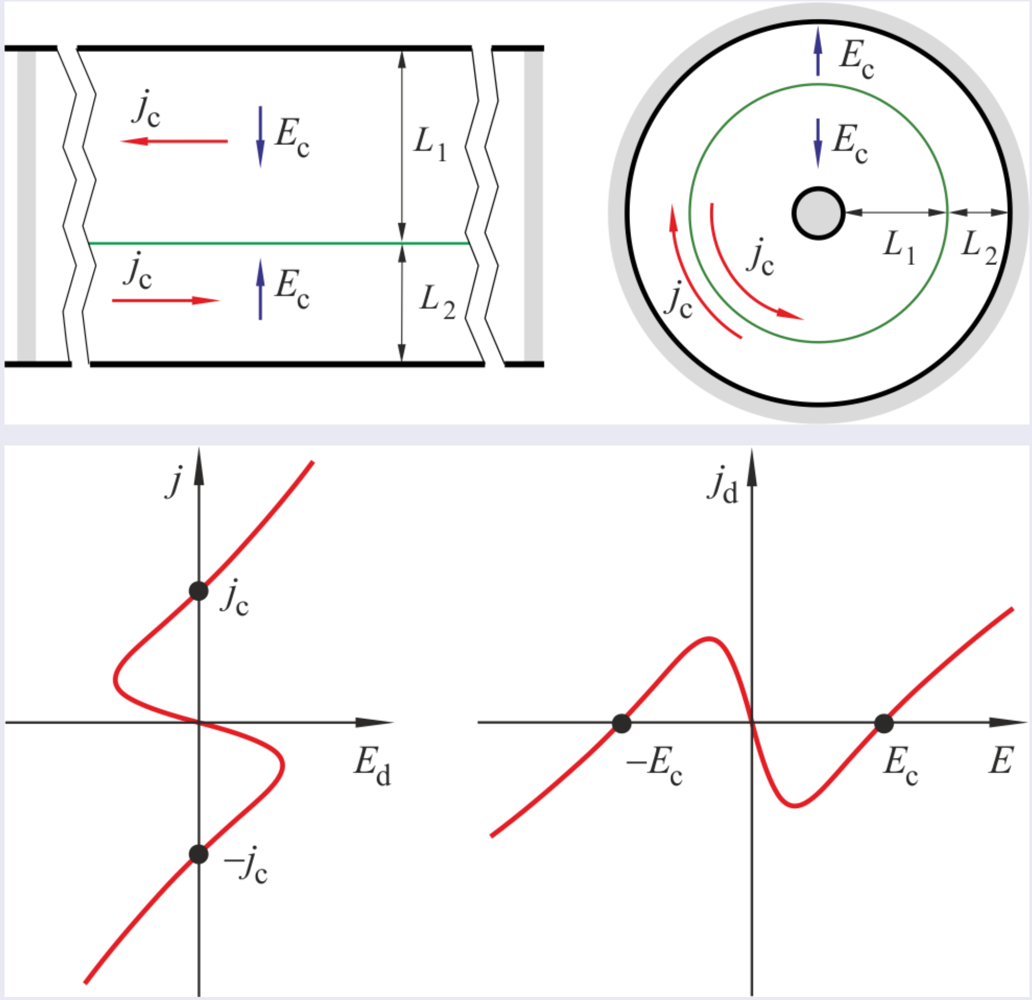
Negative absolute conductivity of homogeneous state, $\mathbf{j} \cdot \mathbf{E} < 0$

$\Rightarrow$ Electrical instability: Translational symmetry spontaneously broken

$\Rightarrow$ Domain state $\equiv$ Spontaneously formed inhomogeneous state

Domains $\Rightarrow$ zero resistance/conductance

Hall bar **Corbino**



Dyakonov, Furman'84, Andreev,Aleiner,Millis'03

Domains with $j_c \perp E_c = \rho_H j_c$,

where $\sigma(E_c) = 0$ and $\rho_H = B/enc$.

