Effects of spin-orbit coupling on the BKT transition and the vortex-antivortex structure in 2D Fermi Gases

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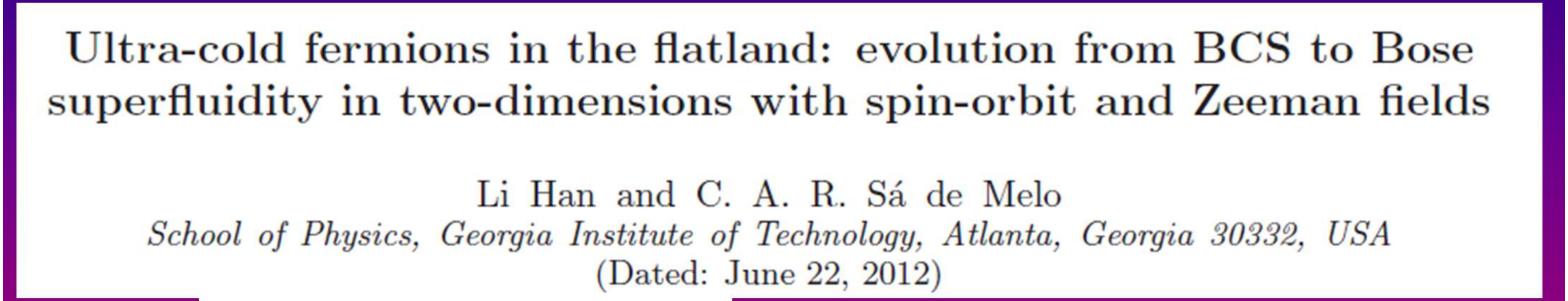
QMath13

Mathematical Results in Quantum Physics

Atlanta: October 10th, 2016

Main References for Talk



Ultra-cold fermions in the flatland: evolution from BCS to Bose superfluidity in two-dimensions with spin-orbit and Zeeman fields

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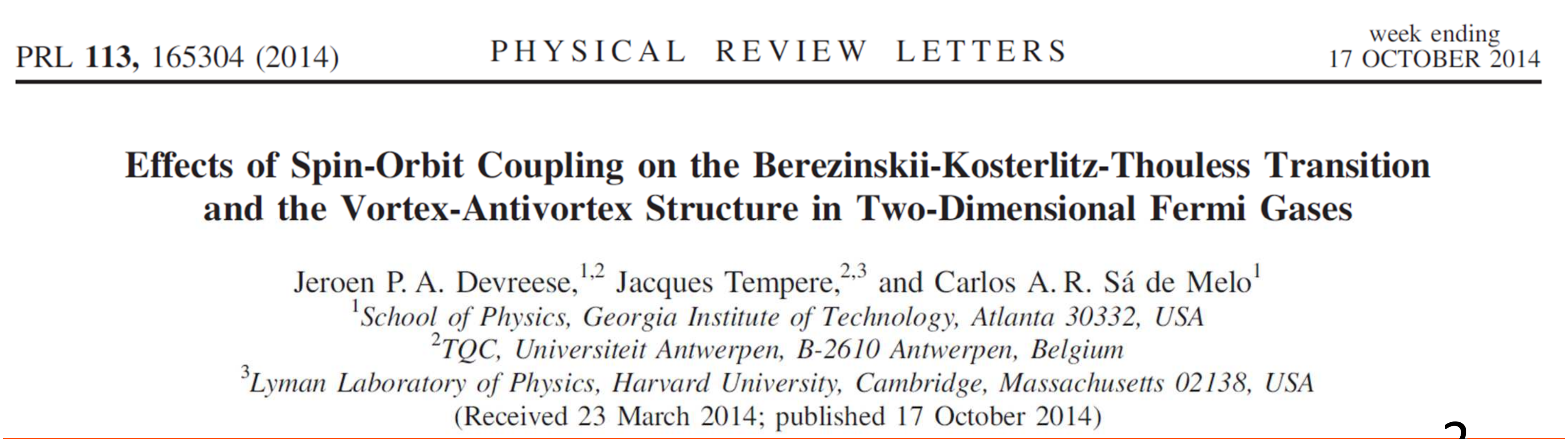

PRL **113,** 165304 (2014) PHYSICAL REVIEW LETTERS week ending 17 OCTOBER 2014

Effects of Spin-Orbit Coupling on the Berezinskii-Kosterlitz-Thouless Transition and the Vortex-Antivortex Structure in Two-Dimensional Fermi Gases

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Ian Spielman

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Outline

1) Introduction to 2D Fermi gases.

2) Creation of artificial spin-orbit coupling (SOC).

3) Quantum phases and topological quantum phase transitions of 2D Fermi gases with SOC.

4) The BKT transition and the vortex-antivortex structure.

5) Conclusions

Conclusions in words

- Ultra-cold fermions in the presence of spin-orbit and Zeeman fields are special systems that allow for the study of exciting new phases of matter, such as topological superfluids, with a high degree of accuracy.

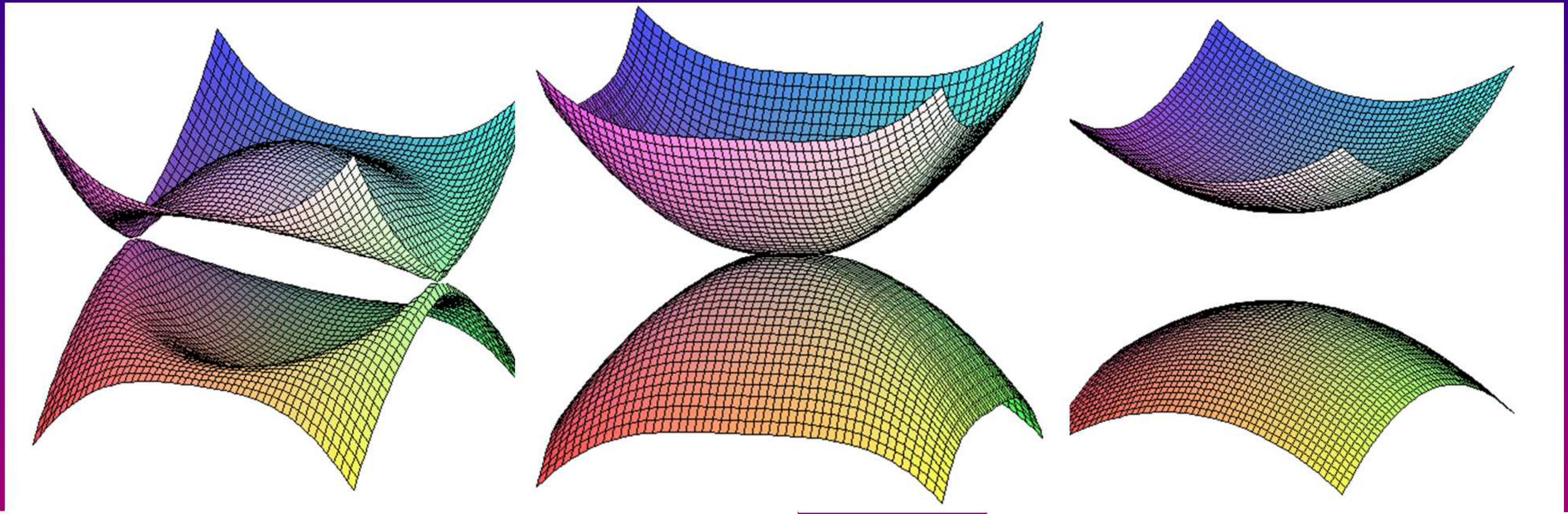
- Topological quantum phase transitions emerge as function of Zeeman fields and binding energy for fixed spin-orbit coupling.

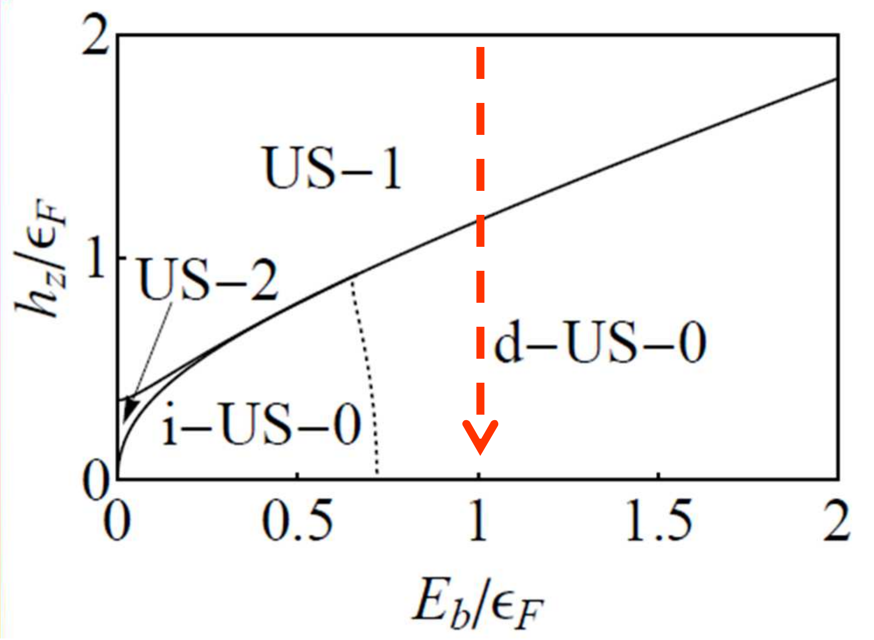
Conclusions in words

- The critical temperature of the BKT transition as a function of pair binding energy is affected by the presence of spin-orbit effects and Zeeman fields. While the Zeeman field tends to reduce the critical temperature, SOC tends to stabilize it by introducing a triplet component in the superfluid order parameter.

- In the presence of a generic SOC the sound velocity in the superfluid state is anisotropic and becomes a sensitive probe of the proximity to topological quantum phase transitions. The vortex and antivortex shapes are also affected by the SOC and acquire a corresponding anisotropy.

Conclusions in Pictures

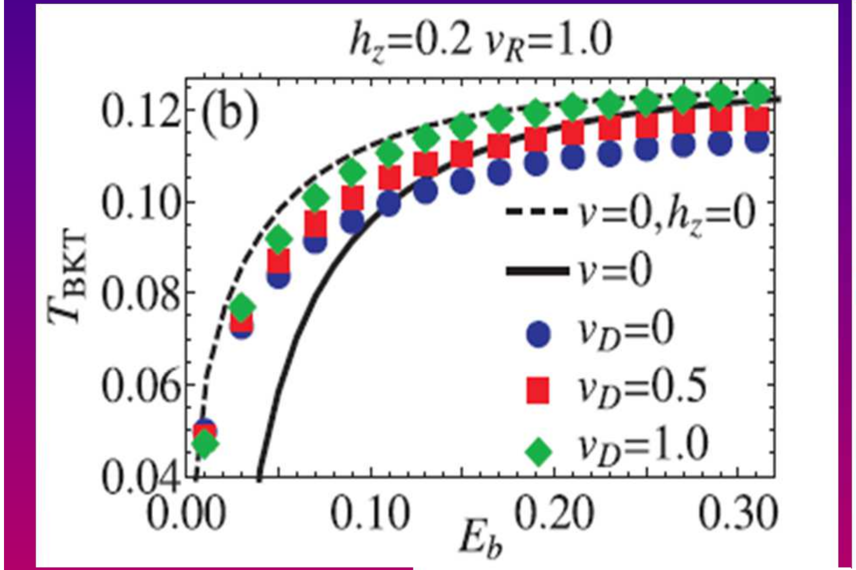


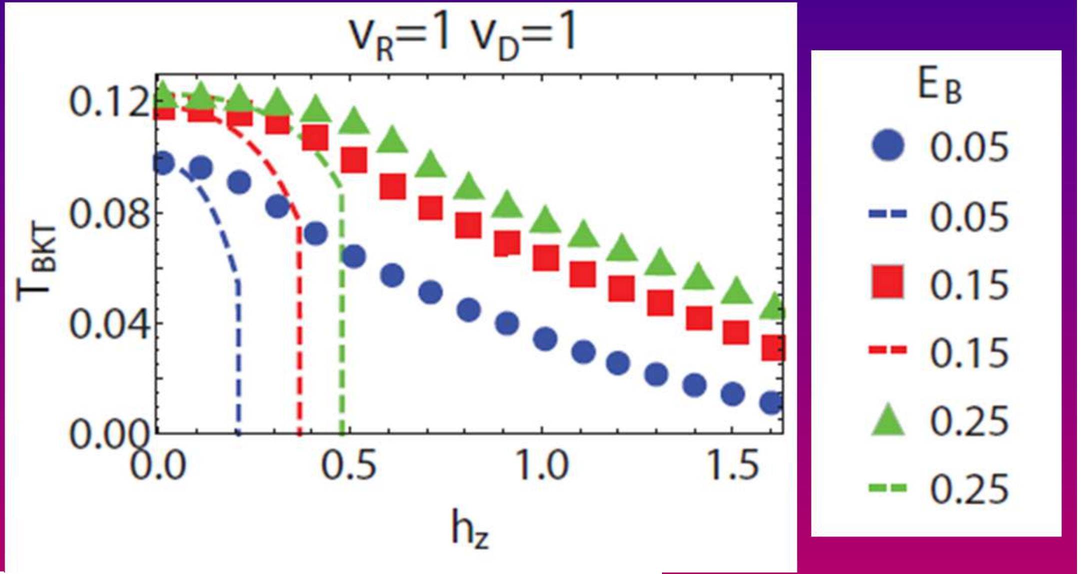


Change in topology

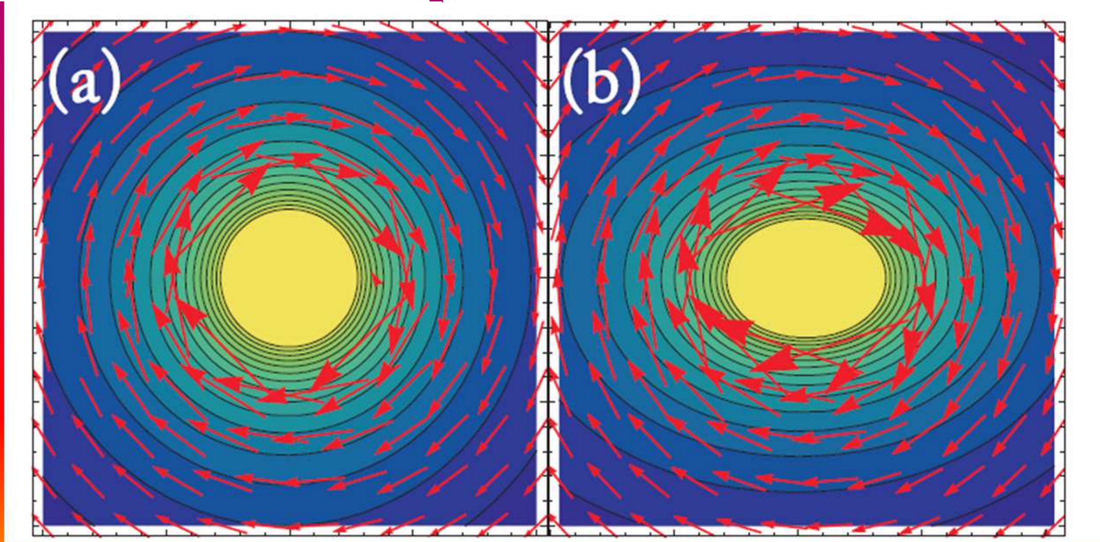
TRANSITION FROM
GAPLESS TO GAPPED SUPERFLUID

BKT transition and vortex-antivortex structure





Rashba



ERD

Outline

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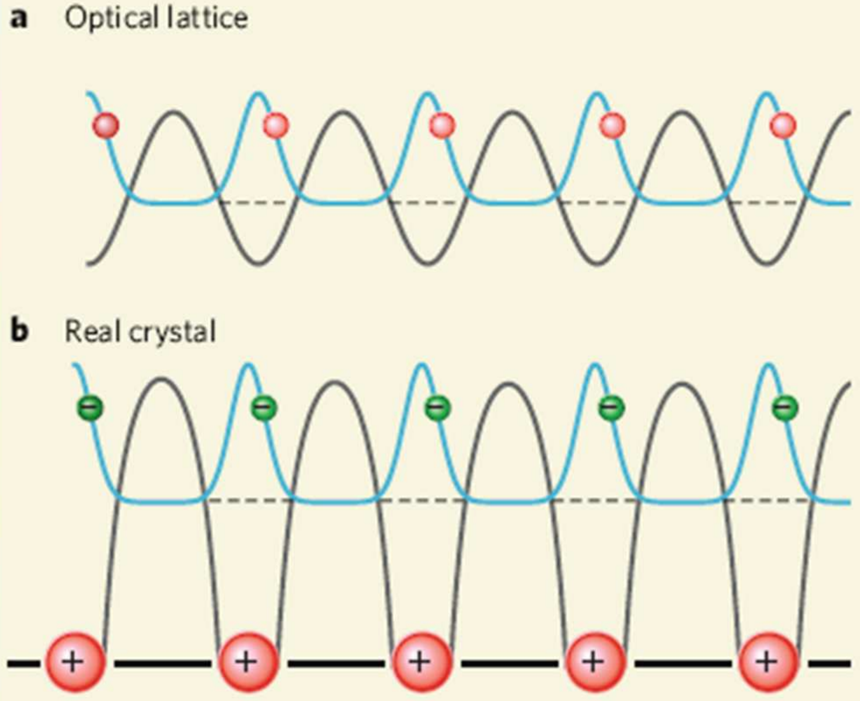
Condensed Matter meets Atomic Physics

In optical lattices many types of atoms can be loaded like bosonic, Sodium-23, Potassium-39, Rubidium-87, or Cesium-133; and fermionic Lithium-6, Potassium-40, Strontium-87, etc…

In real crystals electrons or holes (absence of electrons) may be responsible for many "electronic" phases of condensed matter physics, such as metallic, insulating, superconducting, ferromagnetic, anti-ferromagnetic, etc…

Neutral atoms (bosons or fermions)



Electrons of holes (fermions only)

How atoms are trapped?

