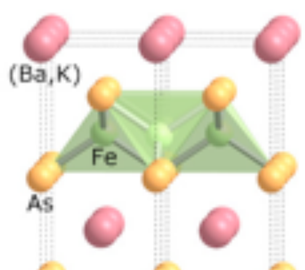
History, Present, Future: Functional RG for unconventional superconductors

Ronny Thomale

Julius-Maximilians Universität Würzburg



Deutsche Forschungsgemeinschaft DFG

SPP 1458

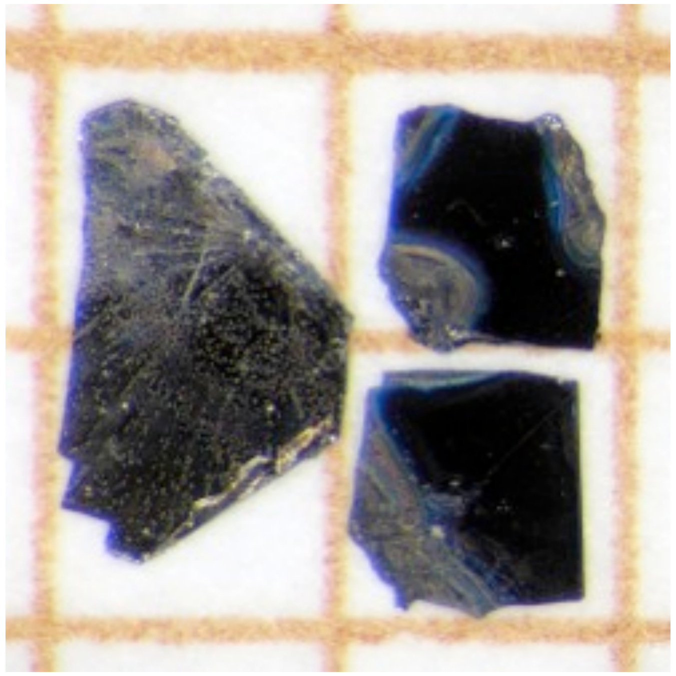