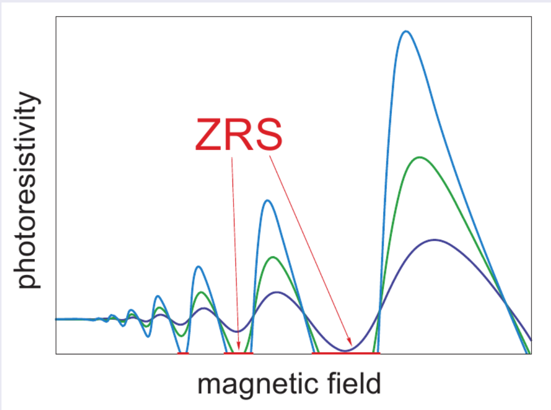
External bias
moves the domain wall

Hall bar: zero resistance state

$V = 0$ for any $I = j_c(L_1 - L_2)$

Corbino: zero conductance state

$I = 0$ for any $V = E_c(L_1 - L_2)$



Overview of the model: Key ingredients

2D charge density $\rho(x)$ & in-plane electric field $E(x)$

Poisson equation: $-\epsilon\Delta\phi = 4\pi\rho\delta(z) \quad \Rightarrow \quad \rho(x) = -\int \frac{\epsilon\, dx'}{2\pi^2}\frac{E(x')}{x-x'}$

Continuity equation: $\partial_t\rho + \nabla\cdot j = 0$ (Static domains $\Rightarrow$ $\partial_t\rho = 0$)

$j = \sigma(E)E - D\nabla\rho$: conductivity $\sigma(0) < 0$, diffusion coefficient $D > 0$

Einstein relation does not hold: $e^2\nu_0 D \neq \sigma(0)$!

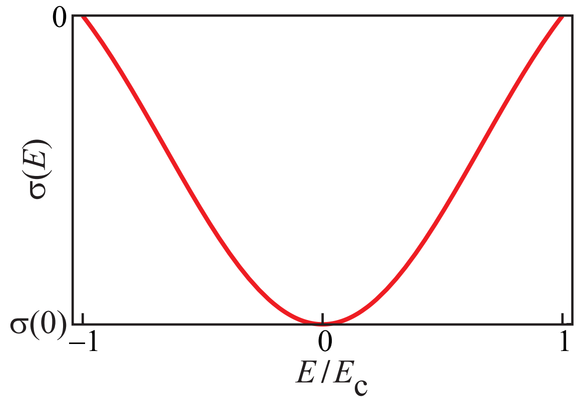
Resulting nonlinear integral equation

$j = \sigma(E)\,E(x) + D\,\partial_x \int \frac{dx'}{2\pi^2}\frac{\epsilon E(x')}{x-x'}$ $+$ boundary conditions

1. Domain solution in infinite system

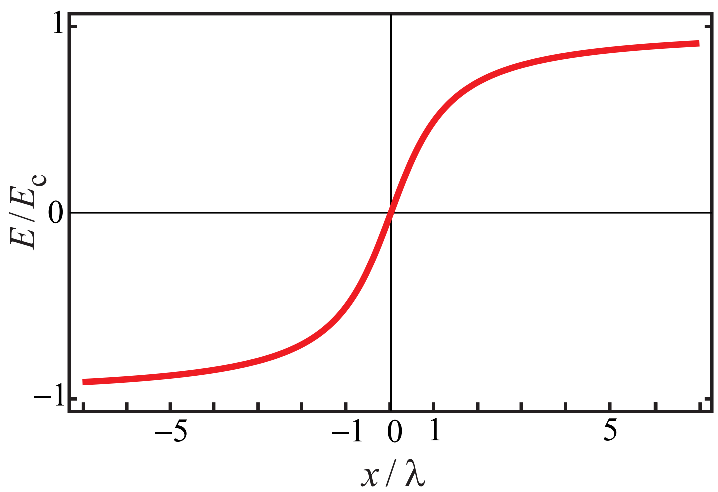
- Solve $j = 0$ with boundary conditions $E|_{x\to\pm\infty} = \pm E_c$

- Sine model: $\sigma(E) = \sigma(0)\dfrac{\sin \pi E/E_c}{\pi E/E_c}, \quad \sigma(0) < 0$



$$\sigma(E)\, E(x) + D\, \partial_x \int \frac{dx'}{2\pi^2} \frac{\epsilon E(x')}{x - x'} = 0 \qquad \Rightarrow \qquad -\sin \frac{\pi E}{E_c} + \lambda\, \partial_x \int \frac{dx'}{x - x'} \frac{E(x')}{E_c} = 0$$

Solution: $\dfrac{E}{E_c} = \dfrac{2}{\pi} \arctan \dfrac{x}{\lambda}, \qquad \lambda = \dfrac{\epsilon D}{2\pi|\sigma(0)|}$