- Atom-laser interaction

- Induced dipole moment.

- Trapping potential

$$V(\mathbf{r},t) = -\mathbf{d} \bullet \mathbf{E}(\mathbf{r},t)$$

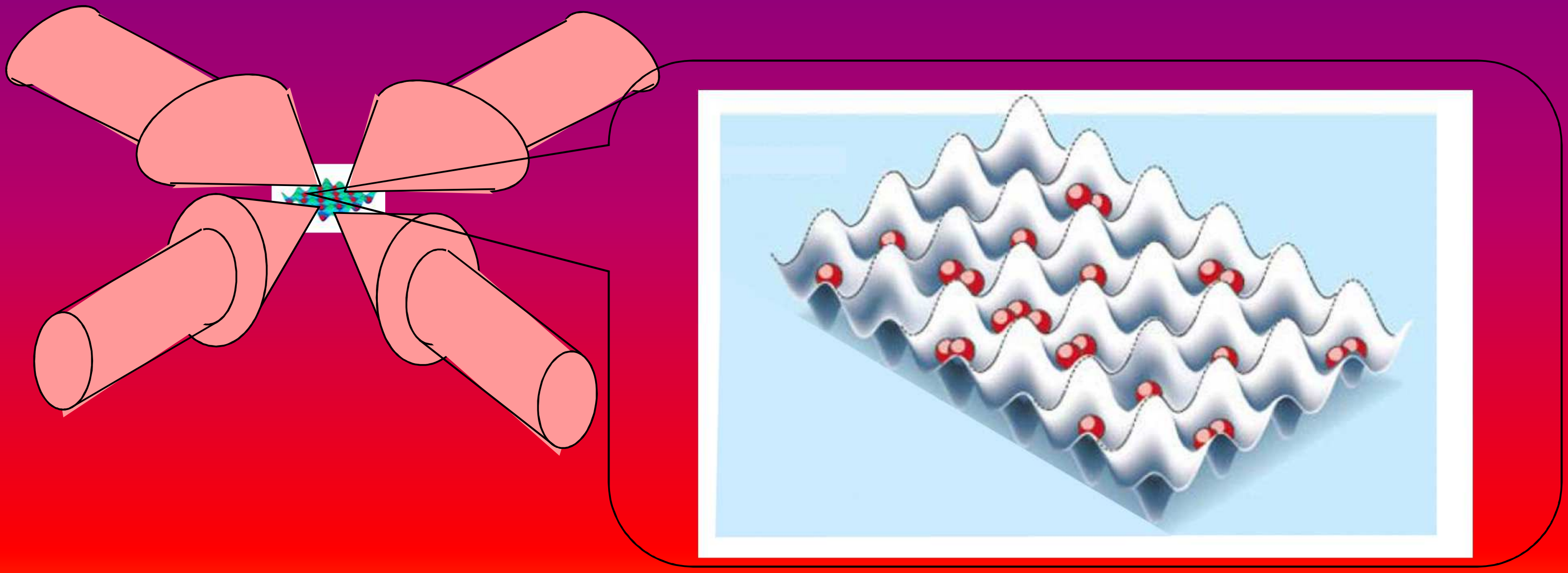
$$\mathbf{d} = -\alpha(\omega)\mathbf{E}(\mathbf{r},t)$$

$$V(\mathbf{r},t) = -\alpha(\omega)[\mathbf{E}(\mathbf{r},t)]^2$$

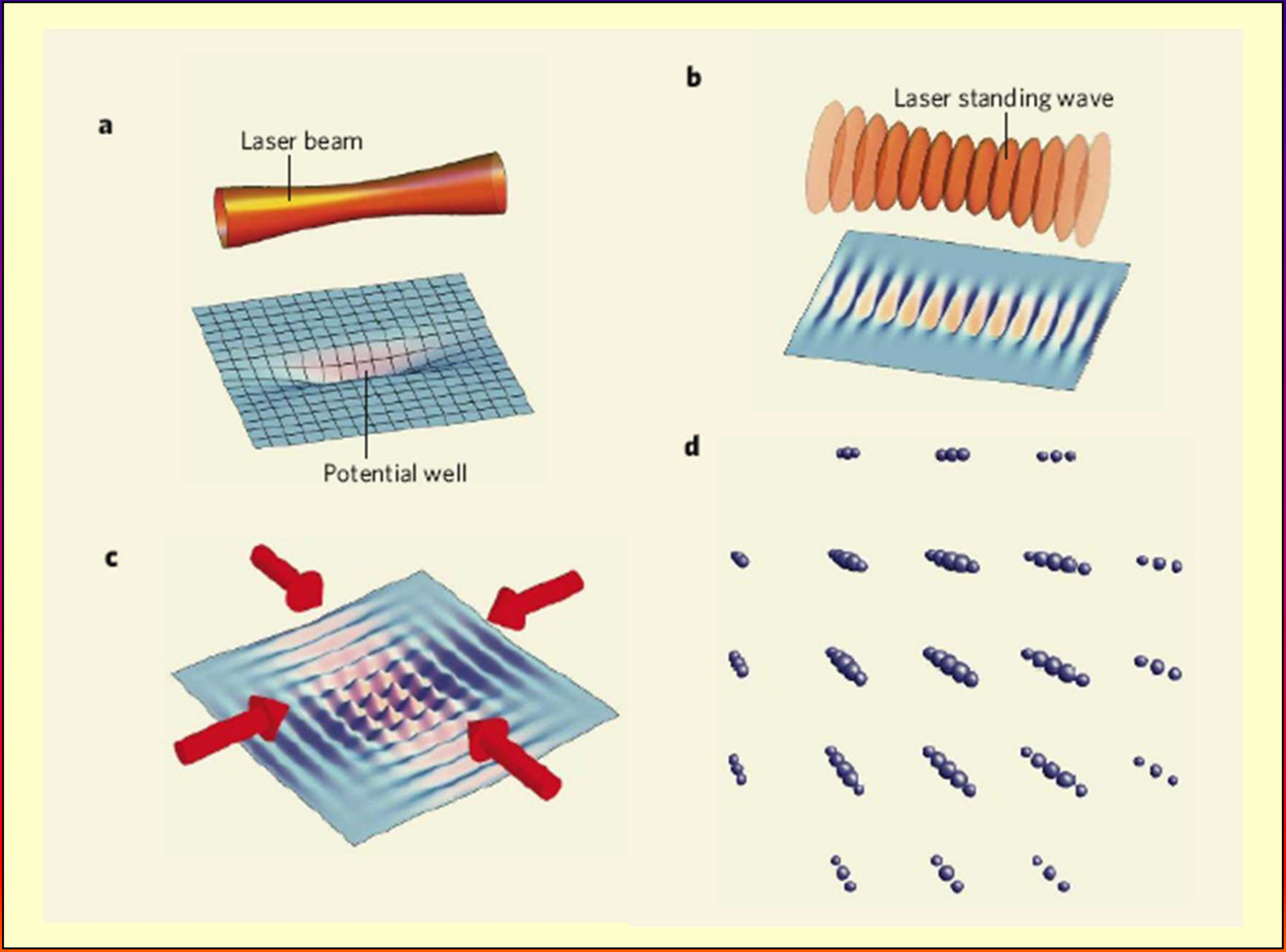
Atoms in optical lattices

$$V(\mathbf{r}) = -\alpha(\omega) < [\mathbf{E}(\mathbf{r},t)]^2 >$$

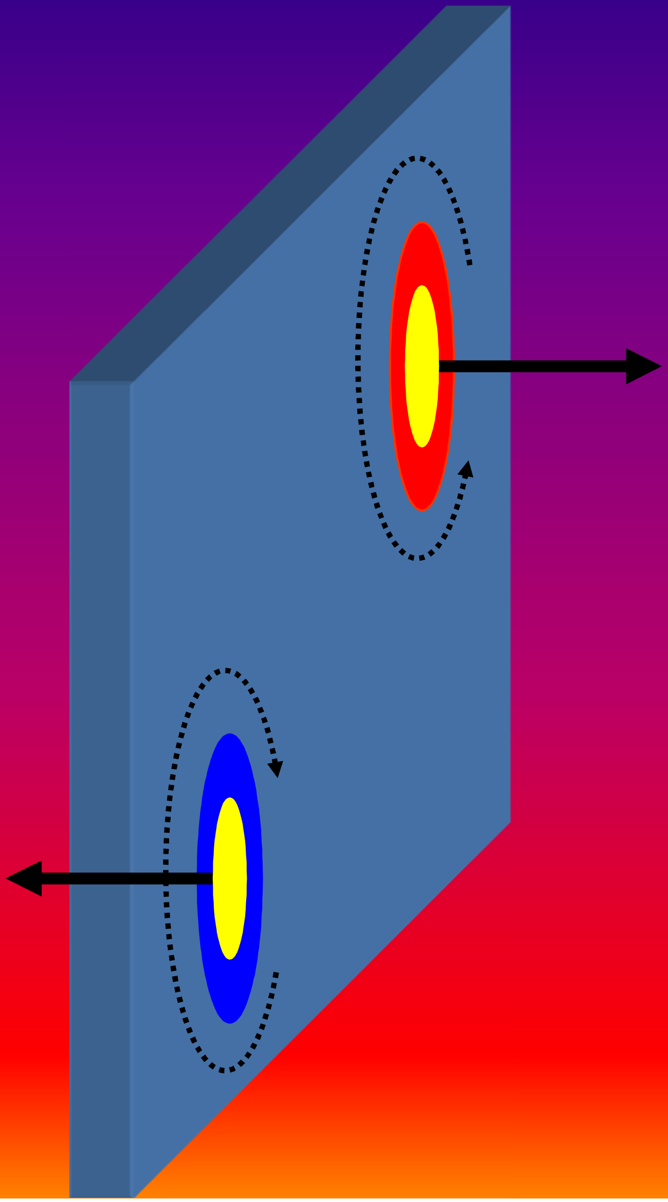
$$V(\mathbf{r}) = -\frac{1}{2}\alpha(\omega)[\mathbf{E}(\mathbf{r})]^2$$



How optical lattices are created?



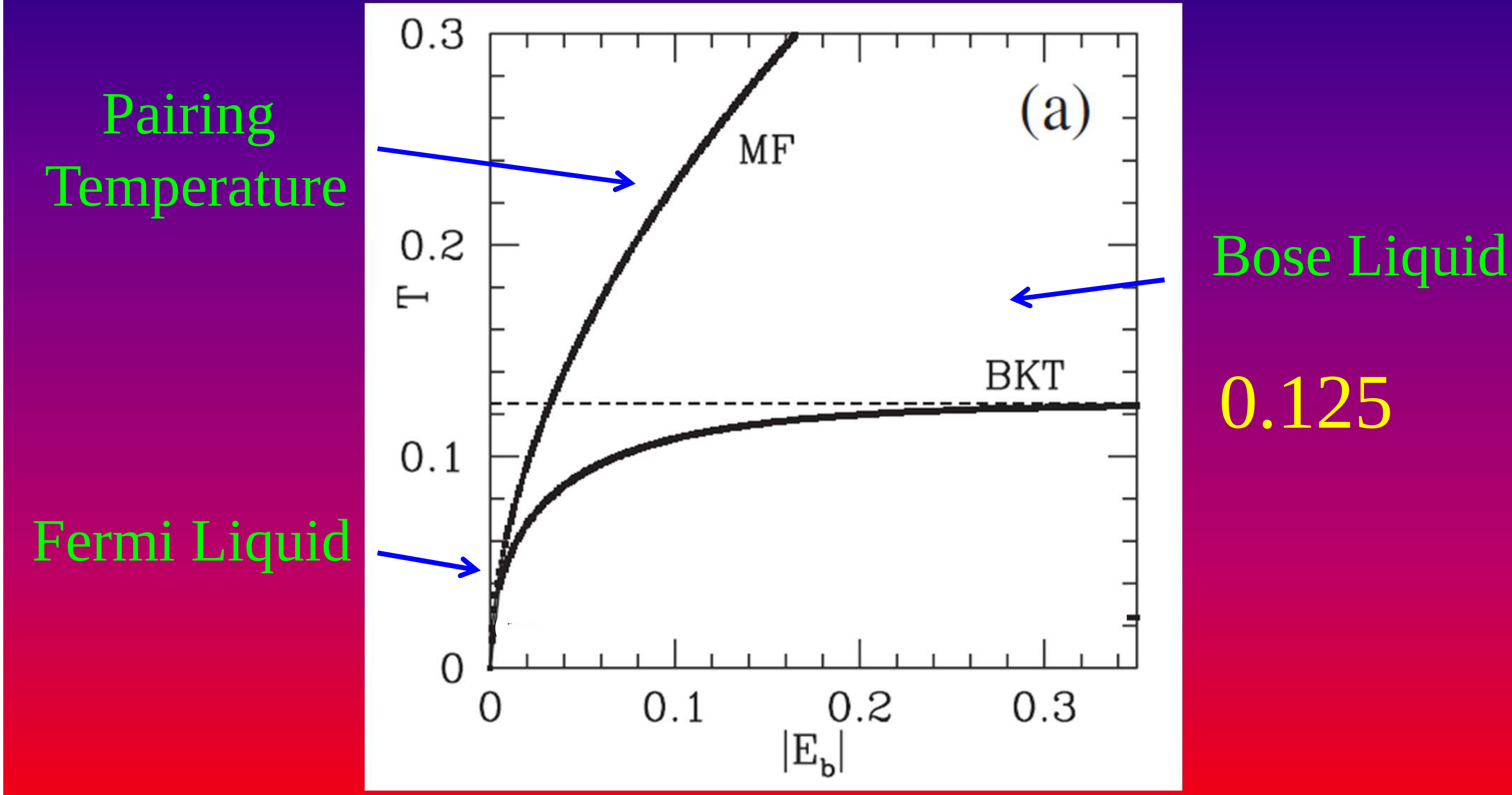
Single plane excitations



Vortex-antivortex pairs

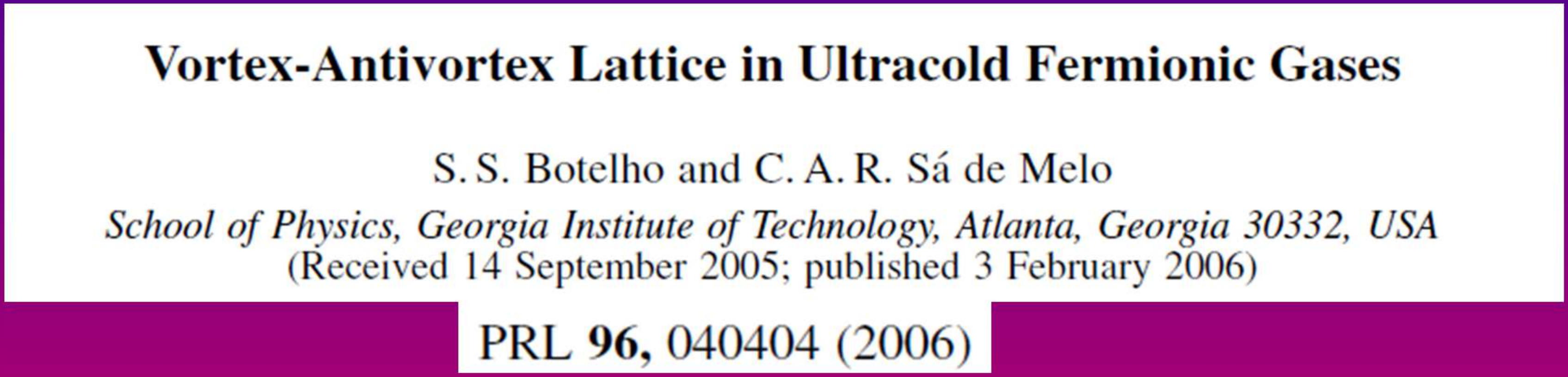
BKT transition:
Physics of 2D XY model

Critical Temperature



BCS-Bose Superfluidity in 2D

2D Fermi gases with increasing attractive interactions, but no SOC.



