Pairing interaction near a nematic instability

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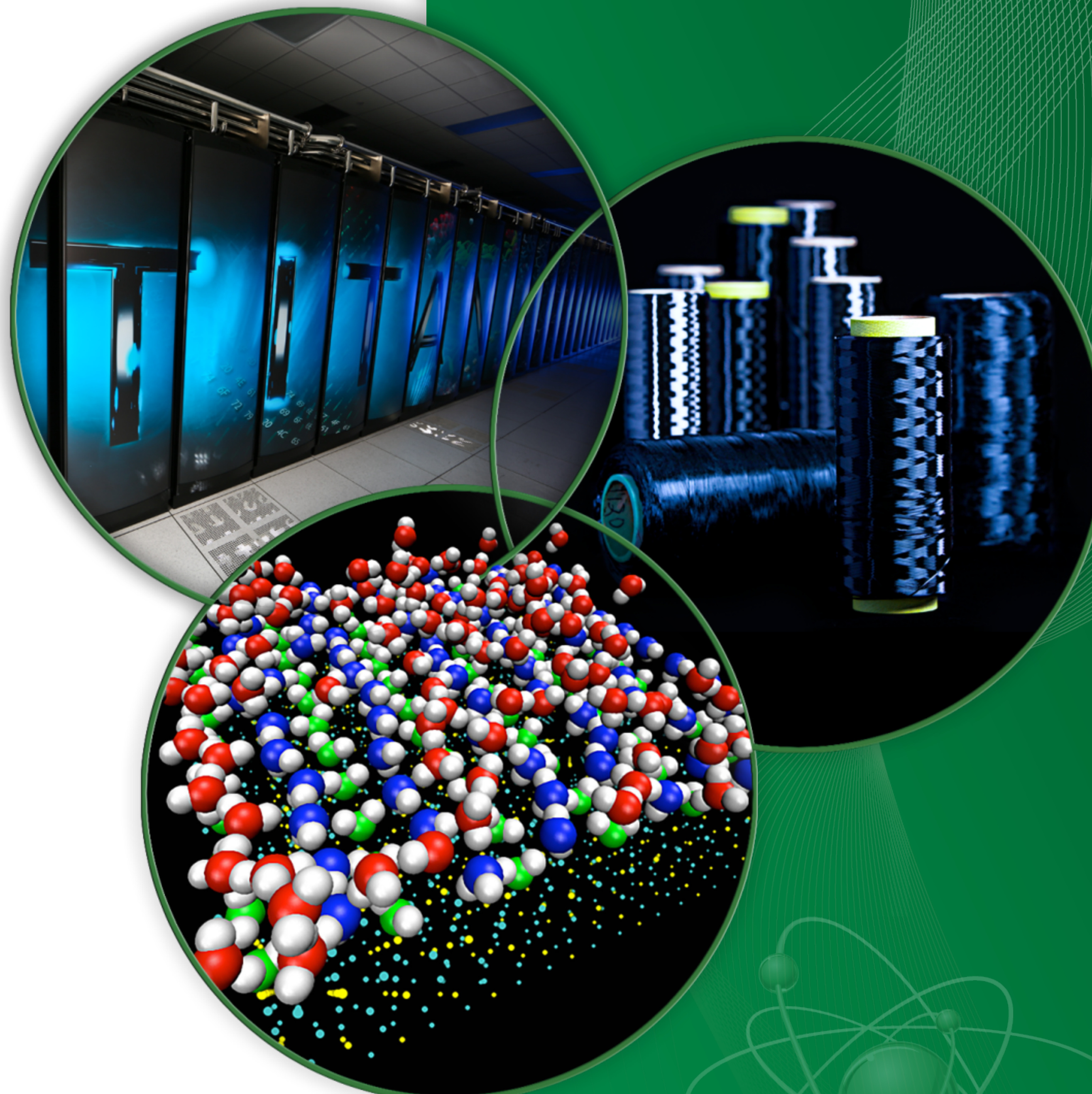
with Doug Scalapino – UCSB



Supported by the Center for Nanophase Materials Sciences at ORNL

Outline

- Underdoped cuprates have charge and nematic order
- 3-band Hubbard model has a nematic instability
- Nematic charge fluctuations contribute to *d*-wave pairing

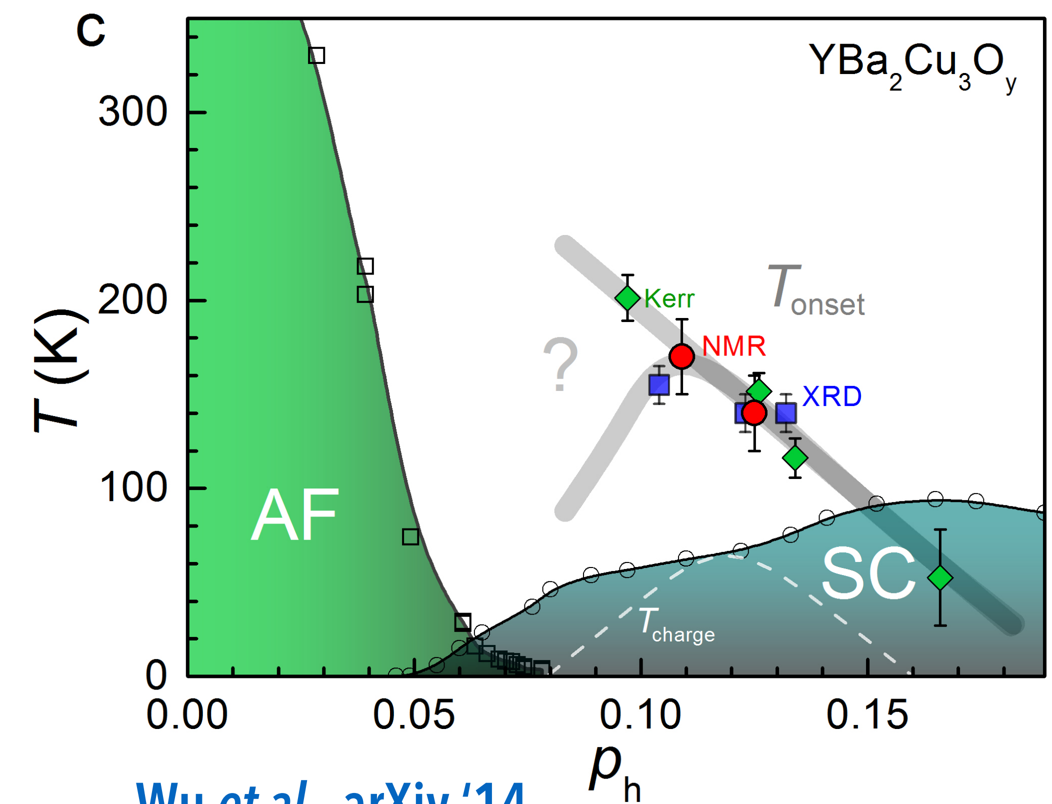
Maier & Scalapino, arXiv:1405.5238
see also: Lederer *et al.*, arXiv:1406.1193

Charge order and nematicity in the cuprates

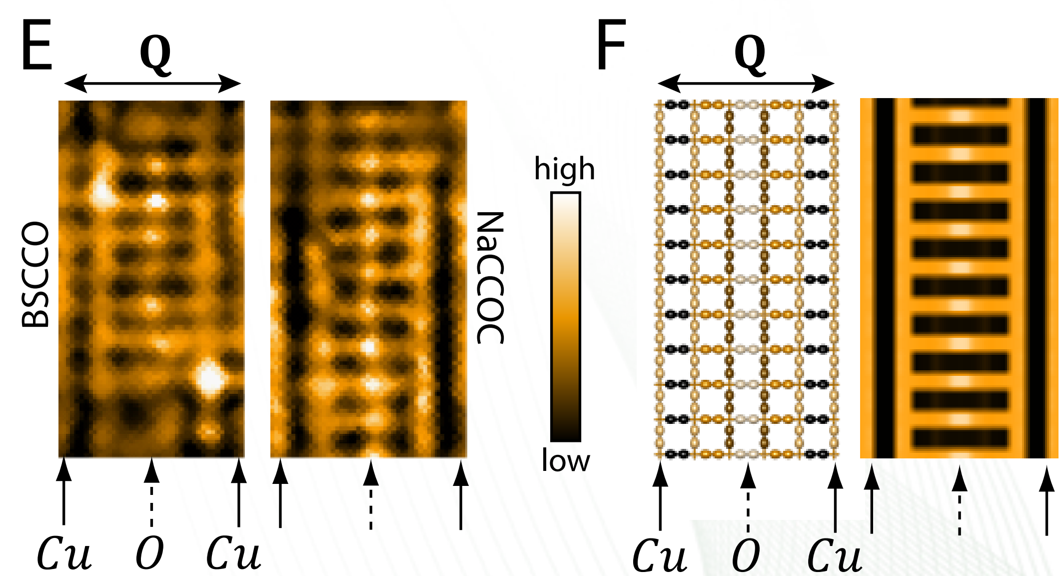
Broken symmetries in underdoped cuprates

- Evidence for static, but short-ranged charge order from NMR, XRD, STM, …
- Charge order accompanied by intra-unit-cell nematic order
- *d*-form factor density wave

Sachdev & La Placa, PRL '13



Wu *et al.*, arXiv '14



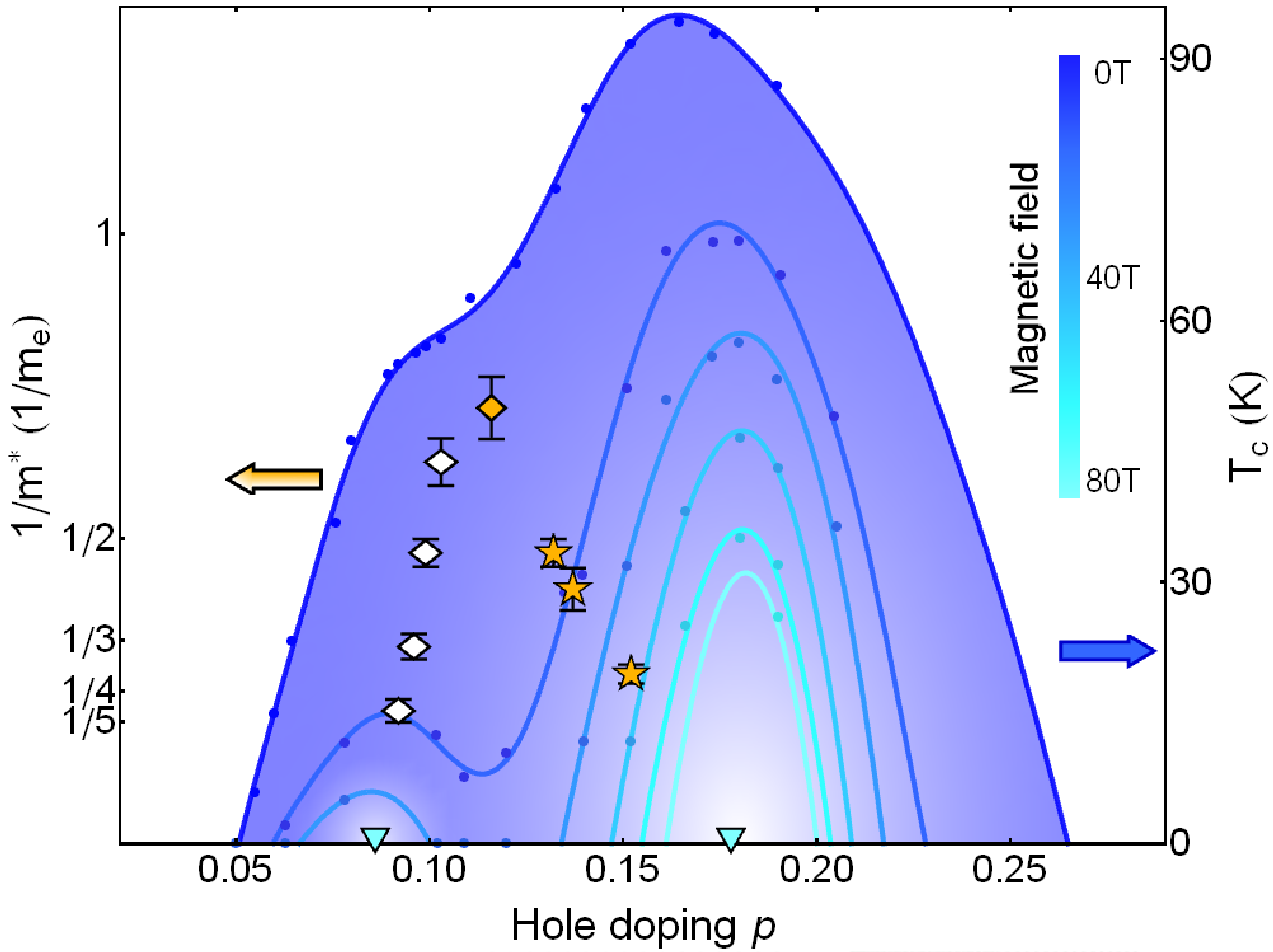
Fujita *et al.*, PNAS '14

Pseudogap quantum critical fluctuations and pairing

Quantum oscillations:

Ramshaw *et al.*, arXiv '14

- $m^* \rightarrow \infty$ identifies QCP at $p_c = 0.18$ where $T^*(p) \rightarrow 0$
- Magnetic field needed to suppress superconductivity peaked at p_c
- Pseudogap quantum critical fluctuations involved in pairing



Ramshaw *et al.*, arXiv '14

Pairing near a nematic QCP: Theory

Doped Mott insulator

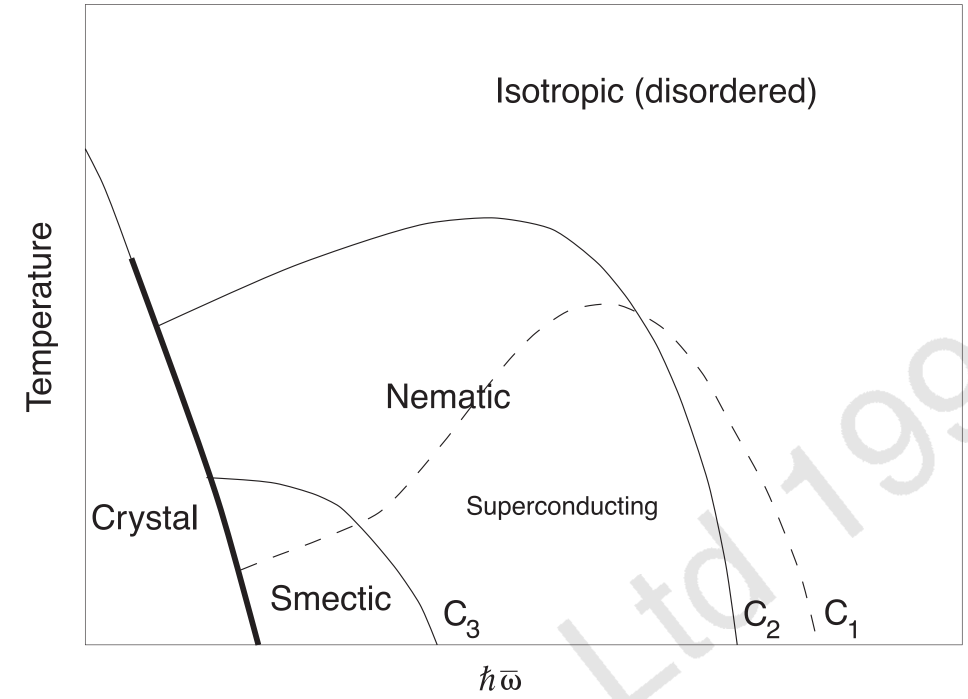
Kivelson, Fradkin, Emery, Nature '89

- Nematic QCP just beyond optimal doping

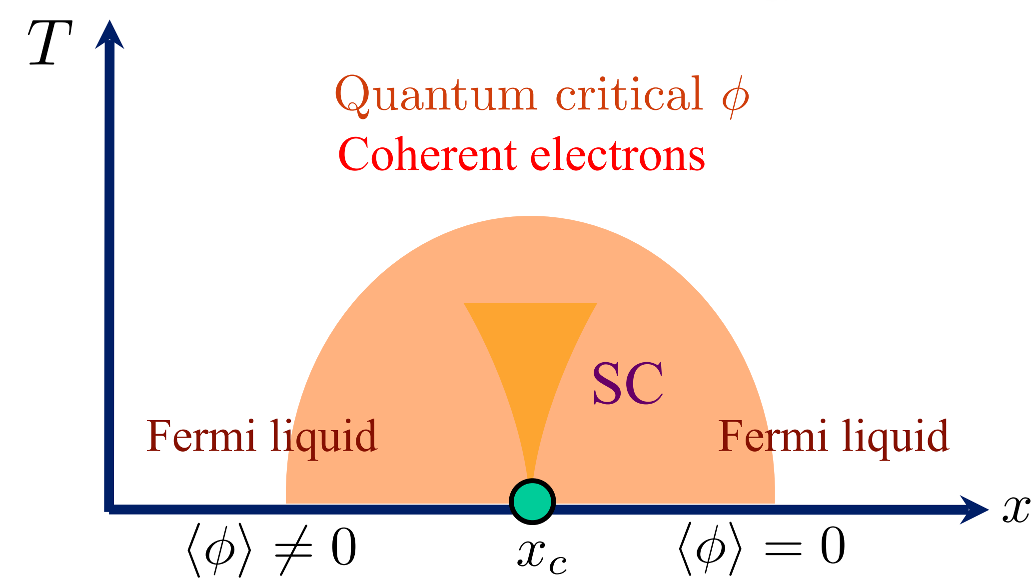
Pairing near nematic QCP

Metlitski *et al.*, NJP '10; arXiv '14

- Nematic charge (bond) ordered phase near SDW
- Nematic fluctuations mediate attractive interaction