Nonequilibrium screening length λ:

- The only spatial scale $\Rightarrow$ width of domain wall
- Diverges at $\sigma(0) \to 0 \quad \Rightarrow \quad$ critical parameter
- R educes to $\lambda_{TF} = \dfrac{\epsilon}{2me^2}$ in equilibrium

2. Domain solution in unbiased finite system

Fluctuations $\delta\rho(t)e^{iq_y y}\sin(q_x x)$: Stability $\leftrightarrow$ $\partial_t \ln \delta\rho(t) < 0$

$$q_x = n\pi/L \;\Rightarrow\; q = \sqrt{q_x^2 + q_y^2} \geqslant \pi/L$$

- Finite L: uniform state $\rho(x) \equiv 0$ is stable for $\sigma > -\epsilon D/2L$ $\Leftrightarrow$ $l = L/\pi\lambda < 1$
- $L \to \infty$: usual condition $\sigma > 0$
- Photovoltaics at $-\epsilon D/2L < \sigma < 0$ $(0 < l < 1)$ $\rightarrow$ Dorozhkin, Dmitriev, Mirlin, PRB'11

$l = L/\pi\lambda$

$$\frac{E(x)}{E_c} = -\frac{2}{\pi}\,\mathrm{arctan}\left(\sqrt{l^2-1}\cos\frac{\pi x}{L}\right)$$

$$\frac{2\pi\rho(x)}{\epsilon E_c} = \frac{2}{\pi}\,\mathrm{artanh}\left(\sqrt{1-l^{-2}}\sin\frac{\pi x}{L}\right)$$

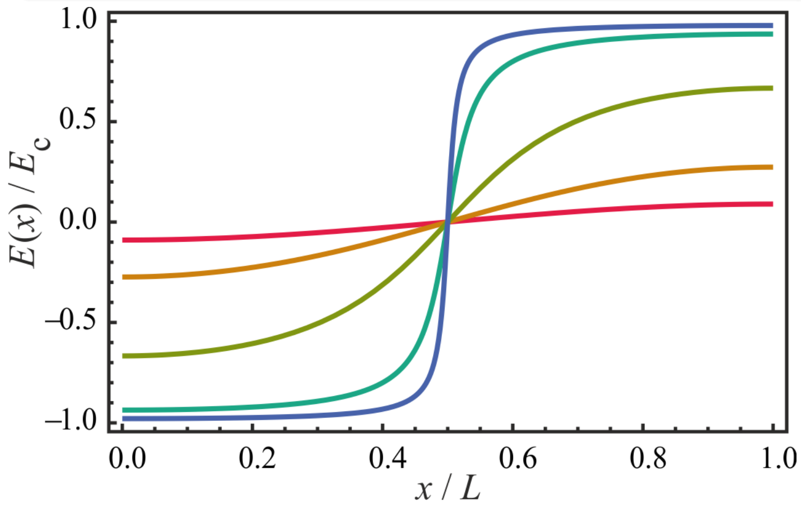
$l = 30$

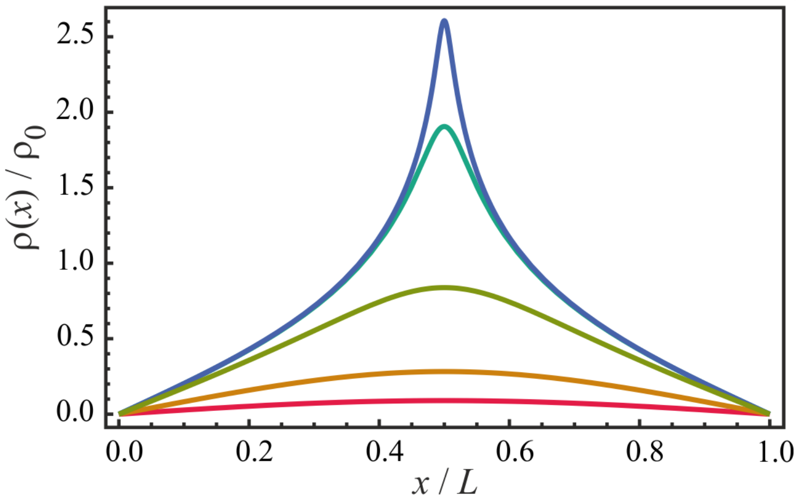
$l = 10$

$l = 2$

$l = 1.1$

$l = 1.01$





General approach to stability: Lyapunov functional

Lyapunov functional $\Phi = K - G$: Stable solution $\equiv$ Global minimum of Φ

Application to ZRS (3D, limit $\lambda \ll L$) Auerbach,Finkler,Halperin,Yacoby'05