Vortex-Antivortex Lattice in Ultracold Fermionic Gases

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(Received 14 September 2005; published 3 February 2006)

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PRL **105,** 030404 (2010) PHYSICAL REVIEW LETTERS week ending 16 JULY 2010

Observation of a Two-Dimensional Fermi Gas of Atoms

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(Received 20 May 2010; published 15 July 2010)

Outline

1) Introduction to 2D Fermi gases.

2) Creation of artificial spin-orbit coupling (SOC).

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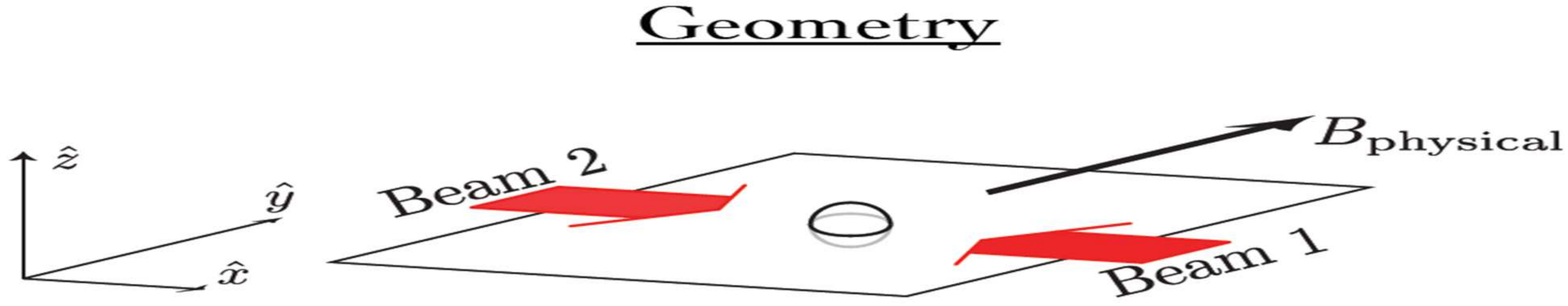
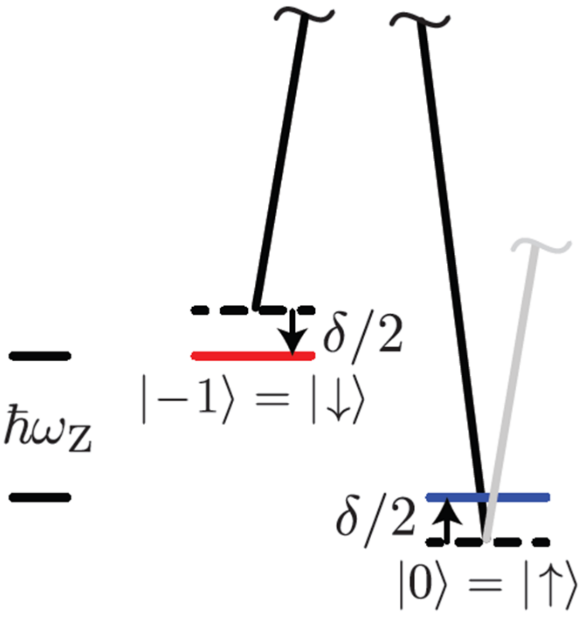
Raman process and spin-orbit coupling

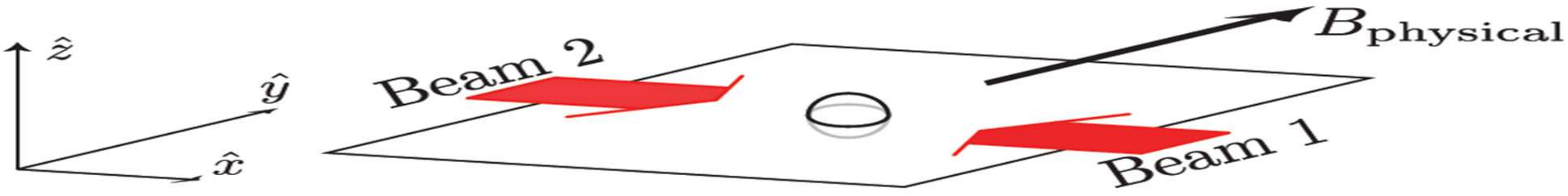


$$\begin{pmatrix} \frac{(\mathbf{k}-\mathbf{k}_R)^2}{2m}+\frac{\delta}{2} & \frac{\Omega}{2} \\ \frac{\Omega}{2} & \frac{(\mathbf{k}+\mathbf{k}_R)^2}{2m}-\frac{\delta}{2} \end{pmatrix}$$

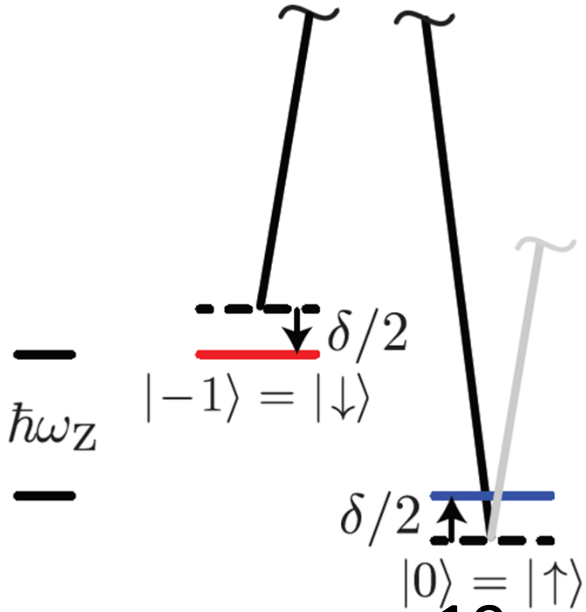


SU(2) rotation to new spin basis:
$\sigma_x \rightarrow \sigma_z$; $\sigma_z \rightarrow \sigma_y$; $\sigma_y \rightarrow \sigma_x$

Geometry



$$\begin{pmatrix} \frac{\mathbf{k}^2+k_R^2}{2m}+\frac{\Omega}{2} & -i\left(\frac{\delta}{2}-\frac{k_R}{m}k_x\right) \\ i\left(\frac{\delta}{2}-\frac{k_R}{m}k_x\right) & \frac{\mathbf{k}^2+k_R^2}{2m}-\frac{\Omega}{2} \end{pmatrix}$$



3 MARCH 2011 | VOL 471 | NATURE | 83

LETTER

doi:10.1038/nature09887

Spin–orbit-coupled Bose–Einstein condensates

Y.-J. Lin[1], K. Jiménez-García[1,2] & I. B. Spielman[1]

$$\begin{pmatrix} \frac{\mathbf{k}^2+k_R^2}{2m}+\frac{\Omega}{2} & -i\left(\frac{\delta}{2}-\frac{k_R}{m}k_x\right) \\ i\left(\frac{\delta}{2}-\frac{k_R}{m}k_x\right) & \frac{\mathbf{k}^2+k_R^2}{2m}-\frac{\Omega}{2} \end{pmatrix}$$

spin-orbit

detuning

Raman coupling

Hamiltonian with spin-orbit

Hamiltonian with spin - orbit

$$H = \sum_{k,s} \varepsilon(\mathbf{k}) c^{+}_{ks} c_{ks} - \sum_{k,s} h_{s's}(\mathbf{k}) c^{+}_{ks'} c_{ks}$$

Parallel and perpendicular fields

$$h_{\parallel}(\mathbf{k}) = h_z(\mathbf{k})$$

$$h_{\perp}(\mathbf{k}) = h_x(\mathbf{k}) - ih_y(\mathbf{k})$$

$$\mathbf{H}_0(\mathbf{k}) = \begin{pmatrix} \varepsilon(\mathbf{k}) - h_{\parallel}(\mathbf{k}) & -h_{\perp}(\mathbf{k}) \\ -h_{\perp}^{*}(\mathbf{k}) & \varepsilon(\mathbf{k}) + h_{\parallel}(\mathbf{k}) \end{pmatrix}$$

Hamiltonian in terms of **k**-dependent magnetic fields

Hamiltonian Matrix

$$\mathbf{H}_0(\mathbf{k}) = \varepsilon(\mathbf{k})\mathbf{1} - h_x(\mathbf{k})\boldsymbol{\sigma}_x - h_y(\mathbf{k})\boldsymbol{\sigma}_y - h_z(\mathbf{k})\boldsymbol{\sigma}_z$$

Momentum Space Two - Level System

in a momentum dependent magnetic field

$$\mathbf{h}(\mathbf{k}) = \left[h_x(\mathbf{k}), h_y(\mathbf{k}), h_z(\mathbf{k})\right]$$

Eigenvalues

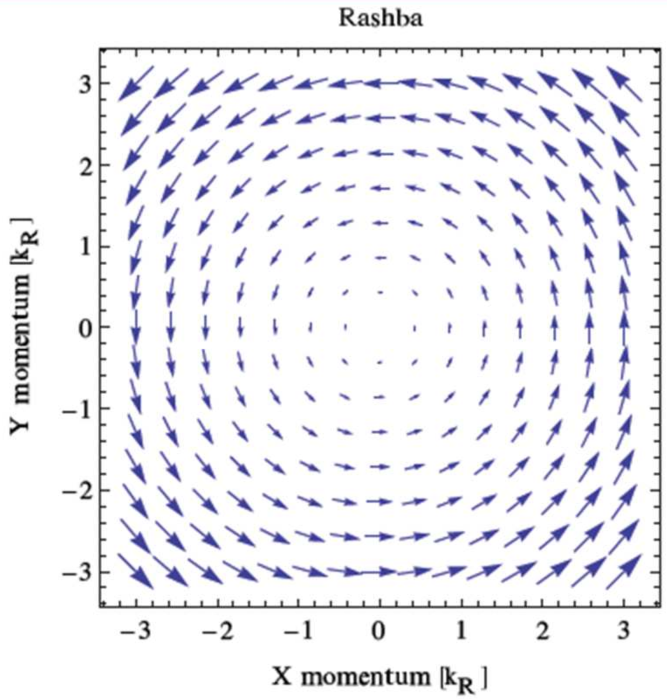
$$\varepsilon_{\Uparrow}(\mathbf{k}) = \varepsilon(\mathbf{k}) - \left|h_{\mathrm{eff}}(\mathbf{k})\right|$$

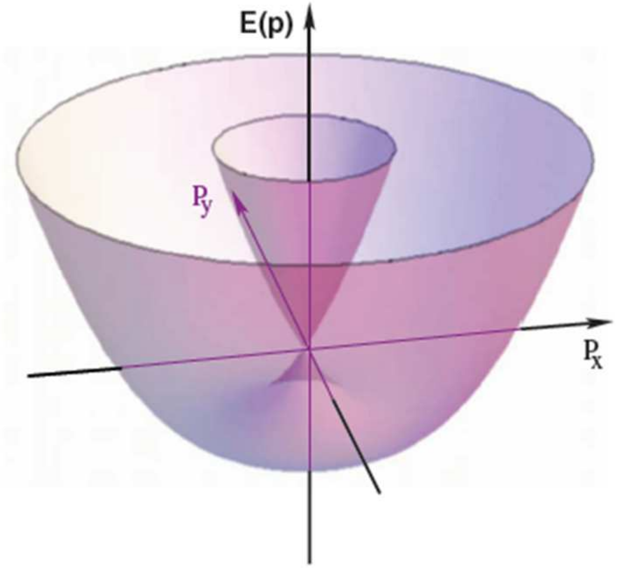
$$\varepsilon_{\Downarrow}(\mathbf{k}) = \varepsilon(\mathbf{k}) + \left|h_{\mathrm{eff}}(\mathbf{k})\right|$$

$$\left|h_{\mathrm{eff}}(\mathbf{k})\right| = \sqrt{\left|h_x(\mathbf{k})\right|^2 + \left|h_y(\mathbf{k})\right|^2 + \left|h_z(\mathbf{k})\right|^2}$$

Rashba Spin-Orbit Coupling

$$\mathbf{H}_R(\mathbf{k}) = v_R \begin{pmatrix} 0 & k_y + ik_x \\ k_y - ik_x & 0 \end{pmatrix}$$



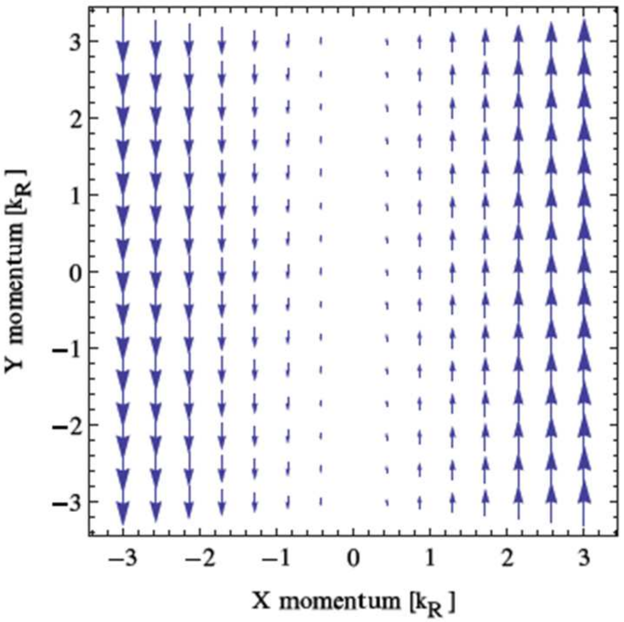


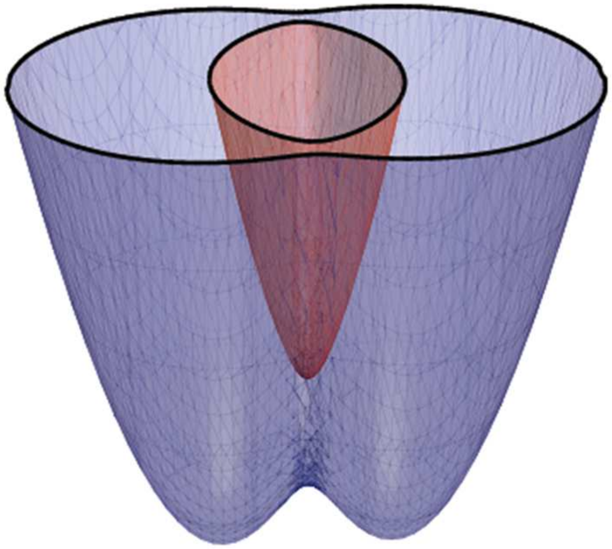
Equal-Rashba-Dresselhaus (ERD) Spin-Orbit Coupling

$$\mathbf{H}_R(\mathbf{k}) = v_R \begin{pmatrix} 0 & k_y + ik_x \\ k_y - ik_x & 0 \end{pmatrix}$$

$$\mathbf{H}_D(\mathbf{k}) = -v_D \begin{pmatrix} 0 & k_y - ik_x \\ k_y + ik_x & 0 \end{pmatrix}$$

$$\mathbf{H}_{ERD}(\mathbf{k}) = v \begin{pmatrix} 0 & ik_x \\ -ik_x & 0 \end{pmatrix}$$





