# Interplay of magnetism, superconductivity and orbital order in 5-pocket FeSC's

## Laura Classen

Ruiqi Xing, Maxim Khodas, Andrey Chubukov
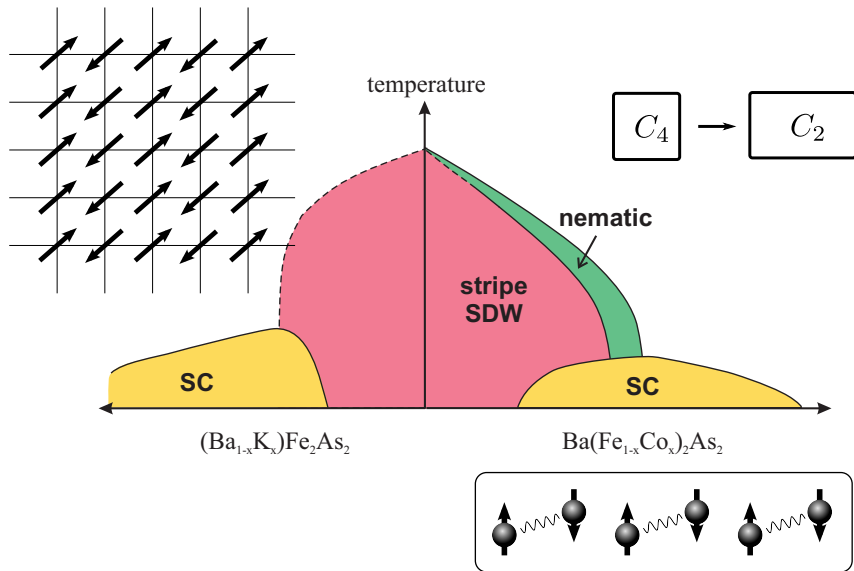
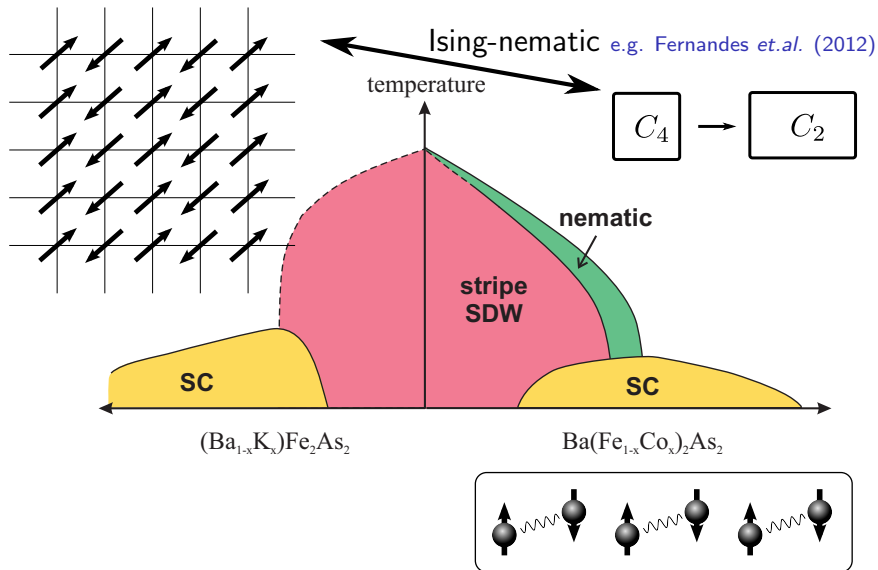ERG 2016, Trieste

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Zukunft. Seit 1386.

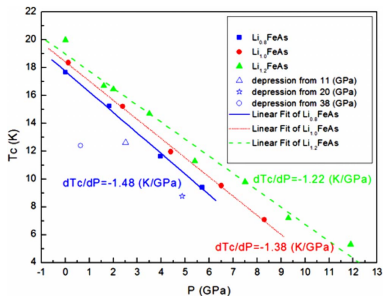UNIVERSITY OF MINNESOTA
Driven to Discover℠
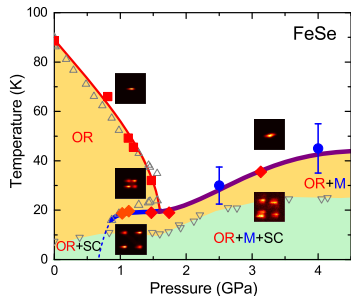
# Phase diagram