erc

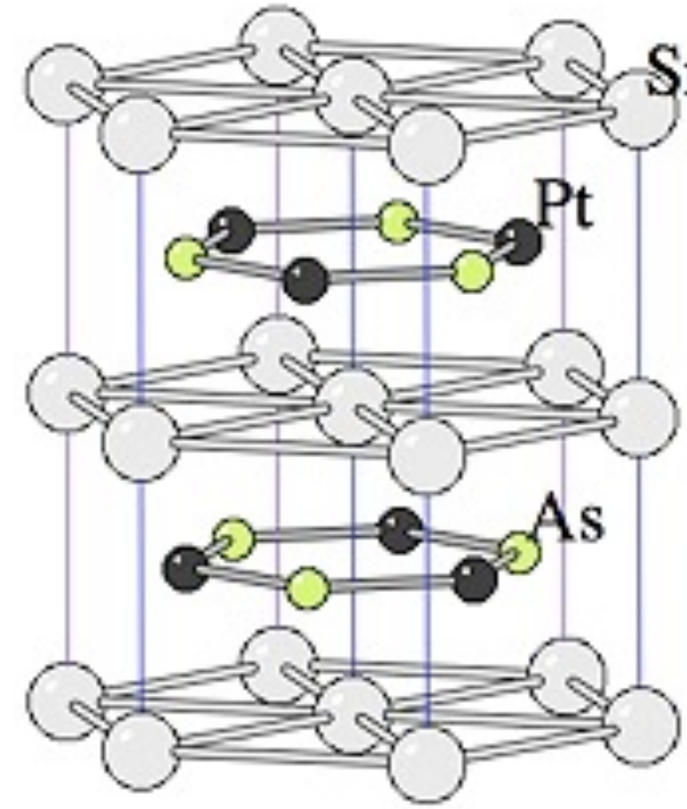
TOPOLECTRICS

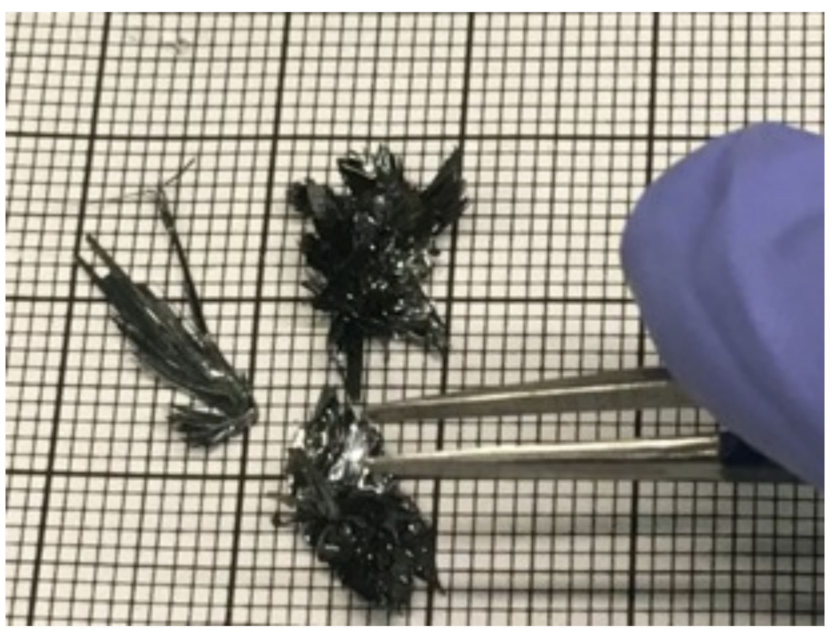
SFB 1170

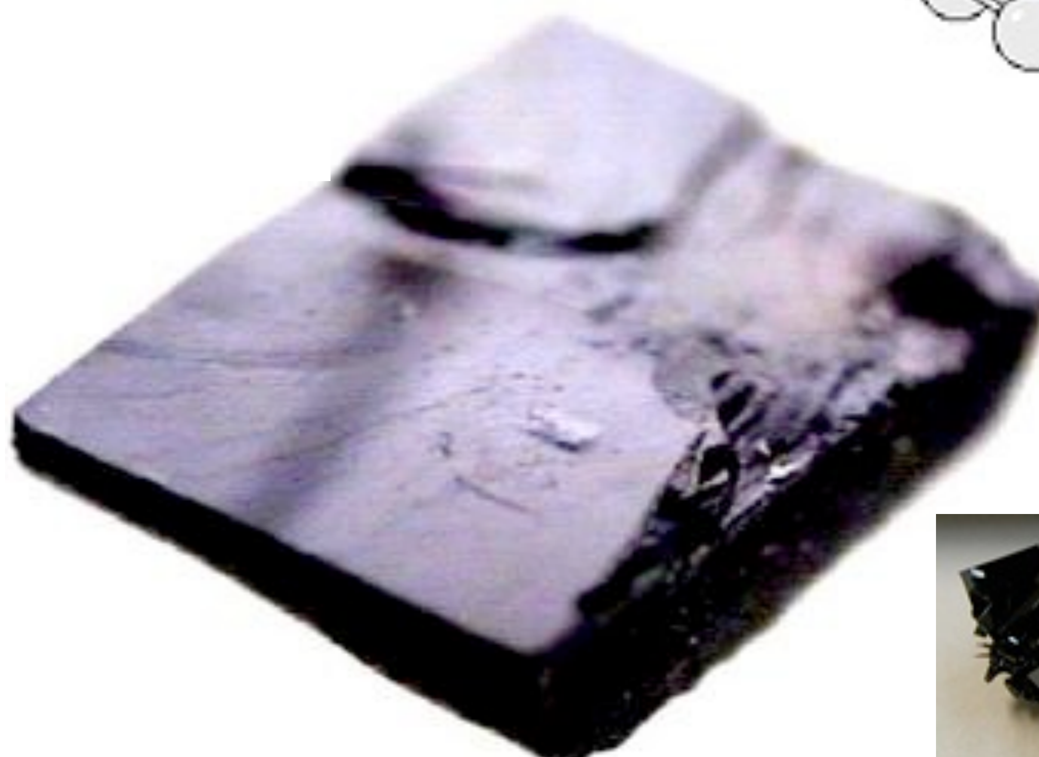
"Functional Renormalization - from quantum gravity and dark energy to ultracold atoms and condensed matter"