Kivelson, Fradkin, Emery, Nature '89

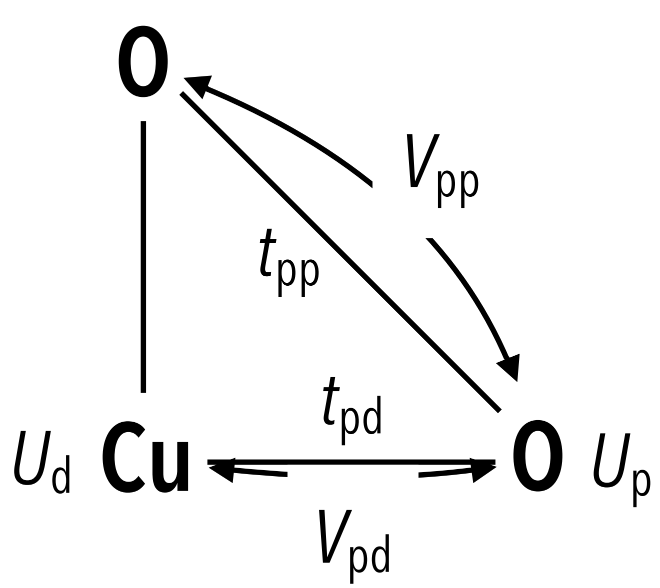


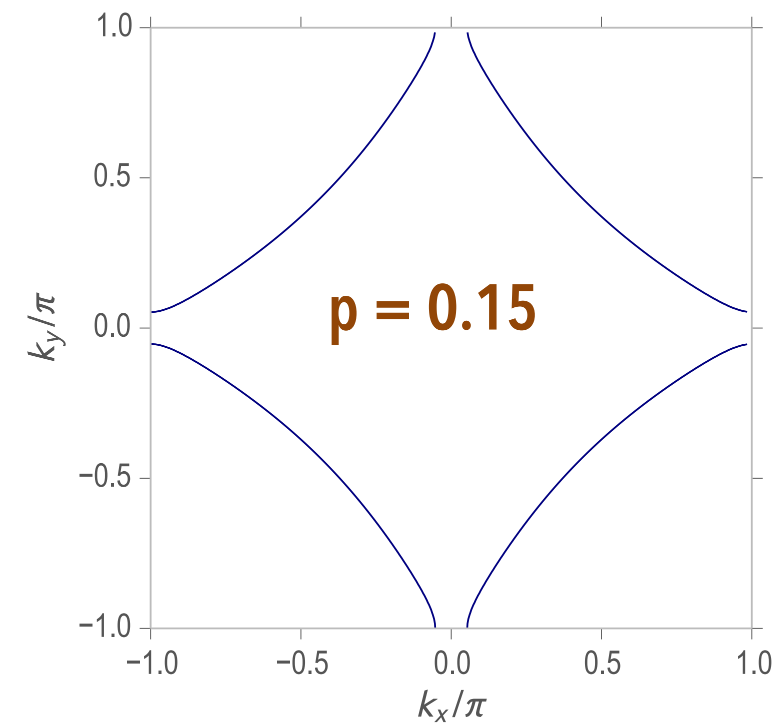
Metlitski *et al.*, arXiv '14

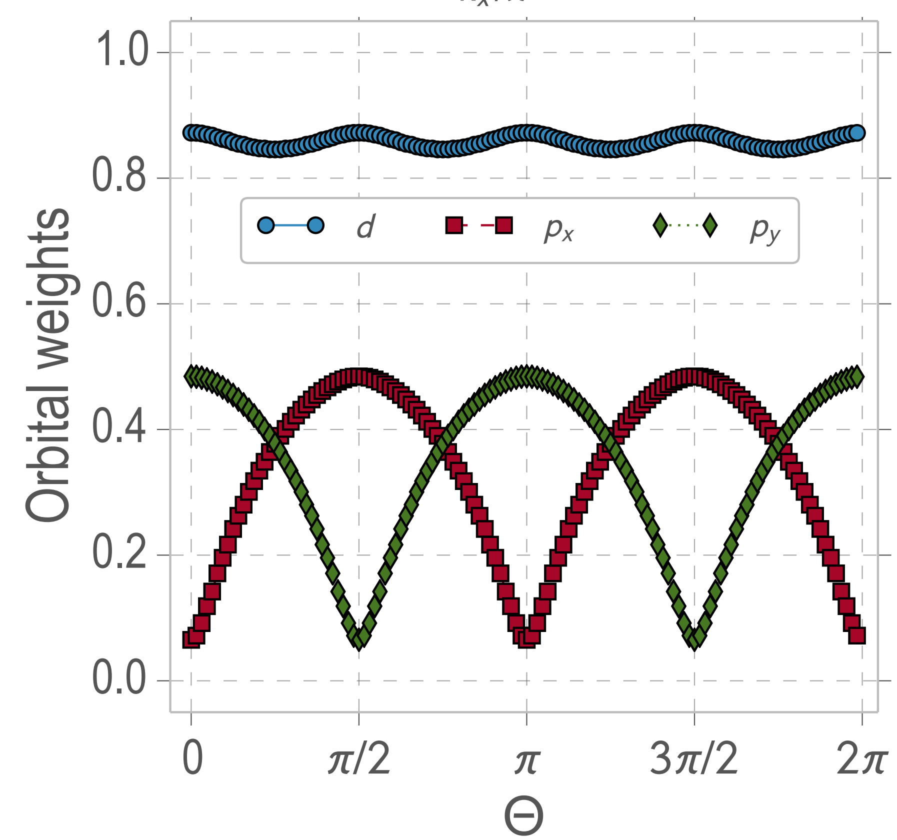
3-band Hubbard model for CuO_2

ε_d-ε_p=2.5, t_{pd} = 1, t_{pp} = 0.5

$$H = \sum_{i,\sigma} \varepsilon_d d^\dagger_{i\sigma} d_{i\sigma} + \sum_{j,\sigma} \varepsilon_p p^\dagger_{i\sigma} p_{i\sigma} + \sum_{\langle ij \rangle} t_{pd} \left(d^\dagger_{i\sigma} p_{j\sigma} + h.c. \right) + \sum_{\langle jj' \rangle} t_{pp} p^\dagger_{j\sigma} p_{j\sigma} + \sum_i U_d n^d_{i\uparrow} n^d_{i\downarrow} + \sum_j U_p n^p_{j\uparrow} n^p_{j\downarrow} + \sum_{\langle ij \rangle} V_{pd} n^d_i n^p_j + \sum_{\langle jj' \rangle} V_{pp} n^p_j n^p_{j'}$$







Nematicity in 3-band model: RPA

Bulut, Atkinson & Kampf, PRB '13
Mean-field: Fischer & Kim, PRB '11

PHYSICAL REVIEW B **88**, 155132 (2013)

Spatially modulated electronic nematicity in the three-band model of cuprate superconductors

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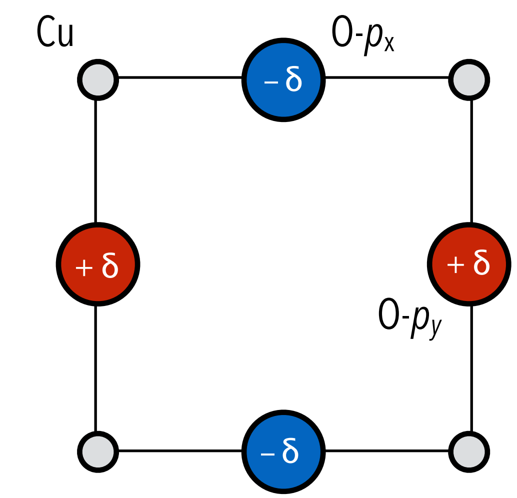
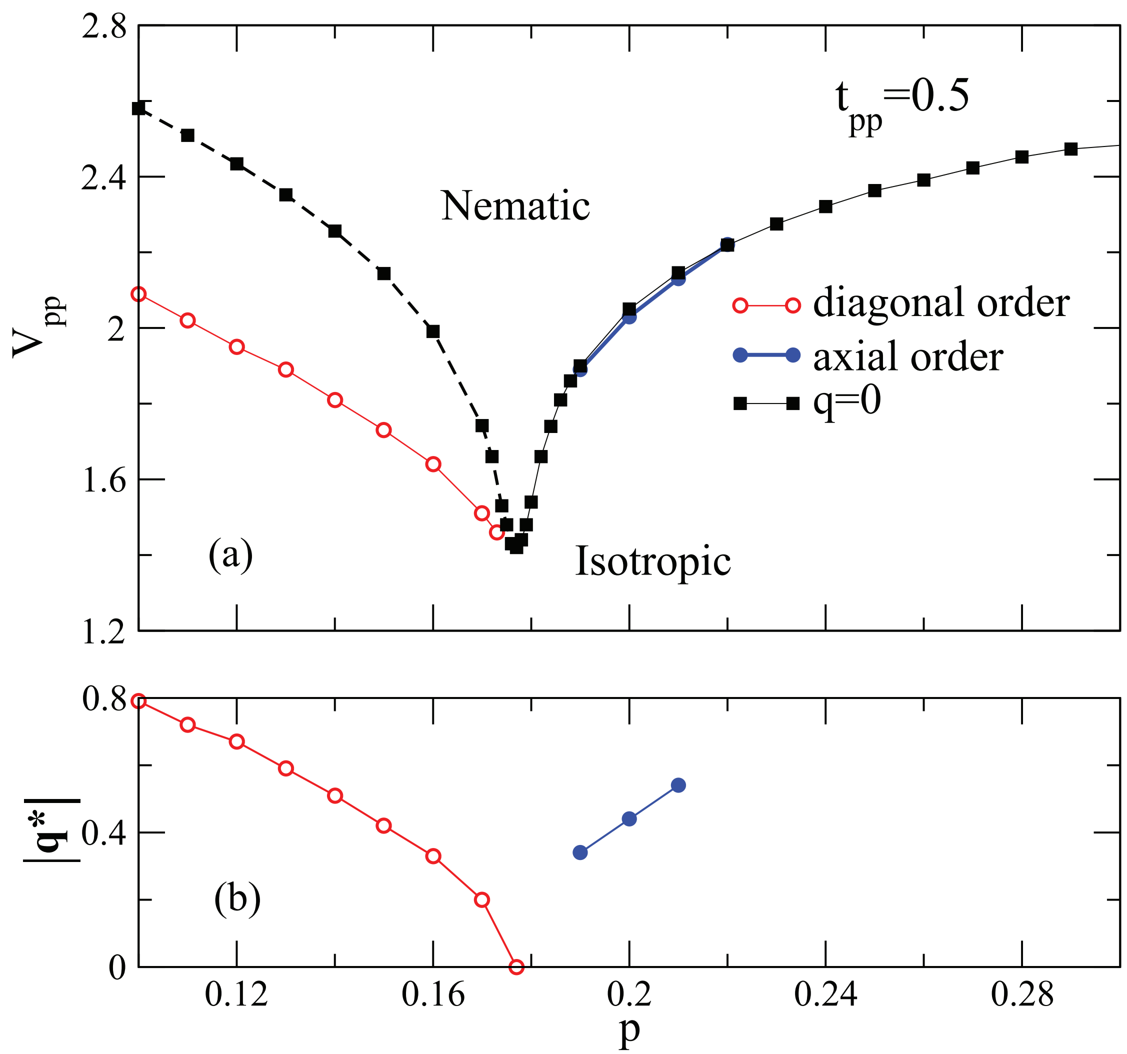
[2]*Department of Physics, Queen's University, Kingston Ontario, Canada, K7L 3N6*
[3]*Theoretical Physics III, Center for Electronic Correlations and Magnetism, Institute of Physics, University of Augsburg, 86135 Augsburg, Germany*



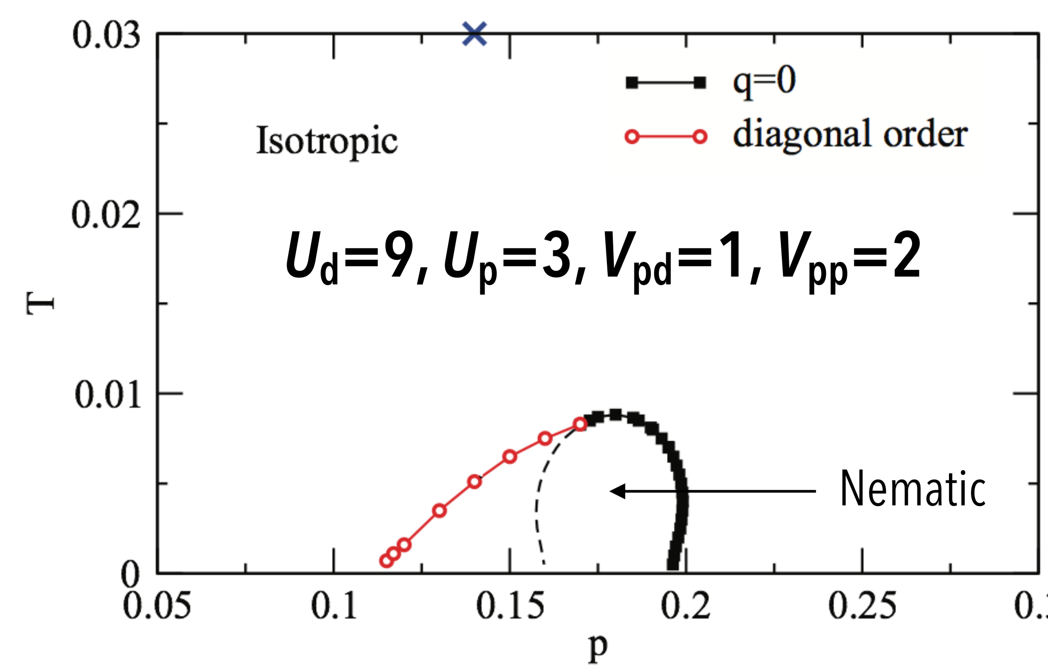


From Bulut, Atkinson & Kampf, PRB '13

Nematic charge susceptibility:

$$\chi_N(q) = \chi_{xx}(q) + \chi_{yy}(q) - \chi_{xy}(q) - \chi_{yx}(q)$$

$$\chi_{\ell_1\ell_2} = \int_0^\beta d\tau \langle \mathcal{T} n_{\ell_1}(q,\tau) n_{\ell_2}(q,0)\rangle$$

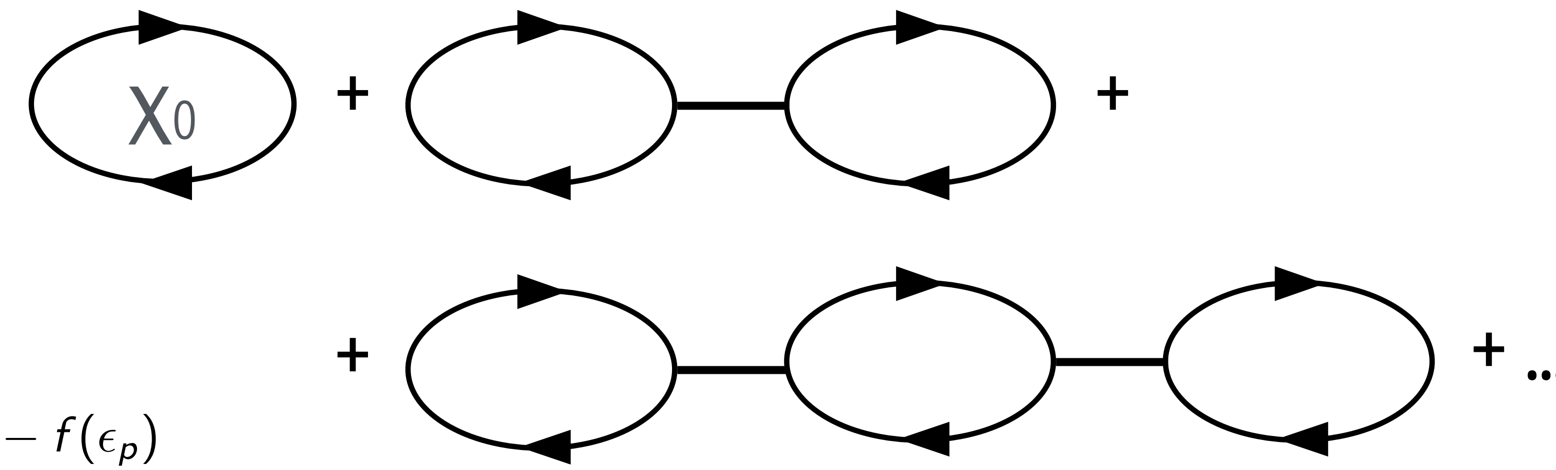


What is the nature of the pairing interaction associated with these nematic fluctuations?