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# Phase diagram II

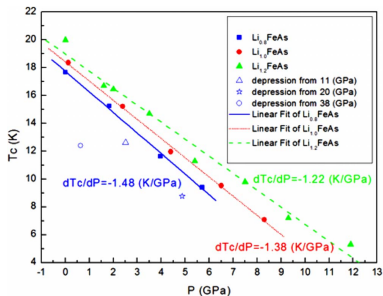- E.g. LiFeAs and FeSe: no (stripe) SDW
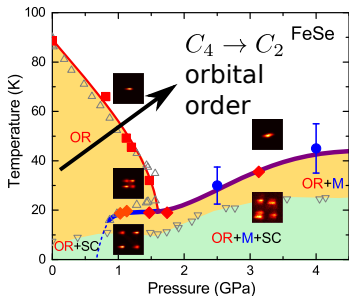


S.J. Zhang *et.al.* (2009)



K. Kothapalli *et.al.* (2016)

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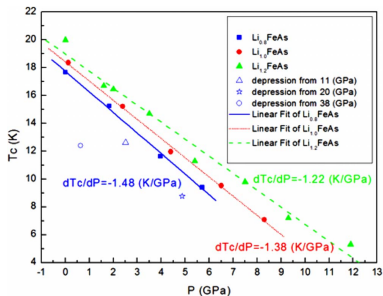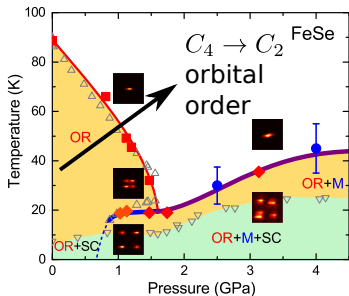- E.g. LiFeAs and FeSe: no (stripe) SDW



S.J. Zhang *et.al.* (2009)



K. Kothapalli *et.al.* (2016)

- Superconductivity without magnetism in parent compound?
- Origin of nematicity? Ising-nematic vs. orbital order?
- Connection between different FeSC's?

# Structure

- Common iron-pnictogen or iron-chalogen plane



FeSe

LiFeAs

SrFe$_2$As$_2$

LaFeAsO/
SrFeAsF

Sr$_3$Sc$_2$O$_5$Fe$_2$As$_2$

A. Kordyuk (2012)

# Band structure



H. Ikeda *et.al.* (2010)

# Band structure



H. Ikeda *et.al.* (2010)

- Before: Band models as simplified descriptions

# Band structure



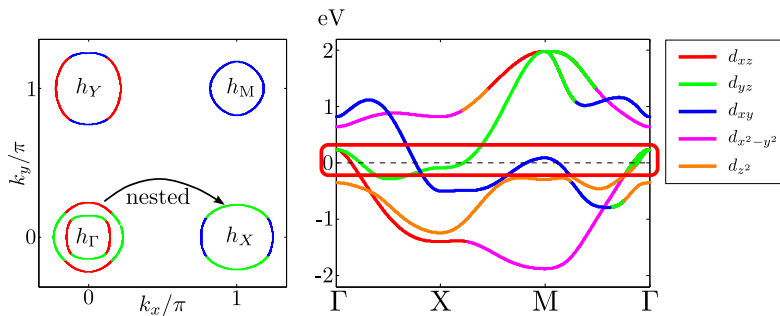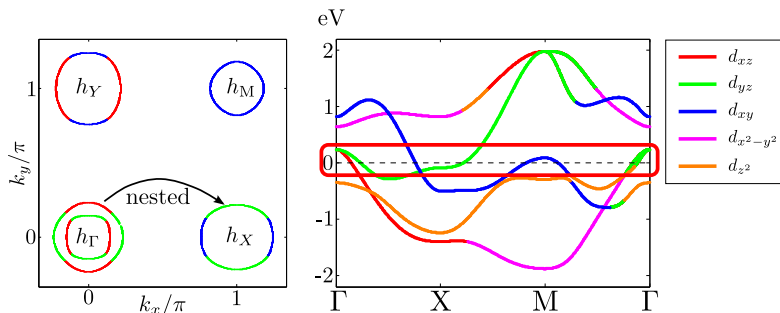H. Ikeda *et.al.* (2010)

