Interplay between nematicity and superconductivity in bulk and thin films of FeSe

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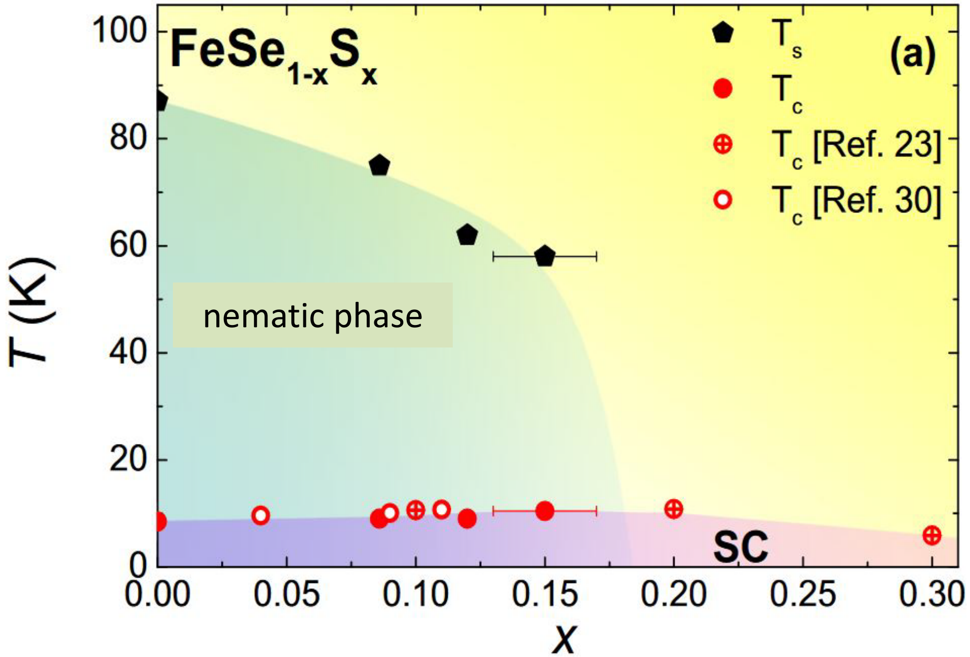


A. I. Coldea, Phys. Rev. B 92, 121108 (2015)

- No magnetic or charge orders
- Provide an ideal platform to study the impact of nematicity on superconductivity.

Thin Films

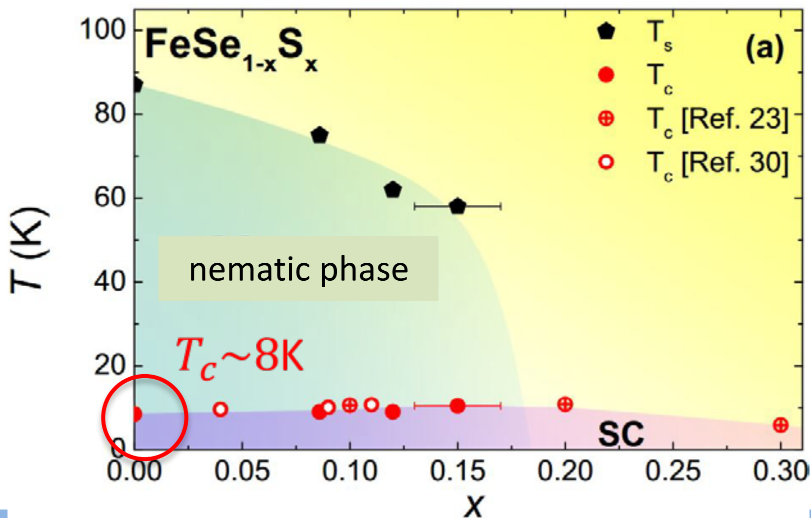
nature materials
LETTERS
PUBLISHED ONLINE: 24 NOVEMBER 2014 | DOI: 10.1038/NMAT4153

Superconductivity above 100 K in single-layer FeSe films on doped $SrTiO_3$

Science Bulletin
July 2015, Volume 60, Issue 14, pp 1301–1304

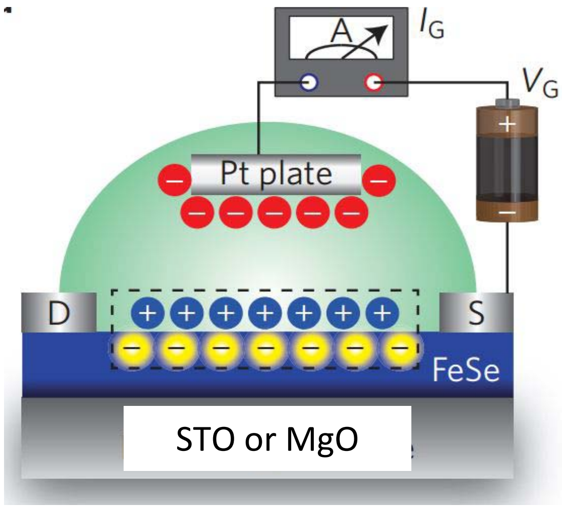
Onset of the Meissner effect at 65 K in FeSe thin film grown on Nb-doped $SrTiO_3$ substrate

65-75K for monolayer on the substrate of $SrTiO_3$ (001)

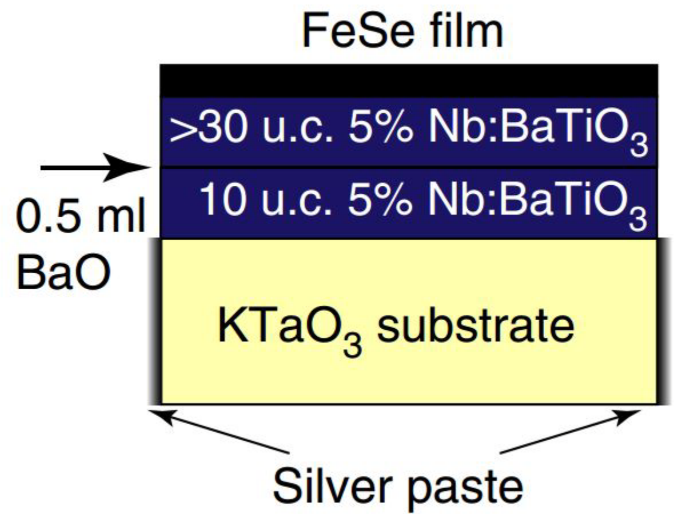


- Role of substrate?
- Mechanism of SC in FeSe thin film?

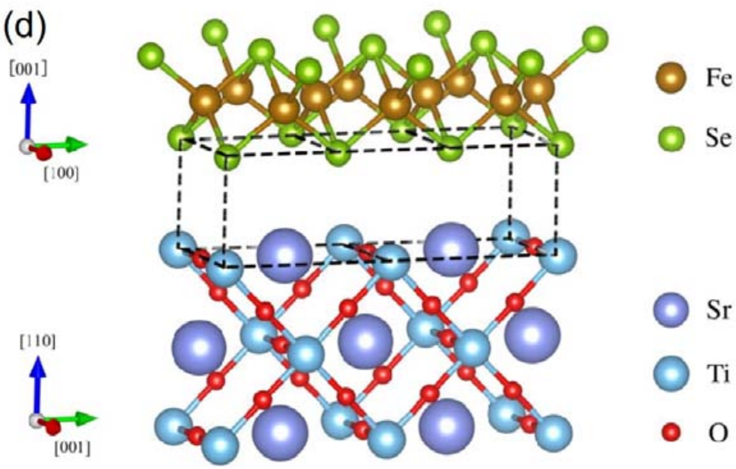
A. I. Coldea, Phys. Rev. B 92, 121108 (2015)



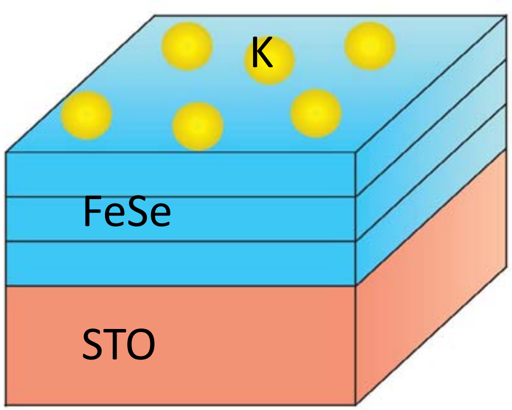
J. Shiogai, *et al.*, Nat. Phys. 12 42 (2016)



R. Peng, *et al.*, Nat. Commun. 5 5044 (2014)



P. Zhang, *et al.*, Phys. Rev. B 94 104510 (2016)



Y. Miyata, *et al.*, Nat. Mater. 14 775 (2015)

T_c~40K for thin films with different substrates bulk FeSe

$T_c = 8K$

?

FeSe thin film

$T_c \sim 40\text{K}$

Take home: SC induced by *nematic* fluctuations with *spin orbital coupling*.