Random phase approximation

For 3-band model see Littlewood, PRB '90;
Bulut, Atkinson & Kampf, PRB '13

Spin/Charge Susceptibility

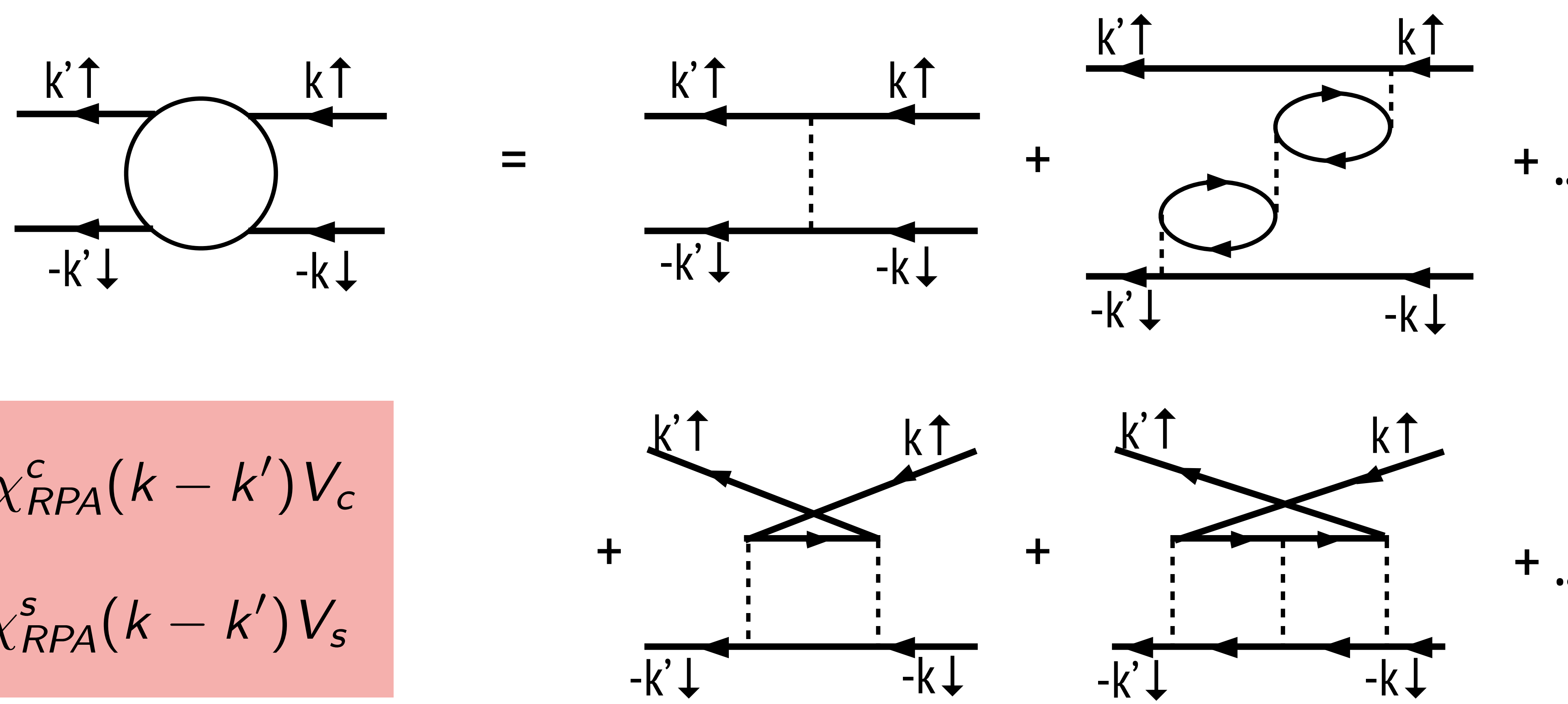


$$\chi_{RPA}(q,\omega) = \frac{\chi_0(q,\omega)}{1 \pm U\chi_0(q,\omega)}$$

$$\chi_0(q,\omega) = \int \frac{d^3p}{(2\pi)^3} \frac{f(\epsilon_{p+q}) - f(\epsilon_p)}{\omega - (\epsilon_{p+q} - \epsilon_p) + i\delta}$$

Pairing interaction

Berk, Schrieffer 1966



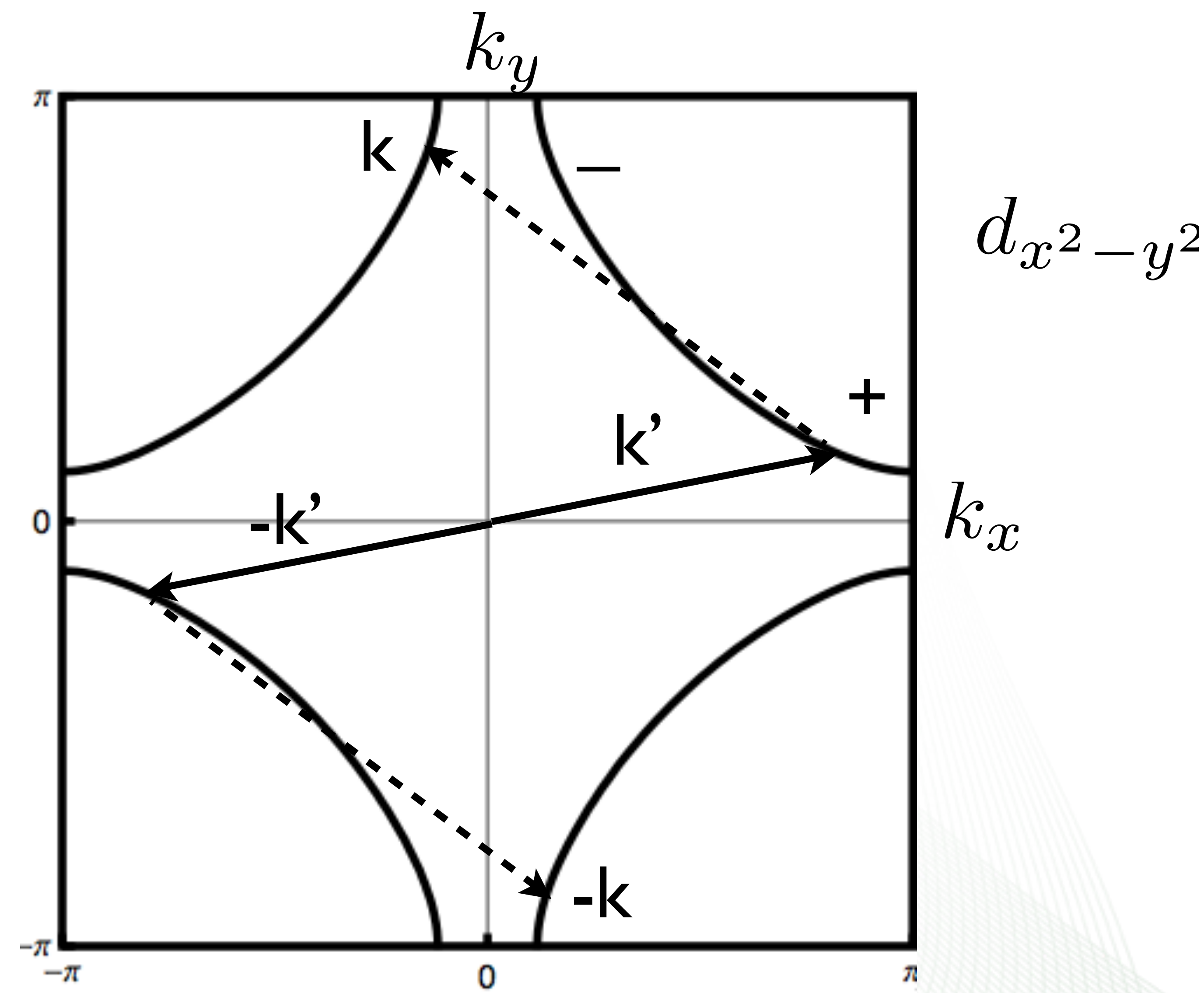
$$\Gamma(k,k') = \frac{V_c}{2} - \frac{1}{2} V_c \chi^c_{RPA}(k-k') V_c + \frac{V_s}{2} + \frac{3}{2} V_s \chi^s_{RPA}(k-k') V_s$$

d-wave pairing near Q=(π,π) SDW

Miyake, Schmitt-Rink, Varma, PRB '86
Scalapino, Loh, Hirsch, PRB '86
Monthoux, Balatsky, Pines, PRL '91

$$\Delta(k) = -\sum_{k'} \frac{\Gamma^{pp}(k-k')\Delta(k')}{E(k')}$$

$$\Gamma(k,k') = \frac{V_c}{2} - \frac{1}{2} V_c \chi^c_{RPA}(k-k') V_c + \frac{V_s}{2} + \frac{3}{2} V_s \chi^s_{RPA}(k-k') V_s$$



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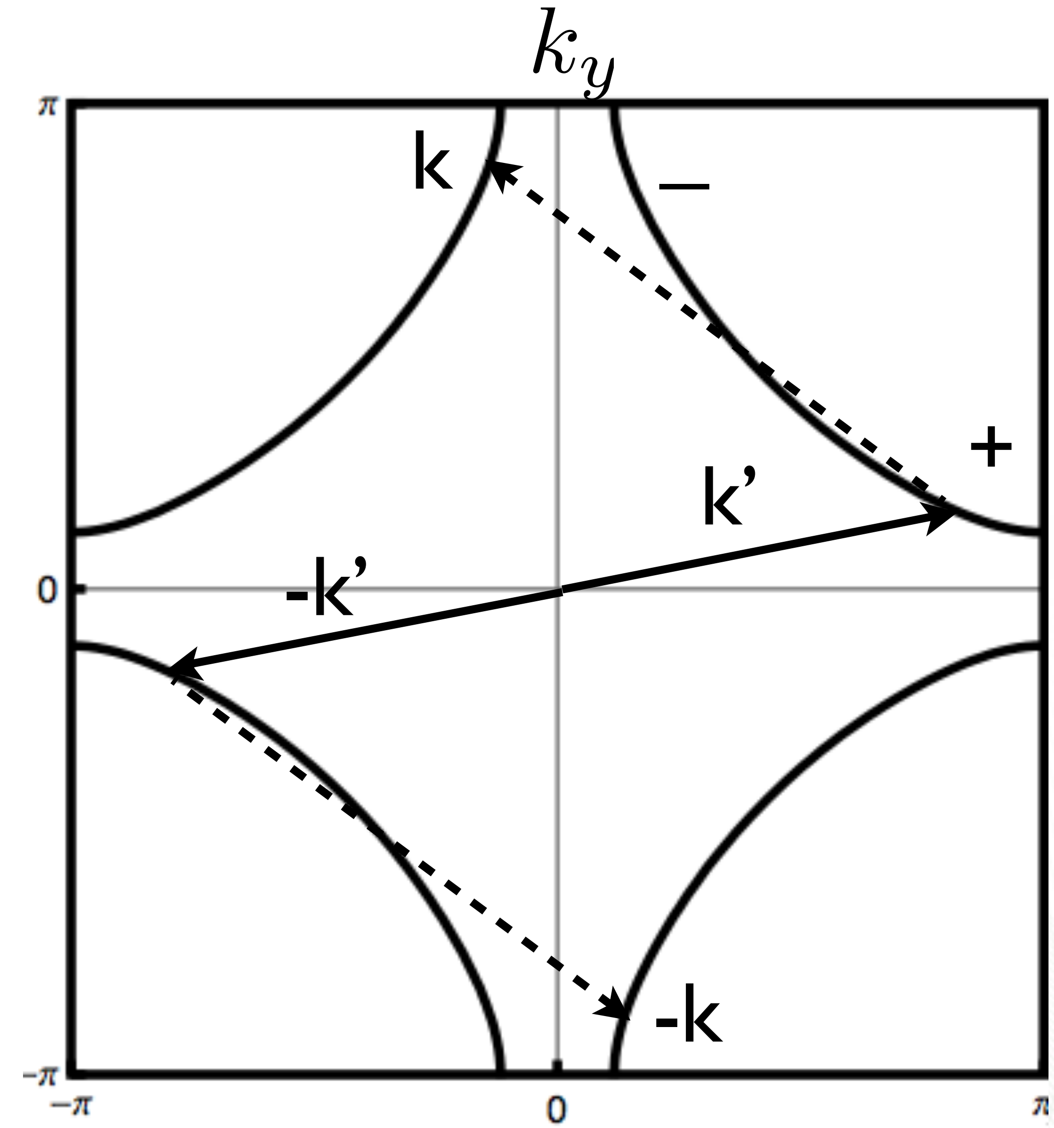
$$\Gamma(k,k') =$$

$$+\frac{V_s}{2} + \frac{3}{2} V_s \chi^s_{RPA}(k-k') V_s$$



$d_{x^2-y^2}$

d-wave pairing near Q=(π,π) SDW

Miyake, Schmitt-Rink, Varma, PRB '86
Scalapino, Loh, Hirsch, PRB '86
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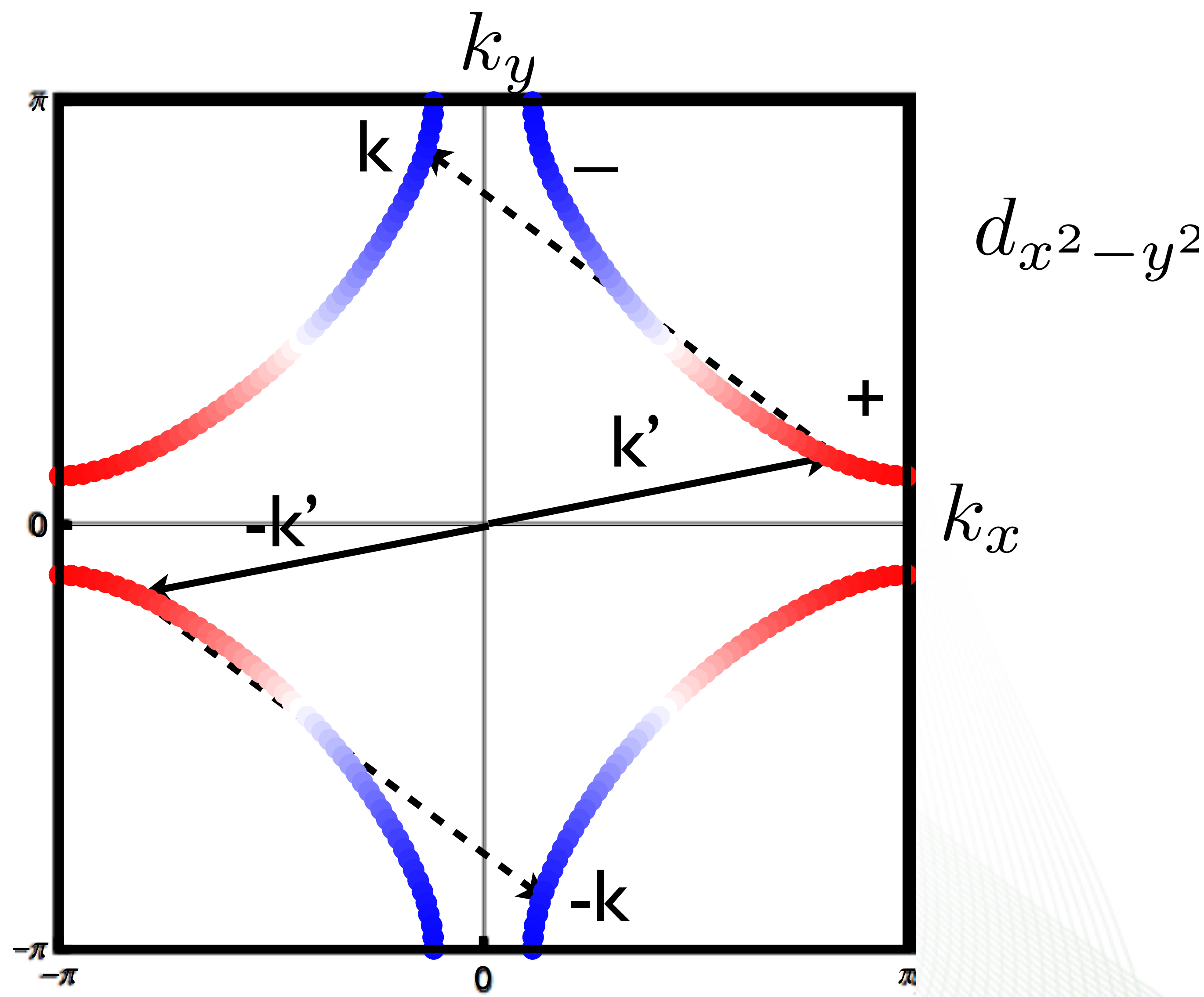