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- Account for orbital dof's: 3 orbitals involved close to Fermi surfaces $d_{xz}, d_{yz}, d_{xy}$

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H. Ikeda *et.al.* (2010)

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- Plus all distinct interactions of low-energy orbital states (full model: 40 couplings)
- Start: onsite interactions $U, U', J, J'$
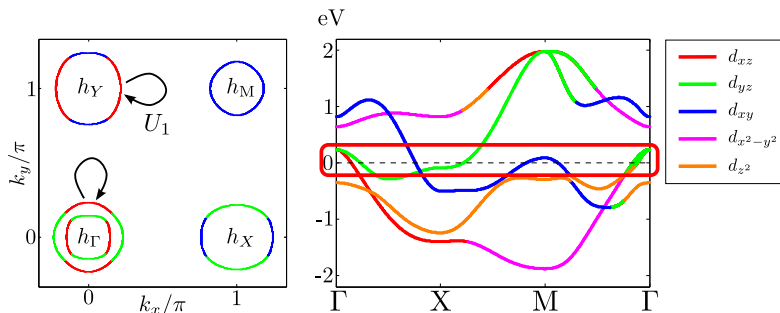- End: RG flow determines relevant processes

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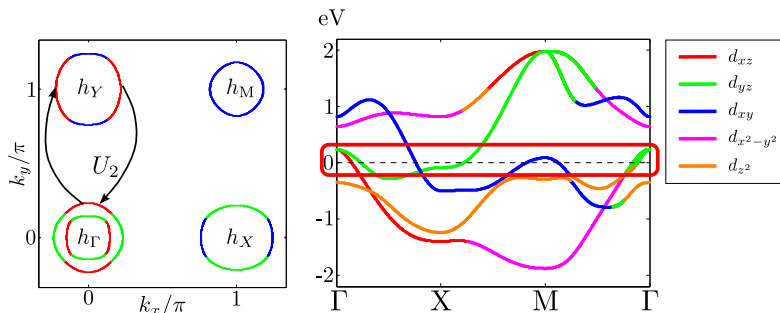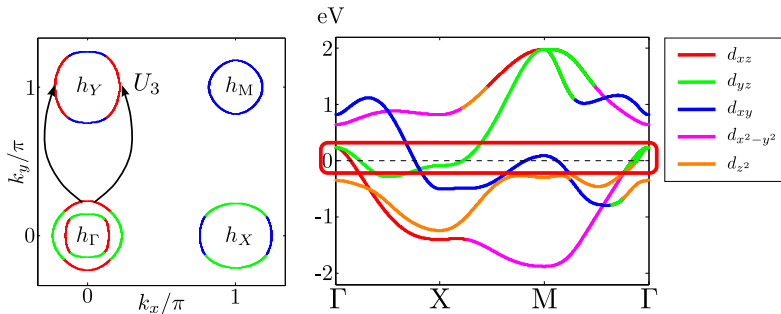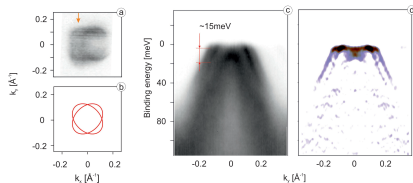- End: RG flow determines relevant processes

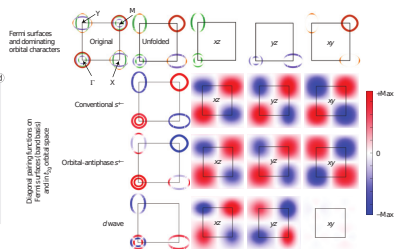# Band structure



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# Advantage: Account for orbital dof's

- Allows to describe orbital dependencies of different orders
- E.g. band splitting due to orbital order or orbital-antiphase $s^{+-}$ SC
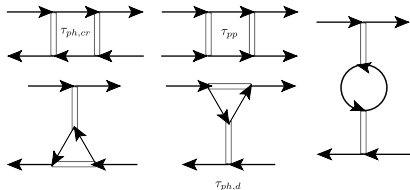


