Superconductivity and anisotropic NFL in 3D Luttinger semimetals

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Simon Fraser U

Vancouver

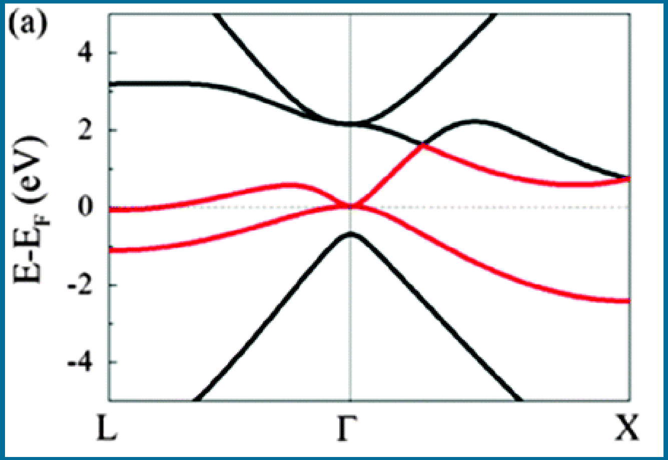
Joint work with Igor Herbut

IB, Herbut, PRB 93, 205138 (2016)

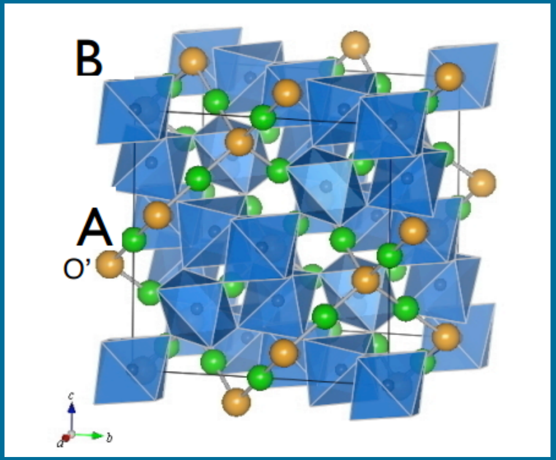
IB, Herbut, in preparation

Deutsche Forschungsgemeinschaft

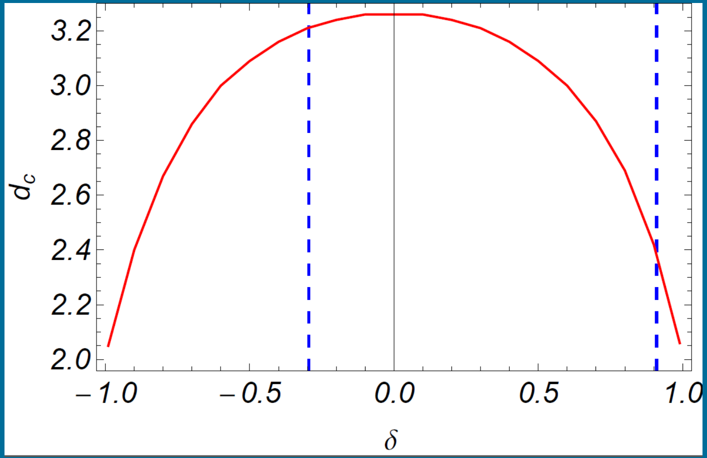
Outline



Quadratic band touching

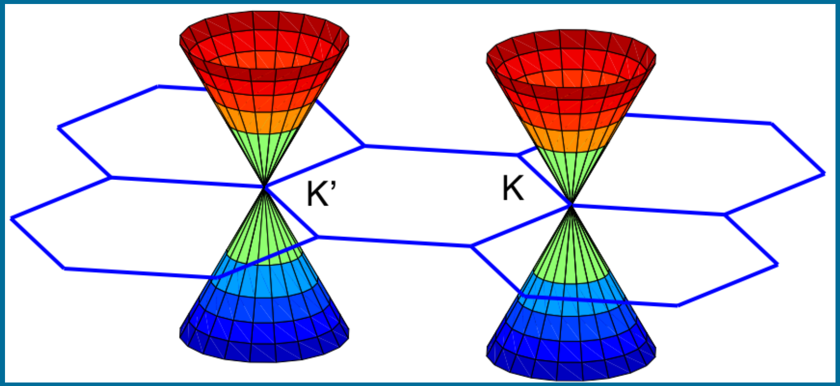


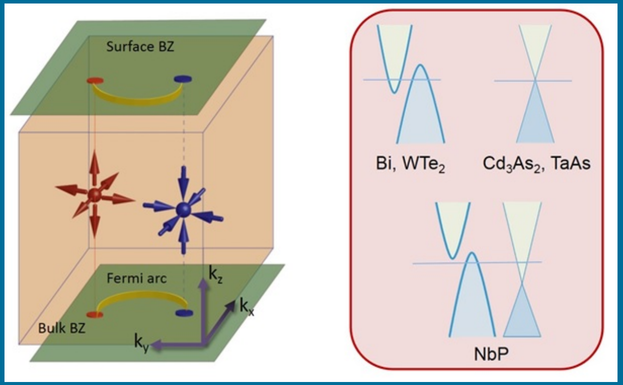
Superconducting quantum criticality



Anisotropic Non-Fermi liquid

Quadratic band touching