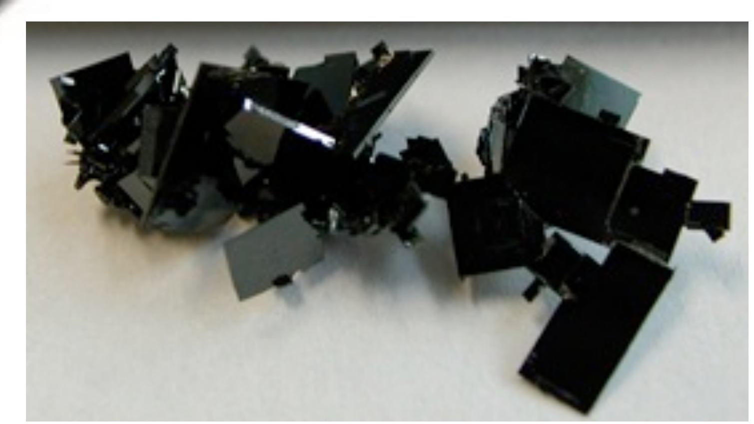
Unconventional superconductors











Outline

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- Timeline of materials studied through FRG
- Recent methodological step: multi-band/orbital superconductivity

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- Recent methodological step: multi-band/orbital superconductivity

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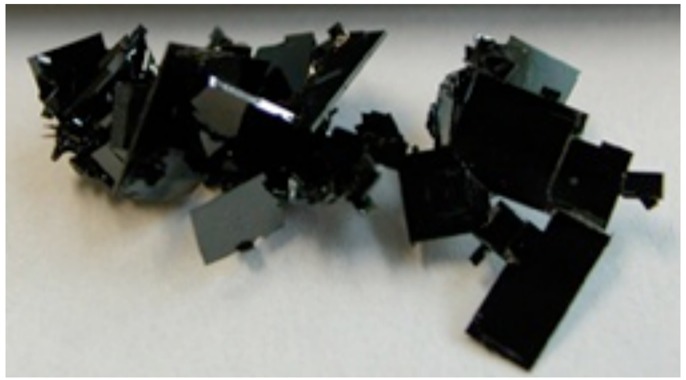
- Pnictides: extended d-wave vs. extended s-wave
- Sodium cobaltates: chiral d-wave?