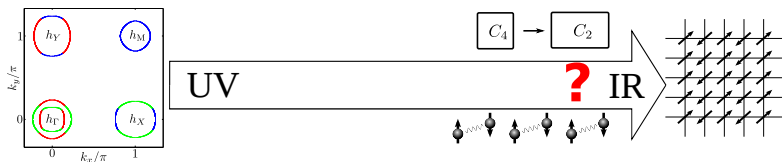A. Fedorov *et.al.* (2016)                                              Yin *et.al.* (2014)

- Pomeranchuk orbital order: $n_{xz}(\Gamma) - n_{yz}(\Gamma) \neq 0$ explains band splitting at $\Gamma$

# Parquet RG

- Describe scale evolution by progressively integrating out high-energy fermions
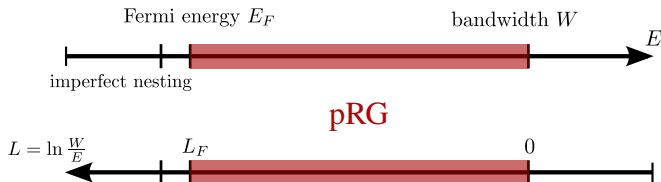  Only 1-loop logarithmic contributions



  - Largest *susceptibility* determines winner of competing orders



- Similar to patching fRG, but number of interactions is chosen by symmetry instead of number of FS patches
  Thomale, Platt, Hanke, Bernevig (2011)
- Advantage: Treat all instabilities on equal footing, analytically feasible
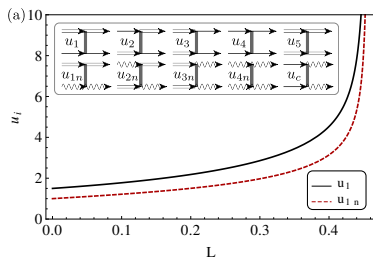
# Hierarchy of energy scales



- PRG works above $E_F$, where channels are coupled
- Below $E_F$ channels decouple $\rightarrow$ RPA physics
- Deviations from nesting cut particle-hole instabilities



S. Maiti and A. Chubukov (2011)

# Fixed trajectories

- Flow to strong coupling - Signals instability



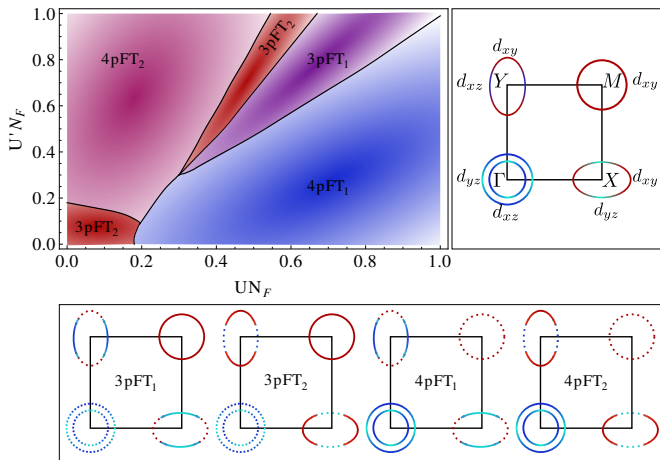- Ratios of couplings tend to universal fixed values
- Fixed ratios $\rightarrow$ Express all in terms of one dominant coupling

$$u_i = \gamma_i u_0 \quad \Rightarrow \quad u_0 \propto \frac{1}{L_0 - L}$$

- Fixed trajectory solution of $\beta_i = \partial_L \gamma_i = \frac{1}{u_i}(\partial_L u_i - \gamma_i \partial_L u_0) = 0$
- Stability matrix $\partial \beta_i / \partial \gamma_j |_{\gamma^*}$

# Flow of full 5p model

- Simple fixed trajectories: decoupling into 4 or 3 pockets



- Basins of attraction depend on initial values $U, U', J, J'$ and quasiparticle masses

# Does order develop? $\rightarrow$ Susceptibilities

- Couplings on FT as input for vertices
  E.g. $\Gamma_{SDW}^M = e_X^\dagger \boldsymbol{\sigma} h_M + h_M^\dagger \boldsymbol{\sigma} e_X$



$$\delta\Gamma_{SDW}^M \qquad \Gamma_{SDW}^M U_{1n} \qquad \Gamma_{SDW}^M U_{3n}$$

- Susceptibilities



$$\delta\chi_{SDW} =$$

- Vertex flows like $\Gamma_i \propto (L_0 - L)^{-\beta}$

$$\Rightarrow \chi_i \propto \int_L dL' \Gamma_i^2(L') \propto (L_0 - L)^{1-2\beta}$$