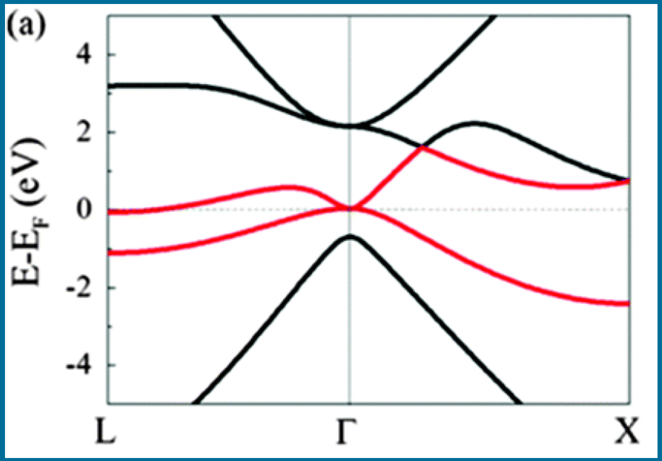


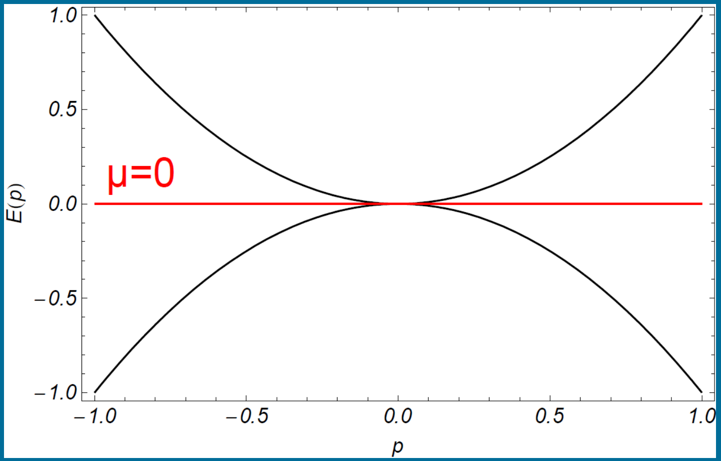


Pics: MPIKS Dresden

Dirac semimetals

Weyl semimetals





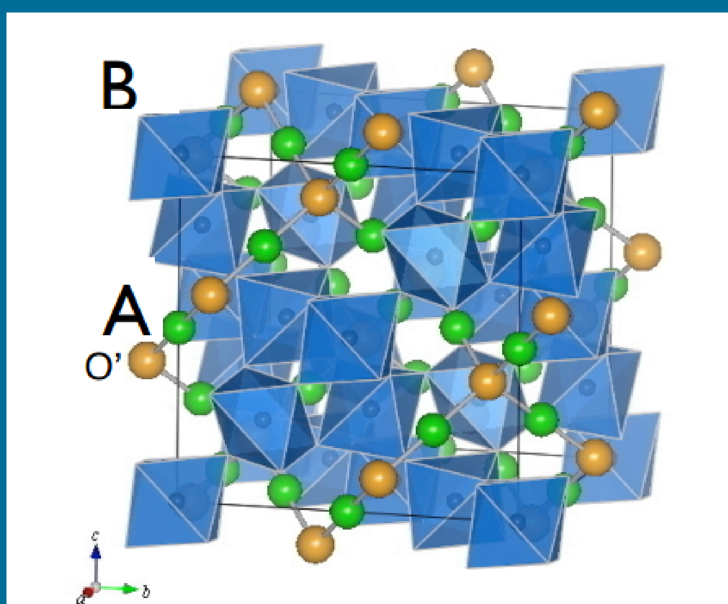
Luttinger Hamiltonian: Luttinger semimetals

Murakami, Nagaosa, Zhang

Quadratic band touching

Pyrochlore iridates $R_2Ir_2O_7$

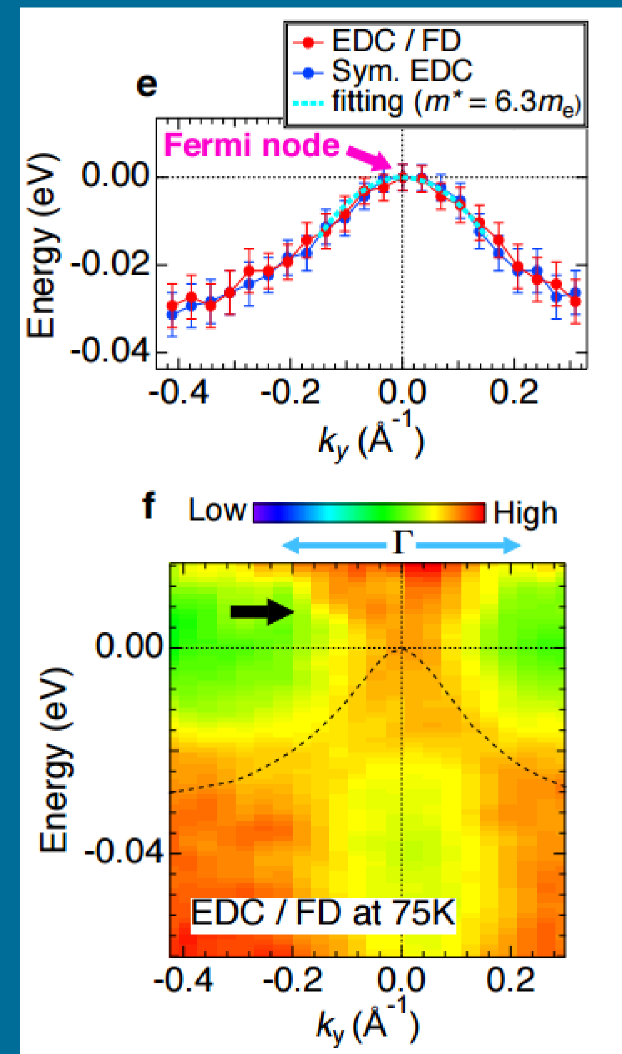
- quadratic band touching
- strong spin-orbit coupling
- unscreened Coulomb



Balents, Pesin, Witczak-Krempa, Chen, Kim

Pr-227

Kondo et al, Nat. Comm. 6, 10042 (2015)



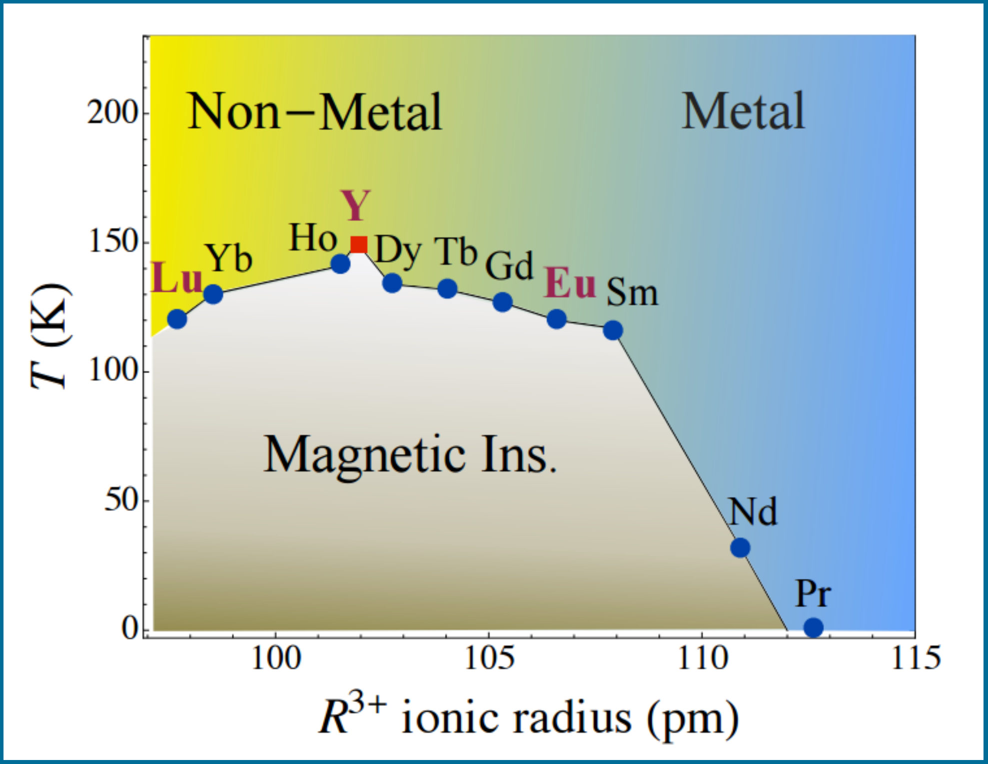
Nd-227: Nakayama et al PRL 117, 056403 (2016)