Charge fluctuations and pairing

$$\Delta(k) = -\sum_{k'} \frac{\Gamma^{pp}(k-k')\Delta(k')}{E(k')}$$

$$\begin{aligned}\Gamma(k,k') = & \frac{V_c}{2} - \frac{1}{2} V_c \chi^c_{RPA}(k-k') V_c \\ & + \frac{V_s}{2} + \frac{3}{2} V_s \chi^s_{RPA}(k-k') V_s\end{aligned}$$

Charge fluctuations and pairing

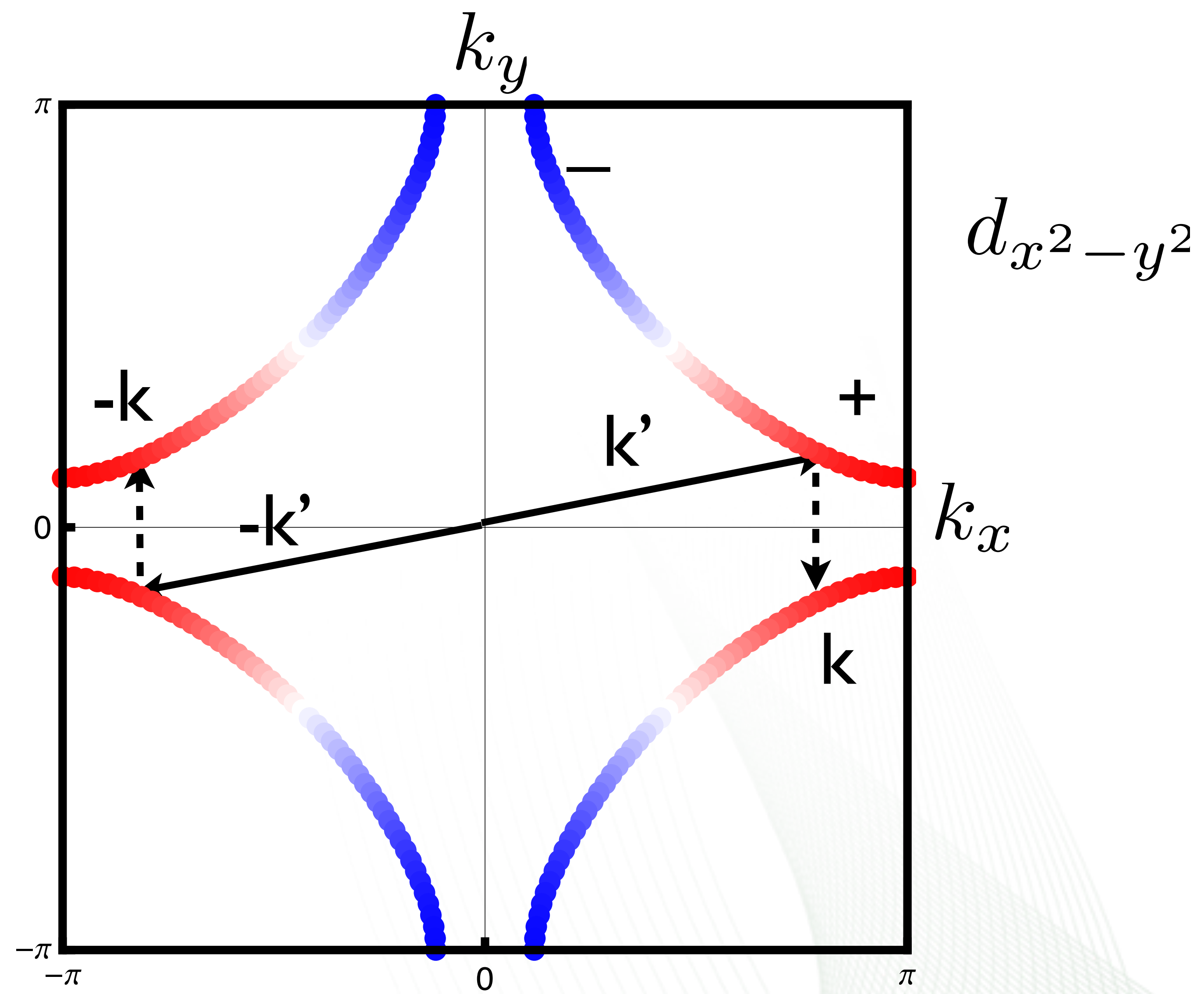
$$\Delta(k) = -\sum_{k'} \frac{\Gamma^{pp}(k-k')\Delta(k')}{E(k')}$$

$$\Gamma(k,k') = \frac{V_c}{2} - \frac{1}{2} V_c \chi^c_{RPA}(k-k') V_c$$

Charge fluctuations and pairing

$$\Delta(k) = -\sum_{k'} \frac{\Gamma^{pp}(k-k')\Delta(k')}{E(k')}$$

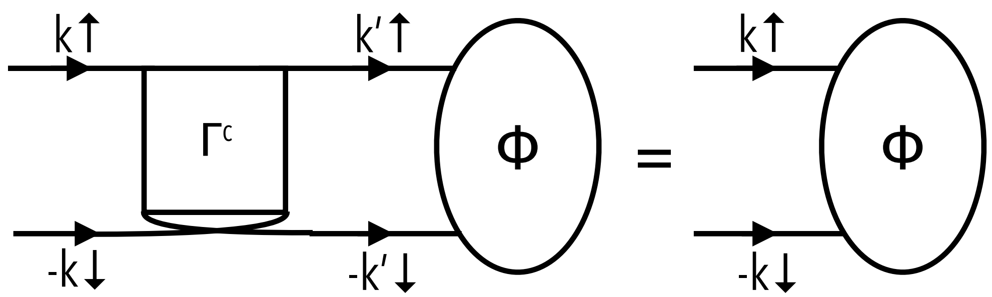
$$\Gamma(k,k') = \frac{V_c}{2} - \frac{1}{2} V_c \chi^c_{RPA}(k-k') V_c$$



Pairing from charge fluctuations in 3-band model

— Consider only charge part of the interaction and neglect spin interaction: $\Gamma(k,k') = \frac{V_c}{2} - \frac{1}{2} V_c \chi^c_{RPA}(k-k') V_c$

— Solve linearized gap equation:



$$\oint \frac{dk'_{\parallel}}{2\pi v_F(k'_{\parallel})} \Gamma_c(k,k')\Phi_\alpha(k') = \lambda_\alpha \Phi_\alpha(k)$$

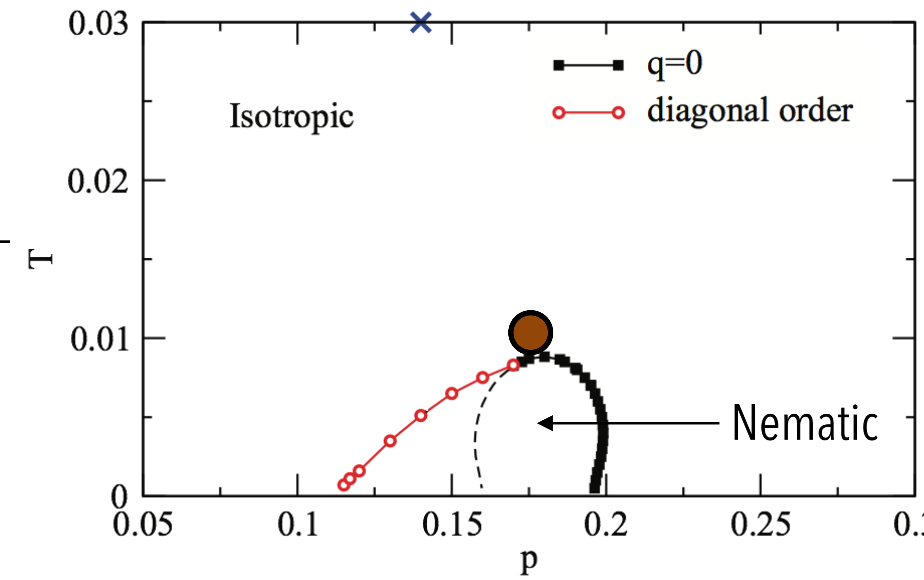
with

$$\Gamma_c(k,k') = \sum_{\ell_1,\ell_2,\ell_3,\ell_4} a_\nu^{\ell_1^*}(k) a_\nu^{\ell_4^*}(-k) \Gamma_{\ell_1\ell_2\ell_3\ell_4}(k,k') a_\mu^{\ell_2}(k') a_\mu^{\ell_3}(-k')$$

U_d=9, U_p=3, V_{pd}=1, V_{pp}=2

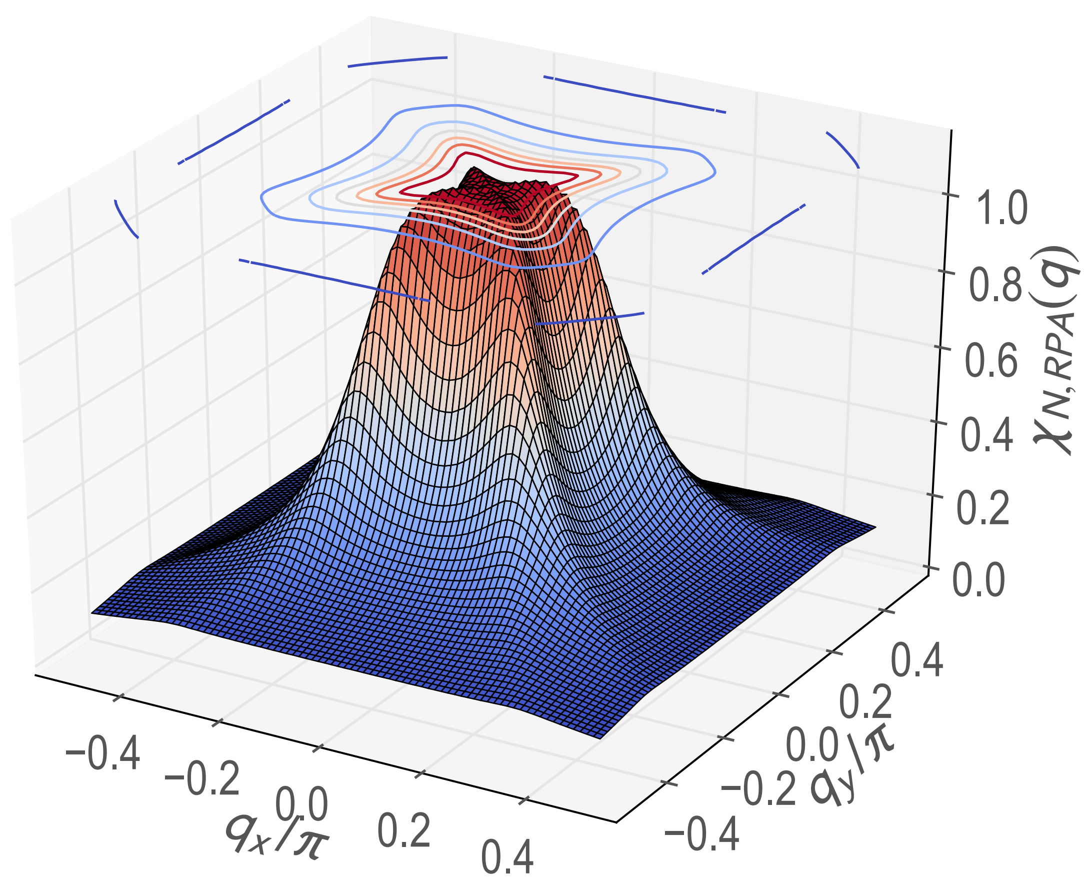
Maier & Scalapino, arXiv (2014)