Energy Dispersions in the ERD case

Simpler case :

$$h_x(\mathbf{k}) = 0$$

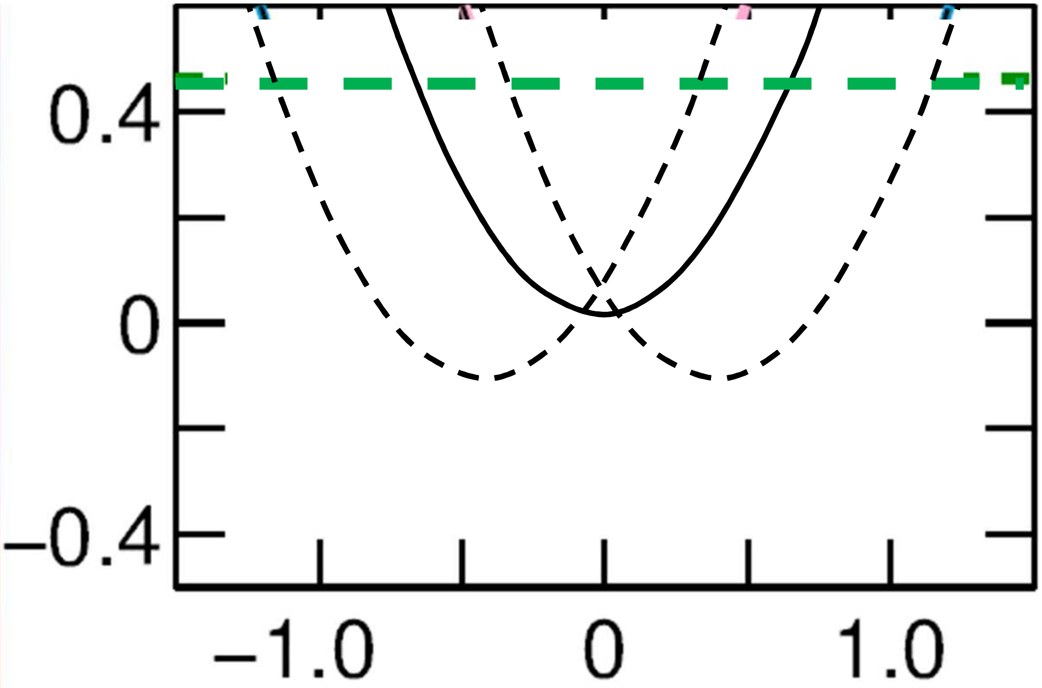
$$h_y(\mathbf{k}) = vk_x$$

$$h_z(\mathbf{k}) = 0$$

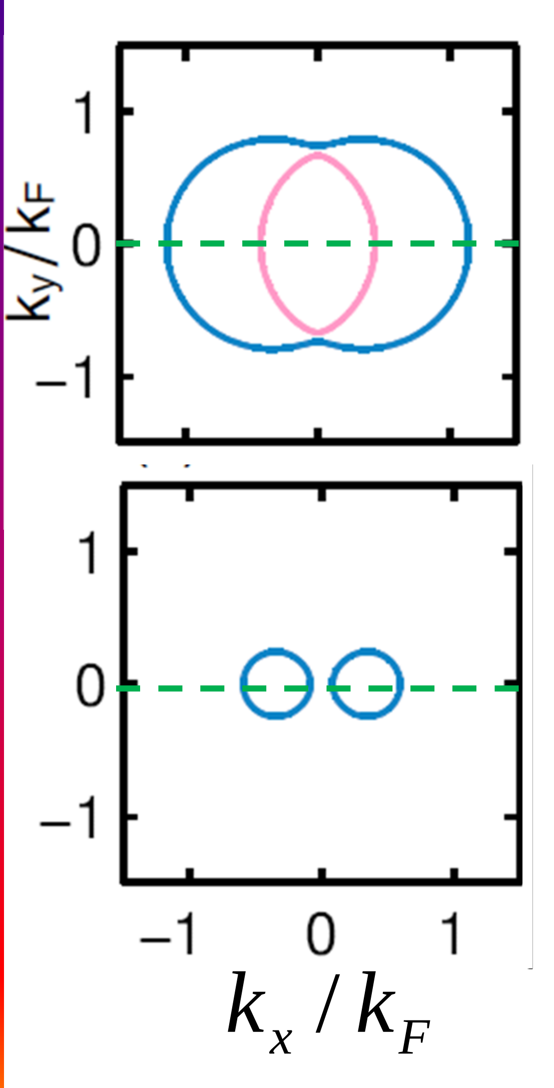
$$\varepsilon_{\Uparrow}(\mathbf{k}) = \varepsilon(\mathbf{k}) - |vk_x|$$

$$\varepsilon_{\Downarrow}(\mathbf{k}) = \varepsilon(\mathbf{k}) + |vk_x|$$

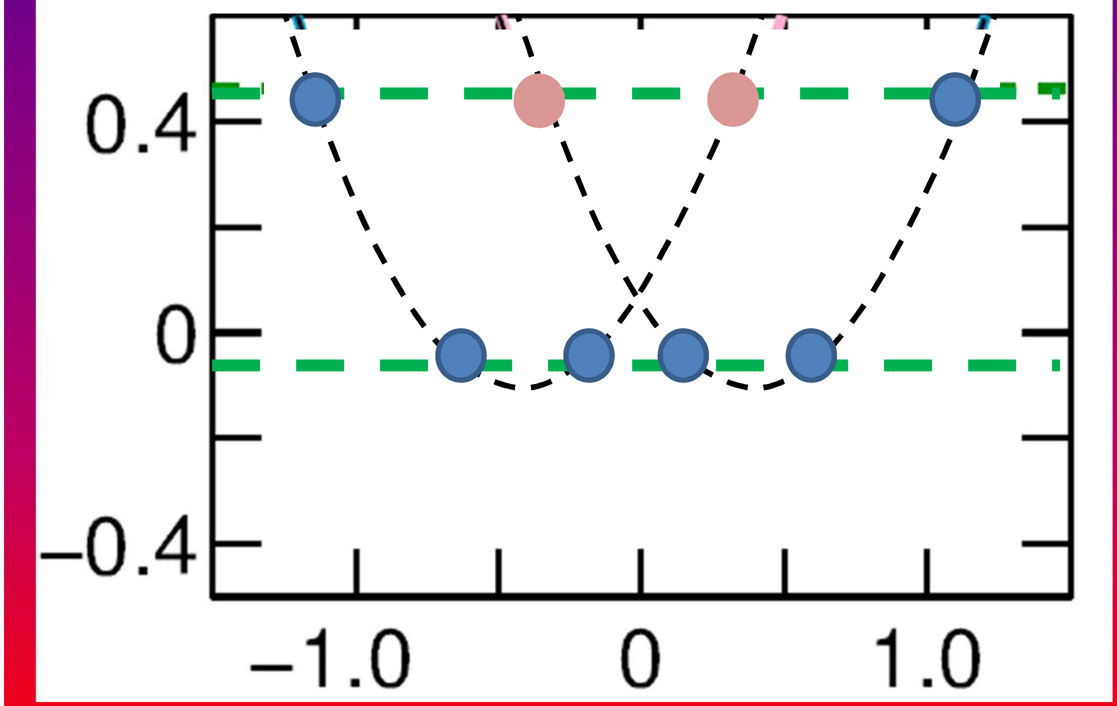
$$\varepsilon(\mathbf{k}) = k^2/(2m)$$



Energy Dispersions and Fermi Surfaces



$$\varepsilon_\alpha(\mathbf{k}) = k^2/(2m) \pm |v k_x|$$

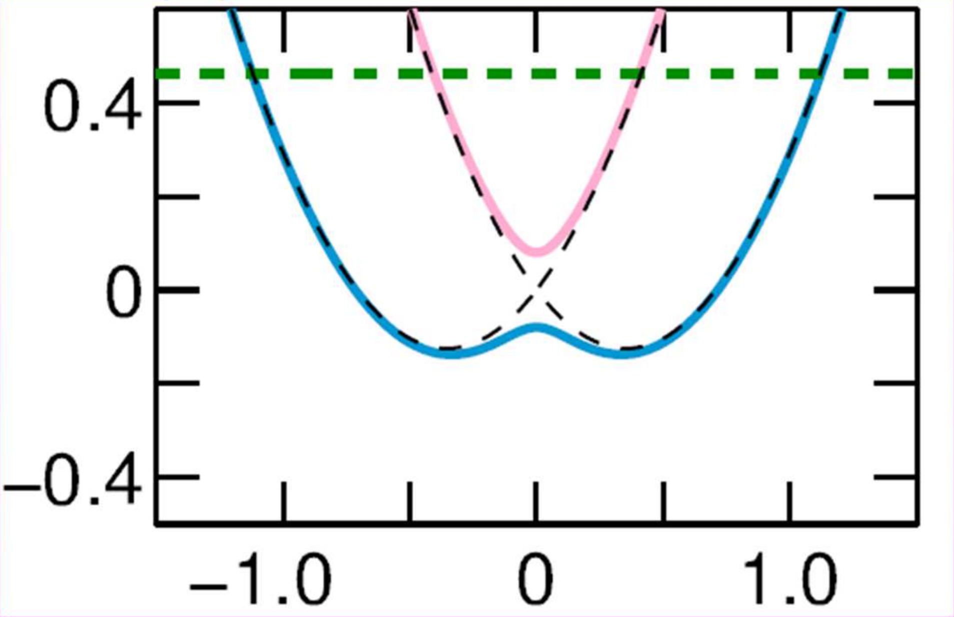


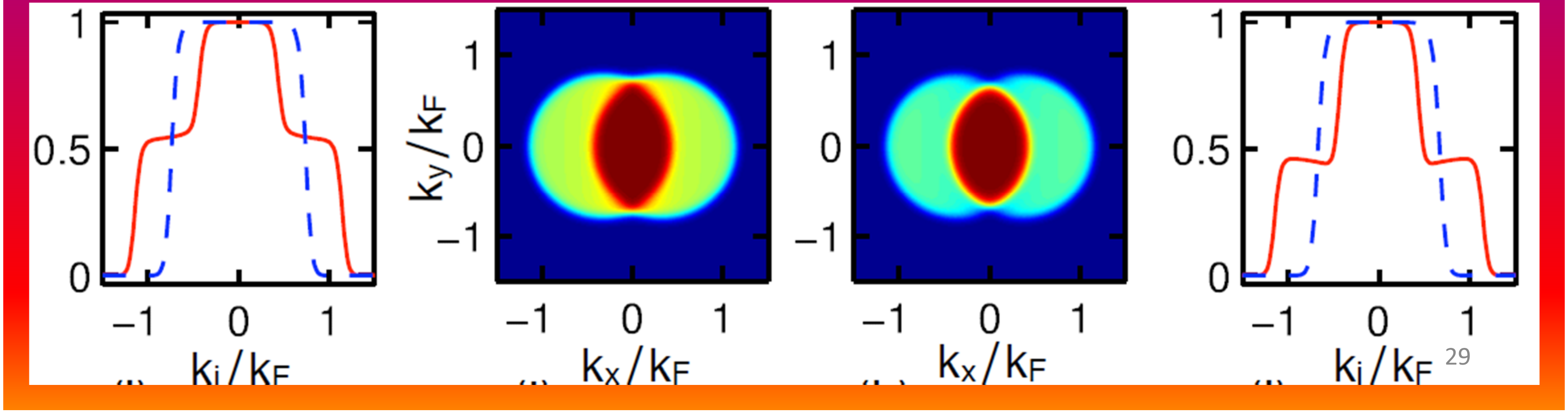
Momentum Distribution (Parity)

$$h_x(\mathbf{k}) = 0$$

$$\frac{h_y(\mathbf{k})}{\varepsilon_F} = 0.71\frac{k_x}{k_F}$$

$$\frac{h_z(\mathbf{k})}{\varepsilon_F} = 0.05$$





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Bring Interactions Back (real space)

$$\mathcal{H}(\mathbf{r}) = \mathcal{H}_0(\mathbf{r}) + \mathcal{H}_I(\mathbf{r})$$

$$\mathcal{H}_0(\mathbf{r}) = \sum_{\alpha\beta} \psi^\dagger_\alpha(\mathbf{r}) \left[\hat{K}_\alpha \delta_{\alpha\beta} - h_i(\mathbf{r}) \sigma_{i,\alpha\beta} \right] \psi_\beta(\mathbf{r})$$

Kinetic Energy

Spin-orbit and Zeeman

$$\mathcal{H}_I(\mathbf{r}) \;\; = \;\; -g\psi^\dagger_\uparrow(\mathbf{r})\psi^\dagger_\downarrow(\mathbf{r})\psi_\downarrow(\mathbf{r})\psi_\uparrow(\mathbf{r})$$

Contact Interaction

Bring Interactions Back (momentum space)

$$\mathcal{H}_I = -g \sum_{\mathbf{q}} b^\dagger(\mathbf{q}) b(\mathbf{q})$$

$$b^\dagger(\mathbf{q}) = \sum_{\mathbf{k}} \psi^\dagger_\uparrow(\mathbf{k}+\mathbf{q}/2)\psi^\dagger_\downarrow(-\mathbf{k}+\mathbf{q}/2)$$

$$\Delta_0 = -g\langle b(\mathbf{q}=0)\rangle \quad \text{and} \quad \Delta_0^* = -g\langle b^+(\mathbf{q}=0)\rangle$$