Quadratic band touching

Pyrochlore iridates $R_2Ir_2O_7$

- quadratic band touching
- strong spin-orbit coupling
- unscreened Coulomb

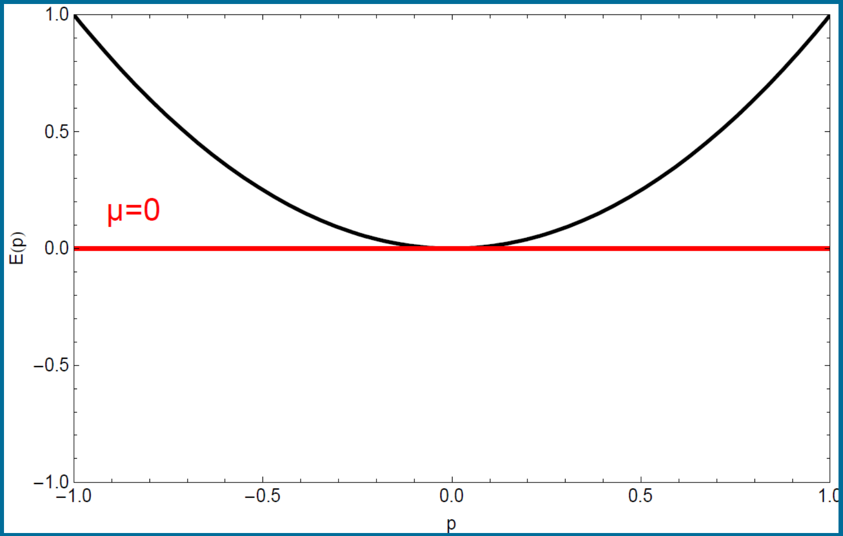
Phase diagram of pyrochlore iridates



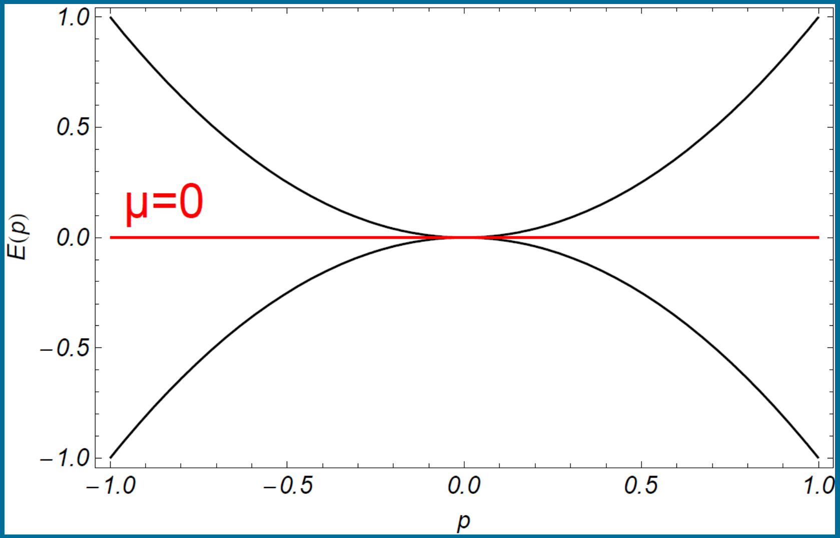
Witczak-Krempa, Chen, Kim, Balents, Ann. Rev. of Cond. Mat. Phys., Vol. 5: 57-82 (2014)

Superconducting quantum criticality

s-wave particle-particle pairing



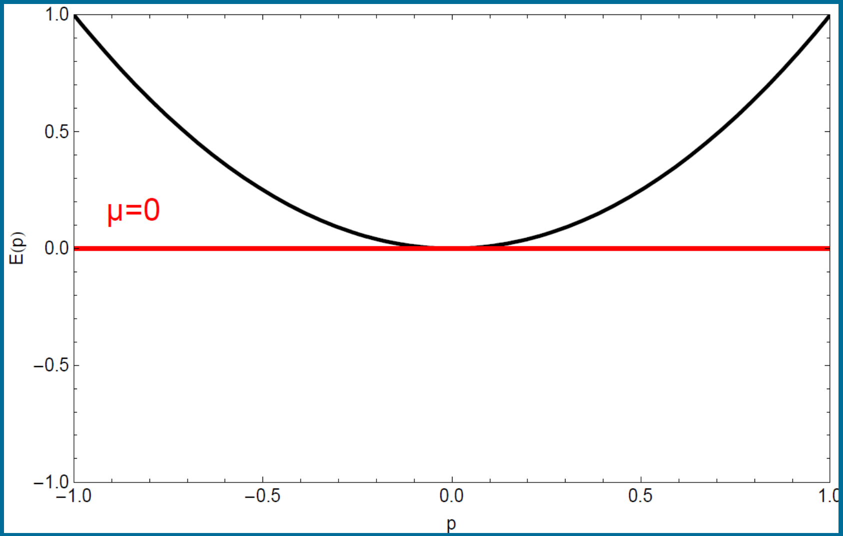
3D ultracold atoms at
a Feshbach resonance