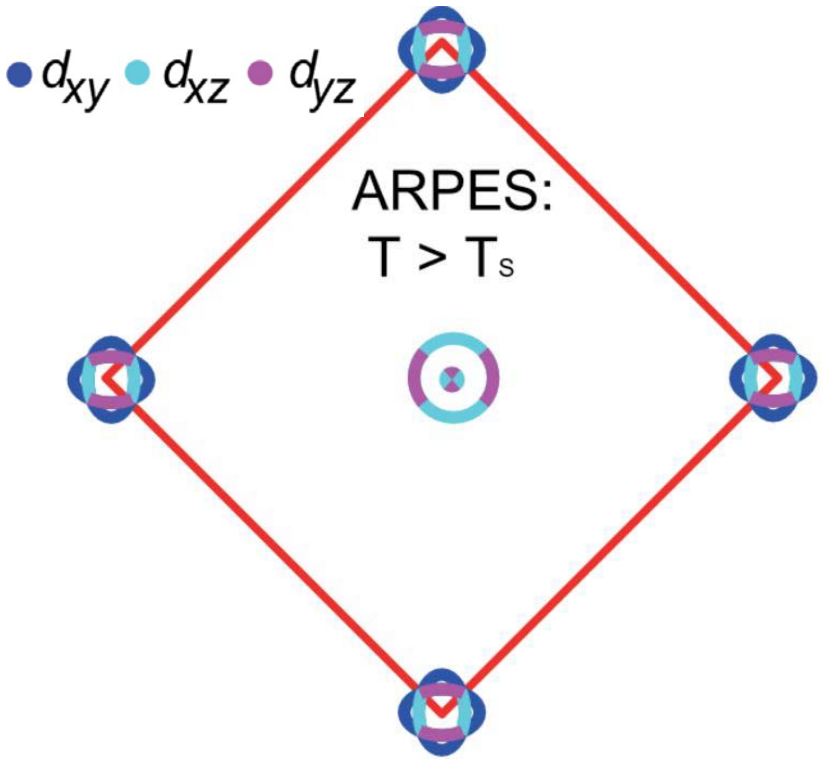
interfacial phonon

J. J. Lee, *et al.*, Nature 515, 245 (2014).
V. Mishra, *et al.*, Sci. Rep. 6, 32078 (2016).
L. Rademaker, *et al.*, New J. Phys. 18, 022001 (2016).
Y. Zhou and A. J. Millis, Phys. Rev. 93, 224506 (2016).
....

monolayer FeSe on STO (001)

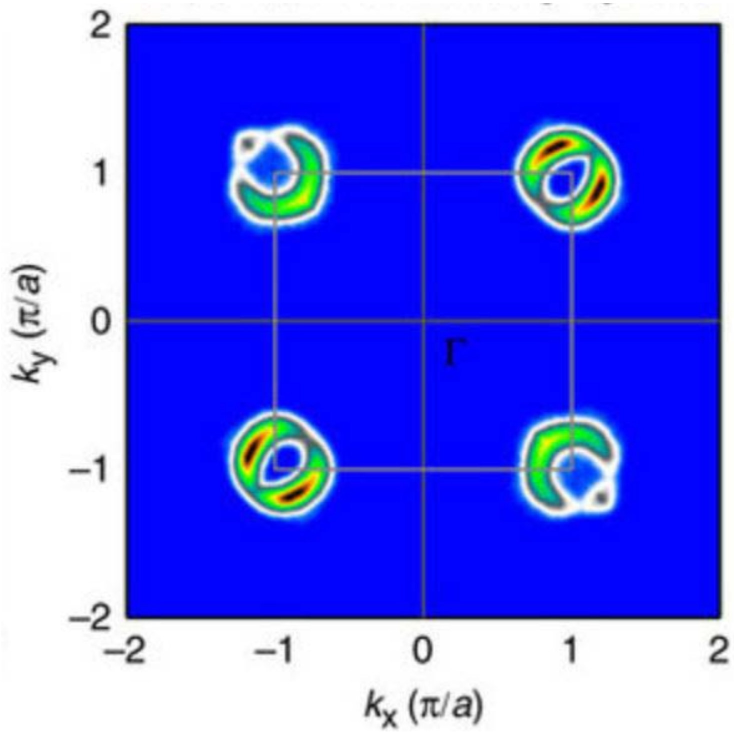
$T_c \sim 70\text{K}$

bulk FeSe



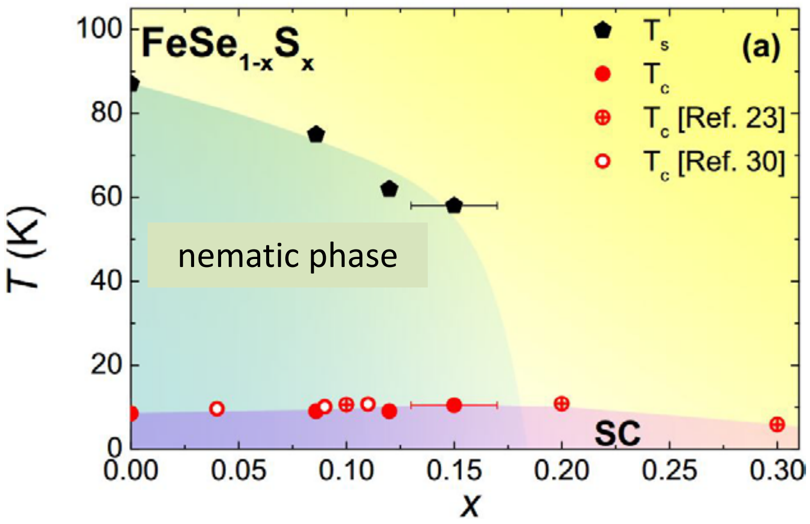
M. D. Watson *et al*., Phys. Rev. B 91, 155106 (2015)

FeSe thin film

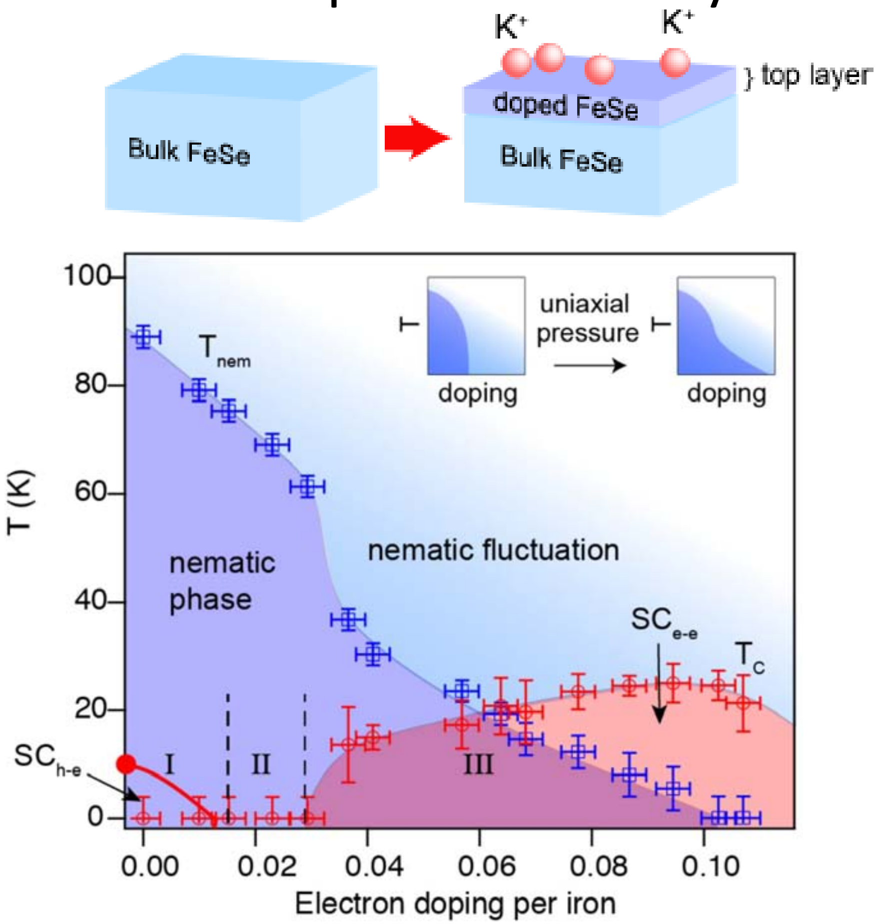


D. F. Liu, *et al*., Nat. Comm. 3 931 (2012)

heavily electron doped in FeSe thin film any critical, soft, bosonic mode to induce superconductivity?