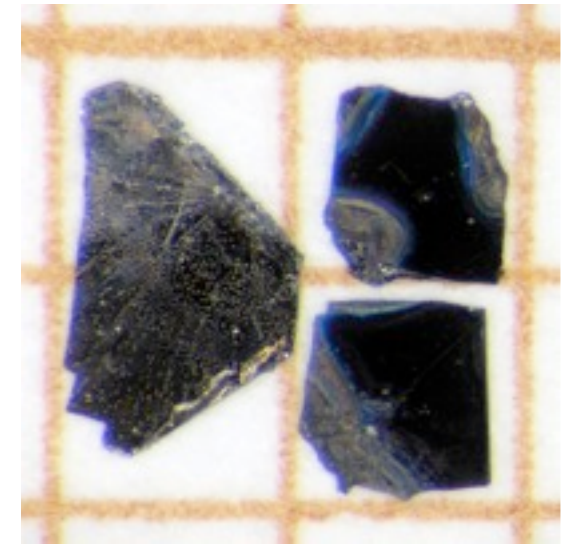
Future

- SrPtAs: Weyl superconductors
- LAO/STO heterostructures

History

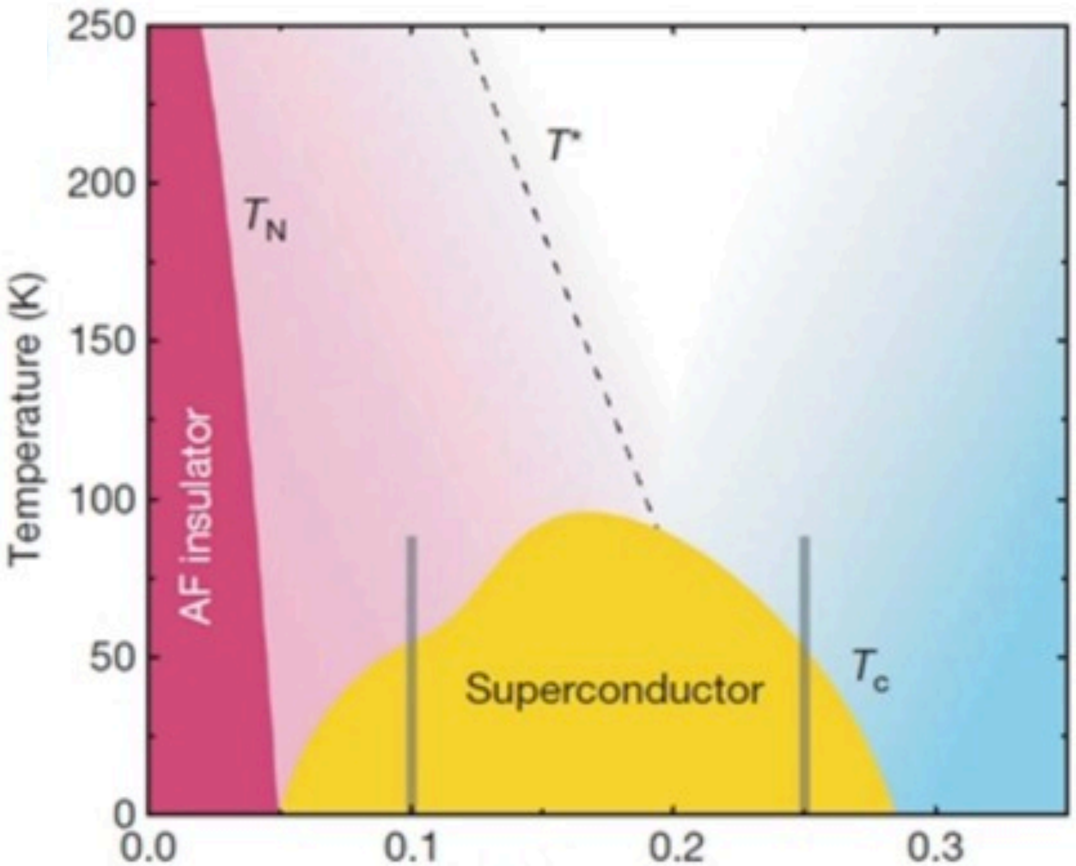