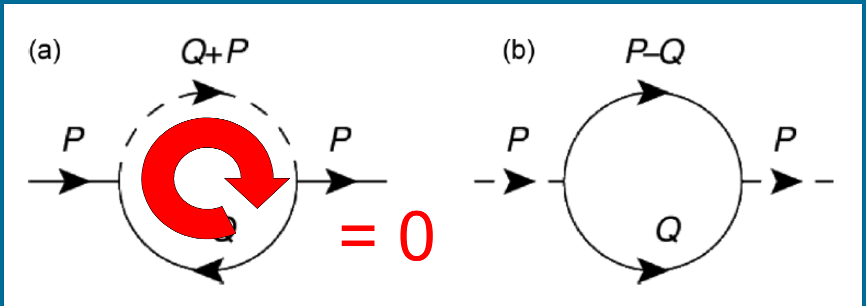


3D Luttinger semimetals
at a superconducting QCP

Superconducting quantum criticality

s-wave particle-particle pairing





3D ultracold atoms at
a Feshbach resonance

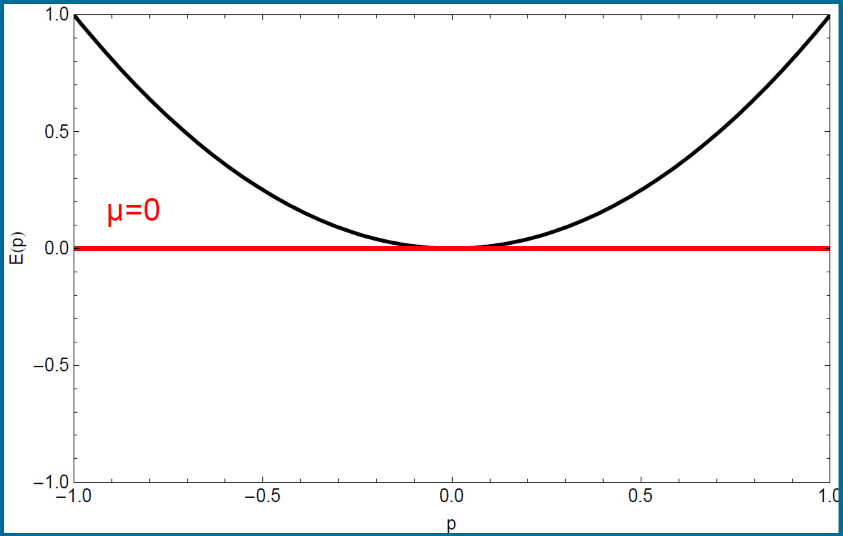
$$\eta_\phi = 1,$$

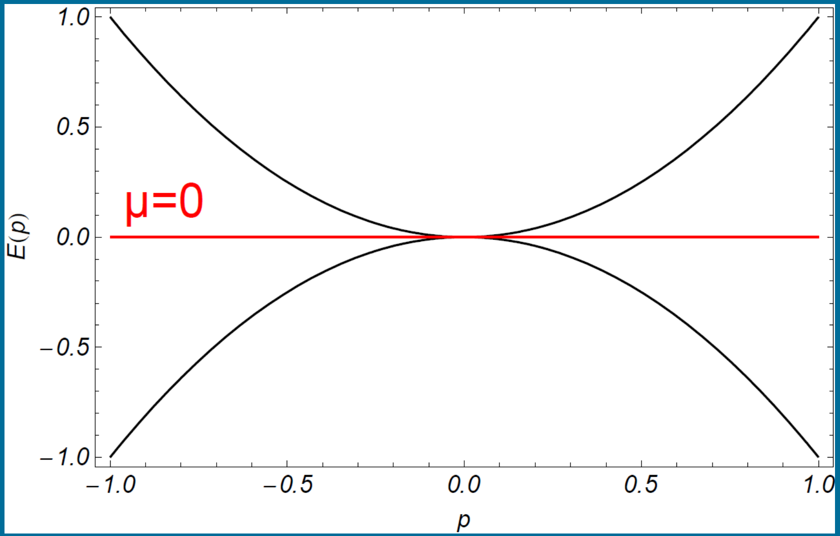
$$\eta_\psi = 0, \ \ z = 2$$

Sachdev, Nikolic; Diehl, Wetterich

Superconducting quantum criticality

s-wave particle-particle pairing





3D ultracold atoms at a Feshbach resonance

3D Luttinger semimetals at a superconducting QCP

$$\eta_\phi = 1,$$

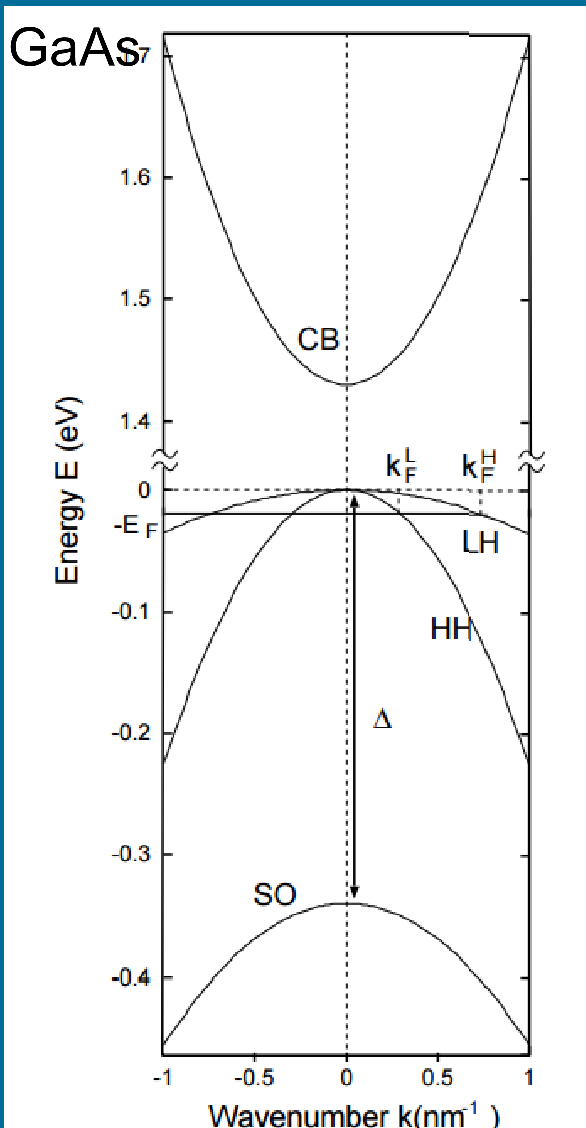
$$\eta_\psi = 0, \ z = 2$$

$$\eta_\phi = \frac{9}{11}\varepsilon = 0.82$$

$$\eta_\psi = \frac{2}{11}\varepsilon = 0.18, \ z = 2 - \frac{2}{11}\varepsilon = 1.82$$

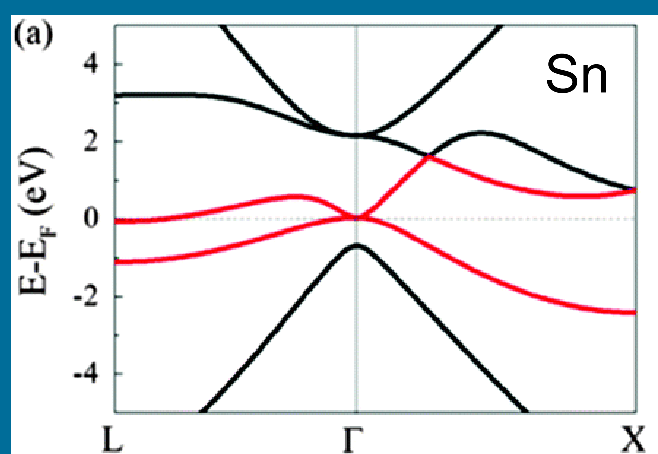
IB, Herbut, PRB 93, 205138 (2016)