A. I. Coldea, Phys. Rev. B 92, 121108 (2015)

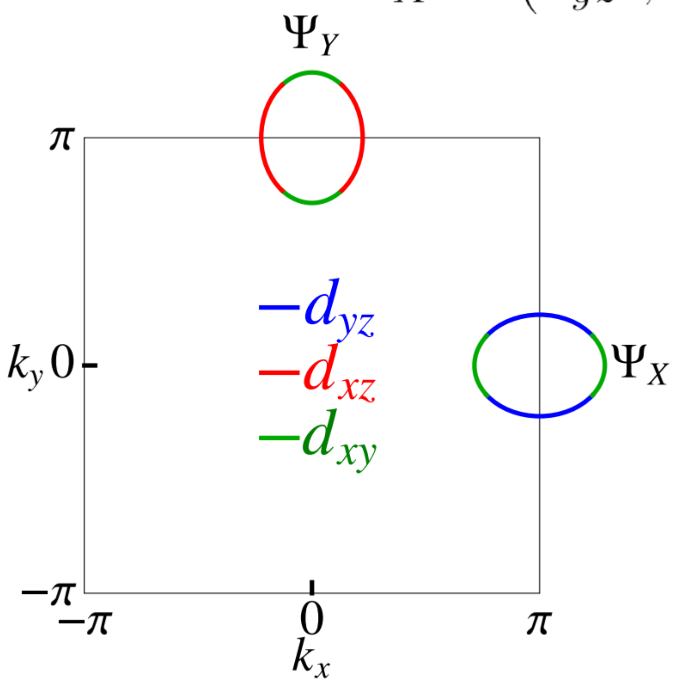


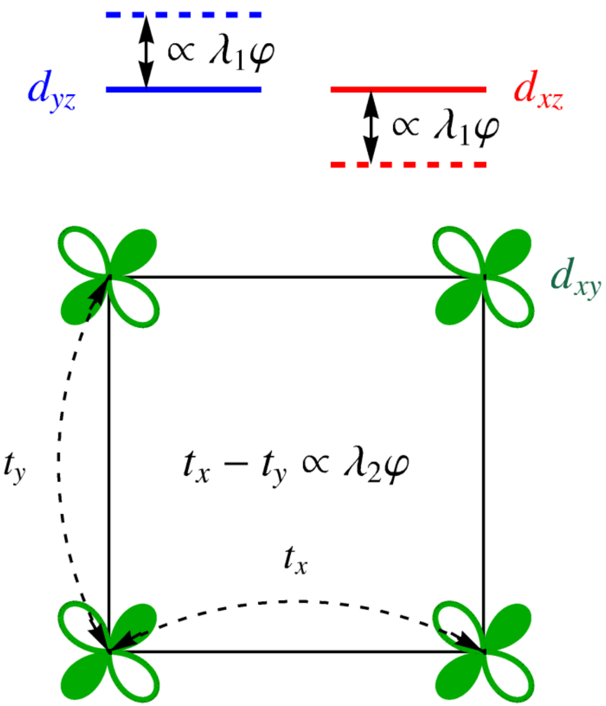
Z. R. Ye, *et al.*, arXiv 1512.02526 (2015).

nematic fluctuation

Introduce spinors to describe the low energy model: (V. Cvetkovic and O. Vafek, PRB 88, 134510 (2013))

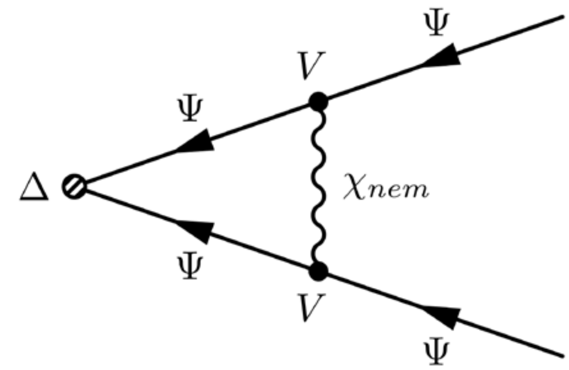
$$\Psi_X = (d_{yz} \ , d_{xy})^T \qquad \Psi_Y = (d_{xz} \ , d_{xy})^T$$



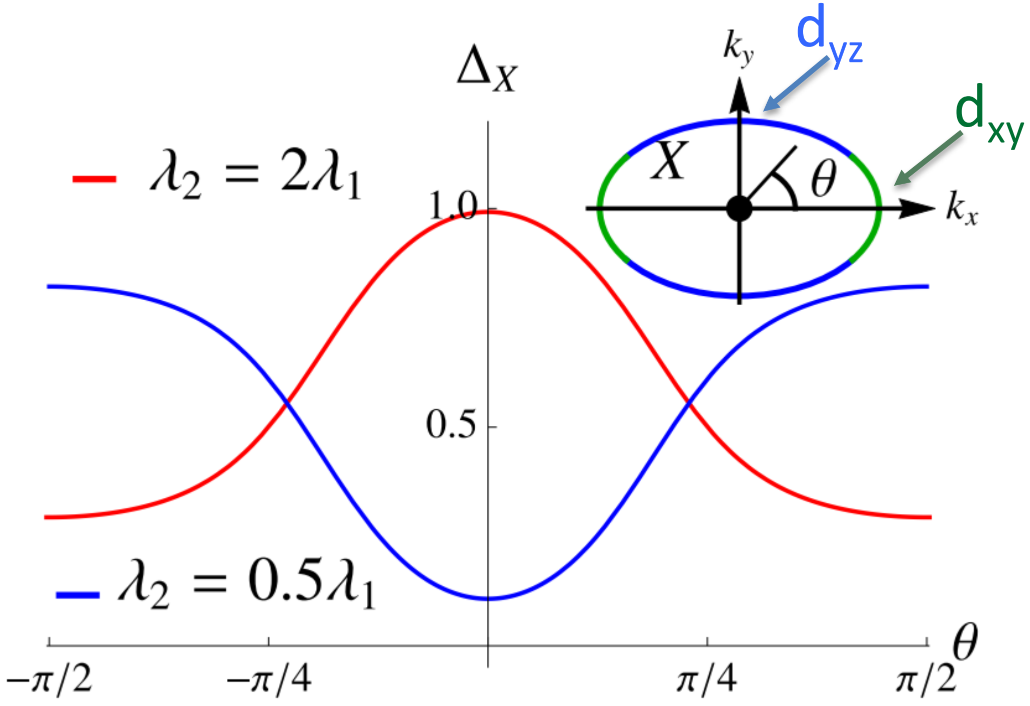


- Two coupling constants λ_1 and λ_2 (R. Fernandes and O. Vafek, PRB 90, 214514 (2014))

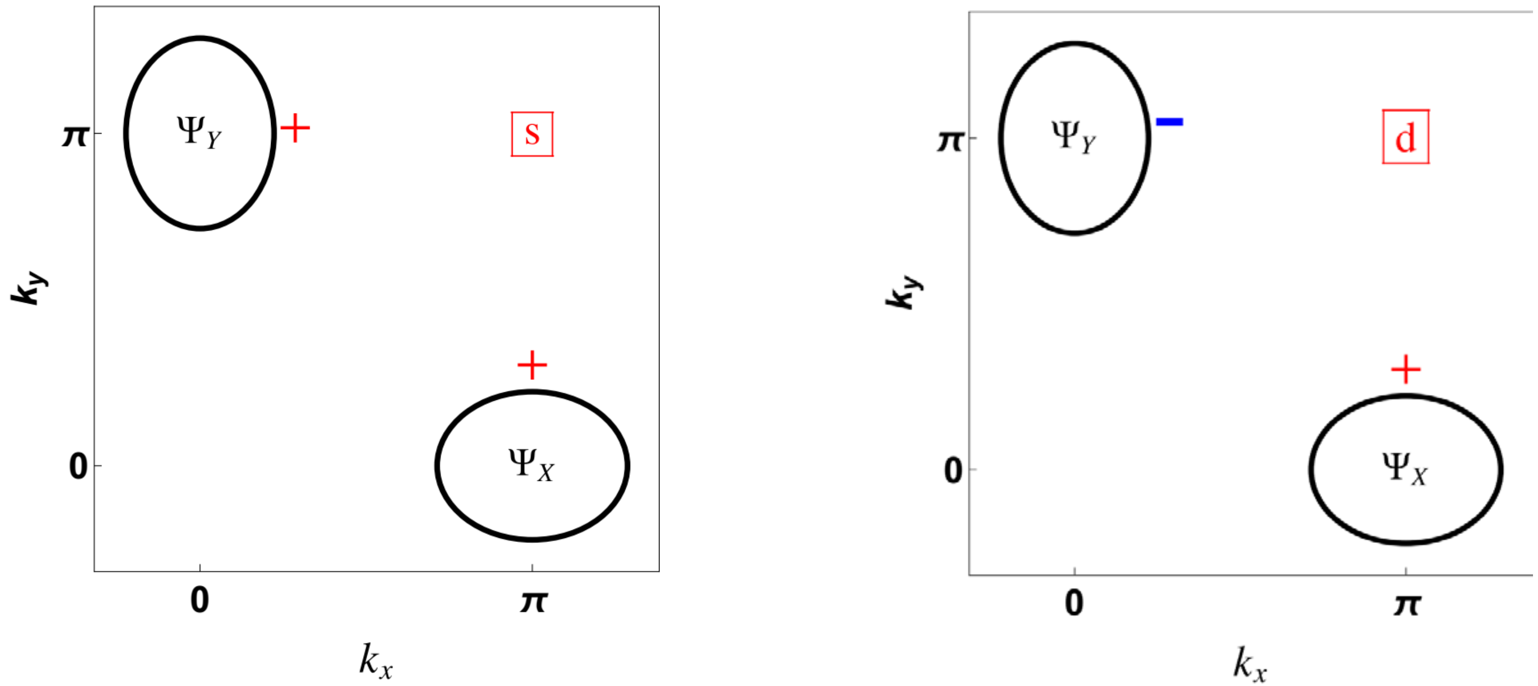
Gap Anisotropy



leading pairing instability: intra-orbital and intra-pocket



gap anisotropy depends on orbital weight and relative coupling strength



Small momentum transfer leads to pairing degeneracy: s- and d wave

$$F_{SC} = \frac{a}{2}\left(|\Delta_s|^2 + |\Delta_d|^2\right) + \frac{u}{4}\left(|\Delta_s|^2 + |\Delta_d|^2\right)^2 + O(\Delta^6)$$