Timeline

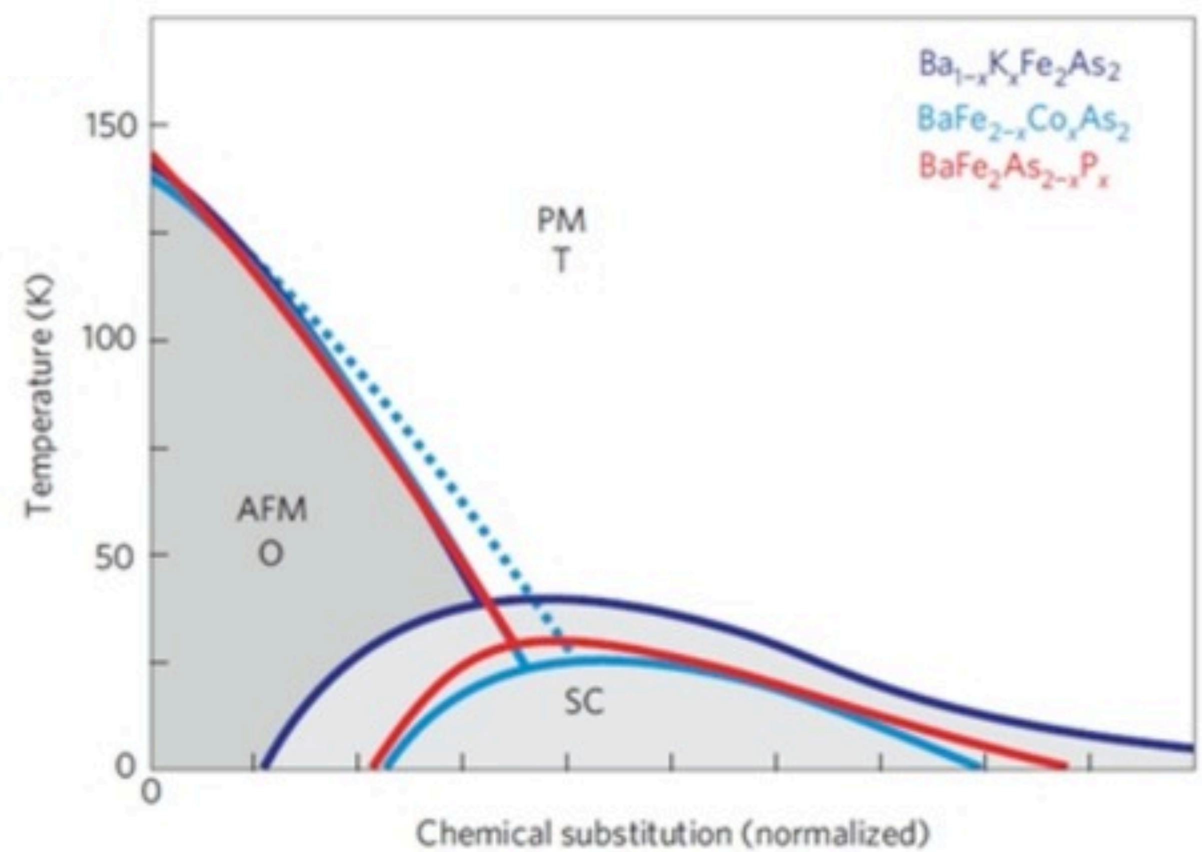




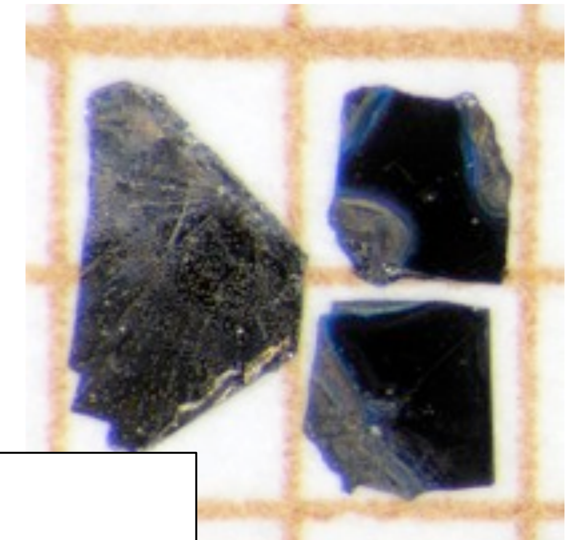
Wetterich '93 | Schulz '99 | Honerkamp, Salmhofer '01 | Thomale '09