Bring interactions back:
Hamiltonian in initial spin basis

$$\mathrm{H}_0 = \left(\begin{array}{c|cccc} & \psi_{k\uparrow} & \psi_{k\downarrow} & \psi^+_{-k\uparrow} & \psi^+_{-k\downarrow} \\ \hline \psi^+_{k\uparrow} & \tilde{K}_\uparrow(\mathbf{k}) & -h_\perp(\mathbf{k}) & 0 & -\Delta_0 \\ \psi^+_{k\downarrow} & -h^*_\perp(\mathbf{k}) & \tilde{K}_\downarrow(\mathbf{k}) & \Delta_0 & 0 \\ \psi_{-k\uparrow} & 0 & \Delta_0^\dagger & -\tilde{K}_\uparrow(-\mathbf{k}) & h^*_\perp(-\mathbf{k}) \\ \psi_{-k\downarrow} & -\Delta_0^\dagger & 0 & h_\perp(-\mathbf{k}) & -\tilde{K}_\downarrow(-\mathbf{k}) \end{array}\right)$$

$$\tilde{K}_s(\mathbf{k}) = \varepsilon(\mathbf{k}) - \mu - s h_z(\mathbf{k})$$

Bring interactions back: Hamiltonian in the generalized helicity basis

$$\tilde{\mathrm{H}}_0 = \begin{array}{ccccc} & \Phi_{k\Uparrow} & \Phi_{k\Downarrow} & \Phi^{+}_{-k\Uparrow} & \Phi^{+}_{-k\Downarrow} \\ \Phi^{+}_{k\Uparrow} & \xi_{\Uparrow}(\mathbf{k}) & 0 & \boxed{\Delta_T(\mathbf{k})e^{-i\varphi_{\mathbf{k}}}} & -\Delta_S(\mathbf{k}) \\ \Phi^{+}_{k\Downarrow} & 0 & \xi_{\Downarrow}(\mathbf{k}) & \Delta_S(\mathbf{k}) & \boxed{-\Delta_T e^{i\varphi_{\mathbf{k}}}} \\ \Phi_{-k\Uparrow} & \boxed{\Delta_T^{*}(\mathbf{k})e^{i\varphi_{\mathbf{k}}}} & -\Delta_S^{*}(\mathbf{k}) & -\xi_{\Uparrow}(\mathbf{k}) & 0 \\ \Phi_{-k\Downarrow} & \Delta_S^{*}(\mathbf{k}) & \boxed{-\Delta_T^{*}(\mathbf{k})e^{-i\varphi_{\mathbf{k}}}} & 0 & -\xi_{\Downarrow}(\mathbf{k}) \end{array}$$

$$\varphi_{\mathbf{k}} = \mathrm{Arg}\left[h_{\perp}(\mathbf{k})\right]$$

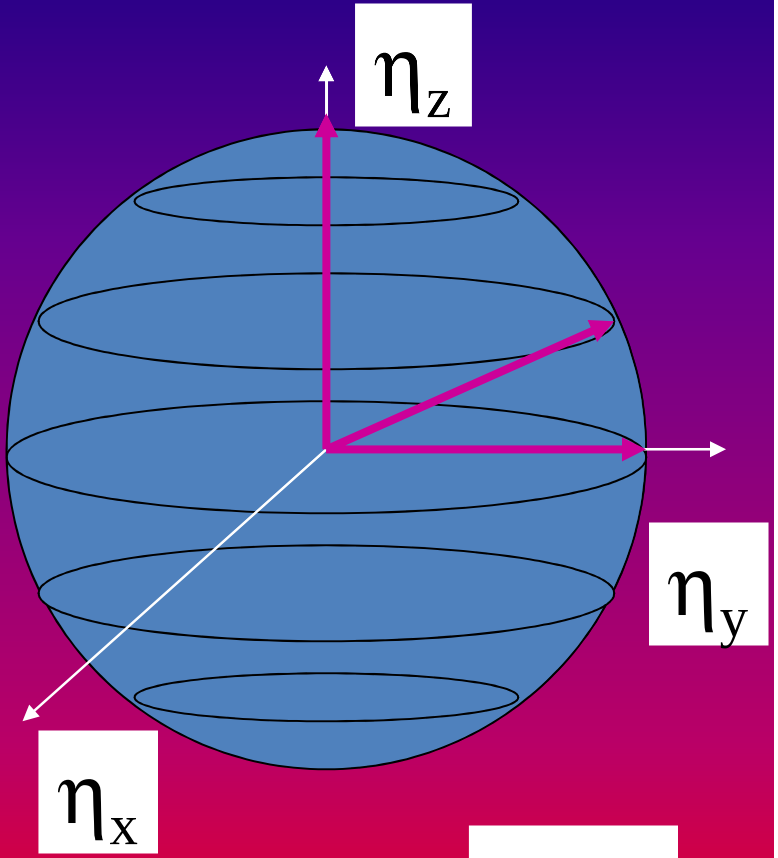
Order Parameter: Singlet & Triplet

$$\Delta_S(\mathbf{k}) = \Delta_0 h_{||}(\mathbf{k})/|\mathbf{h}_{\rm eff}(\mathbf{k})|$$

$$\Delta_T(\mathbf{k}) = \Delta_0|h_\perp(\mathbf{k})|/|\mathbf{h}_{\rm eff}(\mathbf{k})|$$

$$|\Delta_T(\mathbf{k})|^2 + |\Delta_S(\mathbf{k})|^2 = |\Delta_0|^2$$

$$h_\perp(\mathbf{k}) = vk_x \qquad h_z(\mathbf{k}) = h_z$$



ERD

$$h_{\rm eff}(\mathbf{k}) = (0, vk_x, h_z)$$

$$h_{\rm eff}(\mathbf{k}) = \sqrt{|vk_x|^2 + h_z^2}$$

Excitation Spectrum

$$E_1(\mathbf{k}) = \sqrt{\left[\left(\frac{\xi_{\Uparrow} - \xi_{\Downarrow}}{2}\right) - \sqrt{\left(\frac{\xi_{\Uparrow} + \xi_{\Downarrow}}{2}\right)^2 + |\Delta_S(\mathbf{k})|^2}\right]^2 + |\Delta_T(\mathbf{k})|^2},$$

★

$$E_2(\mathbf{k}) = \sqrt{\left[\left(\frac{\xi_{\Uparrow} - \xi_{\Downarrow}}{2}\right) + \sqrt{\left(\frac{\xi_{\Uparrow} + \xi_{\Downarrow}}{2}\right)^2 + |\Delta_S(\mathbf{k})|^2}\right]^2 + |\Delta_T(\mathbf{k})|^2},$$

Can be zero

$$E_3(\mathbf{k}) = -E_2(\mathbf{k})$$

$$\xi_{\Uparrow}(\mathbf{k}) = K_+(\mathbf{k}) - |\mathbf{h}_{\mathrm{eff}}(\mathbf{k})|$$

$$E_4(\mathbf{k}) = -E_1(\mathbf{k})$$

$$\xi_{\Downarrow}(\mathbf{k}) = K_+(\mathbf{k}) + |\mathbf{h}_{\mathrm{eff}}(\mathbf{k})|$$

Excitation Spectrum

Making singlet and triplet sectors explicit

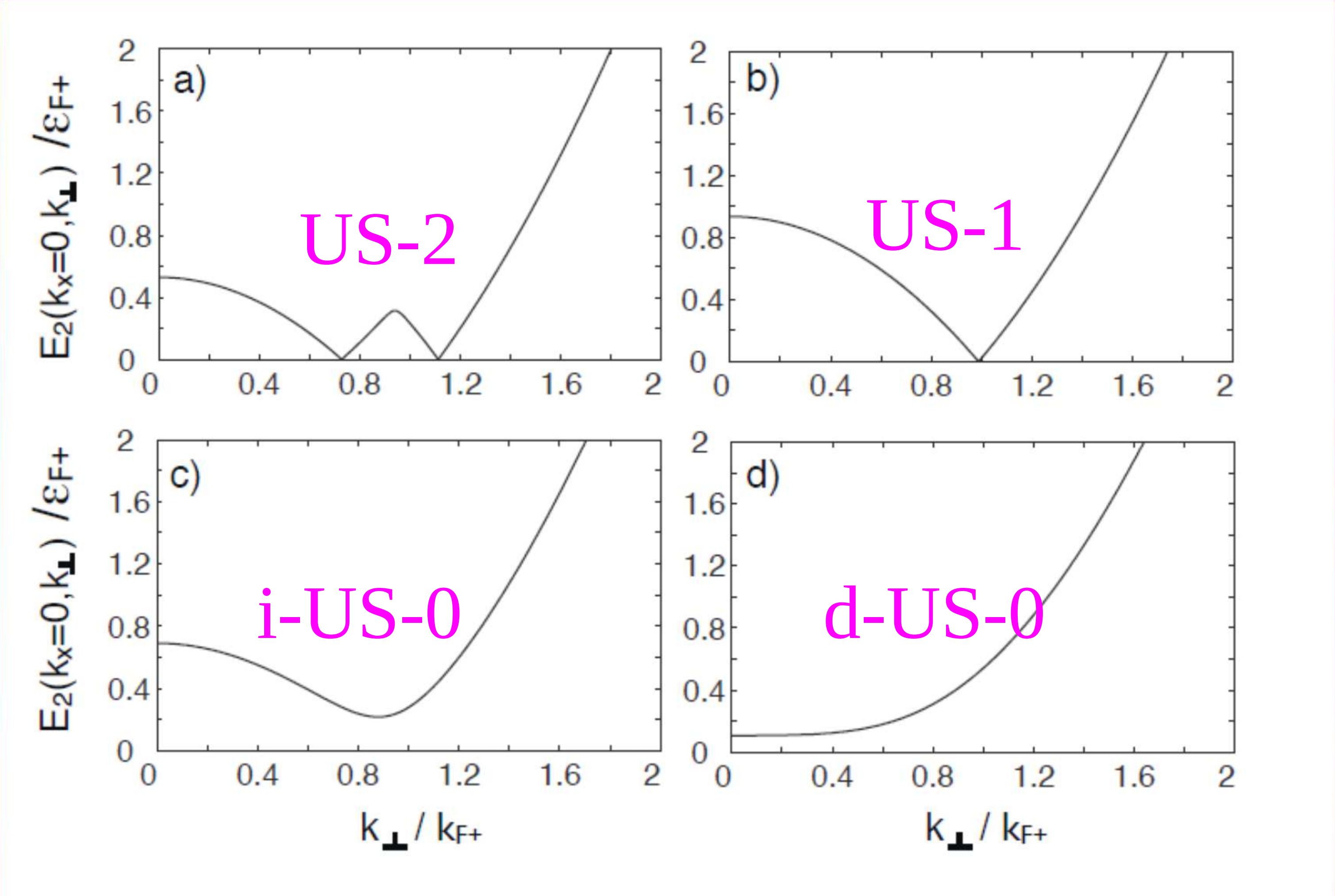
$$E_2(\mathbf{k}) \leftrightarrow E_-(\mathbf{k}) \qquad E_1(\mathbf{k}) \leftrightarrow E_+(\mathbf{k})$$

$$E_{p\pm}(\mathbf{k}) = \sqrt{\left(E_S(\mathbf{k}) \pm |\mathbf{h}_{\text{eff}}(\mathbf{k})|\right)^2 + |\Delta_T(\mathbf{k})|^2}$$

$$E_S(\mathbf{k}) = \sqrt{|K(\mathbf{k})|^2 + |\widetilde{\Delta}_S(\mathbf{k})|^2}$$

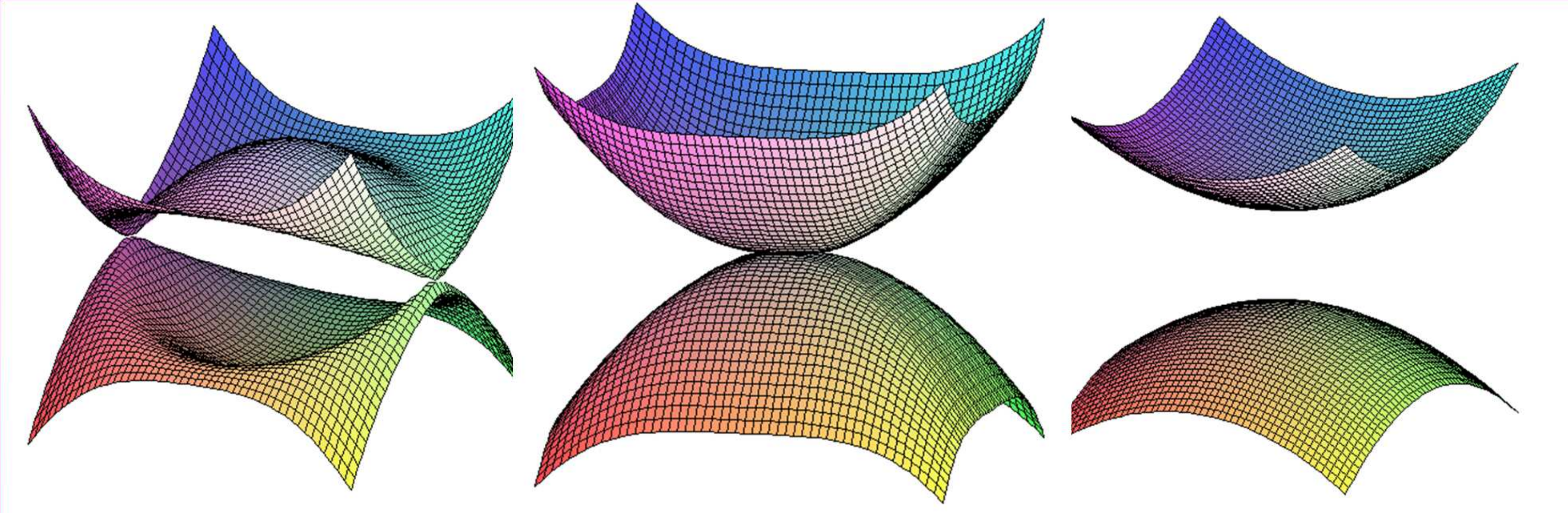
singlet sector

Excitation Spectrum (ERD)



$$\Delta_T(\mathbf{k}) = \Delta_0|h_\perp(\mathbf{k})|/|\mathbf{h}_{\text{eff}}(\mathbf{k})| \quad = 0$$

Lifshitz transition



Change in topology

Topological invariant (charge) in 2D

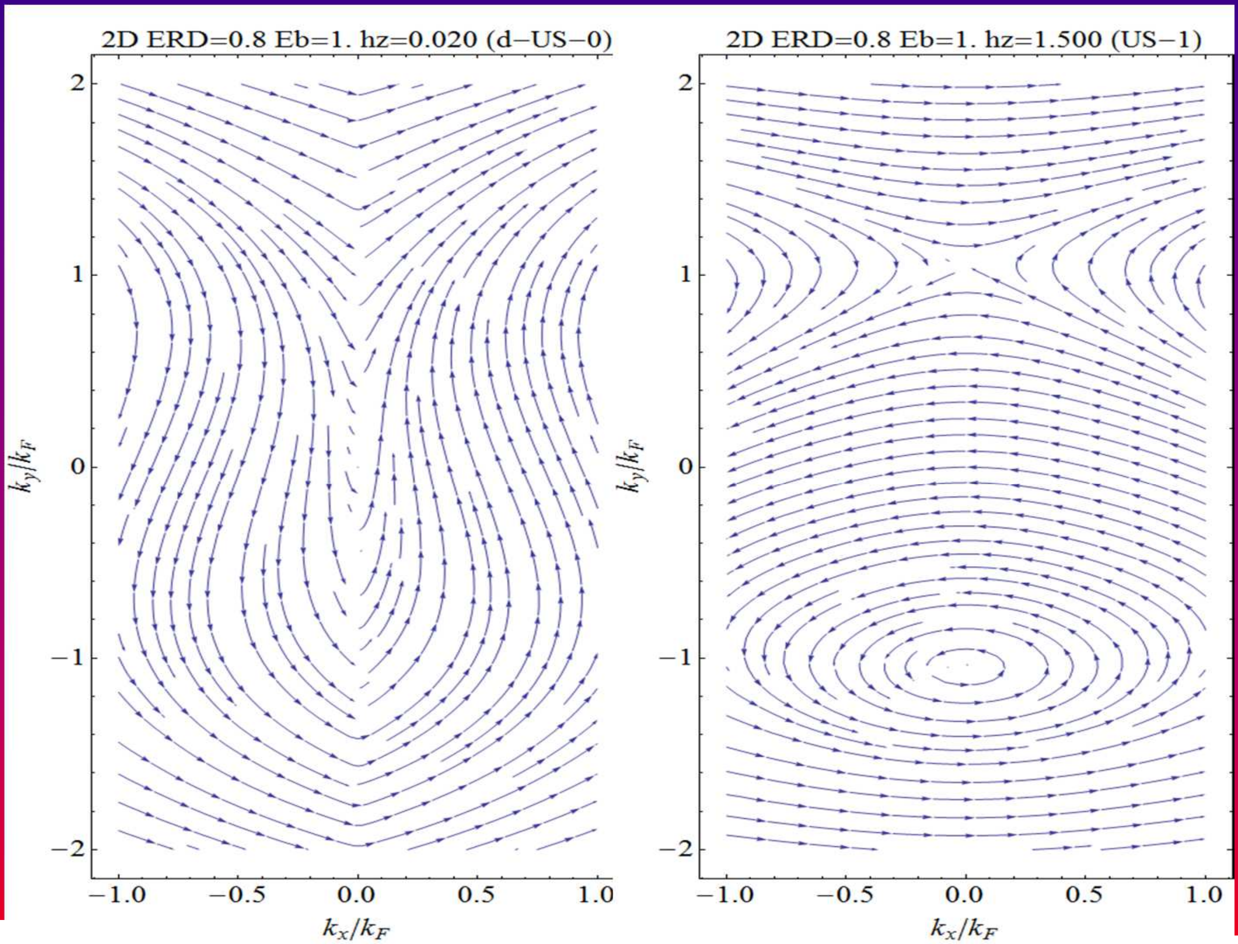
$$\hat{\mathbf{m}}(\mathbf{k}) \;=\; (m_x, m_y)$$

$$N_w = (2\pi)^{-1} \oint d\ell \, \hat{\mathbf{z}} \cdot \hat{\mathbf{m}} \times d\hat{\mathbf{m}}/d\ell$$

$$m_x(\mathbf{k}) \;=\; \left[E_S(\mathbf{k}) - |\mathbf{h}_{\mathrm{eff}}(\mathbf{k})|\right]/E_{p-}(\mathbf{k})$$

$$m_y(\mathbf{k}) \;=\; \Delta_T(\mathbf{k})/E_{p-}(\mathbf{k})$$

Vortices and Anti-vortices of m(k)