Superconducting quantum criticality



4 x 4 Luttinger Hamiltonian

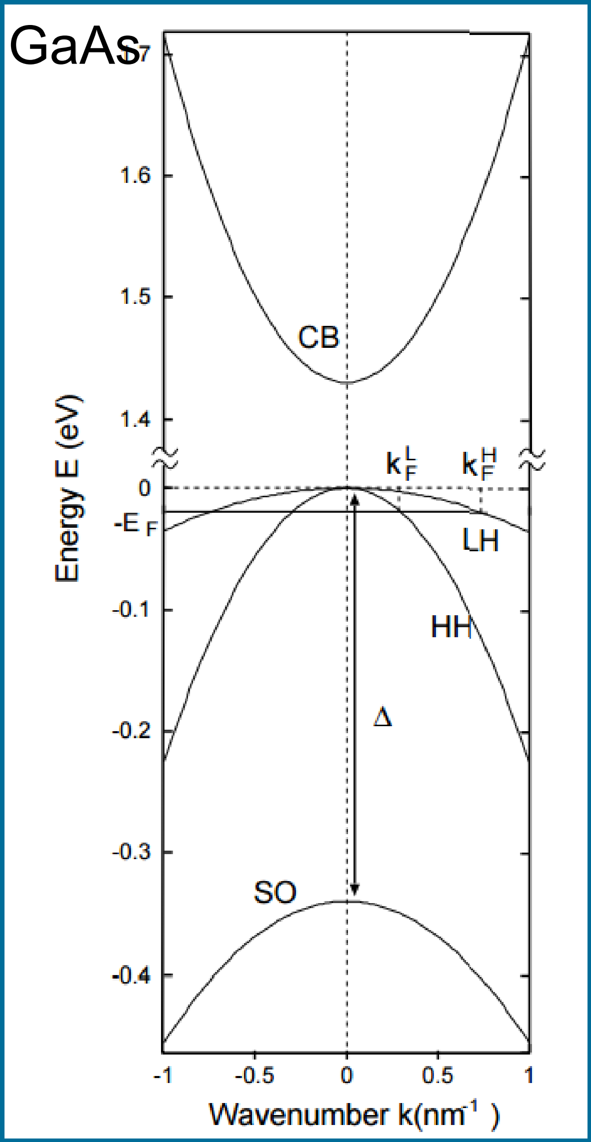
$$H = \frac{\hbar^2}{2m^*}\Big[\Big(\alpha_1 + \frac{5}{2}\alpha_2\Big)p^2 1_4 - 2\alpha_3(\vec{p}\cdot\vec{J})^2 + 2(\alpha_3 - \alpha_2)\sum_{i=1}^{3} p_i^2 J_i^2\Big]$$



J_x, J_y, J_z

spin 3/2 matrices

Superconducting quantum criticality



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$$+ 2(\alpha_3 - \alpha_2)\sum_{i=1}^{3} p_i^2 J_i^2\Big]$$

rotation invariant SO(3)

cubic invariant Oh
≈ permutations of x,y,z

Superconducting quantum criticality

Quantum field theory $L_{\mathrm{kin}} = \psi^\dagger(\partial_\tau + H)\psi$

$$H = \alpha_1 p^2 1_4 - (\alpha_2 + \alpha_3) \sum_{a=1}^{5} d_a(\vec{p})\gamma_a$$

$$+ (\alpha_2 - \alpha_3) \sum_{a=1}^{5} s_a d_a(\vec{p})\gamma_a$$

$$x = -\frac{\alpha_1}{\alpha_2 + \alpha_3}$$ particle-hole asymmetry $\{\gamma_a, \gamma_b\} = 2\delta_{ab}$

$$\delta = -\frac{\alpha_2 - \alpha_3}{\alpha_2 + \alpha_3}$$ spatial anisotropy

Abrikosov
Murakami, Nagaosa, Zhang
Herbut, Janssen

Superconducting quantum criticality

$$L = L_{\mathrm{kin}} + \phi^*(y\partial_\tau - \nabla^2)\phi + g\left(\phi\psi^\dagger\gamma_{45}\psi^* + \mathrm{h.c}\right)$$

IB, Herbut, PRB 93, 205138 (2016)

Superconducting quantum criticality

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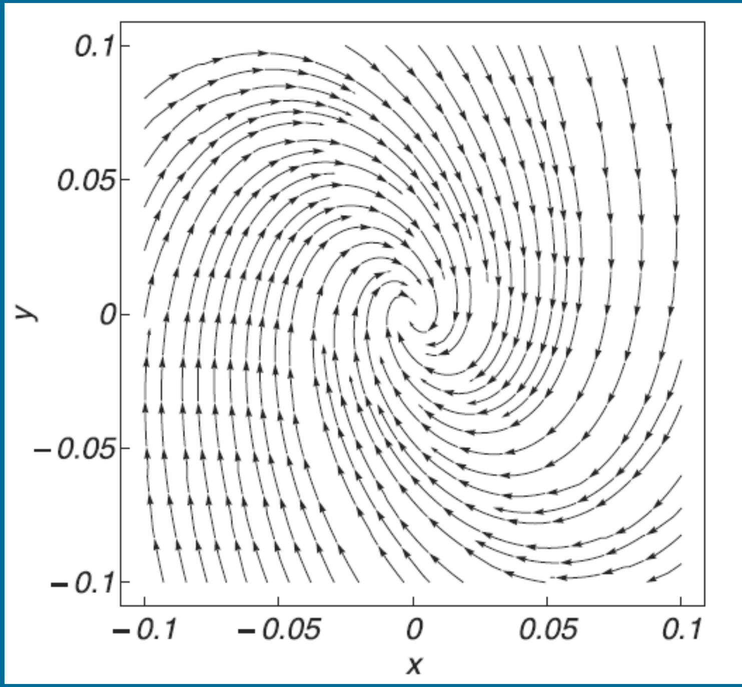

$$x, y \to 0$$

IB, Herbut, PRB 93, 205138 (2016)