'84 Polchinski | '94 Shankar | '00 Metzner | '08 Fa Wang | '11 Qianghua Wang





Timeline



Wetteric
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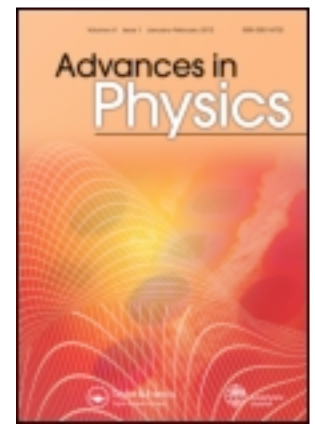
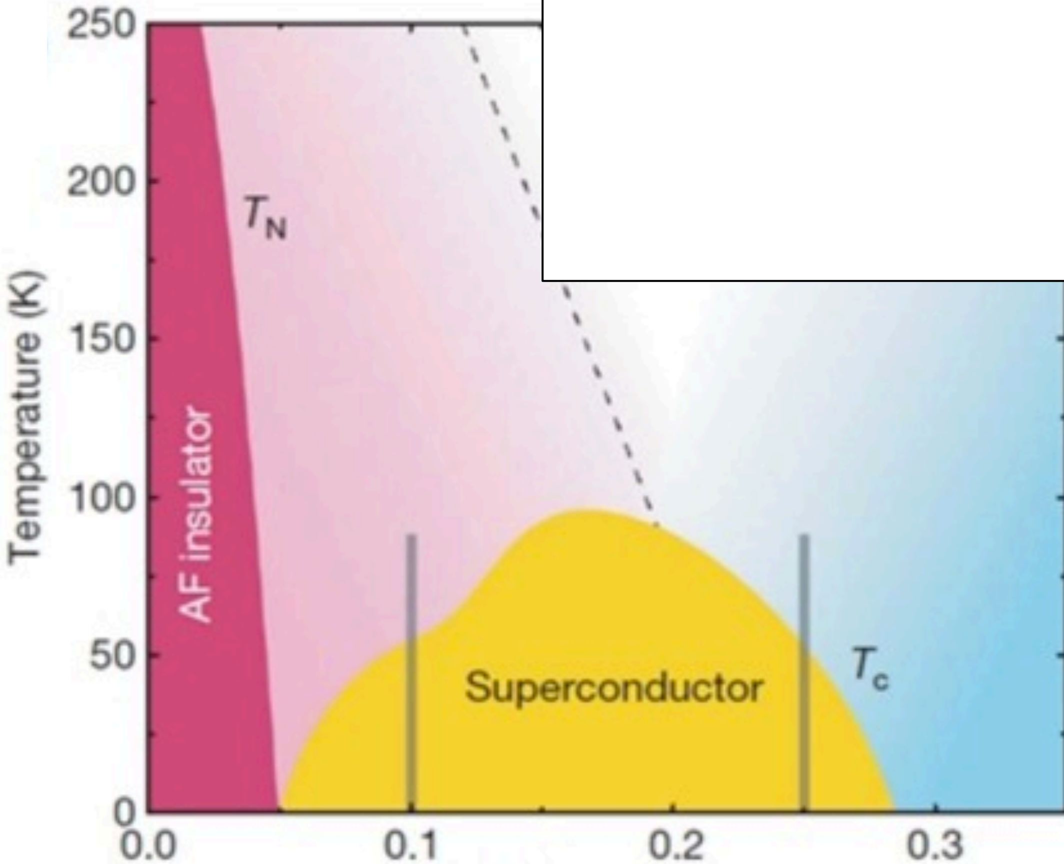
'84 Polchinski