RPA pairing interaction from nematic q=0 charge fluctuations

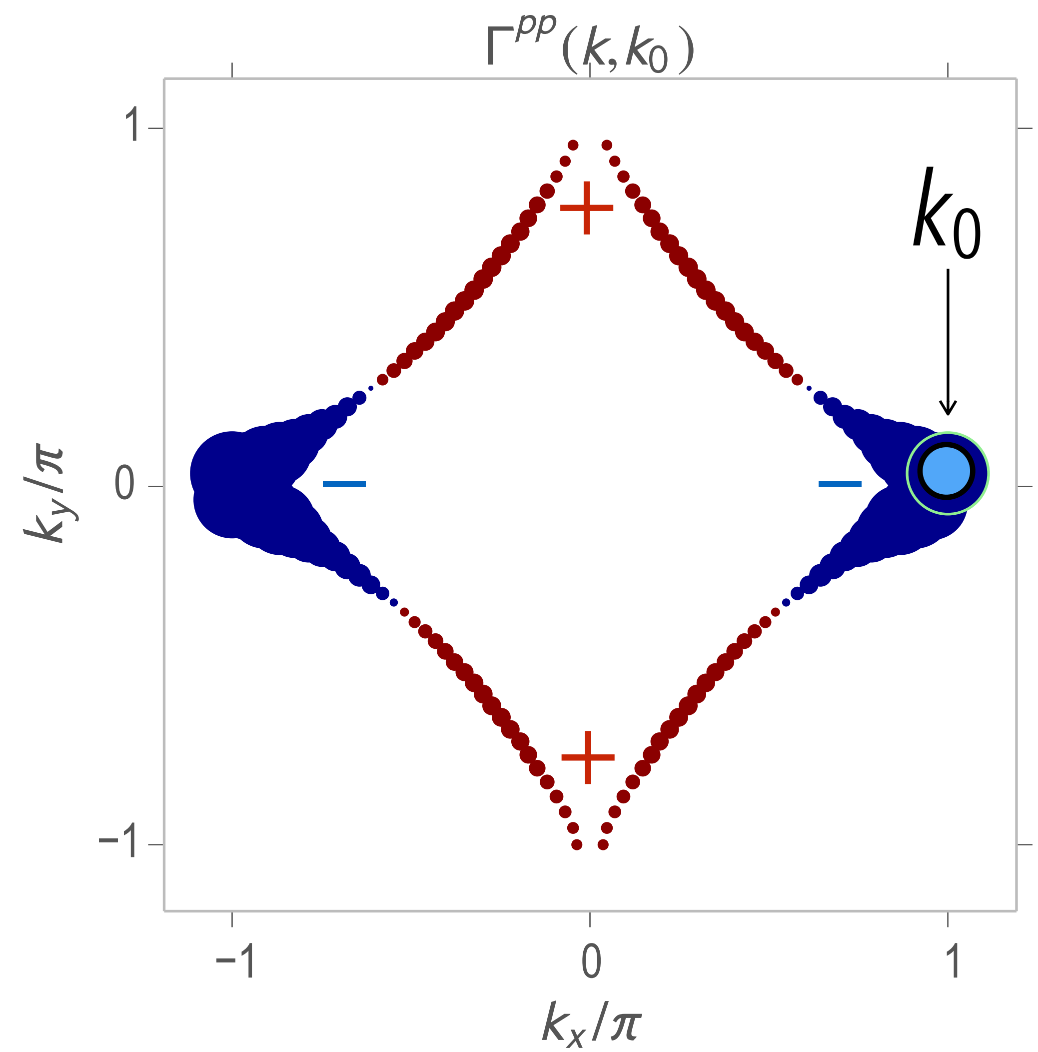


$$\Gamma(k,k') = \frac{V_c}{2} - \frac{1}{2} V_c \chi^c_{RPA}(k-k') V_c$$

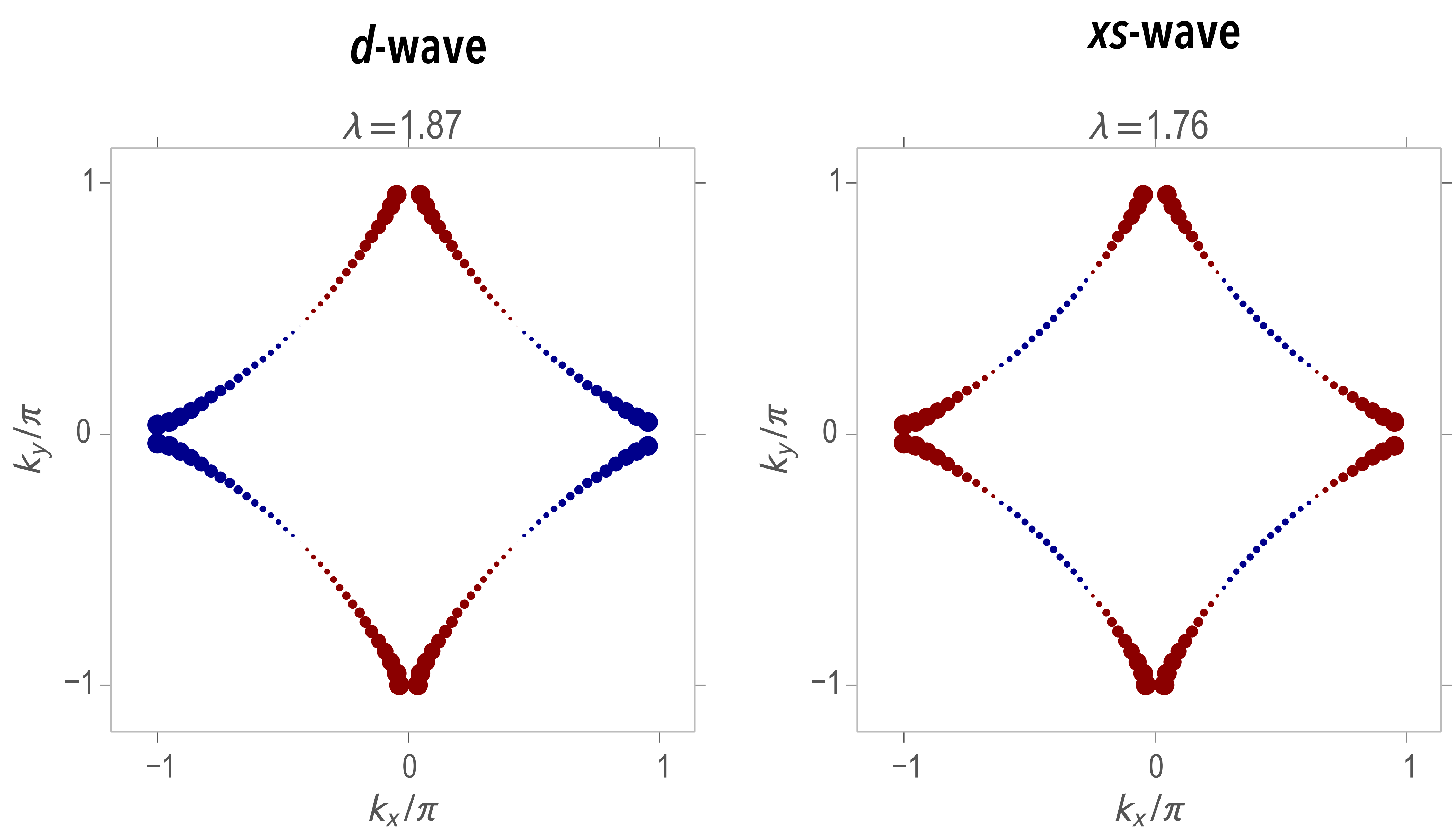
Nematic charge susceptibility



Pairing interaction

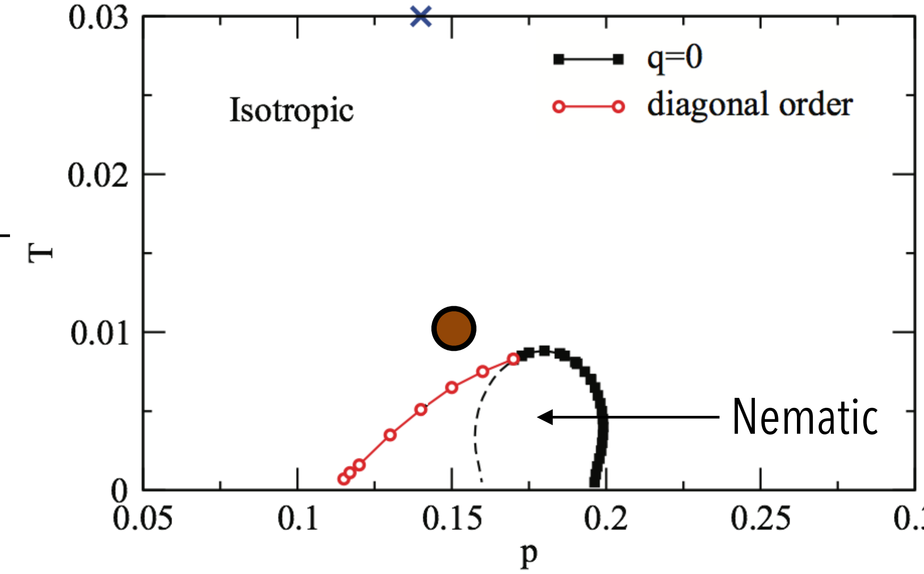


Leading gap structures



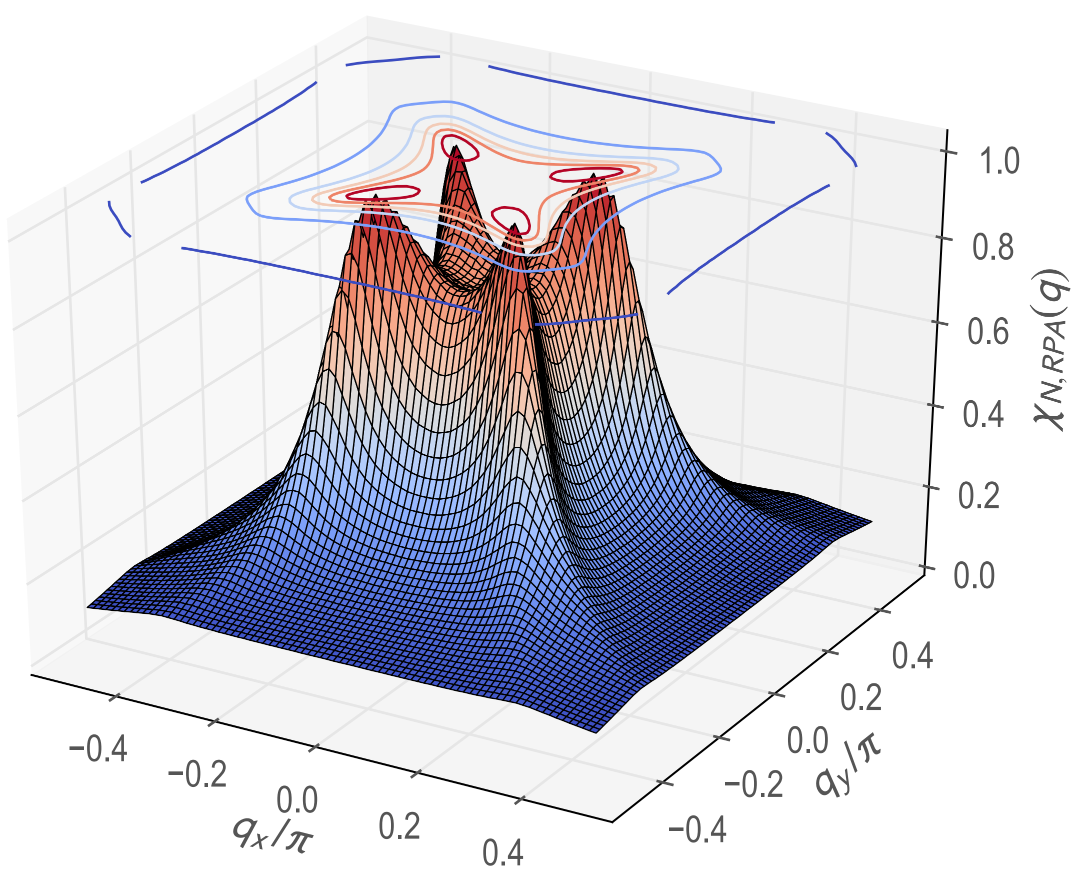
Nematic pairing interaction attractive in *d*-wave and *xs*-wave channels

RPA pairing interaction from nematic $q^*=(q_0,q_0)$ fluctuations

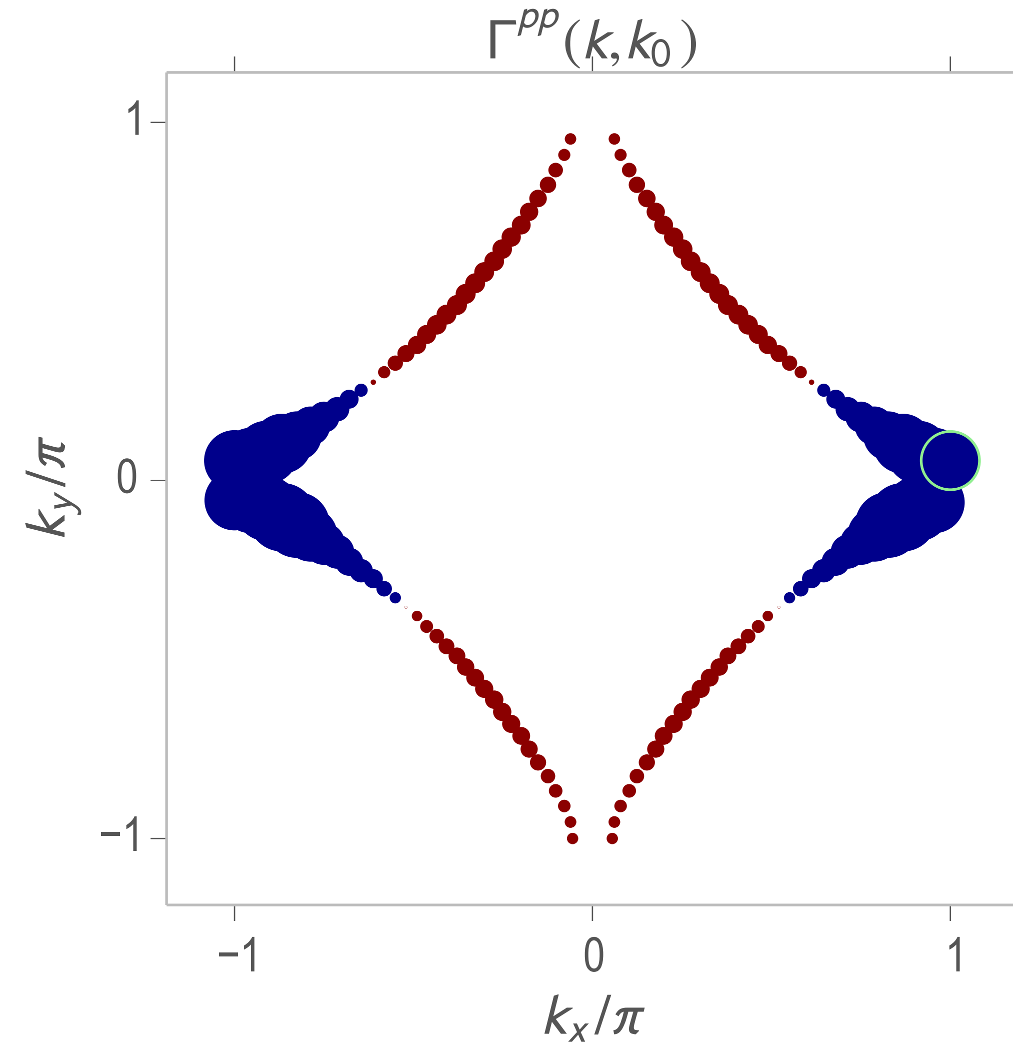


$$\Gamma(k,k') = \frac{V_c}{2} - \frac{1}{2} V_c \chi^c_{RPA}(k-k') V_c$$

nematic charge susceptibility



pairing interaction



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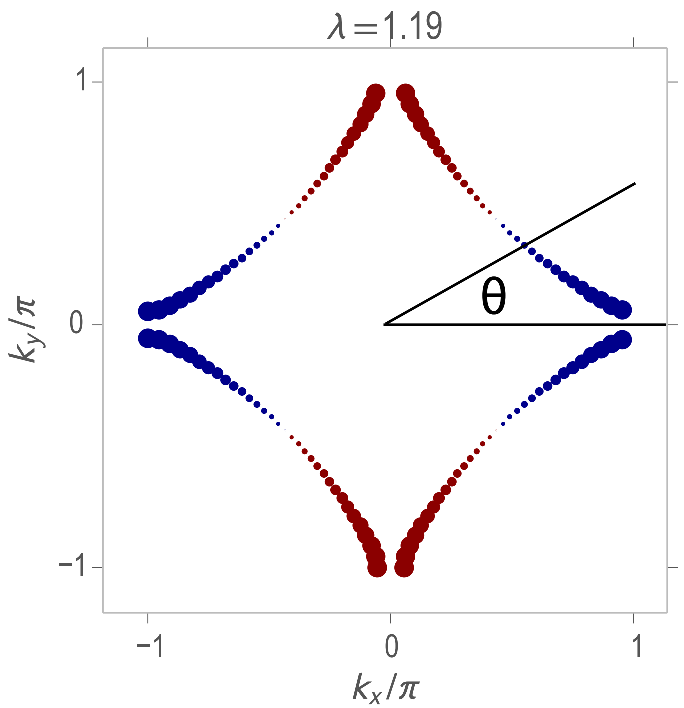
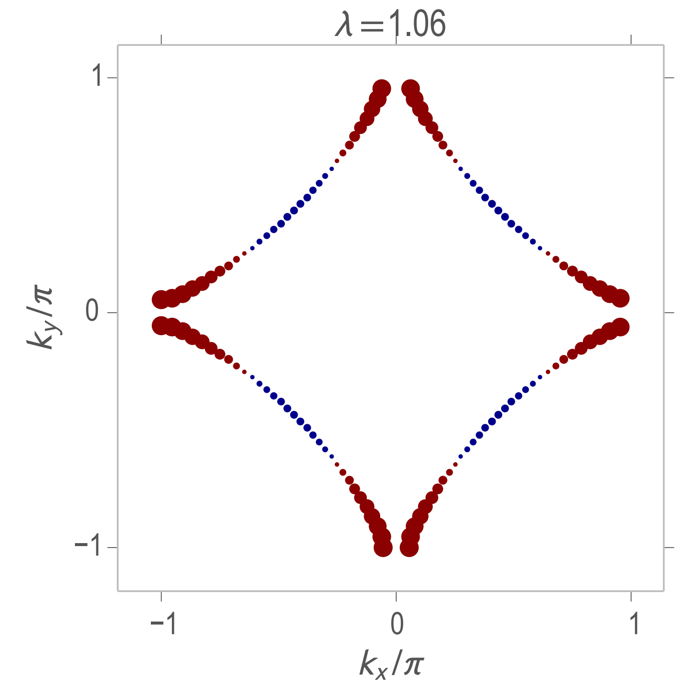
Leading gap structures