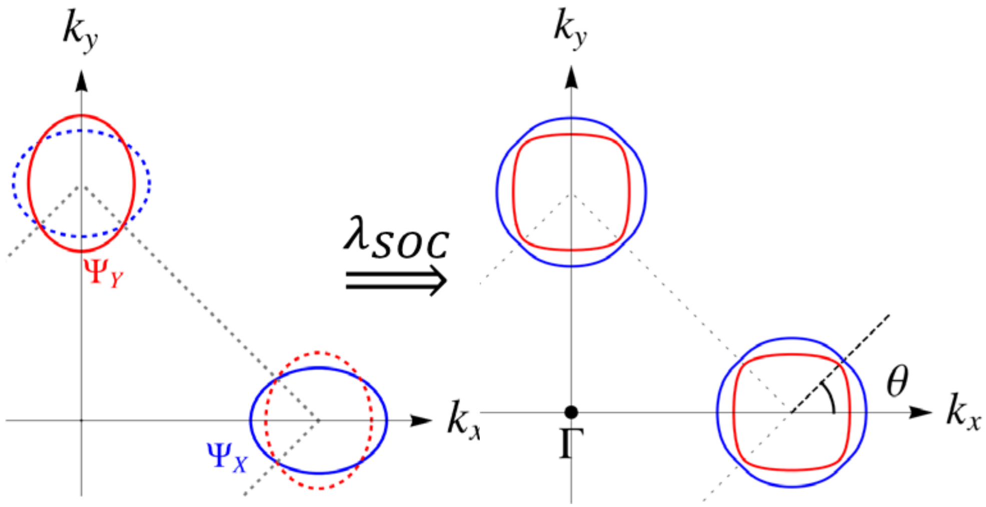
$$\frac{u}{2}|\Delta_s|^2|\Delta_d|^2 \quad \Longrightarrow \quad a_s \to a + u\langle|\Delta_d|^2\rangle \quad a_d \to a + u\langle|\Delta_s|^2\rangle$$

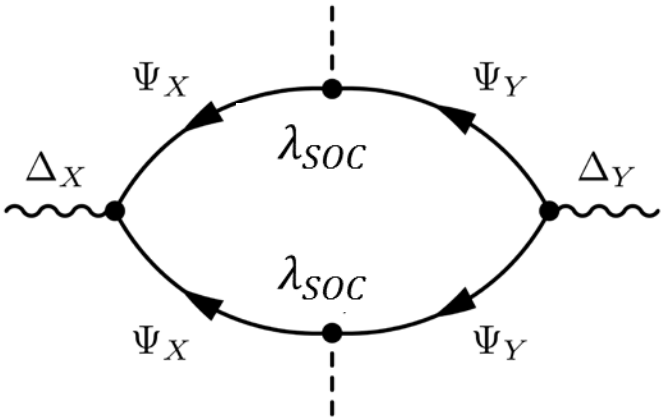
Pairing fluctuation suppressed T_c

How to lift the pairing degeneracy?

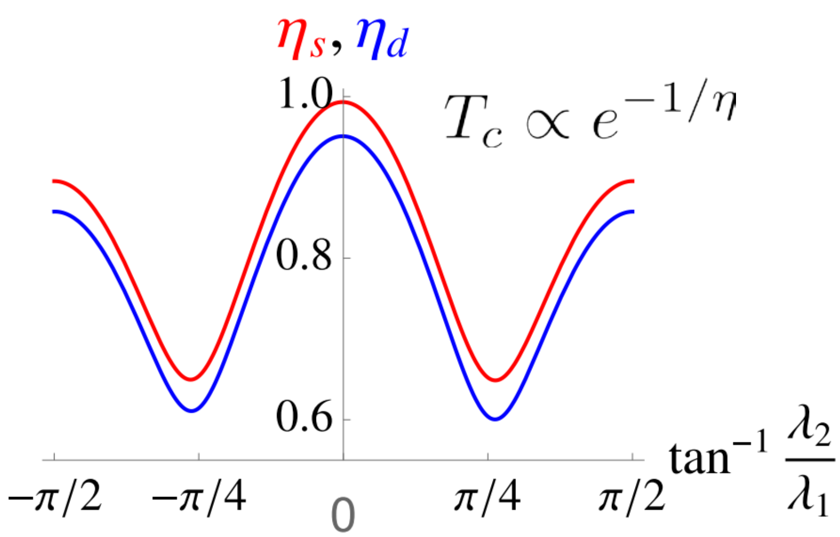
Spin orbital coupling: $\lambda_{SOC}\vec{L}\cdot\vec{S}$

- Hybridization between two electron pockets
- Introduce spin triplet pairing.
- Lift degeneracy between s and d pairing

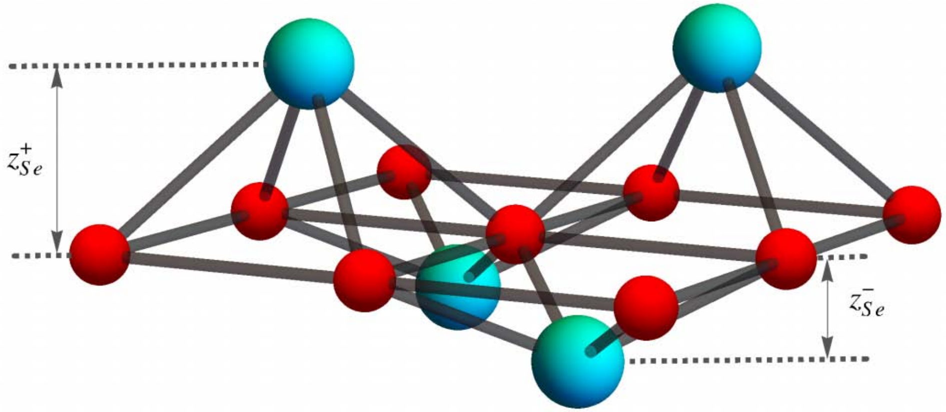




$$\delta F = \gamma\left(\Delta_X \Delta_Y^* + h.c.\right) \qquad \text{with } \gamma < 0$$



- Another mechanism to hybridize electron pockets
  - Inversion symmetry breaking



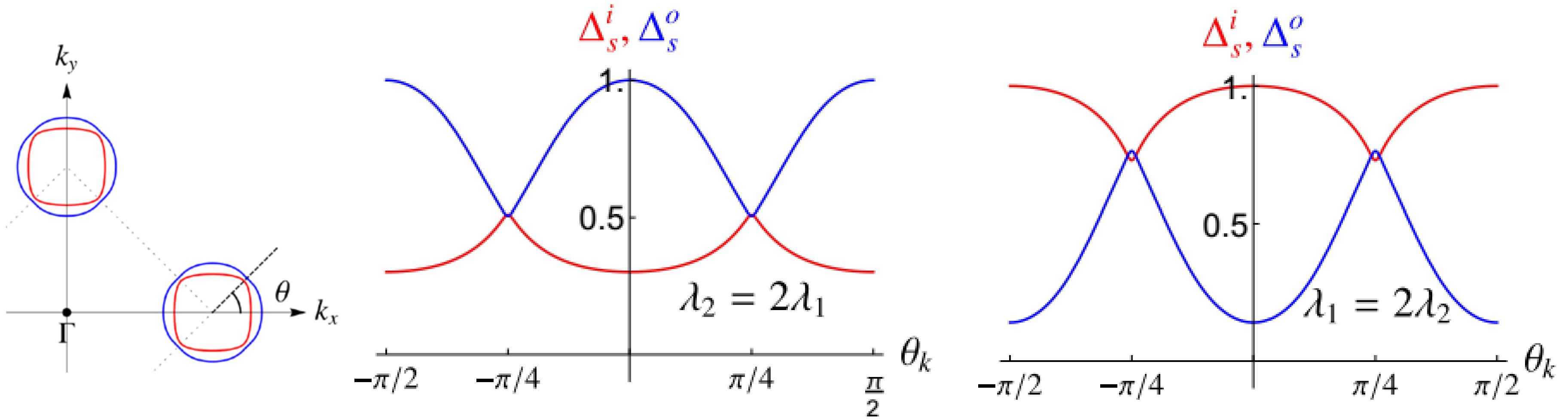
$$z^+_{Se} \neq z^-_{Se}$$

- Hybridize dxz and dyz orbitals
- Impact on SC is similar to SOC
  - s becomes leading instability