$h_z / \varepsilon_F = 0.2$

$US - 0$

$E_b / \varepsilon_F = 1.0$

$h_z / \varepsilon_F = 1.5$

$US - 1$

For T = 0 phase diagram need chemical potential and order parameter

$$\Omega_0 = V\frac{|\Delta_0|^2}{g} - \frac{T}{2}\sum_{\mathbf{k},j}\ln\left\{1+\exp\left[-E_j(\mathbf{k})/T\right]\right\} + \sum_{\mathbf{k}}\bar{K}_+,$$

$$\bar{K}_+ \quad = \quad \left[\widetilde{K}_\uparrow(-\mathbf{k}) + \widetilde{K}_\downarrow(-\mathbf{k})\right]/2$$

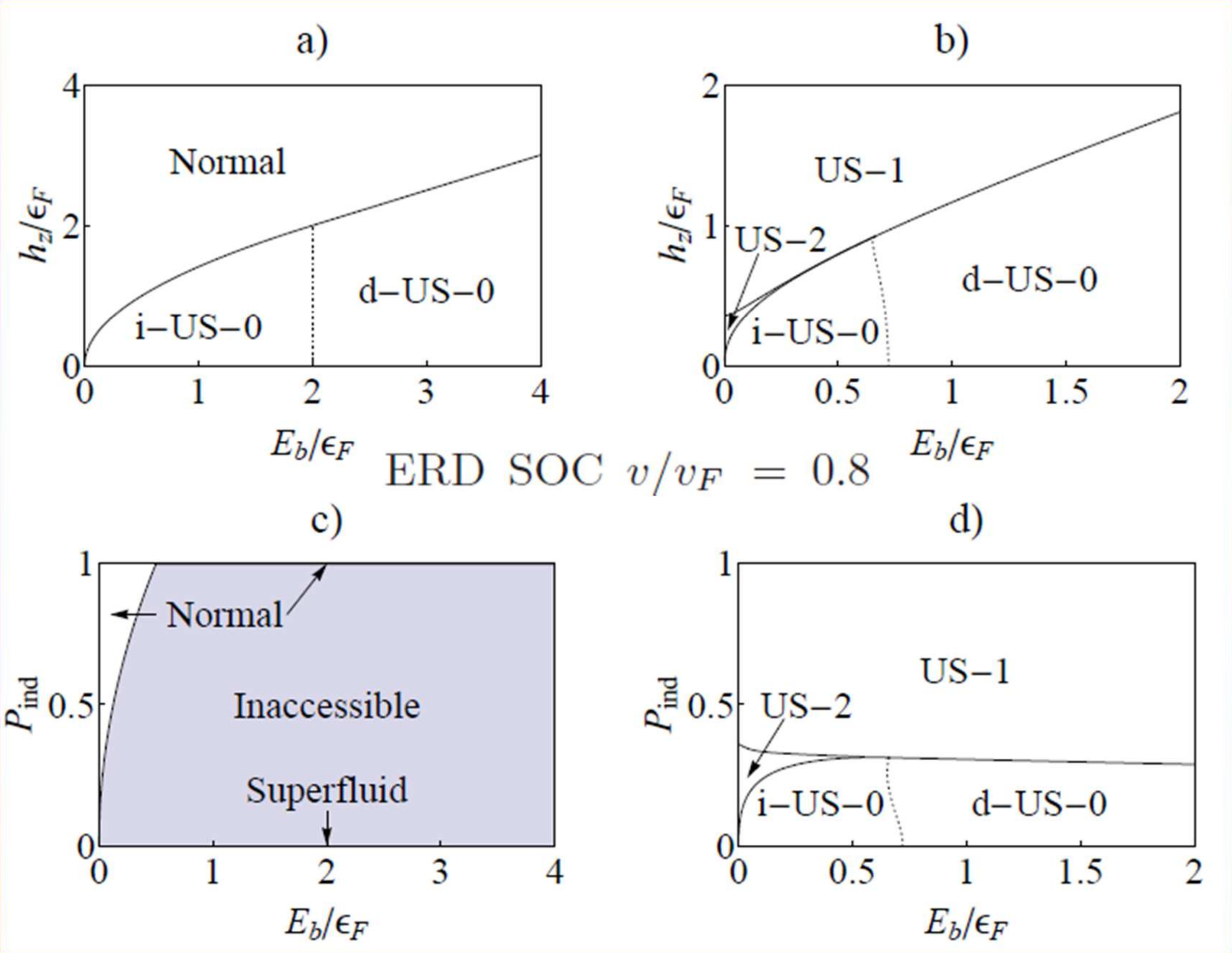
$$\frac{\delta\Omega_0}{\delta\Delta_0} = 0$$

Order Parameter Equation

$$N_+ = -\frac{\partial\Omega_0}{\partial\mu_+} = 0$$

Number Equation

T = 0 Phase Diagram in 2D



ERD SOC $v/v_F = 0.8$

Momentum distributions in 2D

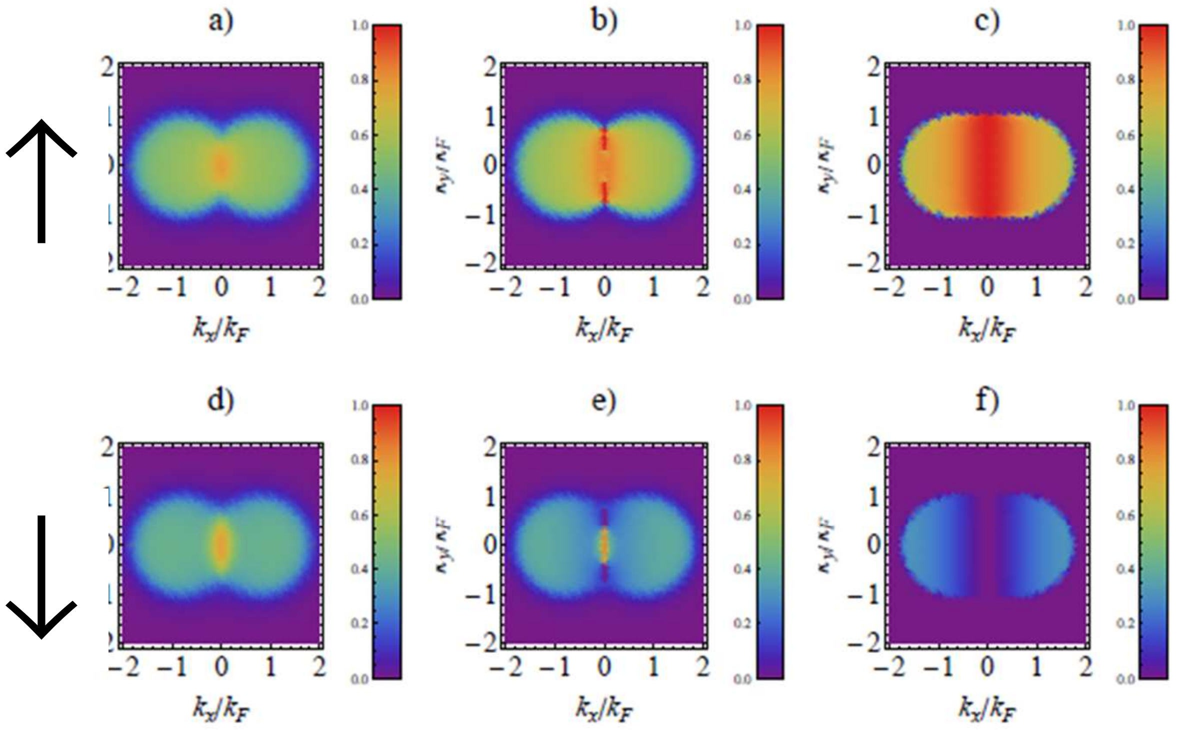
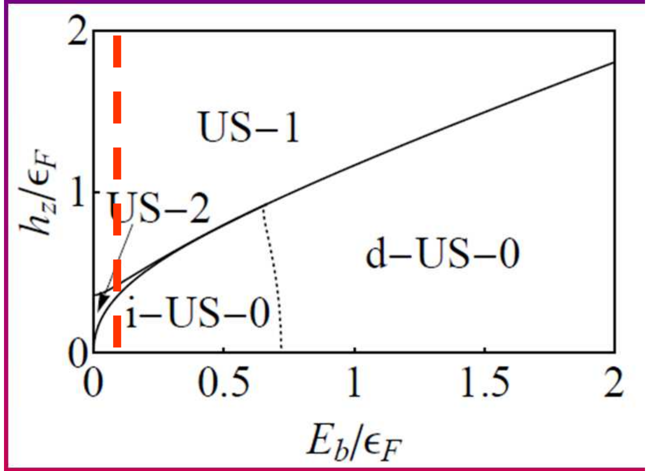
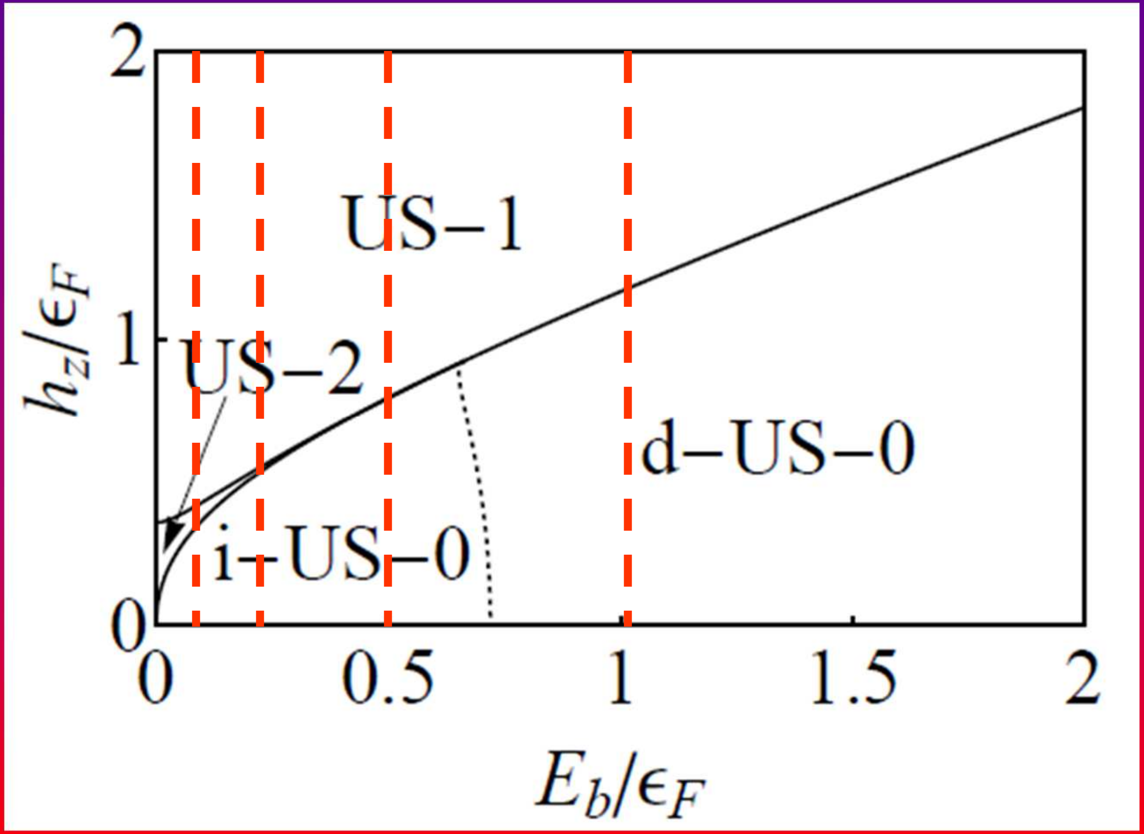


FIG. 3: (color online) The momentum distributions $n_s(k_x, k_y)$ for ERD SOC $v/v_F = 0.8$ and $E_b/\epsilon_F = 0.1$ at $T = 0$, where $s = \uparrow (\downarrow)$ for upper (lower) panels. (a)(d) i-US-0 phase with $h_z/\epsilon_F = 0.2$; (b)(e) US-2 phase with $h_z/\epsilon_F = 0.4$; (c)(f) US-1 phase with $h_z/\epsilon_F = 1.0$. The color coding varies continuously from purple ($n_s = 0$) to red ($n_s = 1$).



Thermodynamic signatures of topological transitions



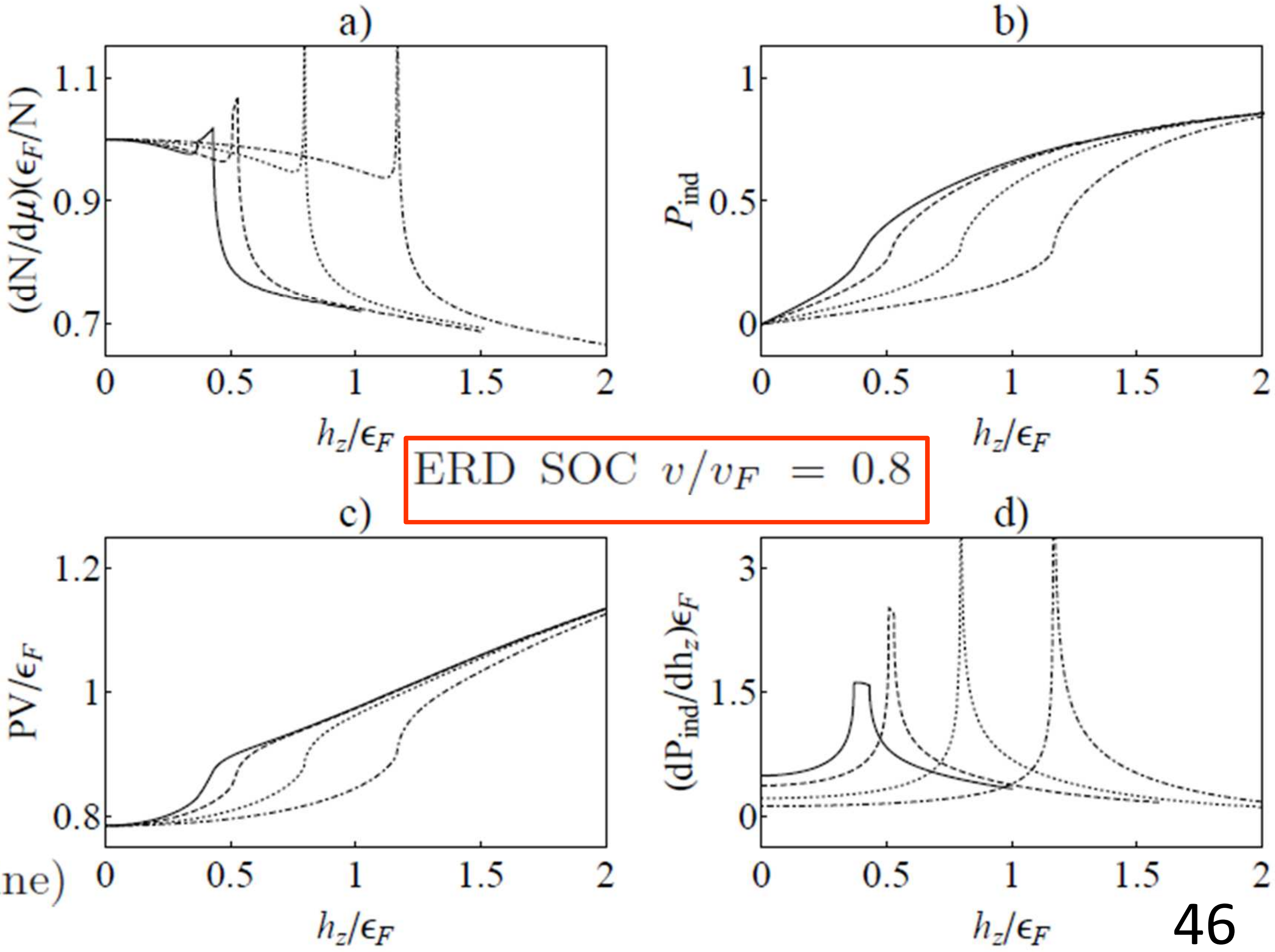
T = 0 Thermodynamic Properties in 2D

$E_b/\epsilon_F = 0.1$ (solid line)

$E_b/\epsilon_F = 0.2$ (dashed line)

$E_b/\epsilon_F = 0.5$ (dotted line)

$E_b/\epsilon_F = 1.0$ (dot-dashed line)



ERD SOC $v/v_F = 0.8$

Outline

1) Introduction to 2D Fermi gases.