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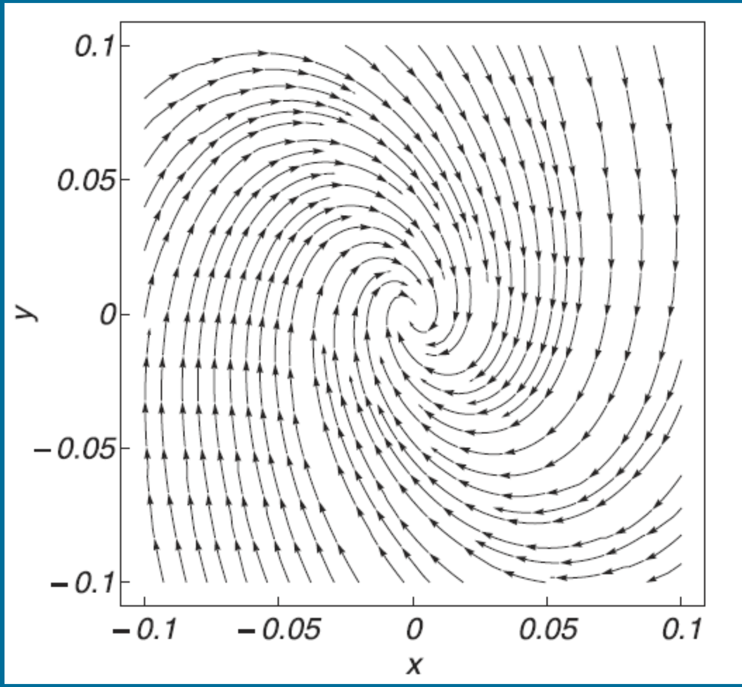

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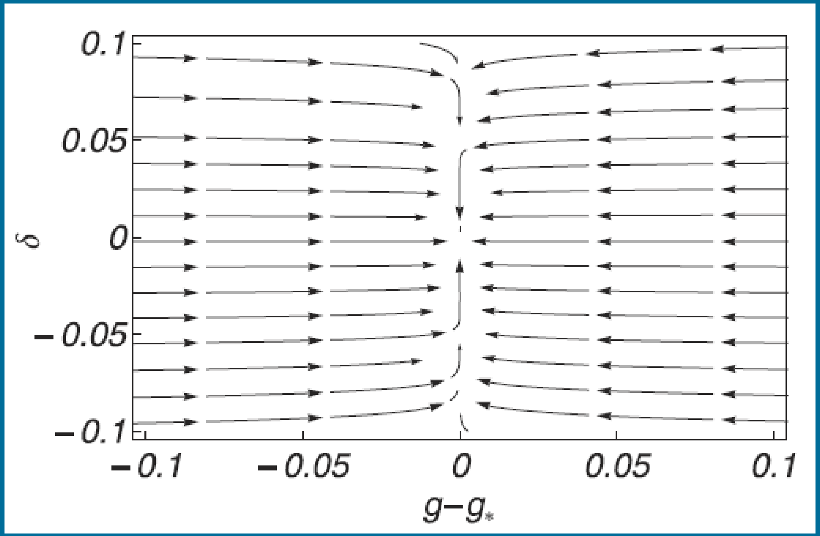


$$\delta \to 0 \qquad \dot{\delta} \simeq -\frac{2}{55}\varepsilon\,\delta$$

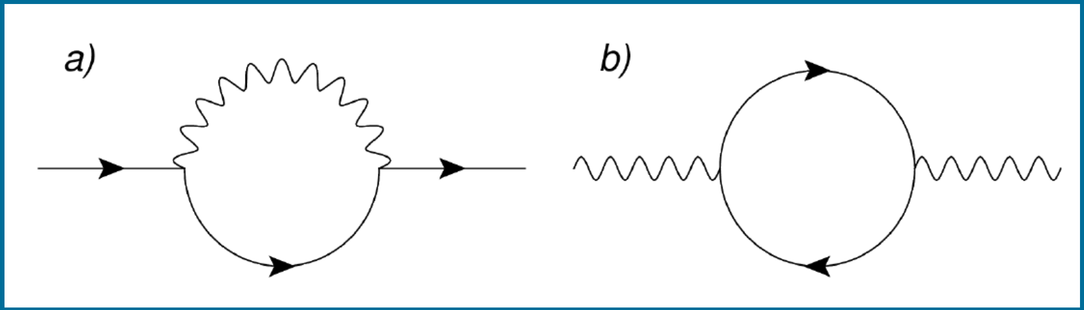
exceptionally slow!

IB, Herbut, PRB 93, 205138 (2016)

Abrikosov's NFL scenario

Quadratic band touching & Long-range Coulomb repulsion

$$L = \psi^\dagger(\partial_\tau + H + \mathrm{i}a)\psi + \frac{1}{2e^2}(\nabla a)^2$$



- charge renormalization
- non-Fermi liquid behavior

$$\frac{\mathrm{d}e^2}{\mathrm{d}\log b} = (z + 2 - d)e^2 - e^4$$

$$\eta_\psi = \frac{4}{15}e^2, \; z = 2 - \eta_\psi$$

Easy route to a NFL?

Abrikosov's NFL scenario

Quadratic band touching & Long-range Coulomb repulsion

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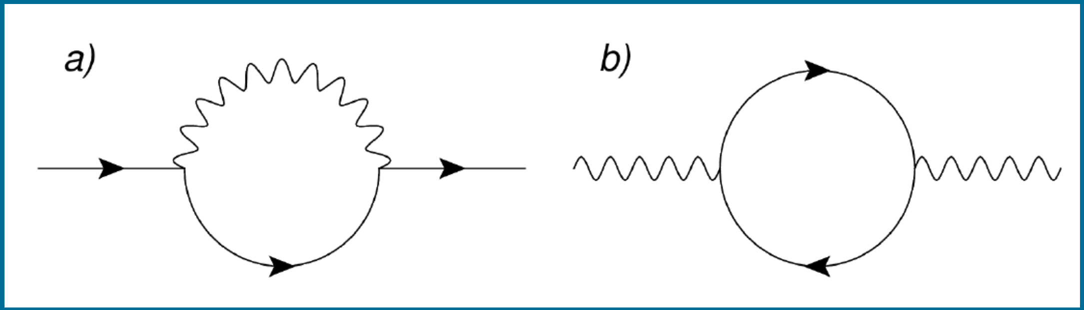