Gap anisotropy revisisted

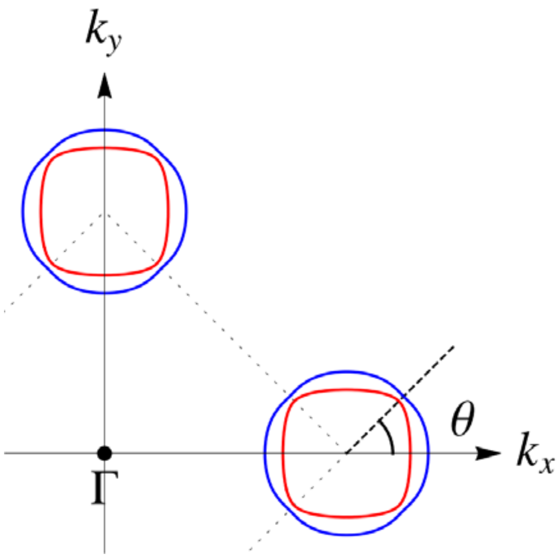
- Gap anisotropy depends on the relative strength between SOC/inv and the mismatch of electron pockets

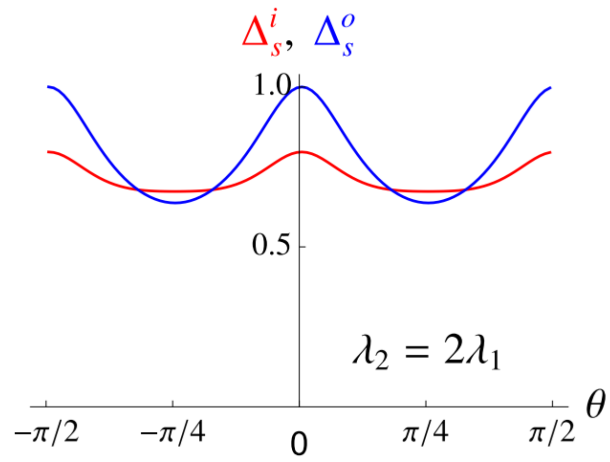
$$\lambda_{SOC}, \lambda_{inv} \ll \delta_m$$



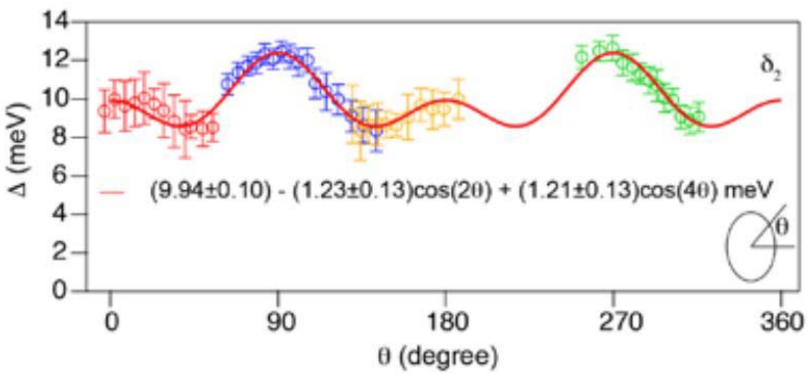
SOC has little impact on gap anisotropy

$$\lambda_{SOC}, \lambda_{inv} \gg \delta_m$$





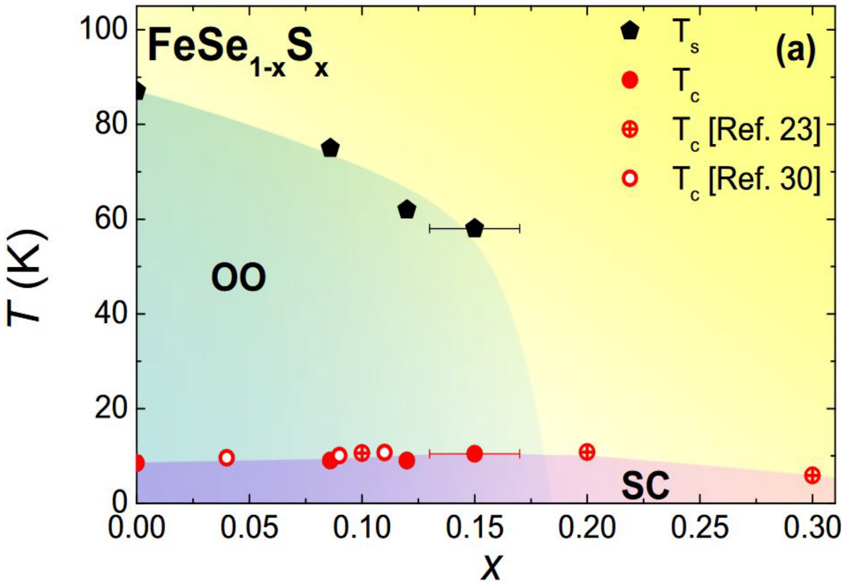
monolayer FeSe



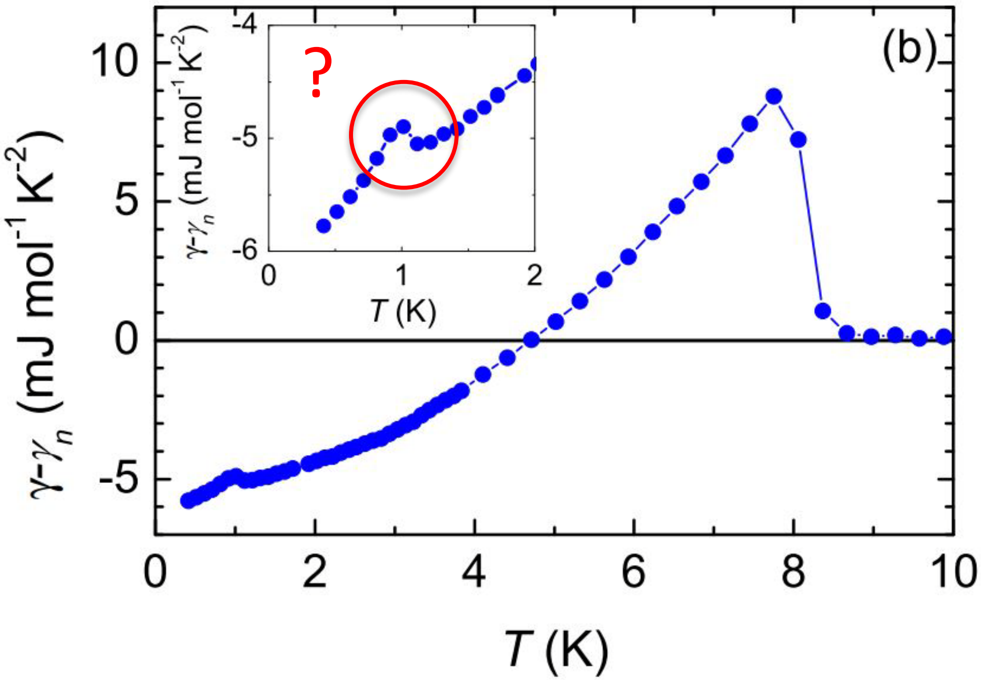
Y. Zhang, *et al*., Phys. Rev. Lett. 117, 117001 (2016)