- Bulk gain $G = -\int dx \int_0^{E(x)} \sigma(E')E'dE'$: $\sigma < 0$ $\Rightarrow$ Maximized for $|E(x)| = E_c$

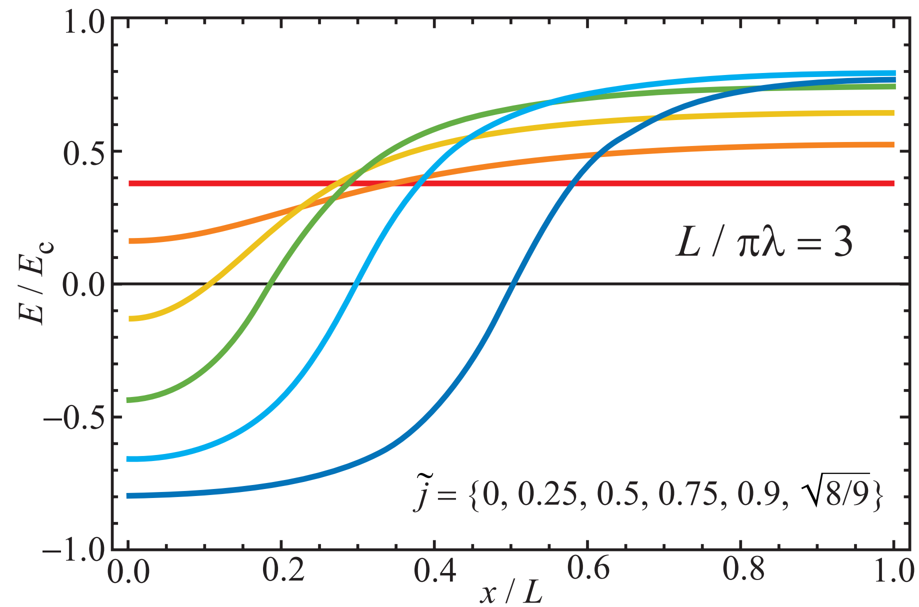
- Domain walls $K = \frac{D}{2}\int dx\, E(x)\, \hat{C}\, E(x) \geqslant 0$ $\Rightarrow$ Minimized for $\partial_x E = 0$

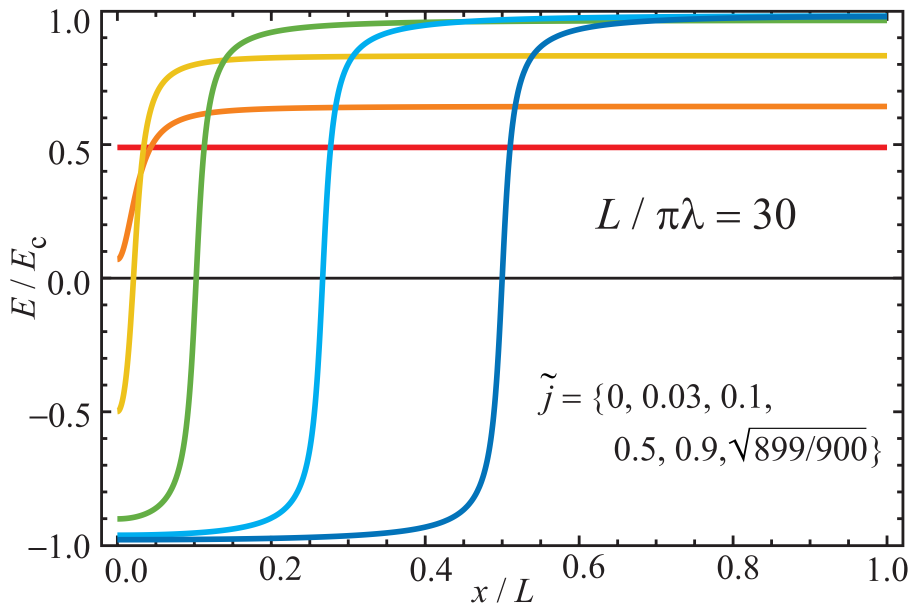
capacitance C: $\rho(x) = \hat{C}\phi(x)$