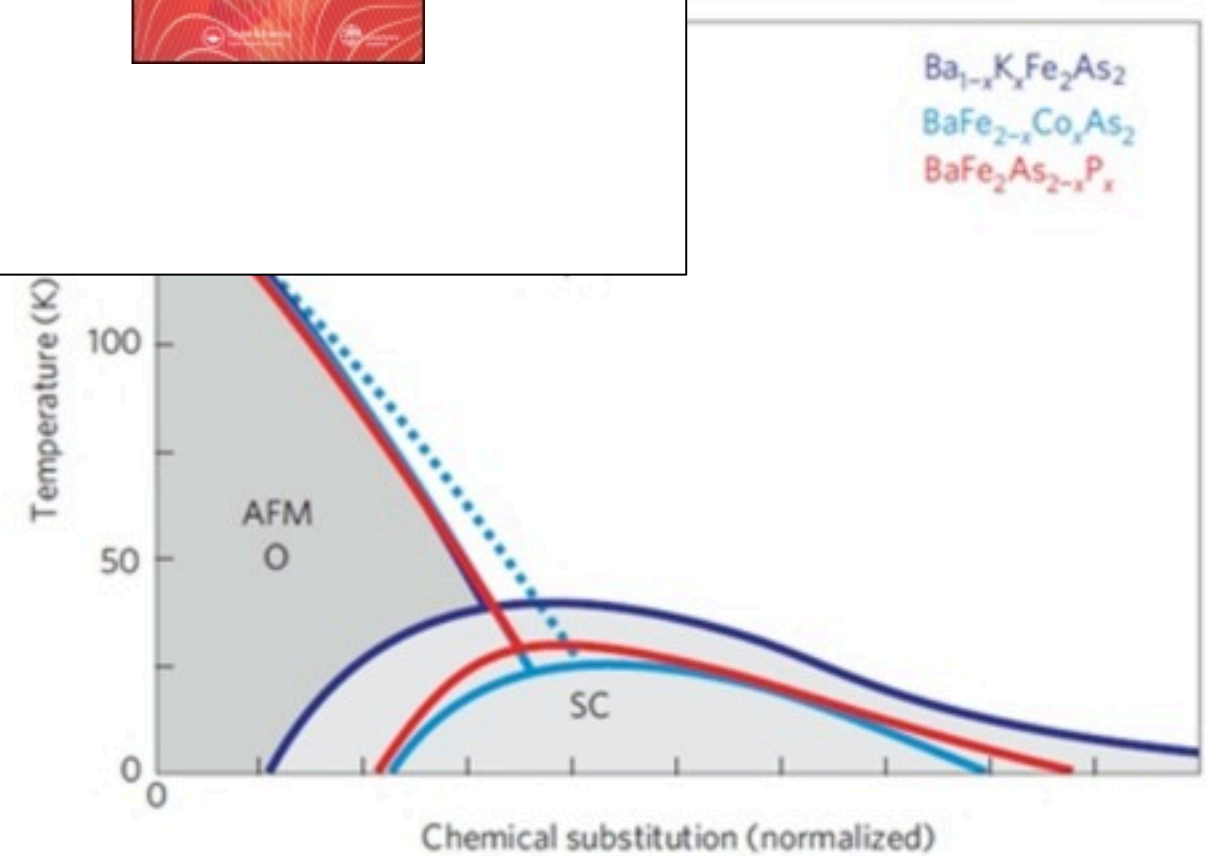
'9 Shar

hua Wang

Platt, Hanke, Thomale
Advances in Physics
Vol. 62, p. 453-562, 2014







Harmonic composition of SC form factors

The favored real space pairing function $\Delta_{i,j} \sim \langle c_i^\dagger c_j^\dagger \rangle$

transforms under irreducible point group representations

C_{4v}	E	C_2	$2C_4$	$2\sigma_v$	$2\sigma_d$
A_1	1	1	1	1	1
A_2	1	1	1	-1	-1
B_1	1	1	-1	1	-1
B_2	1	1	-1	-1	1
E	2	-2	0	0	0