***d*-wave**

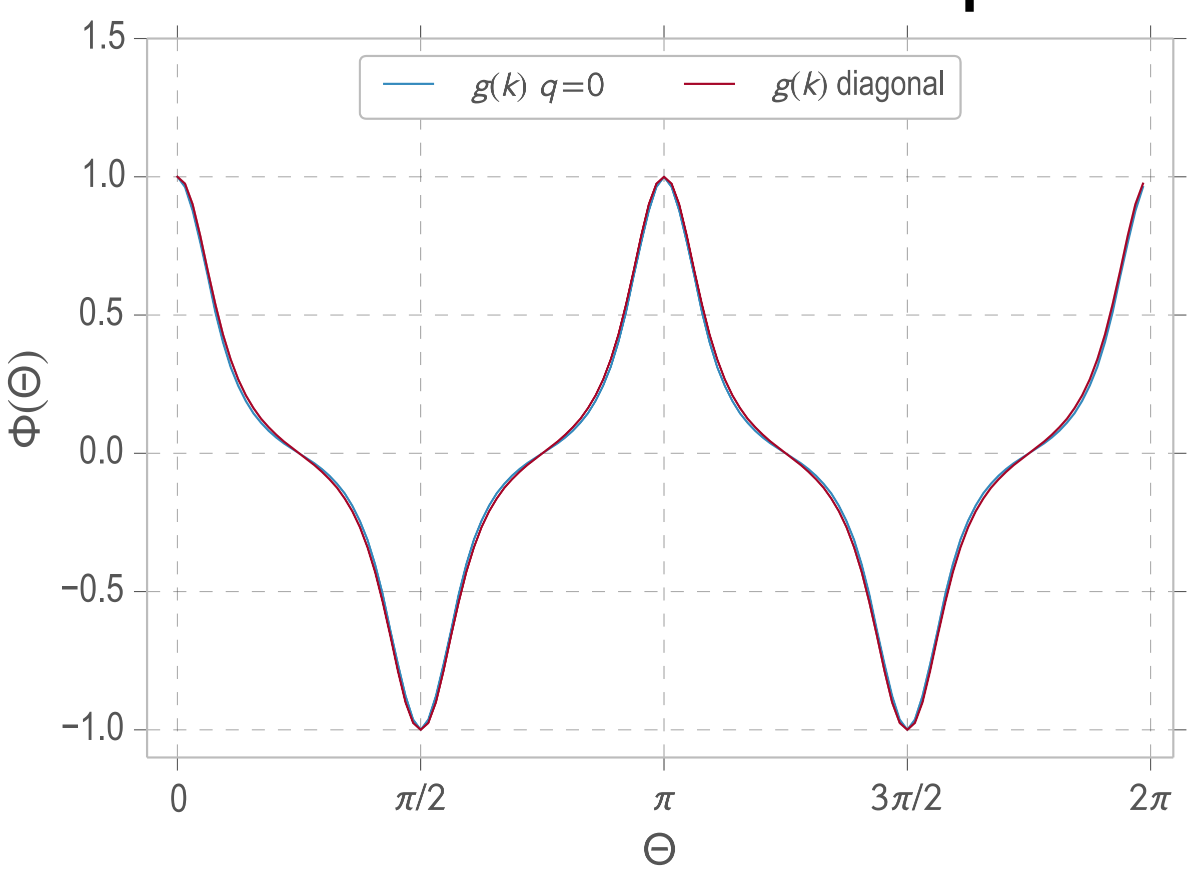
$\lambda_d = 1.2$

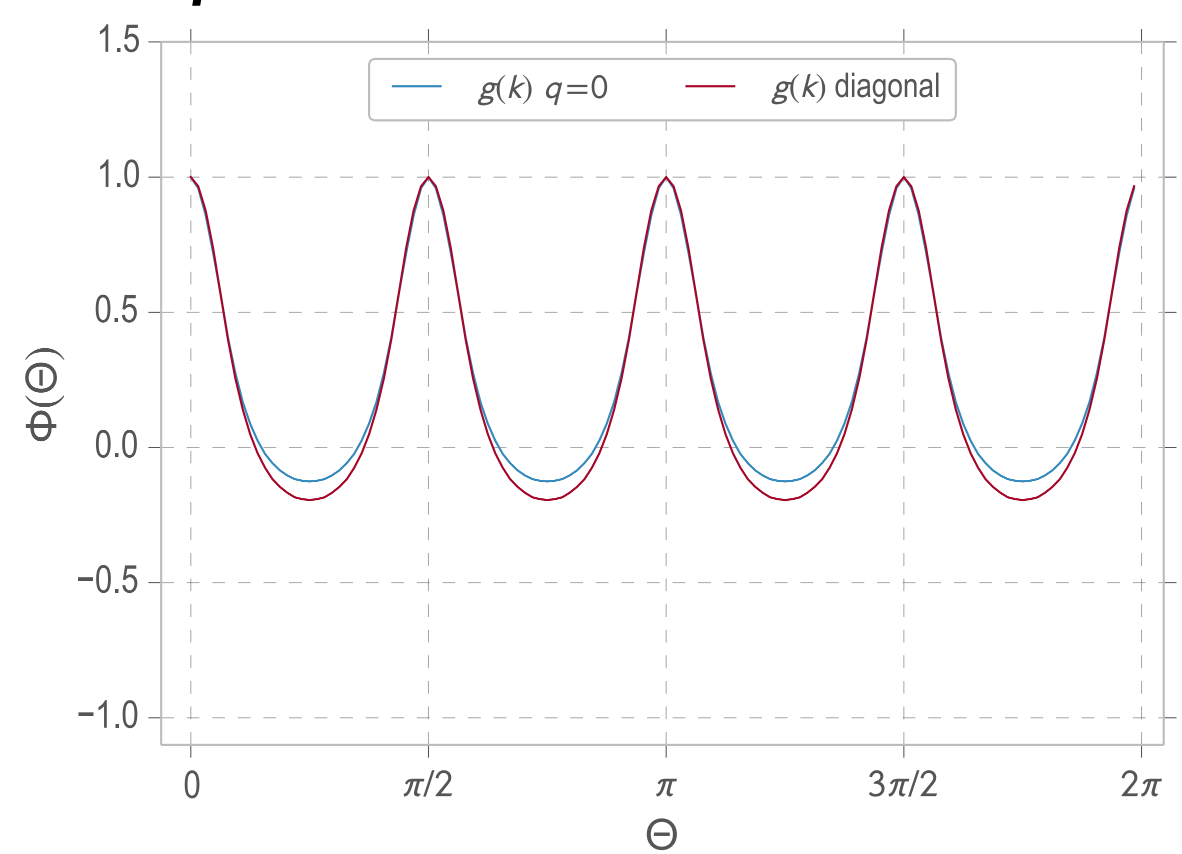


***xs*-wave**

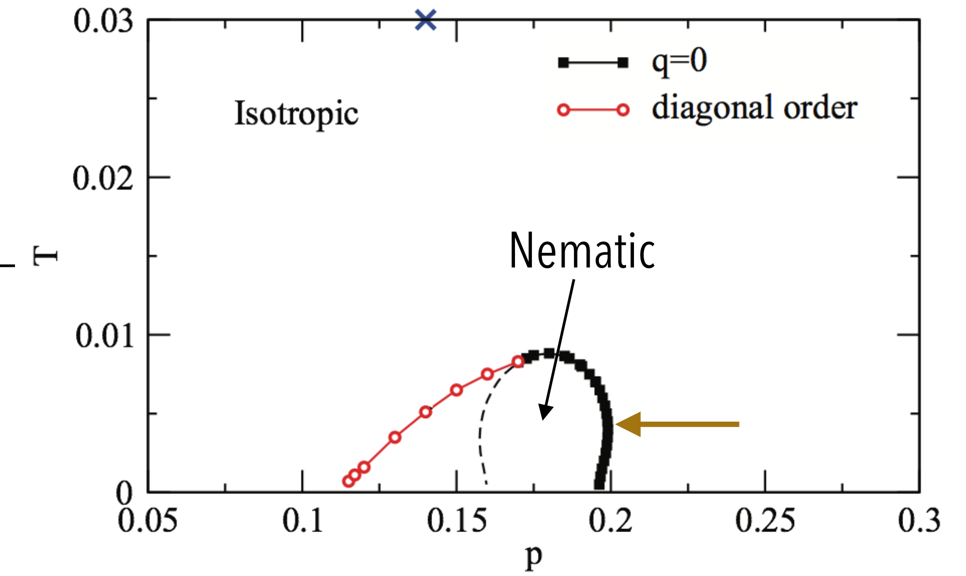
$\lambda_s = 1.1$

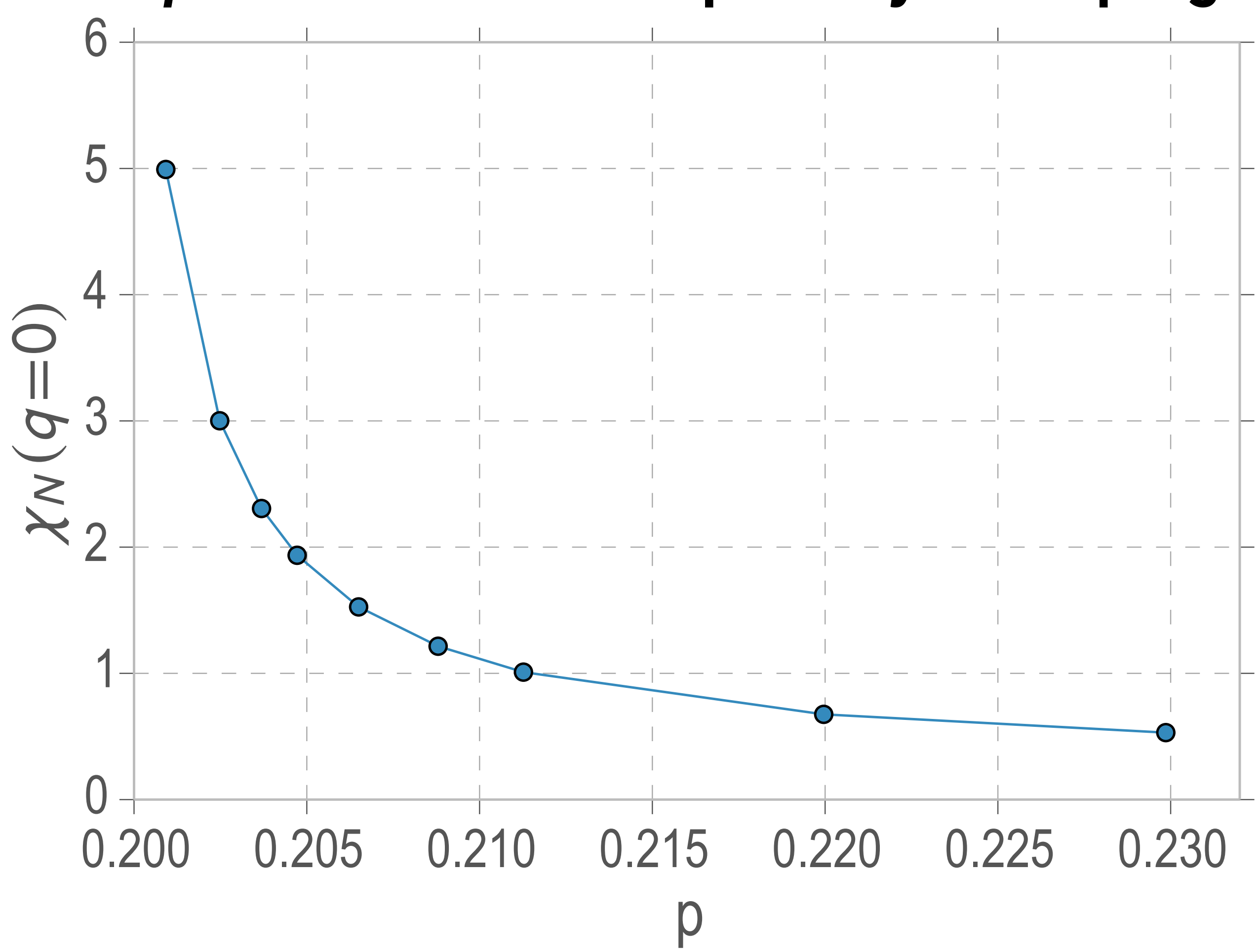
Compared to case with *q=0**

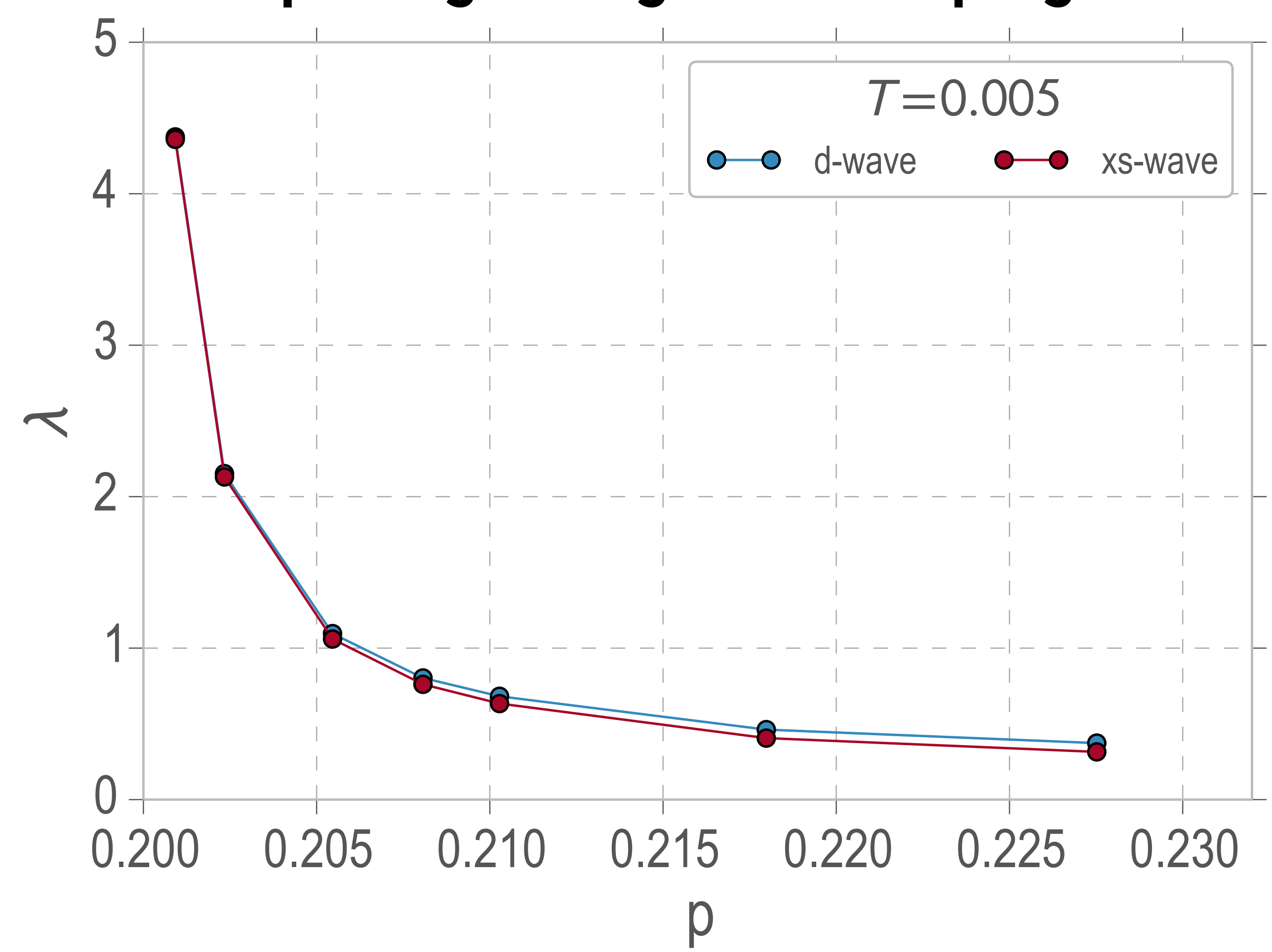




Approaching the QCP



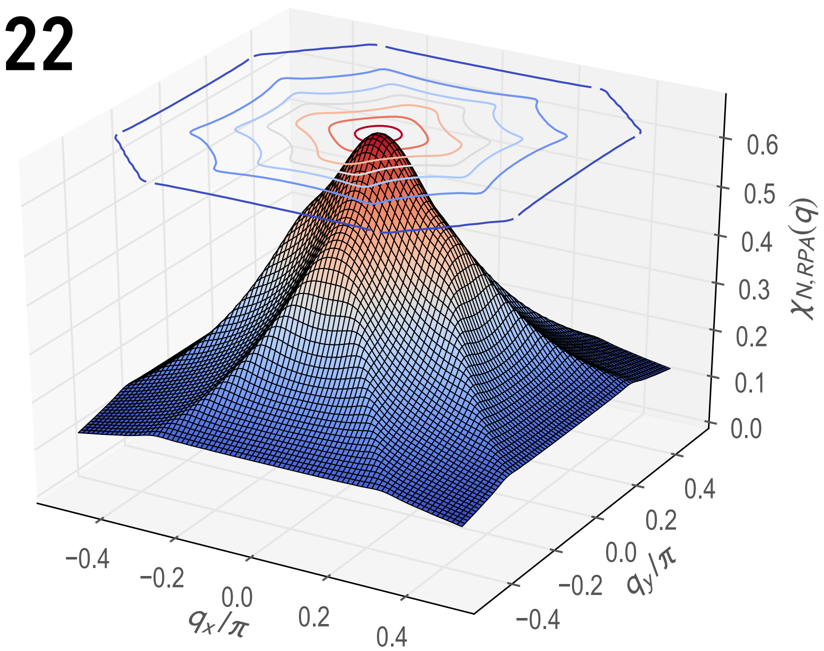