Sine model: $$\Phi = \frac{\pi\lambda}{8E_c^2}\int dx\, dx' \left[\frac{E(x) - E(x')}{x - x'}\right]^2 - \int dx\, \sin^2\frac{\pi E}{2E_c} \geqslant -1$$

3. Domain solution in a biased 2D stripe

- Solve $\sin\frac{\pi E}{E_c} - \lambda\,\partial_x \int \frac{dx'}{E_c}\,\frac{E(x')}{x-x'} = \tilde{j};$ (Anti)dissipative current $\tilde{j} = \frac{\pi j}{\sigma(0) E_c}$



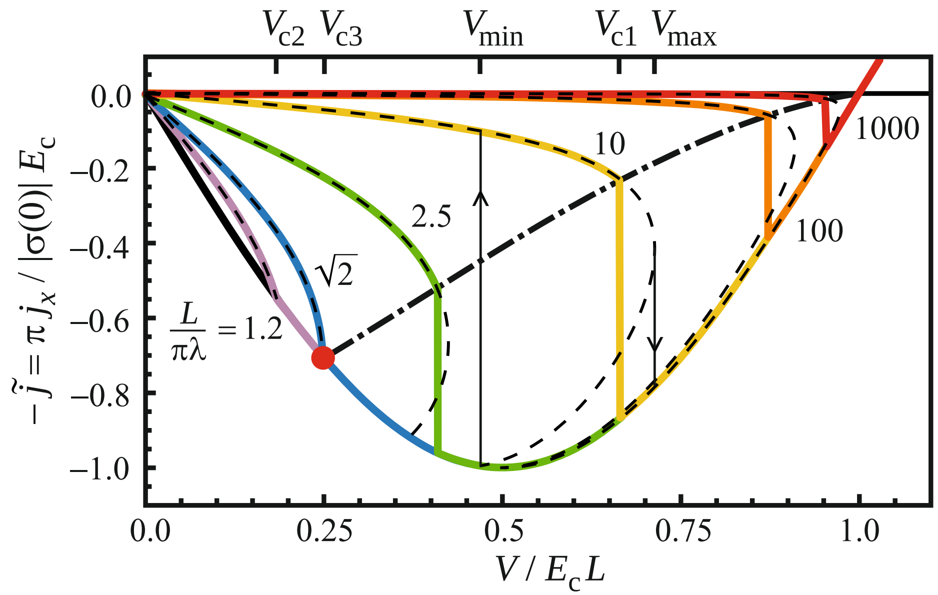


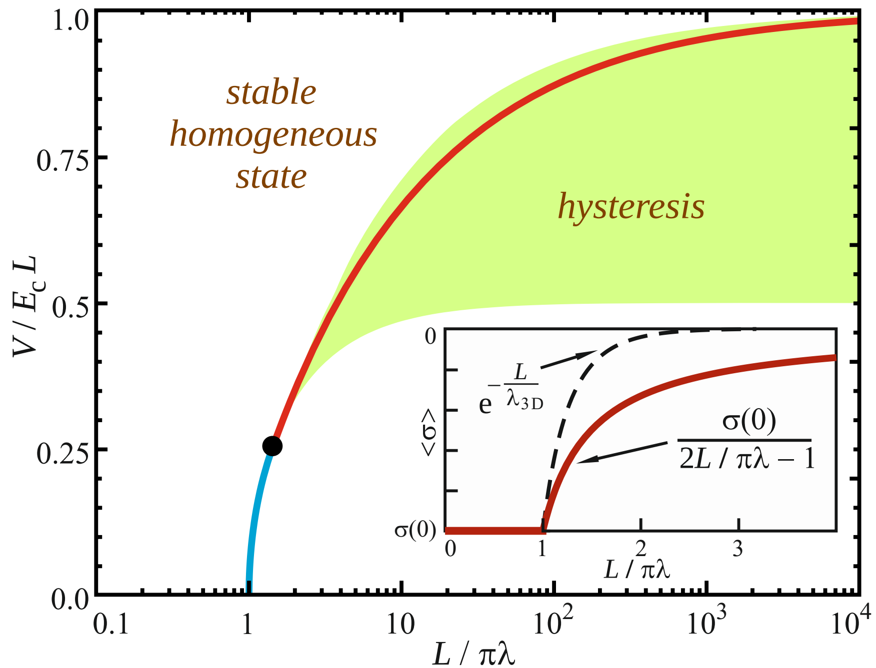
Finite bias $\tilde{j}$: Shift $w(\tilde{j})$ and broadening $\beta(\tilde{j})$ of the domain wall