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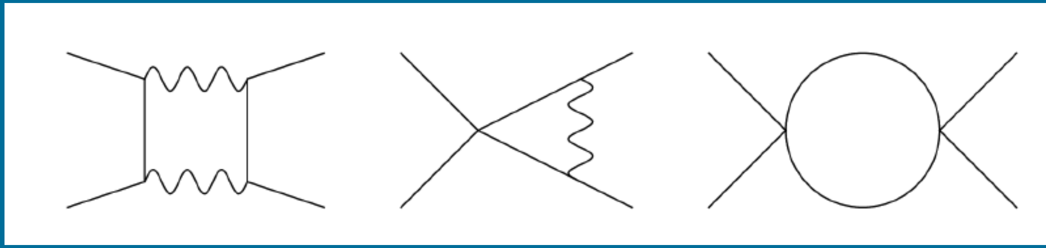
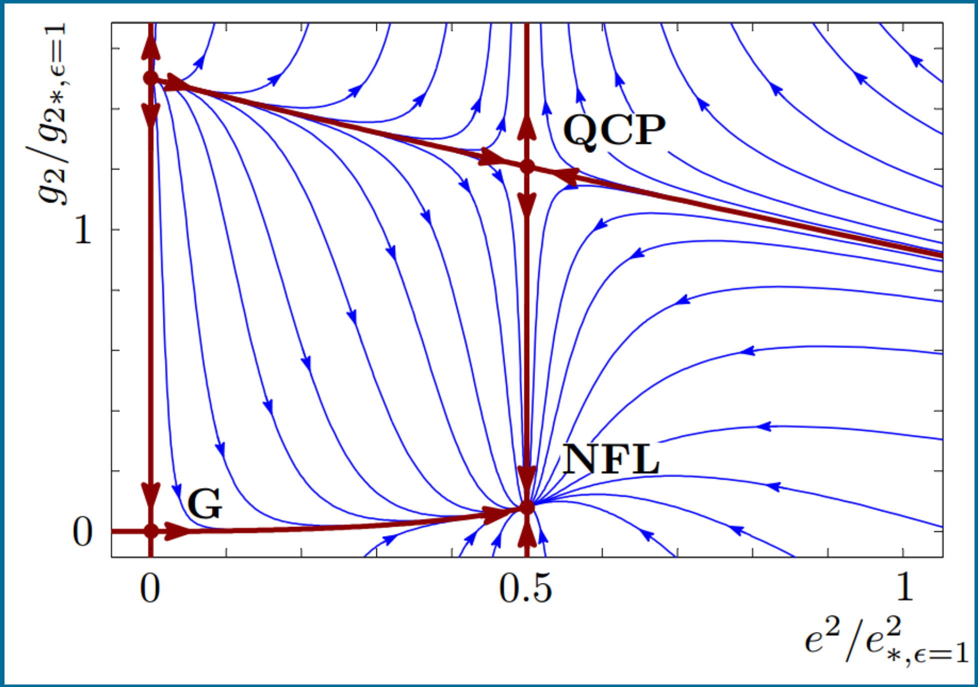
Easy route to a NFL?

No! (Herbut, Janssen)

Abrikosov's NFL scenario

long-range Coulomb repulsion
generates short-range interactions,
even if initially absent





Herbut, Janssen
PRL 113, 106401 (2014)

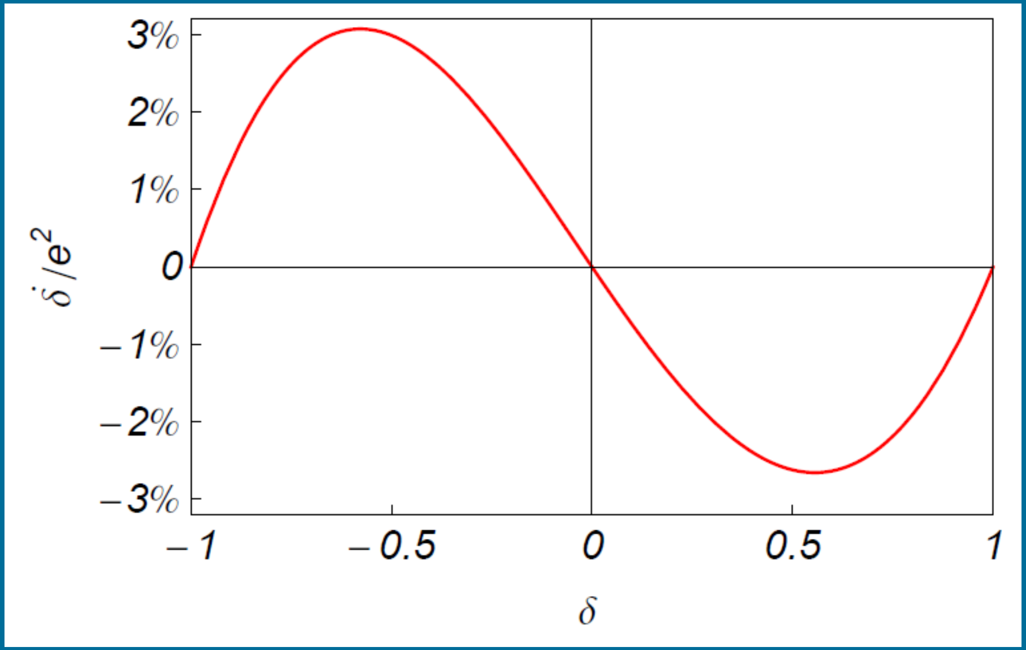
Critical dimension for survival of Abrikosov's NFL: d=3.25

Role of anisotropy δ?

Anisotropy and short-range interactions

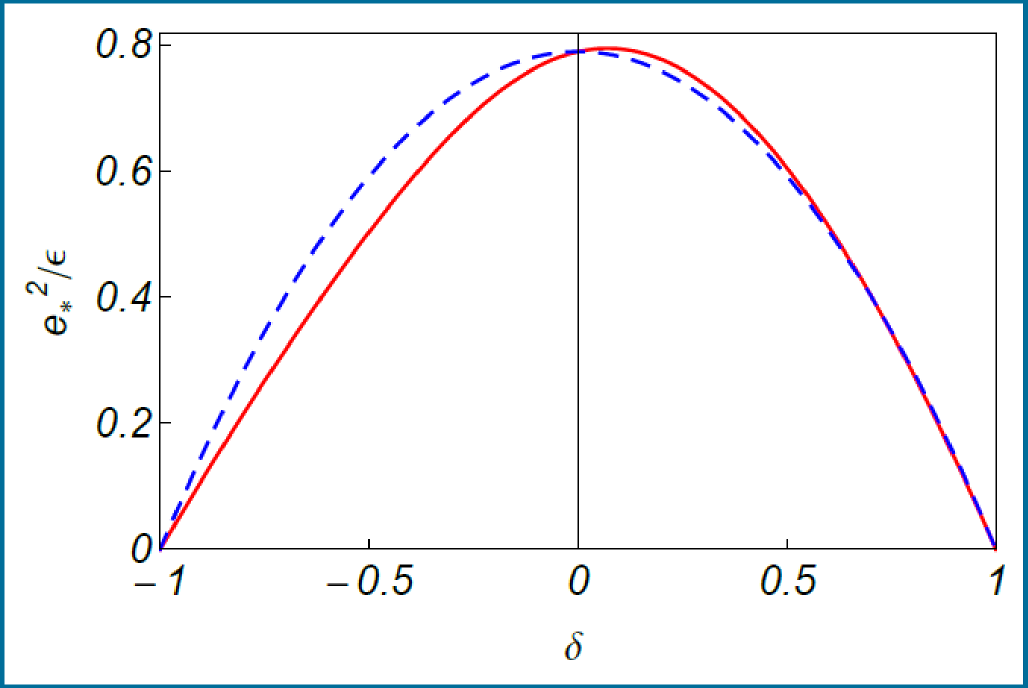
Flow of the anisotropy

$$\dot{\delta} = -\frac{2}{15}(1-\delta^2)\Big[f_{1\mathrm{e}}(\delta) - f_{1\mathrm{t}}(\delta)\Big]e^2$$