Bulk FeSe

SC Phase in bulk FeSe

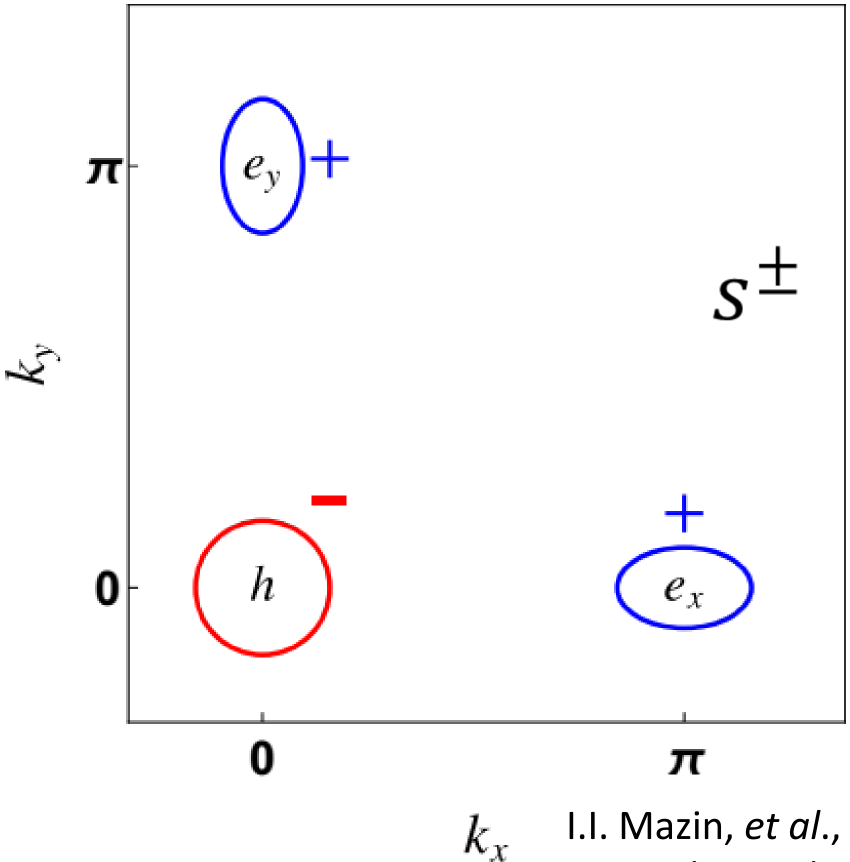


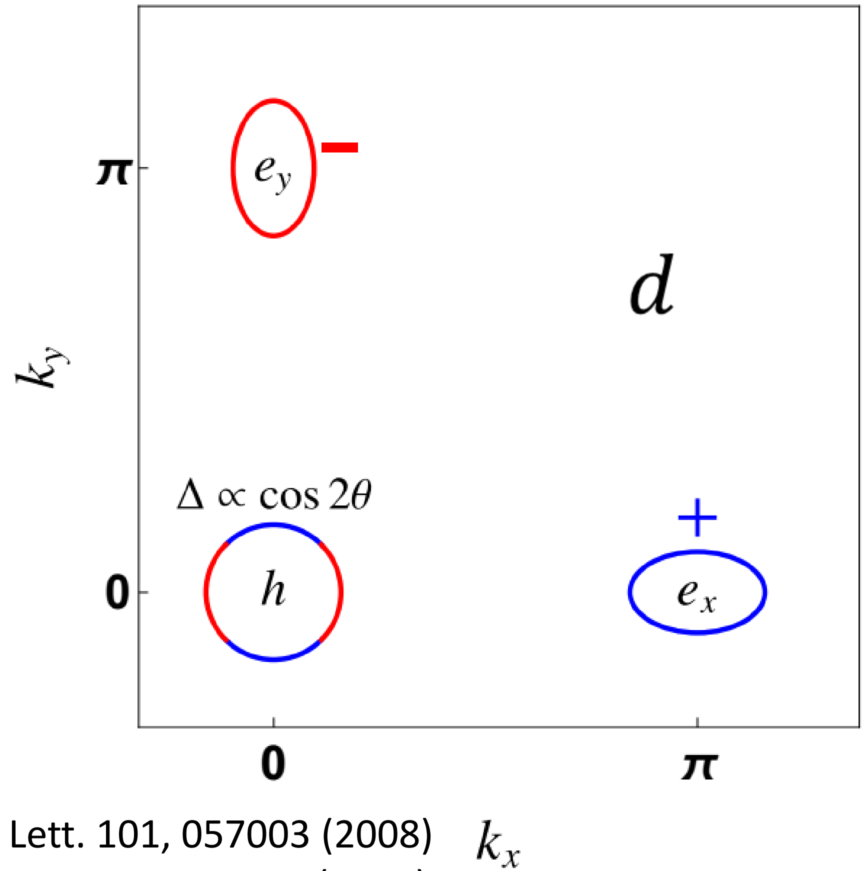
A. I. Coldea, Phys. Rev. B 92, 121108 (2015)



H.-F. Wen,et al., arXiv:1703.08680

Jump in heat capacity at $T < T_c$





I.I. Mazin, *et al*., Phys. Rev. Lett. 101, 057003 (2008)
K. Kuroki, *et al*., Phys. Rev. Lett. 101, 087004 (2008)
A.V. Chubukov, *et al*., Phys. Rev. B 78, 134512 (2008)
J. Zhang, *et al*., Phys. Rev. B 79, 220502 (2009)
F. Wang, *et al*., EPL 85, 37005 (2009)
S. Graser, *et al*,. New J. Phys. 11, 025016 (2009)
S. Maiti, *et al*., Phys. Rev. B 84, 224505 (2011)
F. Kretzschmar, *et al*., Phys. Rev. Lett. **110**, 187002 (2013)
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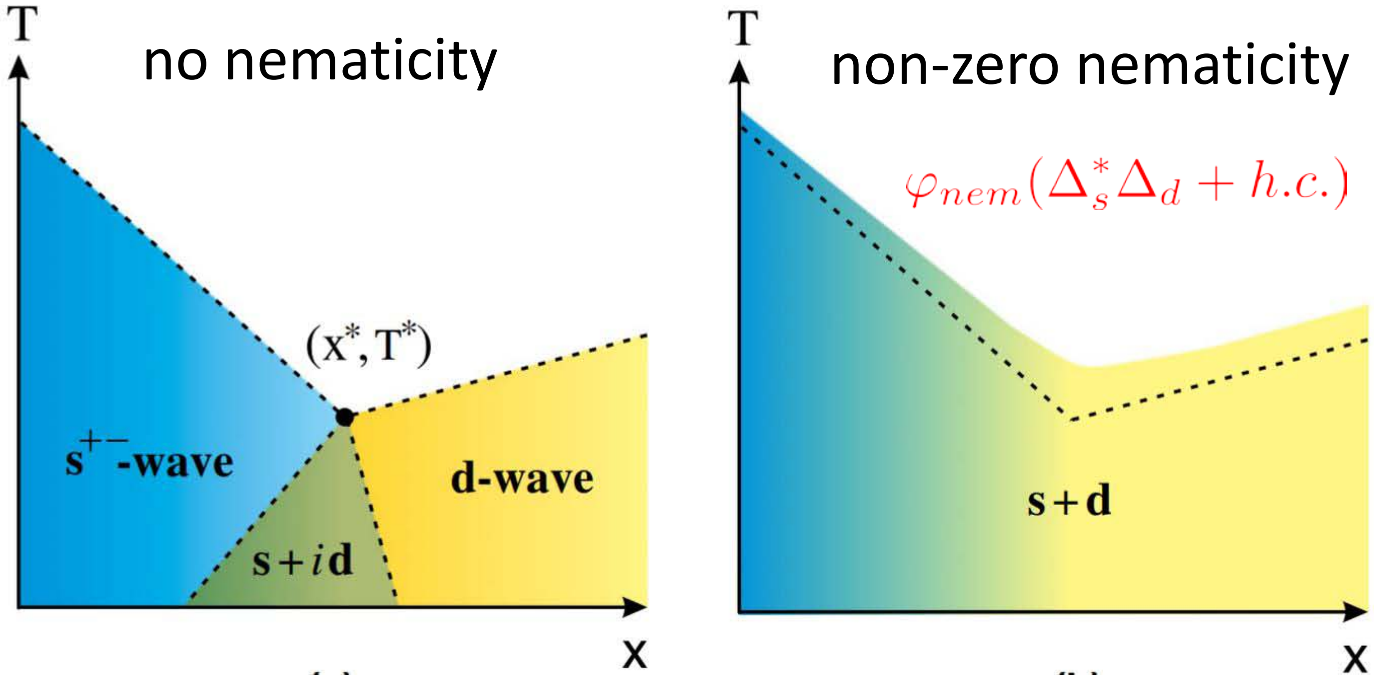
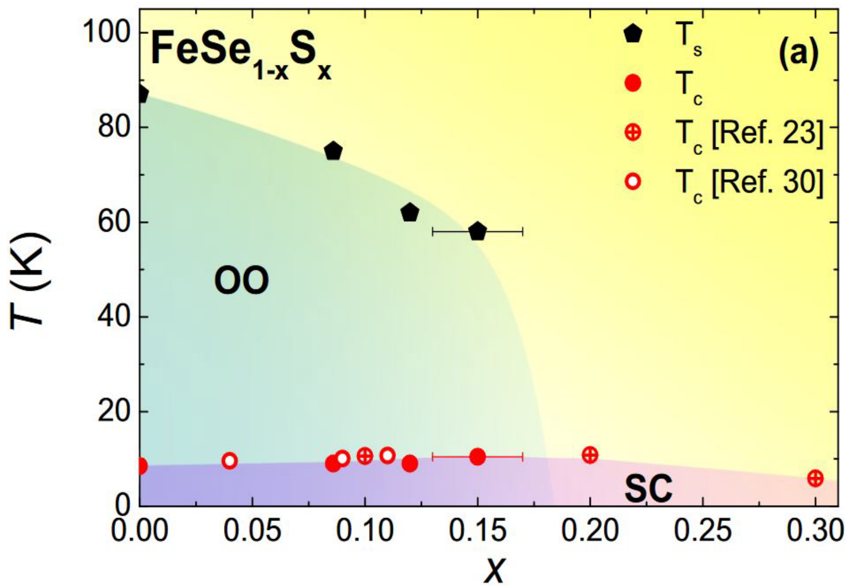
TRSB in iron-based SC