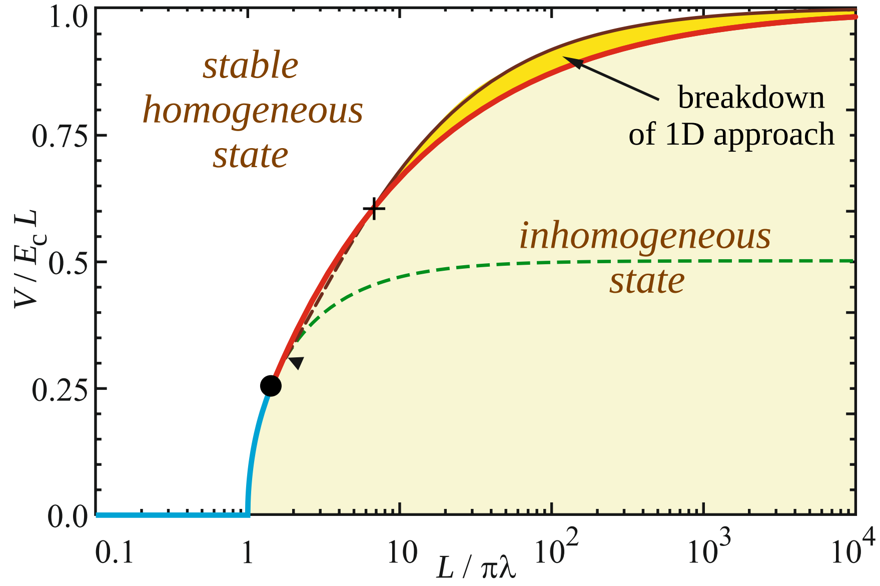
Full solution: $\Psi \equiv \frac{\pi}{2E_c}E + i\frac{\pi^2}{\epsilon E_c}\rho = i\ln\frac{\cosh(\xi - iw)}{\sinh\xi} - \frac{1}{2}\arcsin\tilde{j}, \qquad |\tilde{j}| \leqslant \sqrt{1-l^{-2}},$

where $2\xi = i\pi(x/L - 1/2) + iw + \beta, \quad w = \arctan(\tilde{j}\,l), \quad \beta = \operatorname{arcoth}(l\sqrt{1-\tilde{j}^2})$

Full CVC, phase diagram, and current discontinuity







1st and 2nd order phase transitions:

- $l \leqslant \sqrt{2}$: Kink in $j(V)$
- $l > \sqrt{2}$: Discontinuity in $j(V)$

- Frozen transverse fluctuations $\Rightarrow$ hysteresis
- Transverse fluctuations $\Rightarrow$ instability at large V and L

Summary and Outlook

Summary: Analytic model for the domain state in a biased 2D stripe

- $V - \mathrm{L}$ phase diagram: continuous and discontinuous phase transitions
- Transverse instability at large V and L: transition to a 2D domain state

I.A. Dmitriev, M. Khodas, A.D. Mirlin, D.G. Polyakov, arXiv:1305.1028

Outlook

- Critical behavior at the transition to ZRS: Influence of noise, nature of transition
- Domain structure in "zero admittance states" on surface of liquid He

- Experimental evidence of the domain formation: S. I. Dorozhkin et al., *Nature Phys.* **7**, 336 (2011); D. Konstantinov et al., *J. Phys. Soc. Jpn.* **81**, 093601 (2012).
- Review: I. A. Dmitriev, A. D. Mirlin, D. G. Polyakov, M. A. Zudov, *Rev. Mod. Phys. 84, 1709 (2012)*
- Domains in "3D": M.I. Dyakonov, *JETP Lett.* **39**, 185 (1984); M.I. Dyakonov and A.S. Furman, *Sov. Phys. JETP* **60**, 1191 (1984); A. F. Volkov and V. V. Pavlovskii, *Phys. Rev. B* **69**, 125305 (2004); J. Alicea et al., *Phys. Rev. B* **71**, 235322 (2005); A. Auerbach et al., *Phys. Rev. Lett.* **94**, 196801 (2005); I. G. Finkler and B. I. Halperin, *Phys. Rev. B* **79**, 085315 (2009)