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5) Conclusions

Hamiltonian in Real Space

$$\mathcal{H}(\mathbf{r}) = \mathcal{H}_0(\mathbf{r}) + \mathcal{H}_I(\mathbf{r})$$

$$\mathcal{H}_0(\mathbf{r}) = \sum_{\alpha\beta} \psi^\dagger_\alpha(\mathbf{r}) \left[\hat{K}_\alpha \delta_{\alpha\beta} - h_i(\mathbf{r}) \sigma_{i,\alpha\beta} \right] \psi_\beta(\mathbf{r})$$

Kinetic Energy

Spin-orbit and Zeeman

$$\mathcal{H}_I(\mathbf{r}) \;\; = \;\; -g\psi^\dagger_\uparrow(\mathbf{r})\psi^\dagger_\downarrow(\mathbf{r})\psi_\downarrow(\mathbf{r})\psi_\uparrow(\mathbf{r})$$

Contact Interaction

Effective Action at finite T

$$\psi_{r,s} \rightarrow \psi_{r,s} e^{i\theta_r/2}$$

$$\Delta_r = |\Delta_r| e^{i\theta_r}$$

$$S = -\frac{1}{2}\mathrm{Tr}\left\{\ln\left[\beta\begin{pmatrix}\mathbb{A}_+ & \mathbb{D}_+ \\ \mathbb{D}_- & \mathbb{A}_-^*\end{pmatrix}\right]\right\} - \frac{\beta L^2|\Delta|^2}{g} \qquad (2)$$
$$+ \frac{\beta}{2}\sum_{k,s}(-i\omega_n + \mathbf{k}^2 - \mu_s) + \frac{1}{8L^2}\int dr \sum_k [\nabla_{\mathbf{r}}(\theta_r)]^2.$$

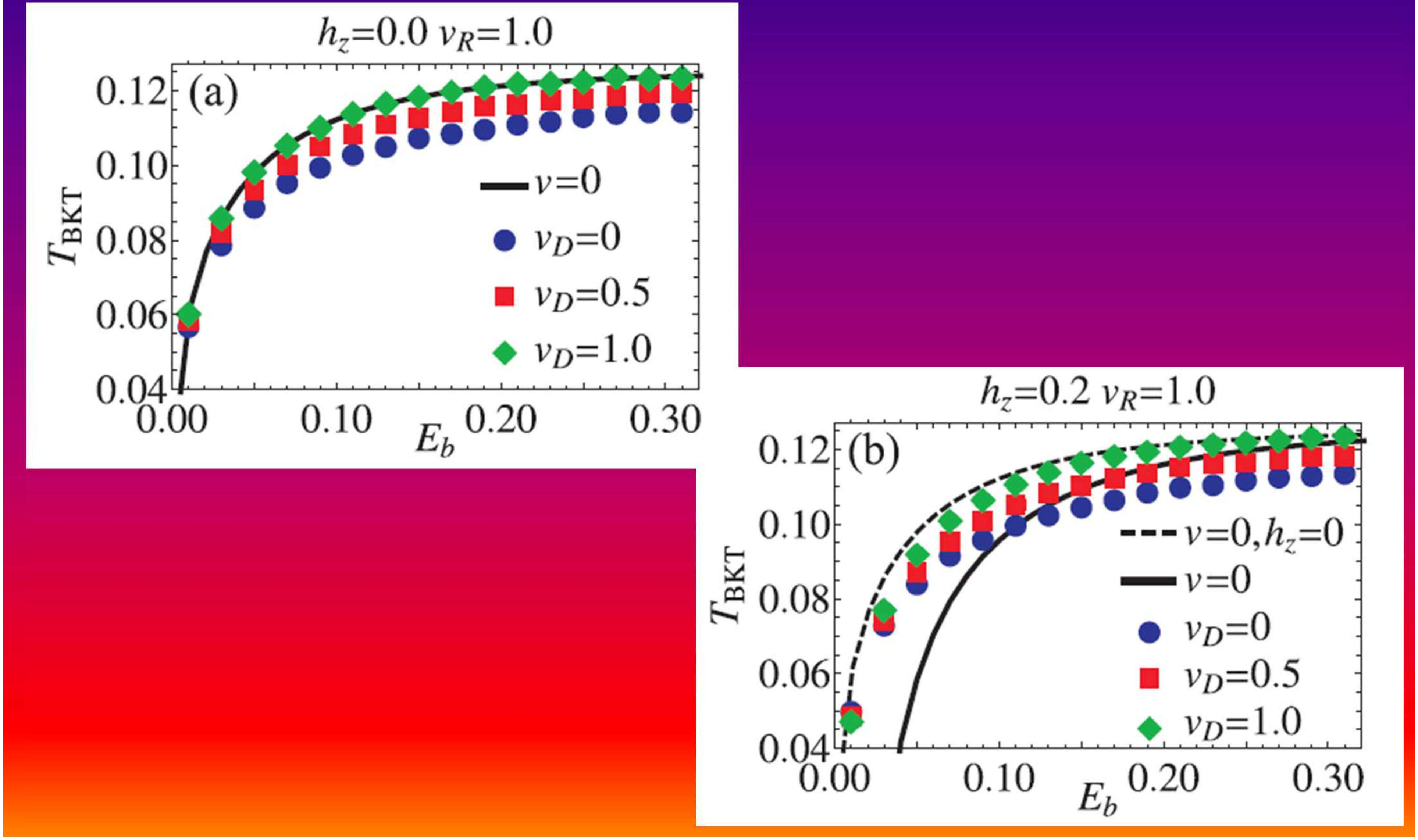
Effective Action at finite T

$$S = S_{sp} + S_{fl}$$

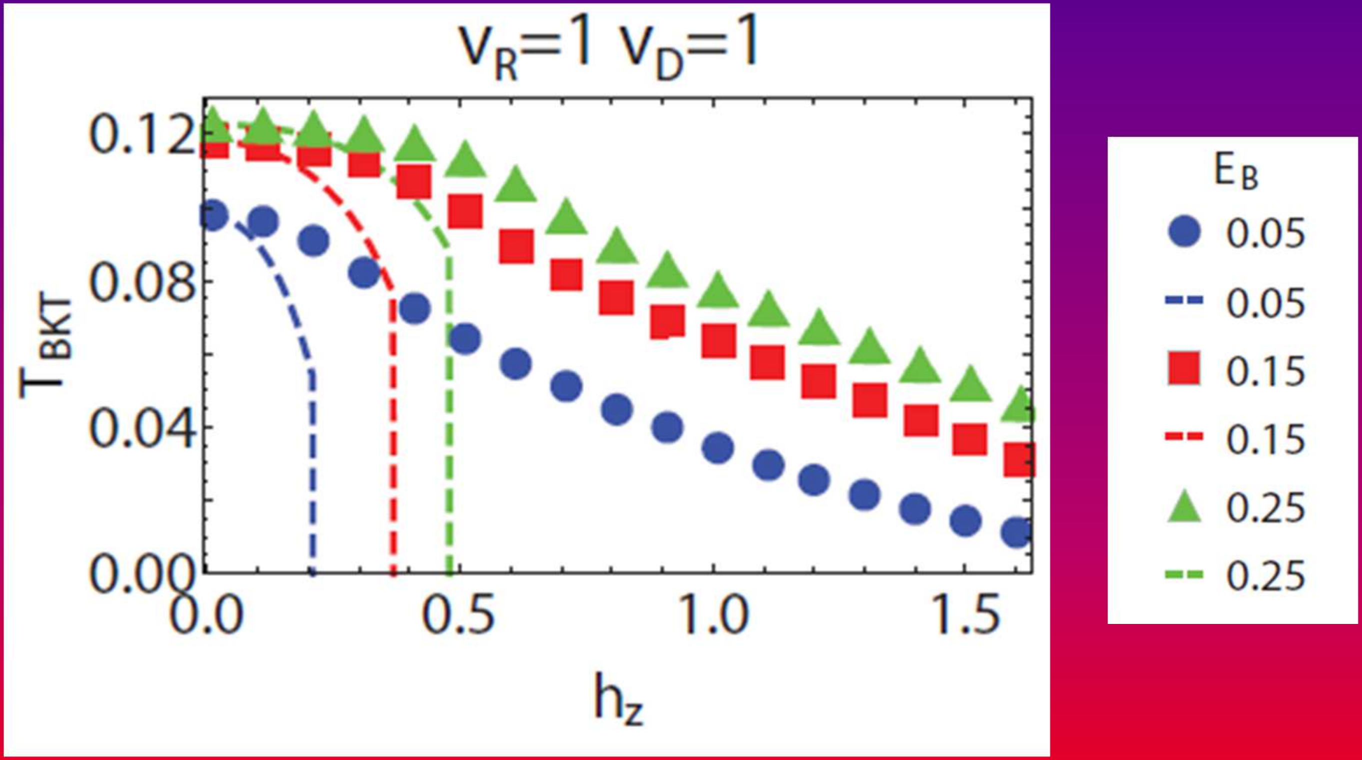
$$S_{sp} = -\frac{1}{2}\mathrm{Tr}\{\ln[\beta \mathbb{M}_k(0,0)]\} + \frac{\beta}{2}\sum_{k,s}(-i\omega_n + \mathbf{k}^2 - \mu_s) - \frac{\beta L^2|\Delta|^2}{g}$$

$$S_{fl} = \frac{1}{2}\int dr \left(\mathcal{A}\left(\frac{\partial\theta_r}{\partial\tau}\right)^2 + \sum_{\nu=\{x,y\}} \rho_{\nu\nu}\left(\frac{\partial\theta_r}{\partial\nu}\right)^2\right)$$