- Near degeneracy between s and d pairing channels.
- Nematicity is generally incompatible with TRSB



R. Fernandes and A. Millis, Phys. Rev. Lett. 111, 127001 (2013)
J. Kang and R. Fernandes, Phys. Rev. Lett. 113, 217001 (2014)

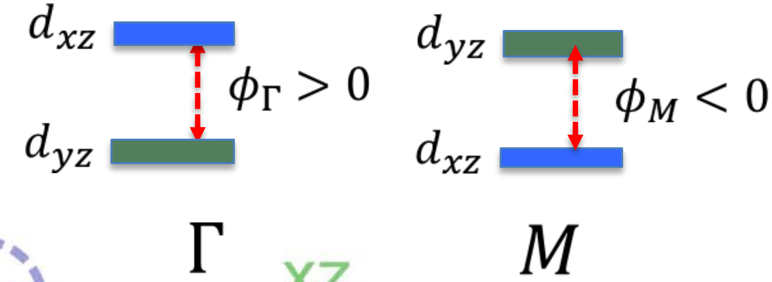


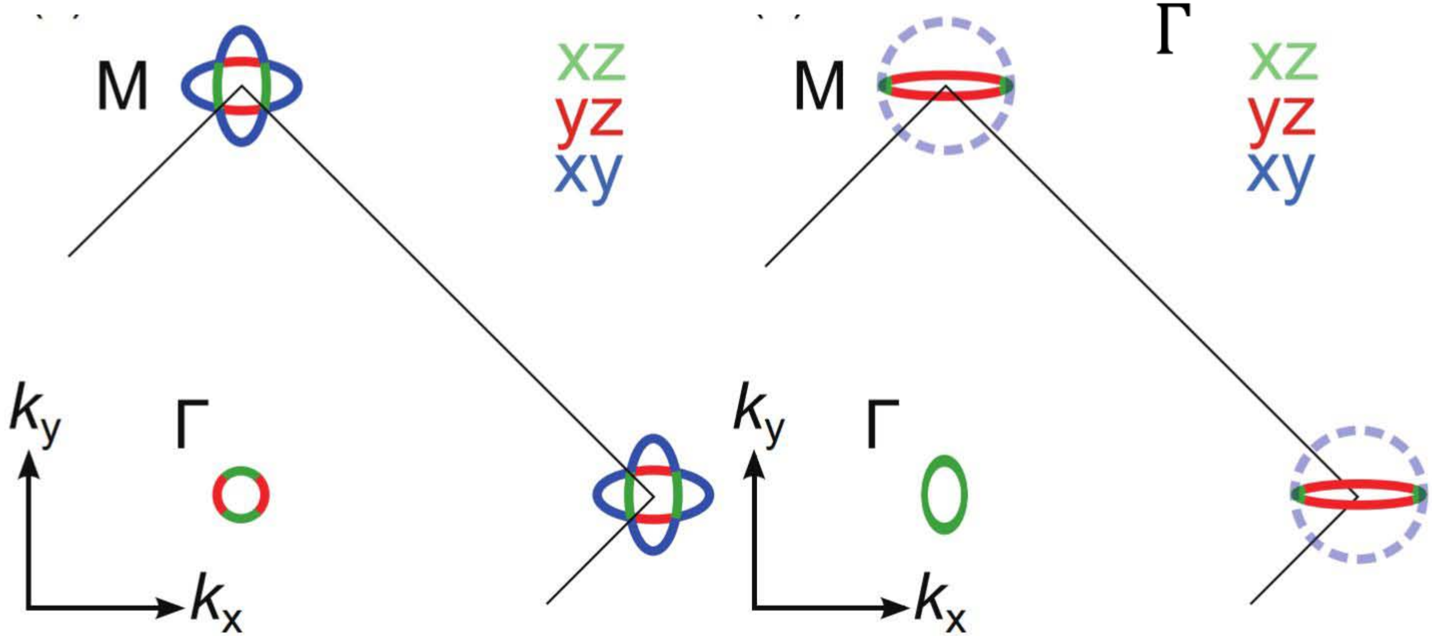
A. I. Coldea, Phys. Rev. B 92, 121108 (2015)

Momentum-dependent nematicity

- Sign inversion nematicity

$$\phi_{\boldsymbol{k}}\left(n_{xz}-n_{yz}\right)$$





Y. Suziki, *et al.*, Phy. Rev. B. 92, 205117 (2015)

$$\sim (\phi_\Gamma + \phi_M)(\Delta_s^* \Delta_d + h.c.)$$

Does the *sign-inversion* nematicity help TRSB SC state?

Pairing interaction

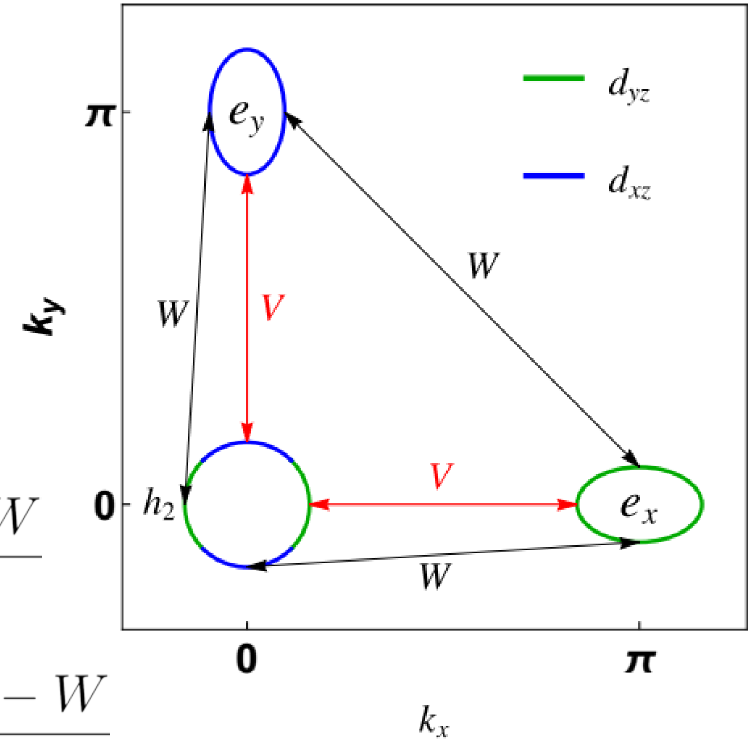
- Inter-pocket pairing interaction:
  - Intra-orbital pairing: V
  - Inter-orbital pairing: W
- SC in s and d channels:
  - $s^{\pm}$ wave:

$$U_{xy}^{eff} = -W \ , \quad U_{hx}^{eff} = U_{hy}^{eff} = \frac{V+W}{2}$$

  - d wave:

$$U_{xy}^{eff} = W \ , \quad U_{hx}^{eff} = -U_{hy}^{eff} = \frac{V-W}{2}$$

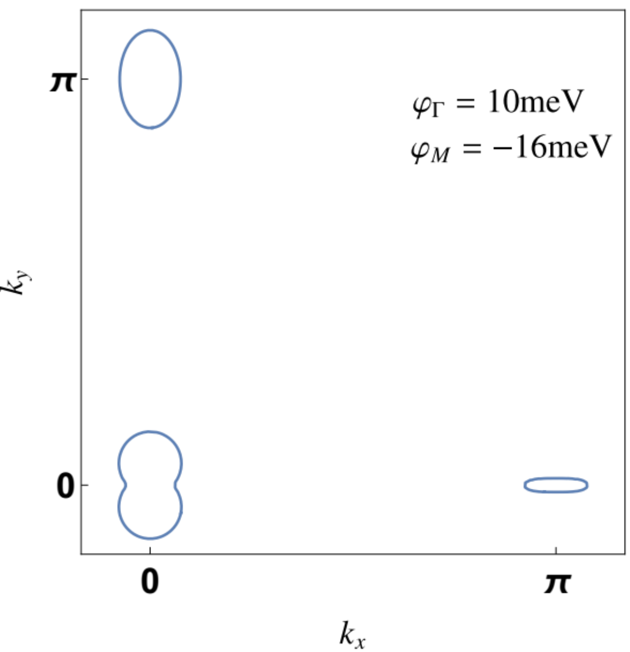
  - $s^{\pm}$ -d degeneracy: $V \sim W$

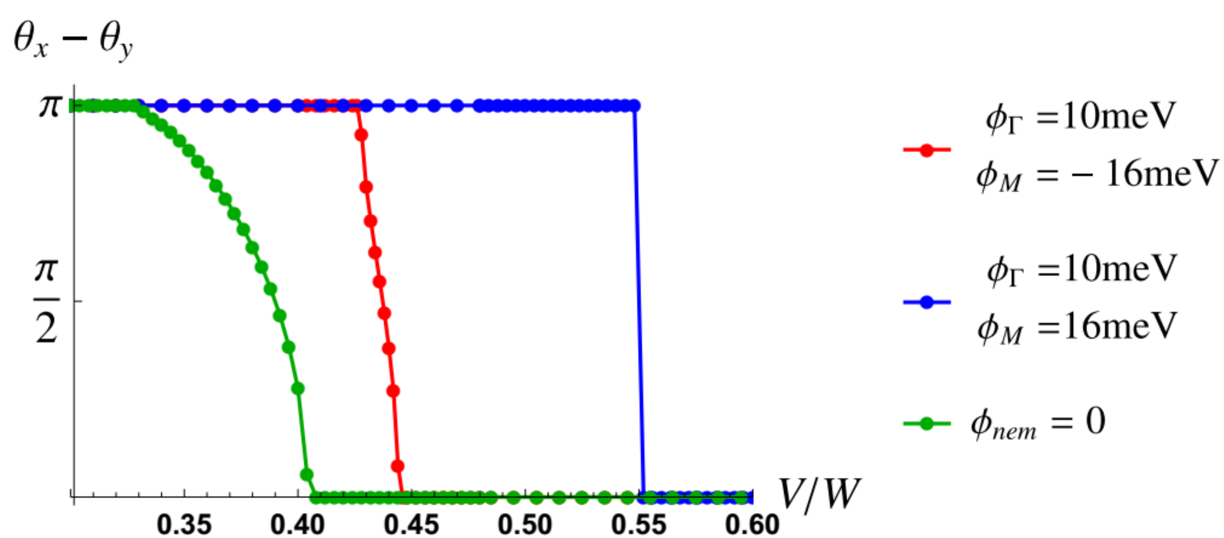


TRSB SC with nematicity

- $\phi_{nem} \sim \epsilon_f$
  - Numerical results with fitting the band structure

$$\Delta_x = |\Delta_x| e^{i\theta_x} \qquad \Delta_y = |\Delta_y| e^{i\theta_y}$$

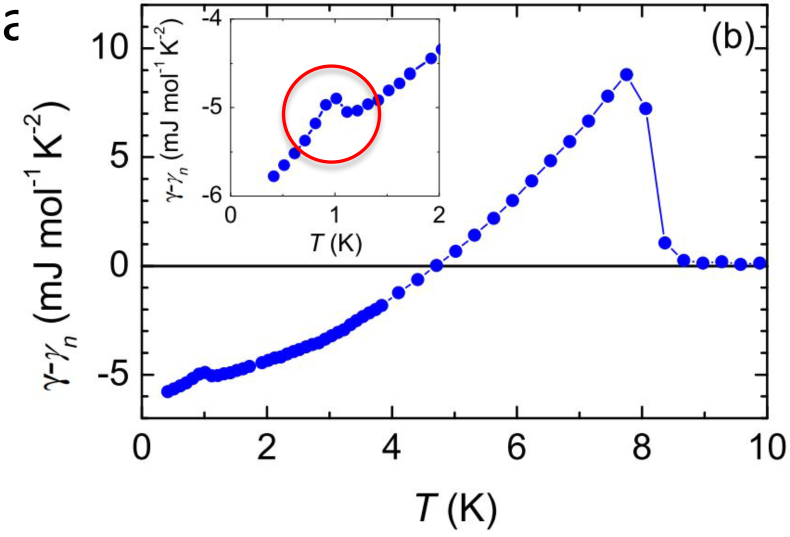




Sizable *sign-inversion* nematicity is compatible with TRSB SC state.

Conclusion

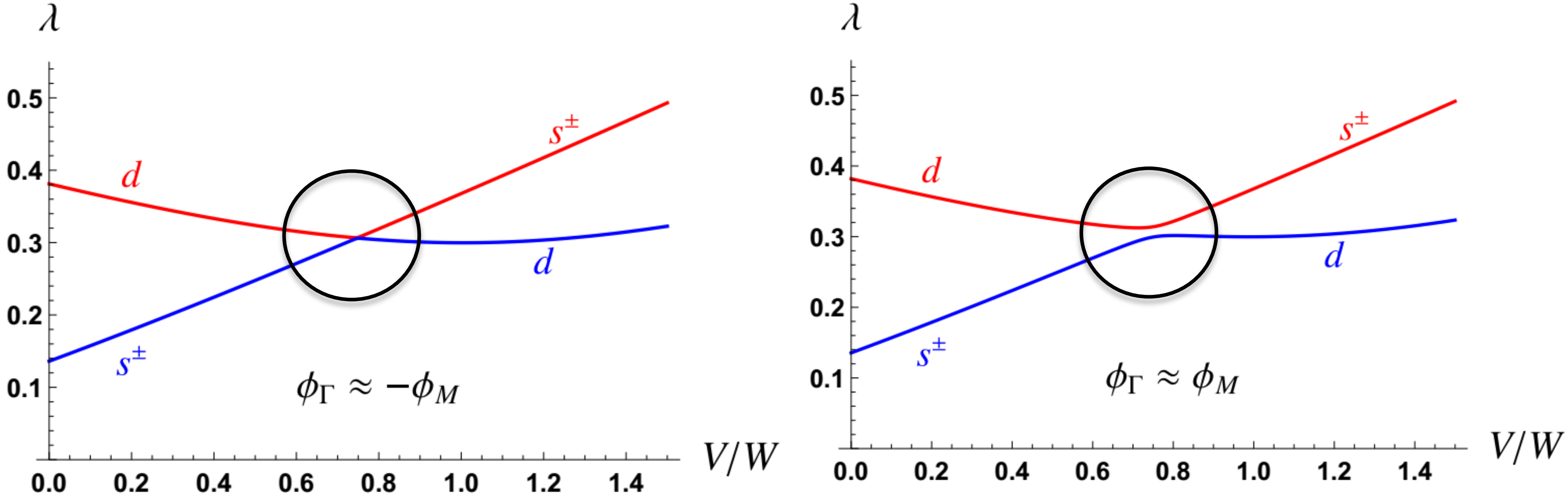
- Nematic fluctuations with SOC may induce SC in ultrathin FeSe film and dramatically enhance Tc.
- Sign-inversion nematicity in the bulk FeSe is compatible with TRSB SC state. It might account for the kink of the specific heat in the superconductivity pha



H.-F. Wen,et al., arXiv:1703.08680

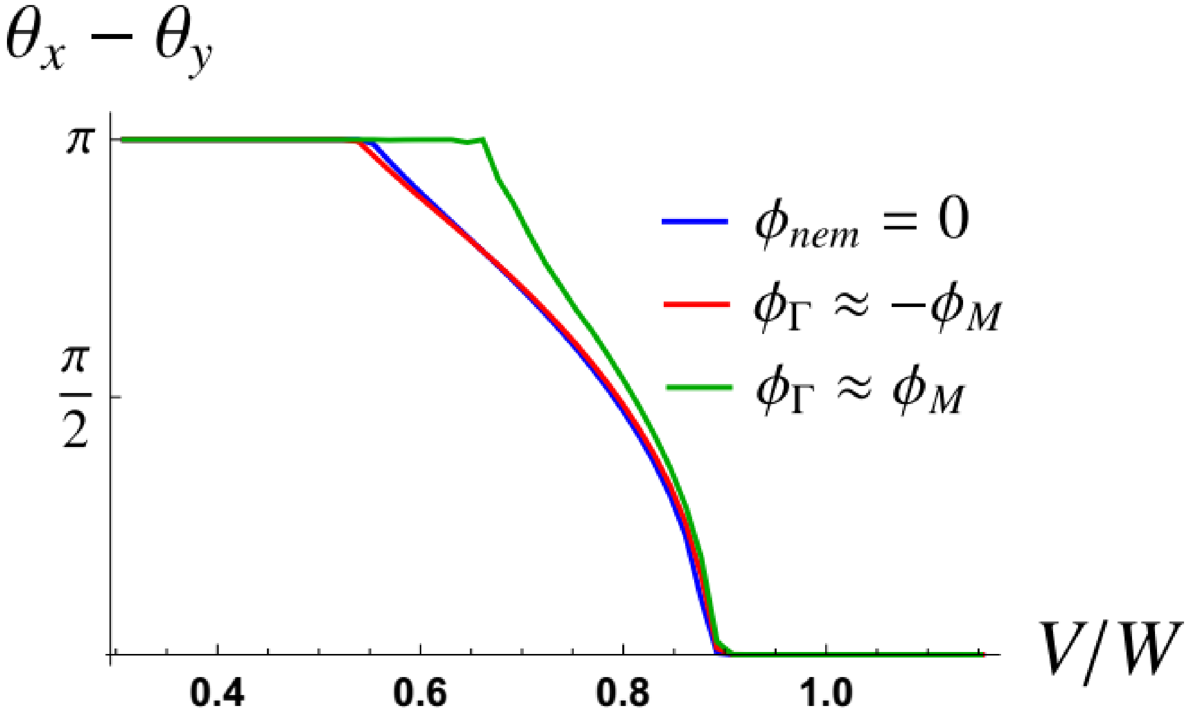
Superconductivity with small nematicity

- Small $\phi_{nem} \ll \varepsilon_f$



Sign-inversion nematicity has little impact on the s-d pairing degeneracy

TRSB with small nematicity



Small sign-inversion nematicity has little impact on the TRSB SC state.