Anisotropy constant for all practical purposes

Anisotropy and short-range interactions



$$e_\star^2 \simeq \frac{15}{19}(1-\delta^2)\varepsilon$$

- Abrikosov fixed point and NFL scaling for each δ
- Fixed point weakly coupled for strong anisotropy

Anisotropy and short-range interactions

four-fermion terms with rotation symmetry $\delta = 0$

$$L_{\text{int}} = g_1(\psi^\dagger\psi)^2 + g_J(\psi^\dagger \mathcal{J}_i \psi)^2 + g_2(\psi^\dagger \gamma_a \psi)^2 + g_W(\psi^\dagger W_\mu \psi)^2$$

1 rank-0-tensor: 1 component, CDW

$\mathcal{J}_i$ rank-1-tensor: 3 components, magnetic order

γ_a rank-2-tensor: 5 components, nematic order

W_μ rank-3-tensor: 7 components, nemagnetic order

2 independent couplings after Fierz

Anisotropy and short-range interactions

four-fermion terms with cubic symmetry $\delta \in [-1, 1]$

$$L_{\mathrm{int}} = g_1(\psi^\dagger\psi)^2 + g_2(\psi^\dagger \vec{E}\psi)^2 + g_3(\psi^\dagger \vec{T}\psi)^2 + g_4(\psi^\dagger \vec{\mathcal{J}}\psi)^2 + g_5(\psi^\dagger \vec{W}\psi)^2 + g_6(\psi^\dagger \vec{W}'\psi)^2 + g_7(\psi^\dagger W_7\psi)^2 + g_8[(\psi^\dagger \vec{\mathcal{J}}\psi)\cdot(\psi^\dagger \vec{W}\psi) + (\psi^\dagger \vec{W}\psi)\cdot(\psi^\dagger \vec{\mathcal{J}}\psi)]$$

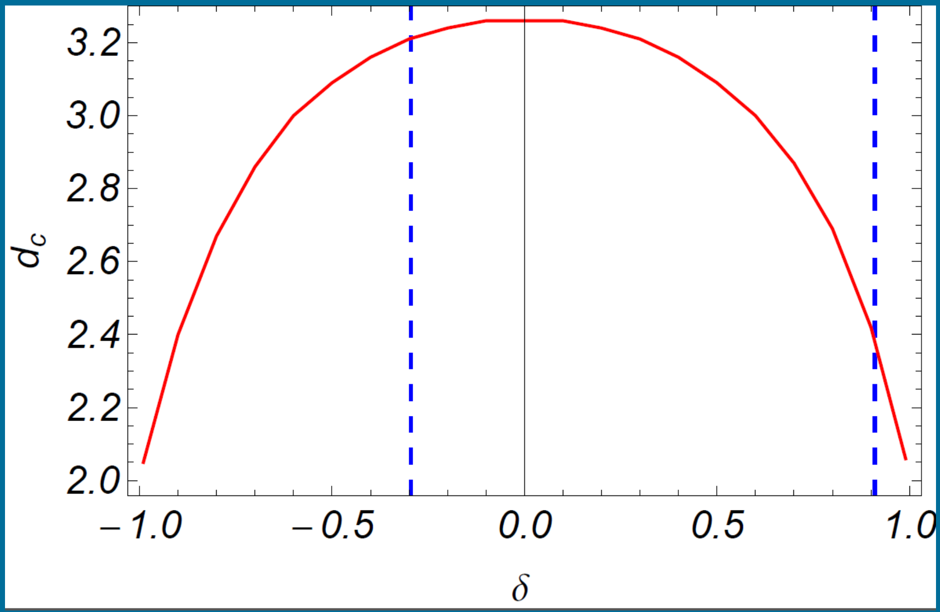
$$\vec{E} = \begin{pmatrix}\gamma_1\\ \gamma_2\end{pmatrix},\ \vec{T} = \begin{pmatrix}\gamma_3\\ \gamma_4\\ \gamma_5\end{pmatrix},\ \vec{W} = \begin{pmatrix}W_1\\ W_2\\ W_3\end{pmatrix},\ \vec{W}' = \begin{pmatrix}W_4\\ W_5\\ W_6\end{pmatrix}$$

3 independent couplings after Fierz

Anisotropic Non-Fermi liquid

- Fixed point collision scenario also with anisotropy
- Critical dimension lowered due to $e_\star^2 \simeq \frac{15}{19}(1-\delta^2)\varepsilon \to 0$

NFL from anisotropy



IB, Herbut
in preparation

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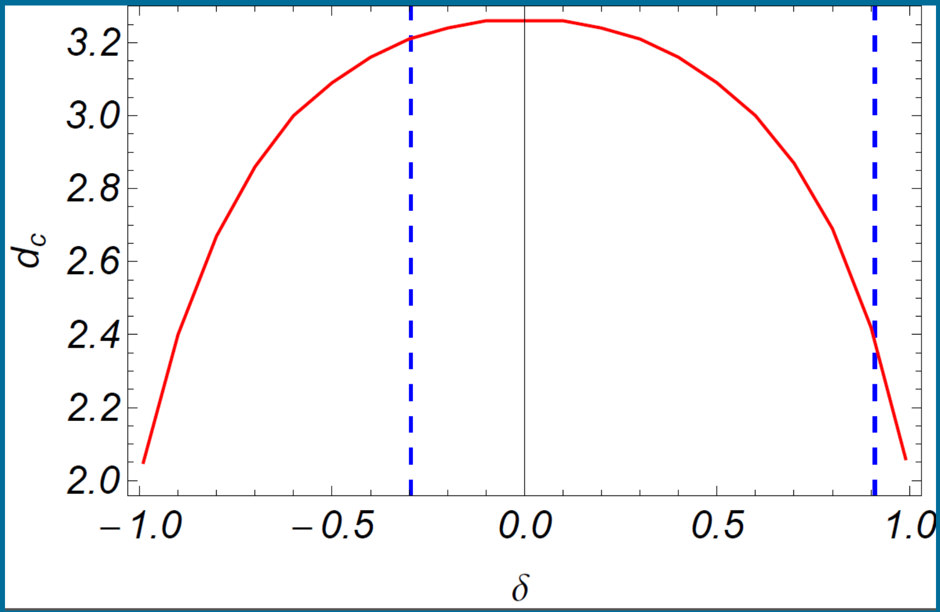

Thank you for your attention

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in preparation