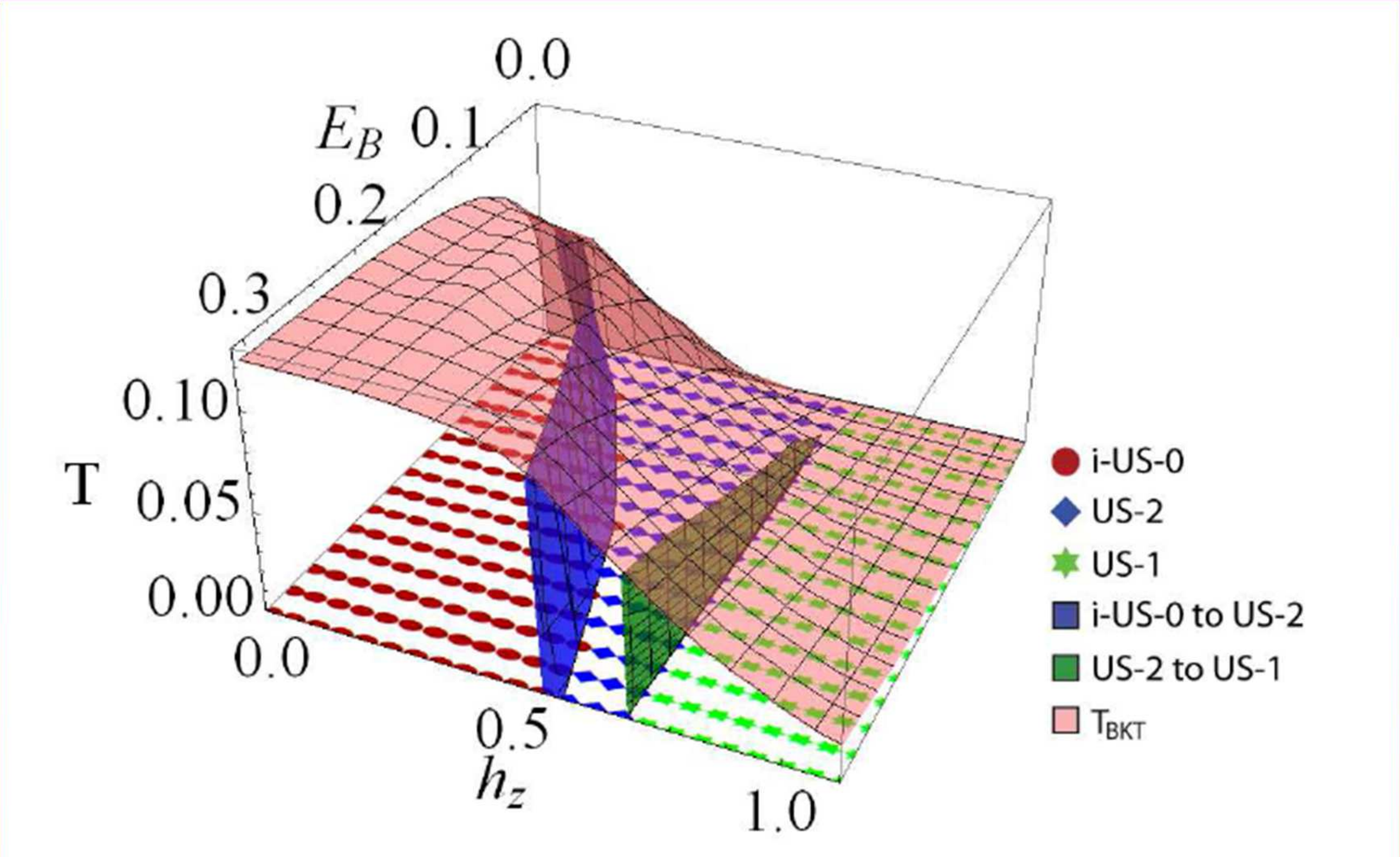
BKT Transition Temperature



Beyond the Clogston Limit

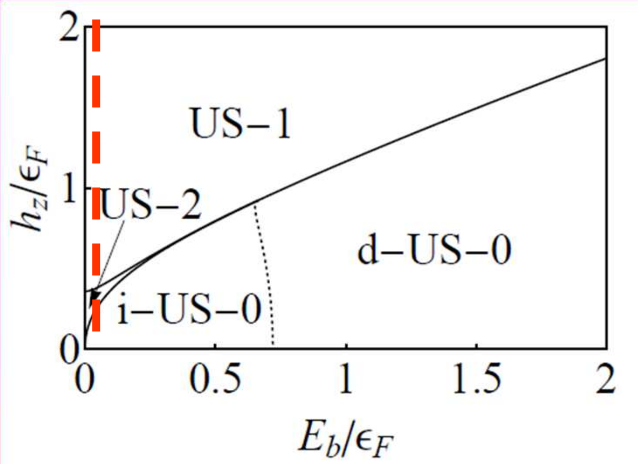


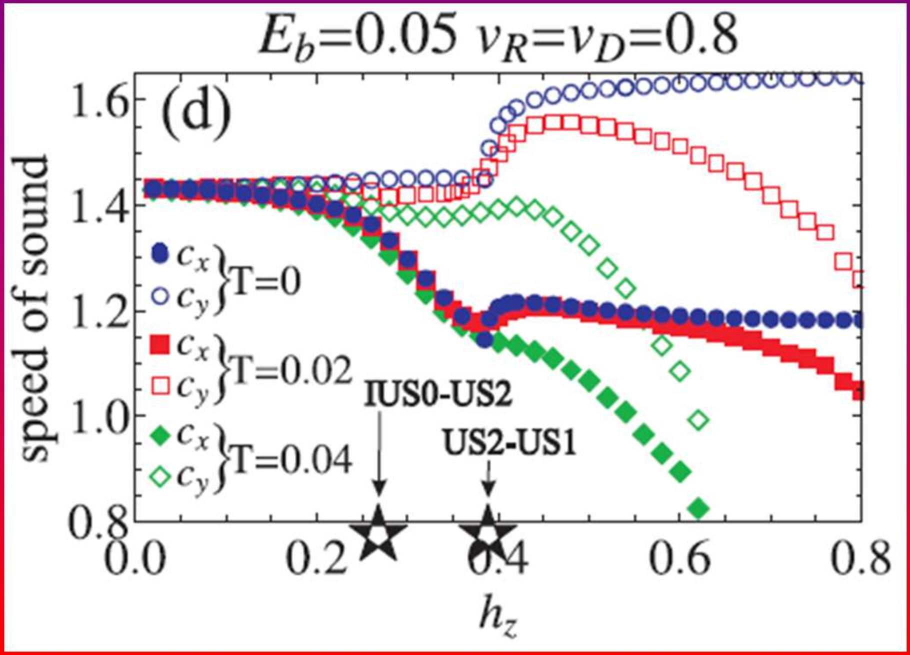
Full Finite Phase Diagram



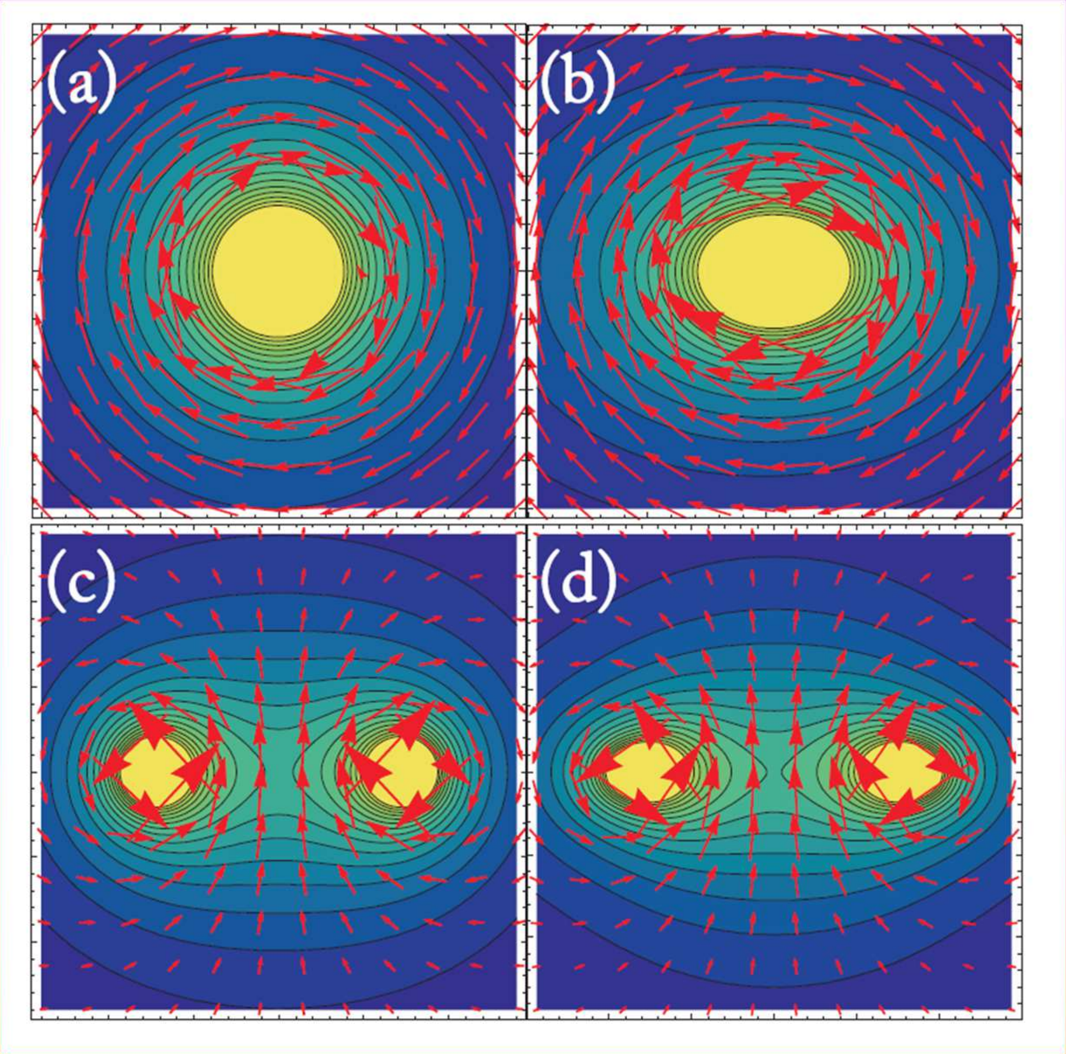
Anisotropic speed of sound

$$\widetilde{\mathcal{A}}\varpi^2 - \begin{pmatrix} q_x & q_y \end{pmatrix}\begin{pmatrix}\rho_{xx} & \rho_{xy}\\ \rho_{xy} & \rho_{yy}\end{pmatrix}\begin{pmatrix}q_x\\ q_y\end{pmatrix} = 0$$





Vortex-Antivortex Structure



RASHBA

ERD

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5) Conclusions

Conclusions in words

- Ultra-cold fermions in the presence of spin-orbit and Zeeman fields are special systems that allow for the study of exciting new phases of matter, such as topological superfluids, with a high degree of accuracy.

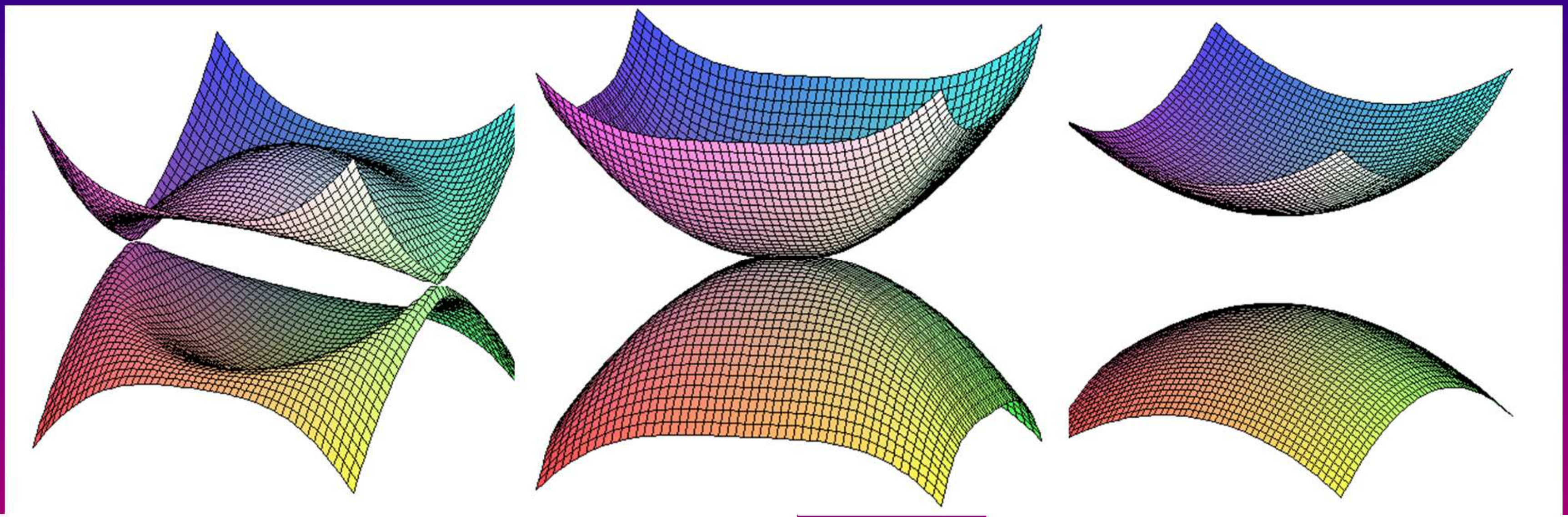
- Topological quantum phase transitions emerge as function of Zeeman fields and binding energy for fixed spin-orbit coupling.

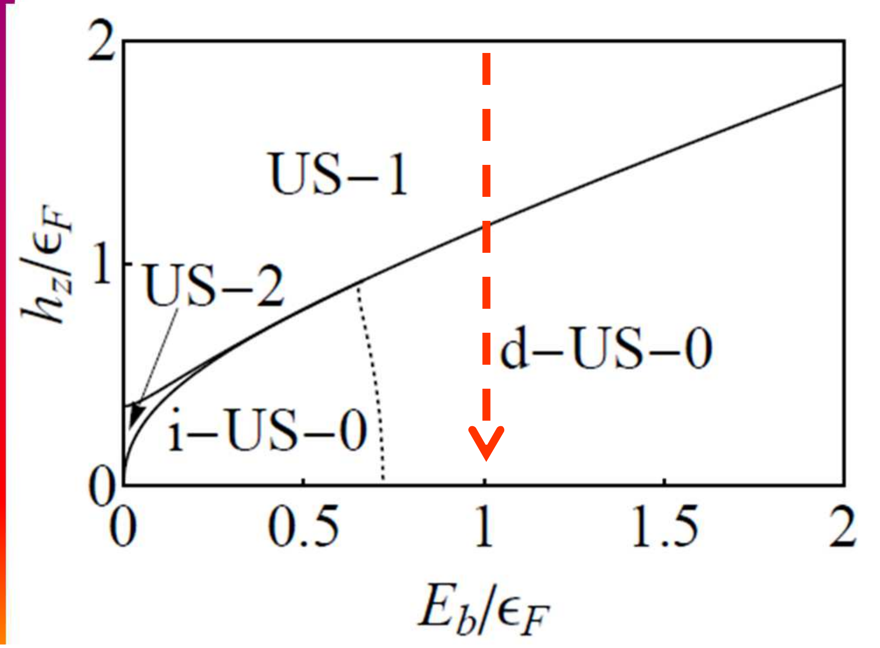
Conclusions in words

- The critical temperature of the BKT transition as a function of pair binding energy is affected by the presence of spin-orbit effects and Zeeman fields. While the Zeeman field tends to reduce the critical temperature, SOC tends to stabilize it by introducing a triplet component in the superfluid order parameter.

- In the presence of a generic SOC the sound velocity in the superfluid state is anisotropic and becomes a sensitive probe of the proximity to topological quantum phase transitions. The vortex and antivortex shapes are also affected by the SOC and acquire a corresponding anisotropy.

Conclusions in Pictures

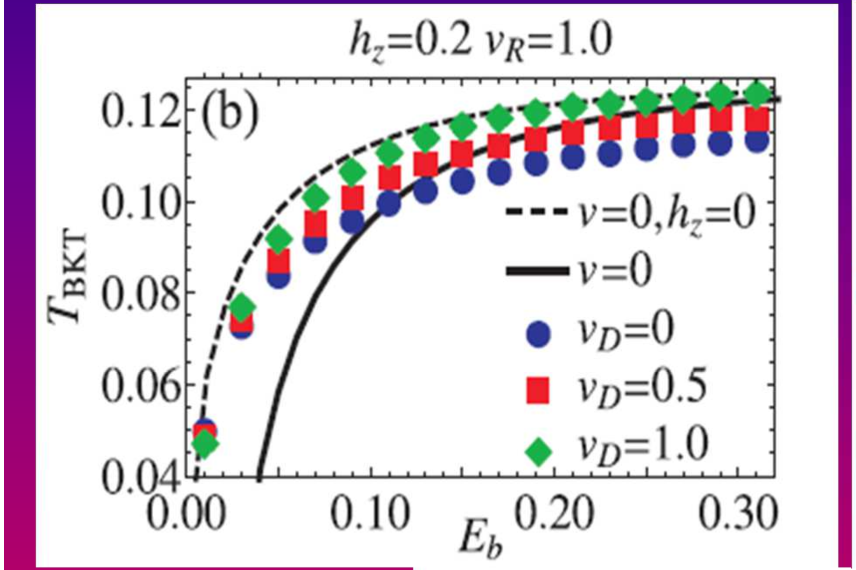


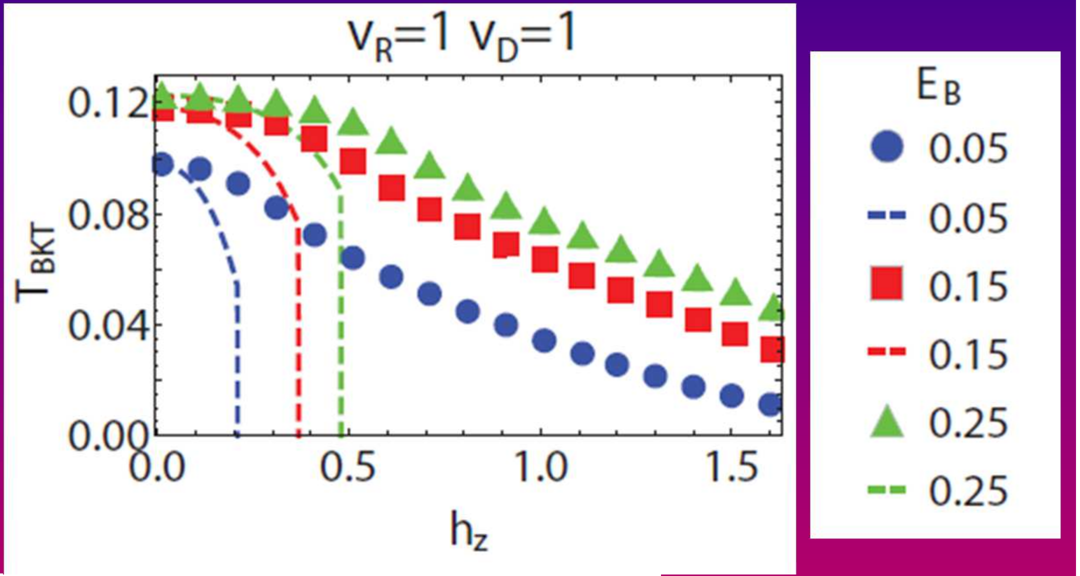


Change in topology

TRANSITION FROM
GAPLESS TO GAPPED SUPERFLUID

BKT transition and vortex-antivortex structure





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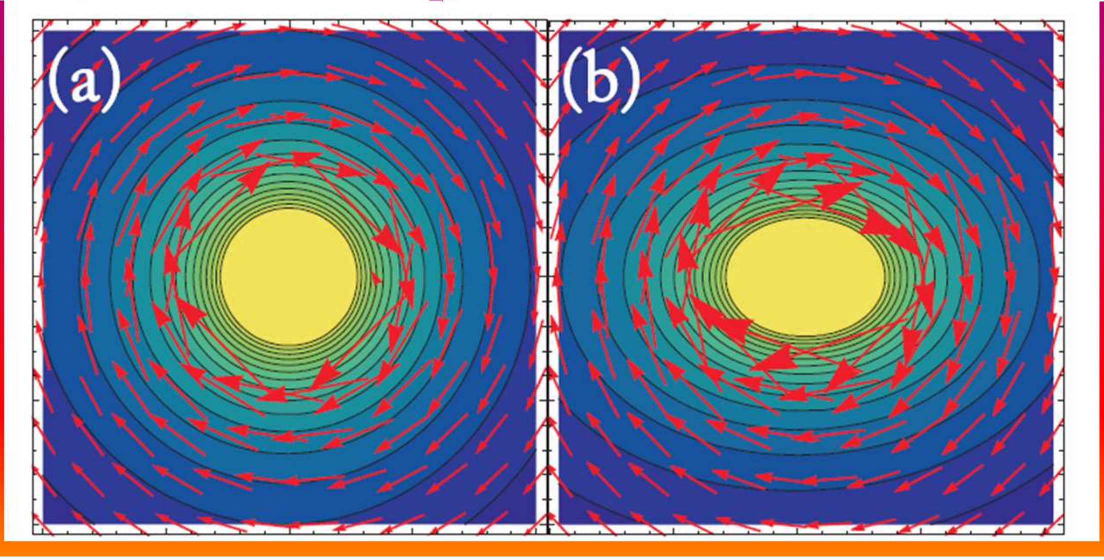

ERD

THE END