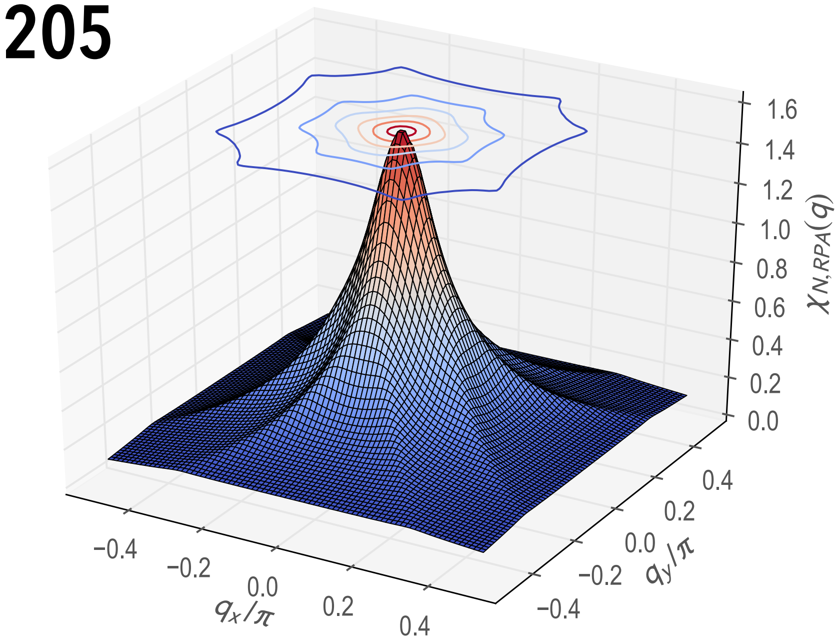
Pairing strength increases as nematic QCP is approached

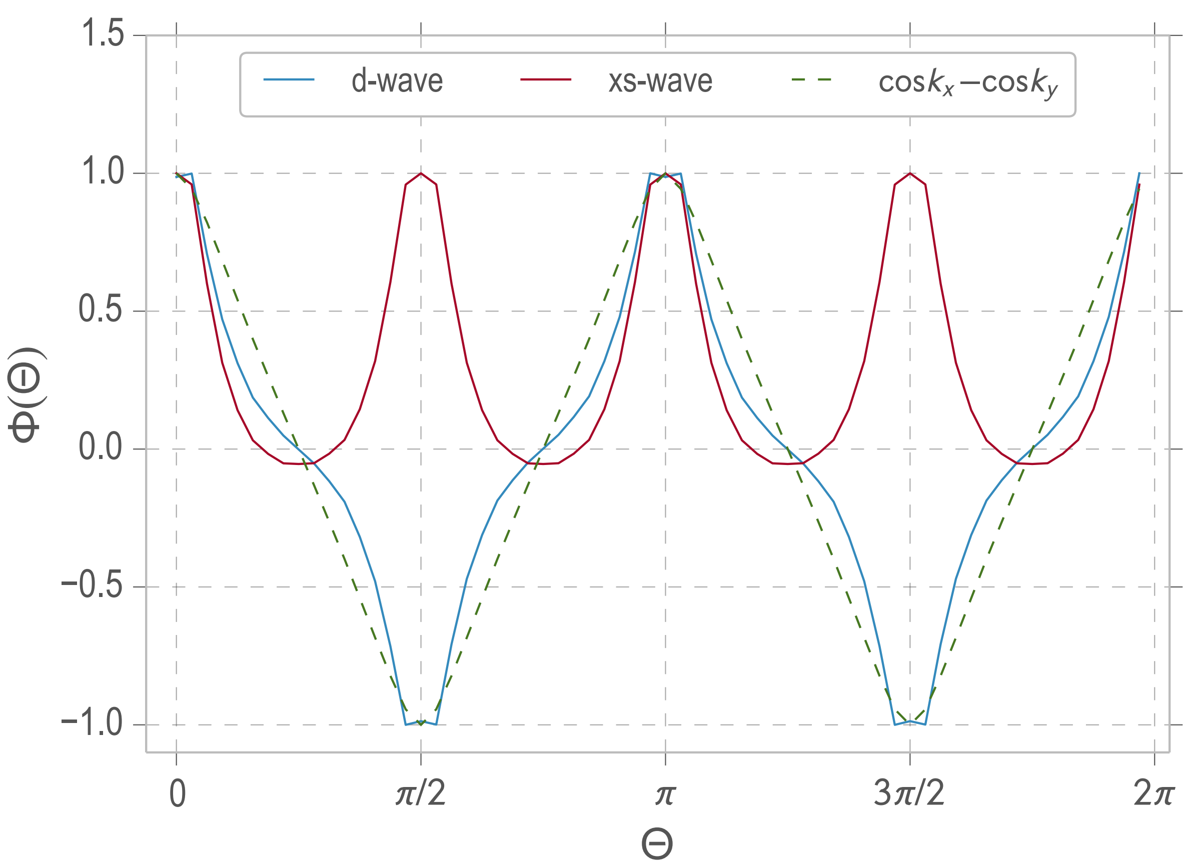
Gap momentum structure on approaching the QCP

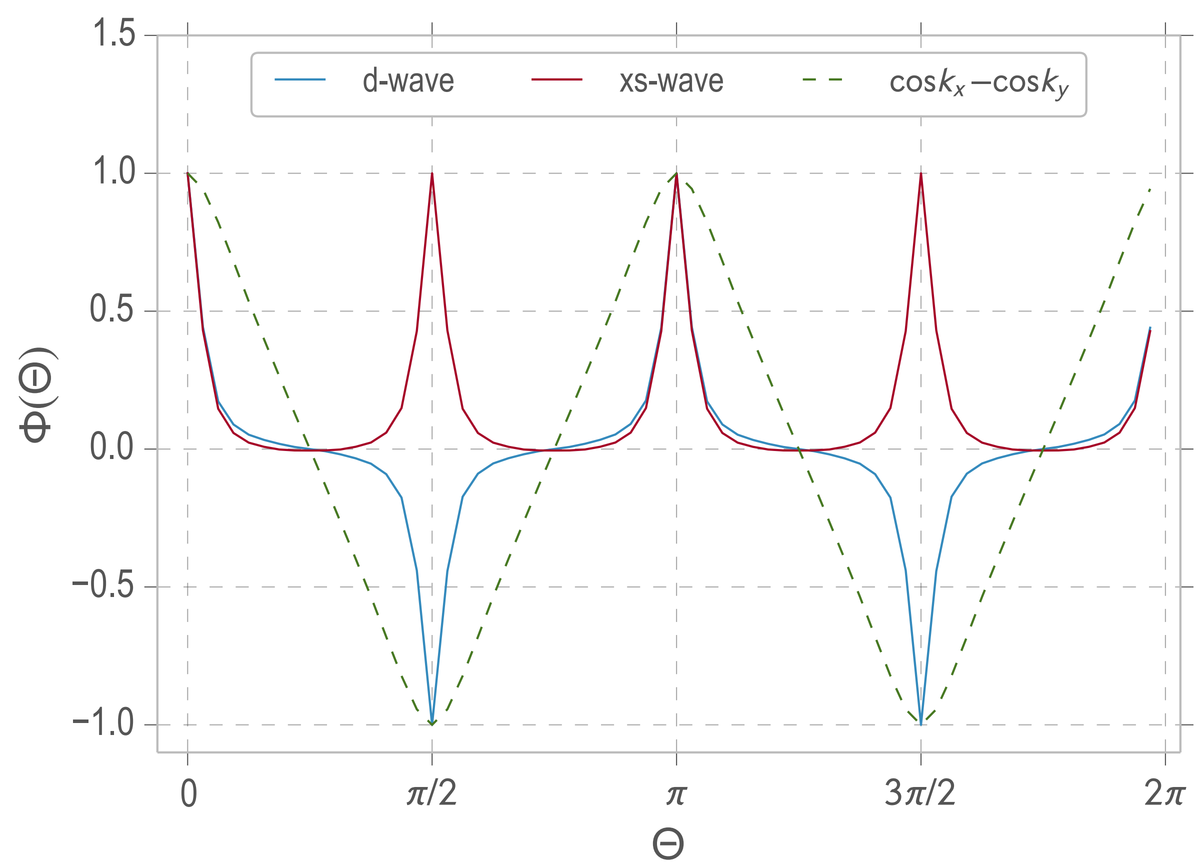
***p* = 0.22**



***p* = 0.205**





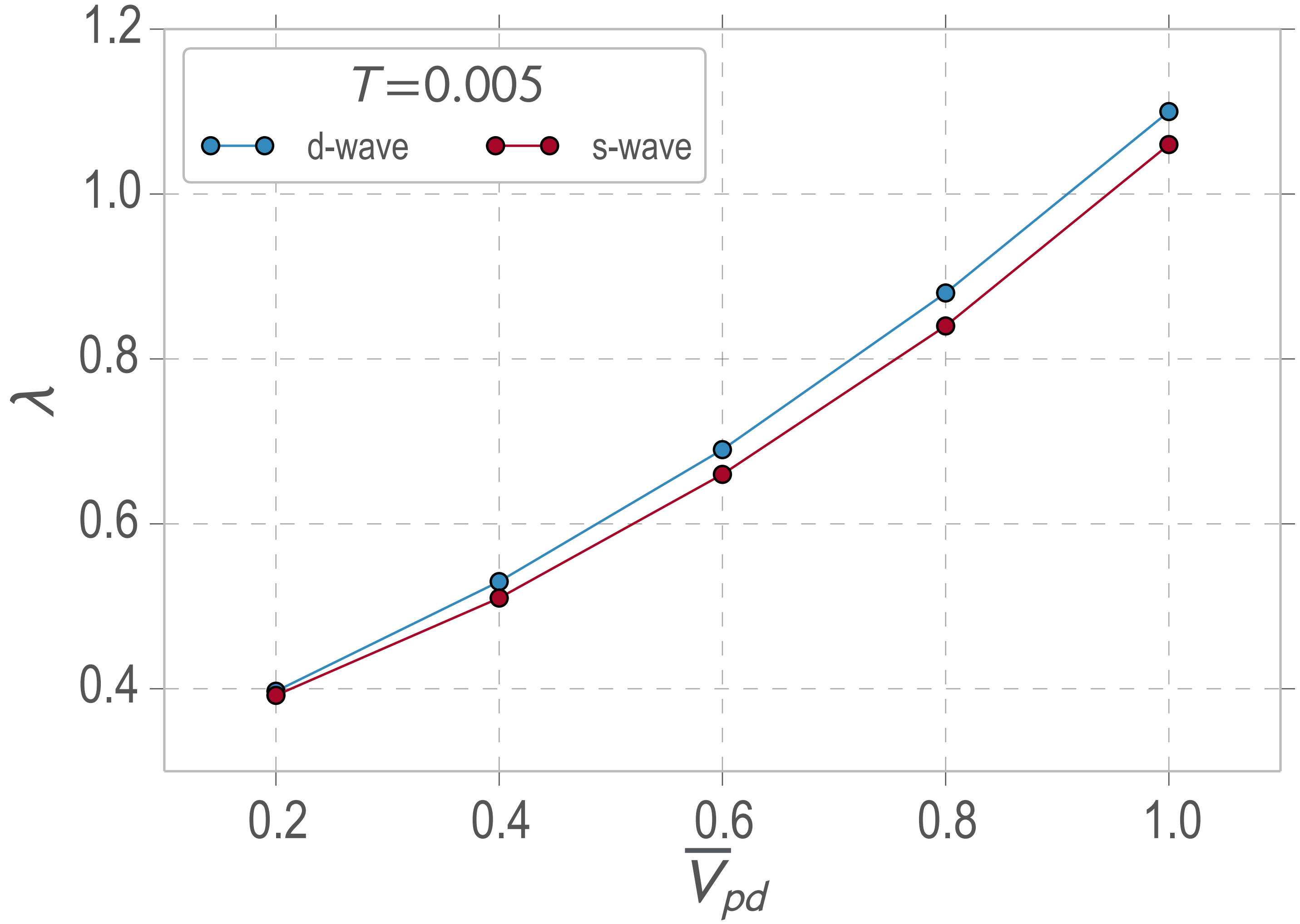


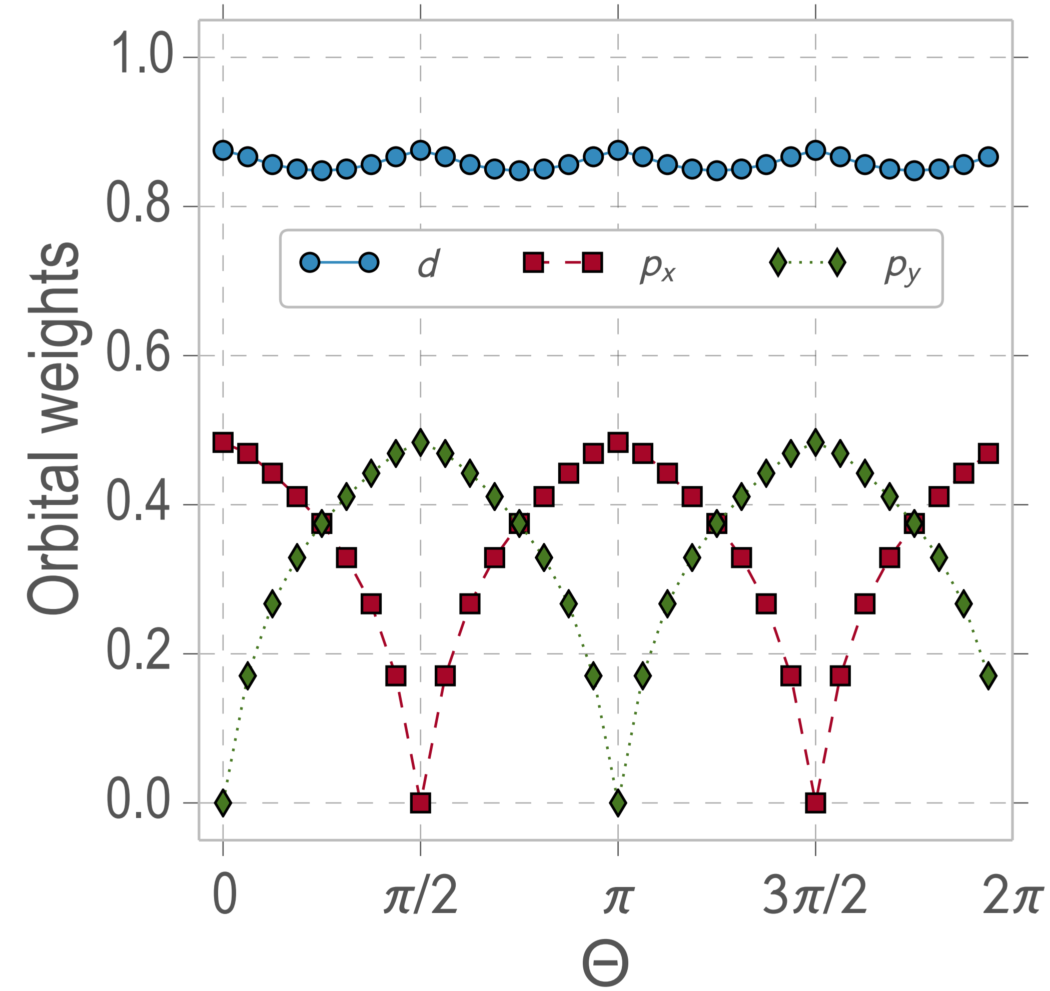
Longer ranged interaction reflected in higher *d*-wave harmonics