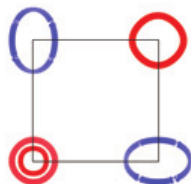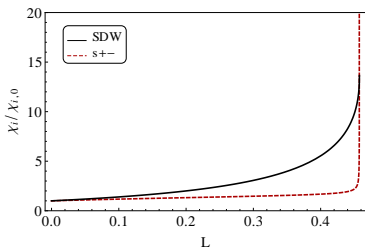- Order only develops if $\beta > \frac{1}{2}$ for $T_{ins} > E_F$

# Superconductivity without magnetism?

- On stable fixed trajectories

$$4\text{-pocket:} \quad \beta_{SDW} = 0.30 \quad \beta_{SC} = 0.86$$
$$3\text{-pocket:} \quad \beta_{SDW} = 0.43 \quad \beta_{SC} = 0.72$$

- $\Rightarrow$ If $E_F$ small enough, SC wins over magnetism
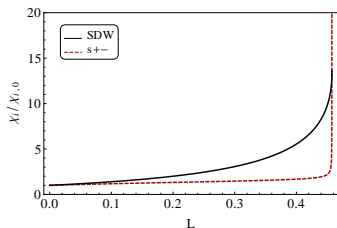  cf. also Thomale, Platt, Hanke, Bernevig (2011)



- SC is of $s^{+-}$ type (Orbital antiphase $s^{+-}$ subleading)
- Gap magnitudes on hole pockets differ for flow to 3 and 4 pocket model

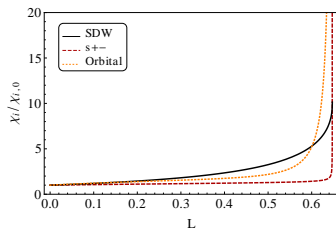# Type of magnetism and origin of nematicity

Flow to 3 pocket model

- If $E_{ins} > E_F$



Flow to 4 pocket model



- No orbital order at Γ
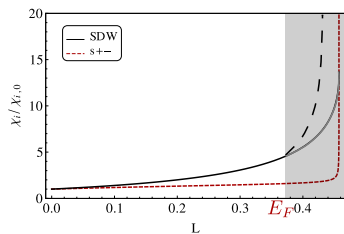
- Orbital order wins competition

*Eremin, Chubukov (2014): Fernandes, Chubukov, Khodas (2016)

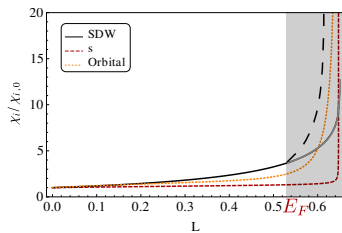# Type of magnetism and origin of nematicity

Flow to 3 pocket model

- If $E_{ins} > E_F$ If $E_{ins} < E_F$



Flow to 4 pocket model



- No orbital order at $\Gamma$
- Ginzburg-Landau[*]: stripe SDW
  $\rightarrow$ Ising-nematic order

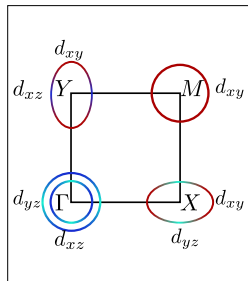  [*]Eremin, Chubukov (2014); Fernandes, Chubukov, Khodas (2016)

- Orbital order wins competition
- checkerboard SDW
  $\rightarrow$ no nematic order

# Conclusion

- PRG flow of full 5-pocket low-energy model for FeSC's analyzed

- Amazingly simple fixed trajectories: decoupling into 3-pocket or 4-pocket model

- Same microscopic model provides 2 different scenarios for SC



e.g. $BaFe_2As_2$ with $E_F > E_{ins}$

- Stripe SDW in parent compounds
- SC upon doping
- Ising-nematic order

e.g. LiFeAs, FeSe with $E_F < E_{ins}$

- Superconductivity without magnetism in parent compound
- Orbital Order possible

See also: LC,Xing, Khodas,Chubukov submitted
First simplified model: Chubukov, Khodas, Fernandes arXiv:1602:05503

Role of weakly unstable fixed trajectories: Xing, LC, Khodas, Chubukov in preparation