The role of V_{pd}

$$\Gamma(k,k') = \frac{V_c}{2} - \frac{1}{2}\bar{V}_c \chi^c_{RPA}(k-k')\bar{V}_c$$

$$\Gamma_c(k,k') = \sum_{\ell_1,\ell_2,\ell_3,\ell_4} a_\nu^{\ell_1^*}(k) a_\nu^{\ell_4^*}(-k) \Gamma_{\ell_1\ell_2\ell_3\ell_4}(k,k') a_\mu^{\ell_2}(k') a_\mu^{\ell_3}(-k')$$

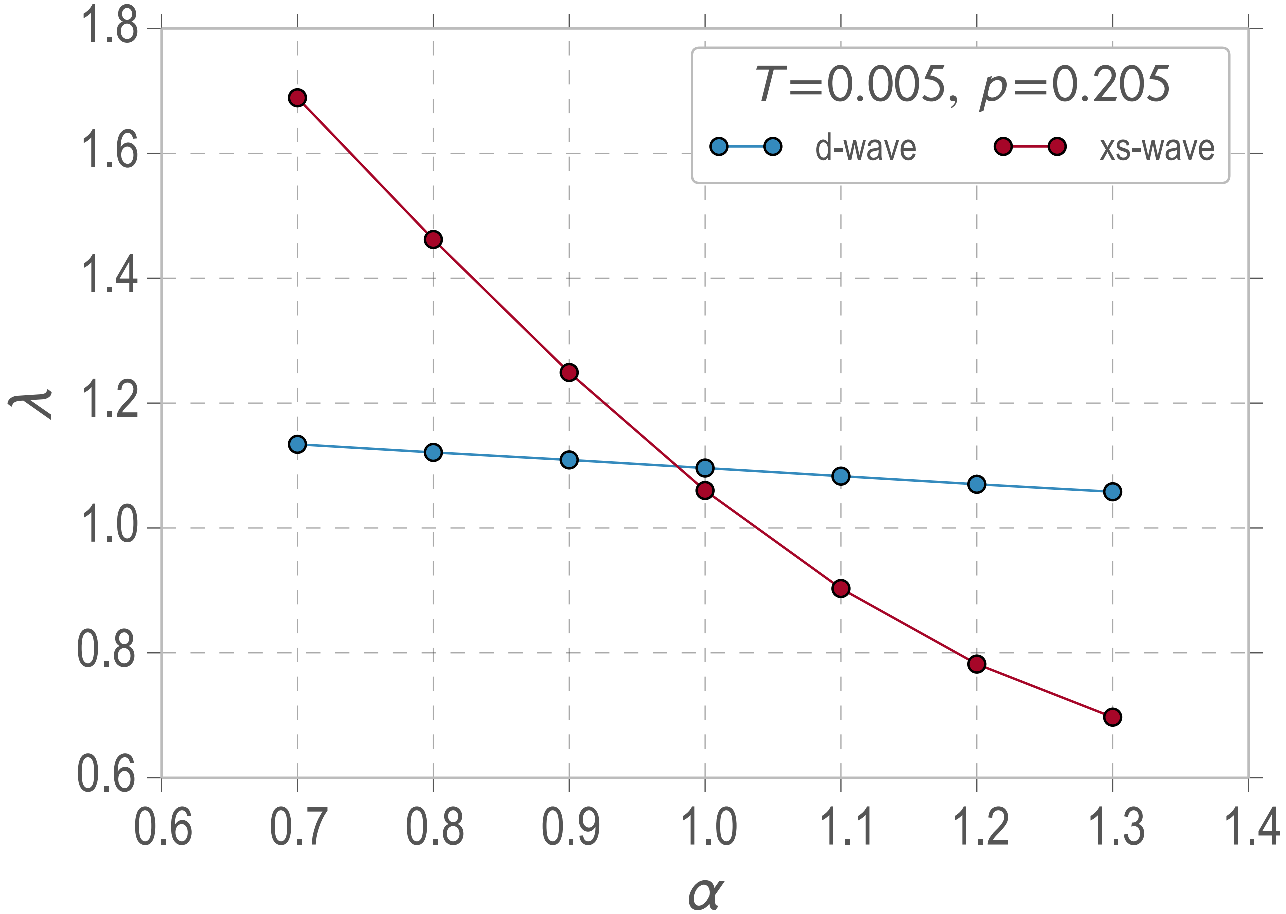




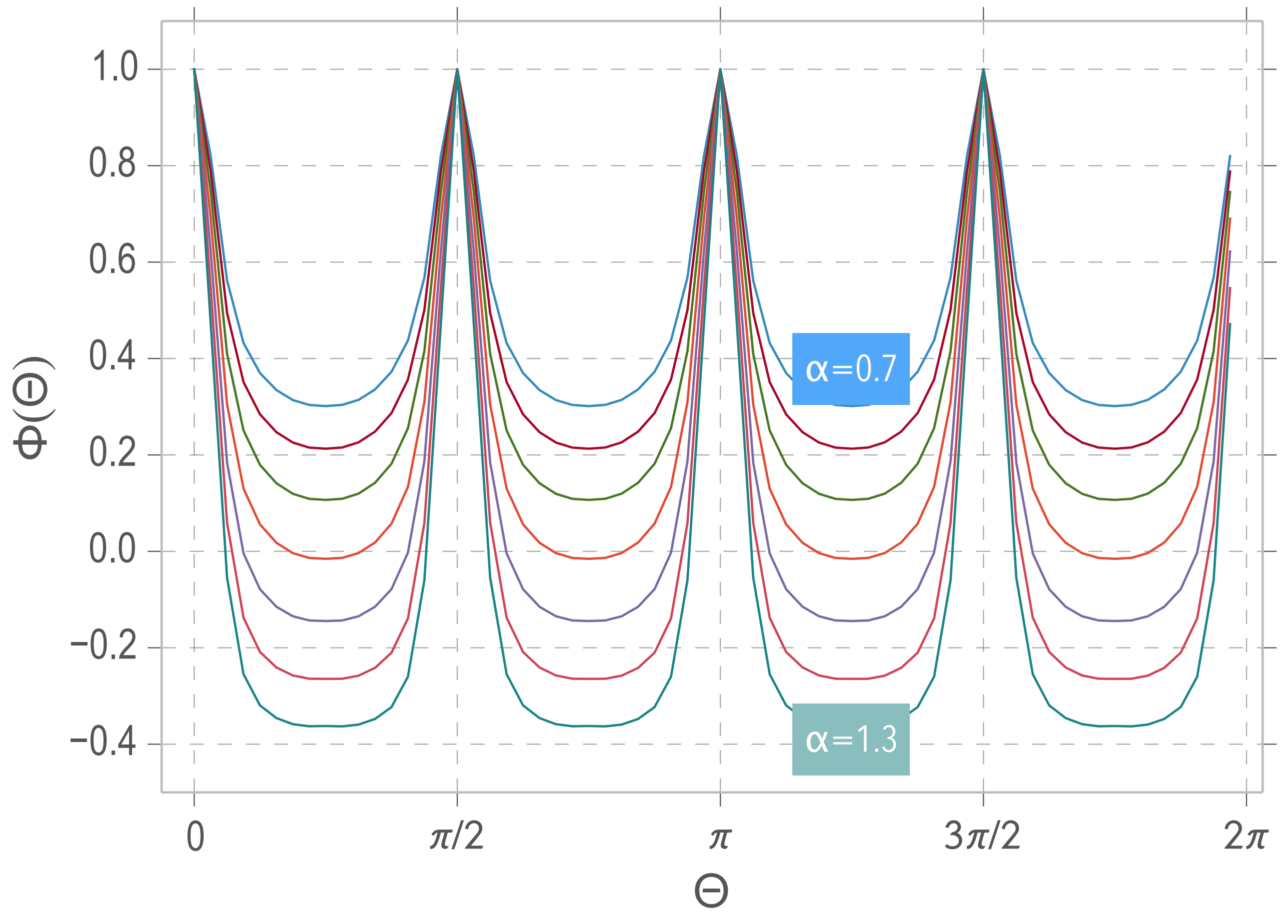
V_{pd} couples *d*-band to nematic fluctuations on *p*-orbitals

The role of the repulsive static interaction

$$\Gamma(k, k') = \alpha \frac{V_c}{2} - \frac{1}{2} V_c \chi^c_{RPA}(k - k') V_c$$



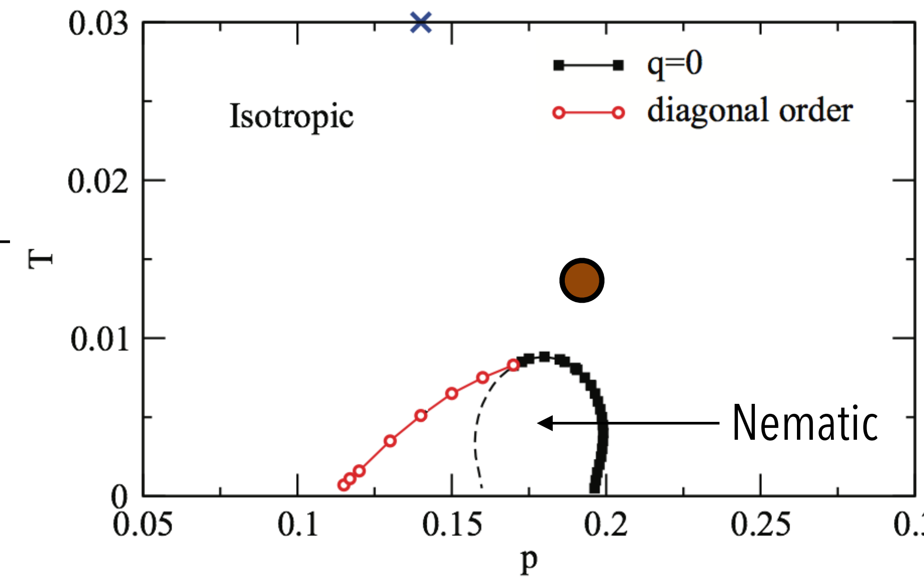
s-wave g(θ)



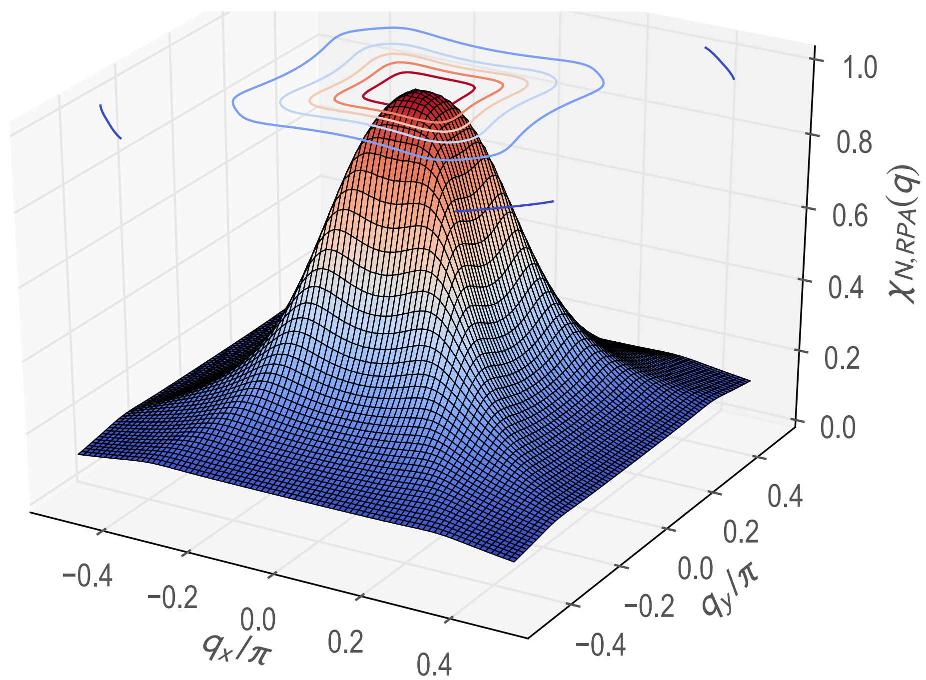
Who is the main player: Charge or spin?

$$\Gamma(k,k') = \frac{V_c}{2} - \frac{1}{2}\bar{V}_c \chi^c_{RPA}(k-k')\bar{V}_c + \frac{V_s}{2} + \frac{3}{2}\bar{V}_s \chi^s_{RPA}(k-k')\bar{V}_s$$

Charge vs. Spin



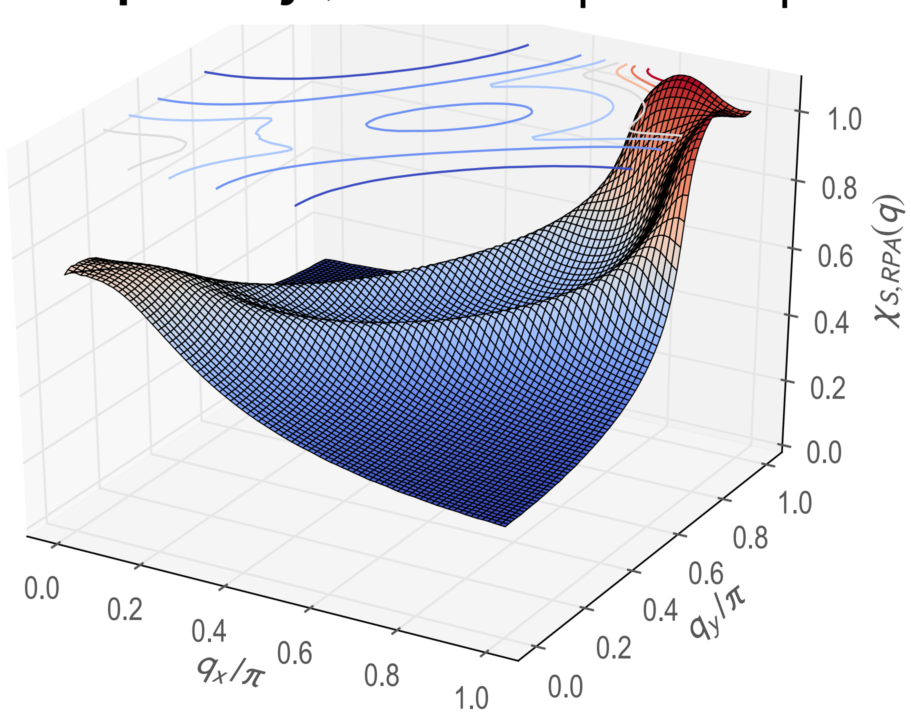
Charge susceptibility (U_d=9, U_p=3, V_{pd}=1, V_{pp}=2)



$$\Gamma(k,k') = \frac{V_c}{2} - \frac{1}{2}\bar{V}_c \chi^c_{RPA}(k-k')\bar{V}_c + \frac{V_s}{2} + \frac{3}{2}\bar{V}_s \chi^s_{RPA}(k-k')\bar{V}_s$$

$$\bar{U}_d = 4,\ \bar{U}_p = 1,\ \bar{V}_{pd} = 0.8,\ \bar{V}_{pp} = 0.6$$

Spin susceptibility (U_d=0.7, U_p=0.2, V_{pd}=0.1, V_{pp}=0.1)



Pairing strength from *charge* interaction: λ_d = 0.76

Pairing strength from *spin* interaction: λ_d = 16

Conclusions

Maier & Scalapino, arXiv:1405.5238
see also: Lederer *et al.*, arXiv:1406.1193

— The nematic pairing interaction is attractive for small momentum transfer

— Nematic charge fluctuations contribute to the d-wave pairing interaction with increasing strength as the nematic QCP is approached.

— It can cooperate with the repulsive, large momentum transfer spin fluctuation interaction so that both the spin and the charge channel contribute to the d-wave pairing strength.