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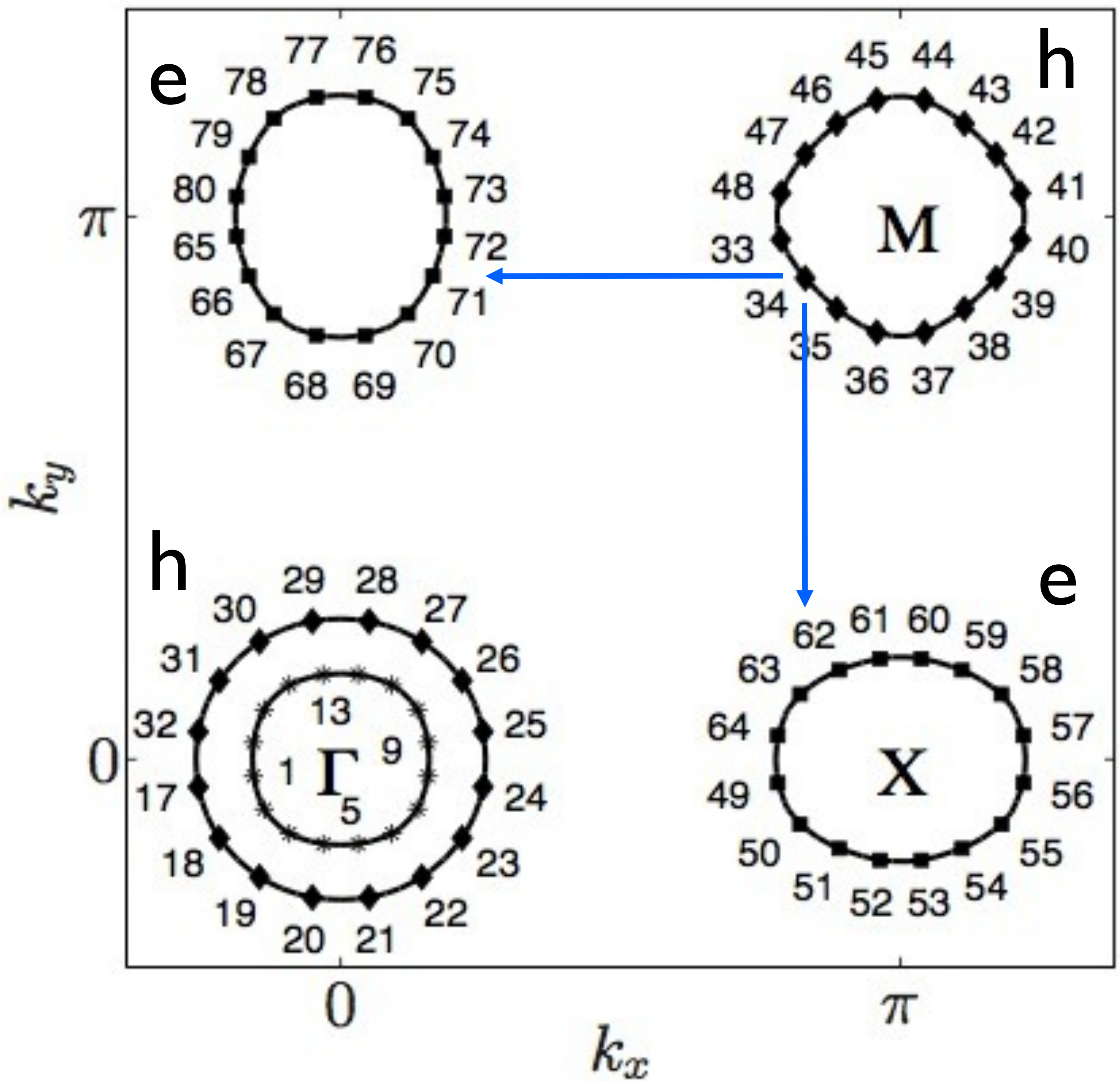
The point group representation does not fix the form of the superconducting gap function, even without further symmetry breaking

$$\Delta_s(\mathbf{k}) = 1 + \alpha(\cos k_x + \cos k_y)$$

$$\Delta_{d_{x^2-y^2}}(\mathbf{k}) = \cos k_x - \cos k_y + \alpha(\cos 2k_x - \cos 2k_y)$$

Extended s-wave in the pnictides



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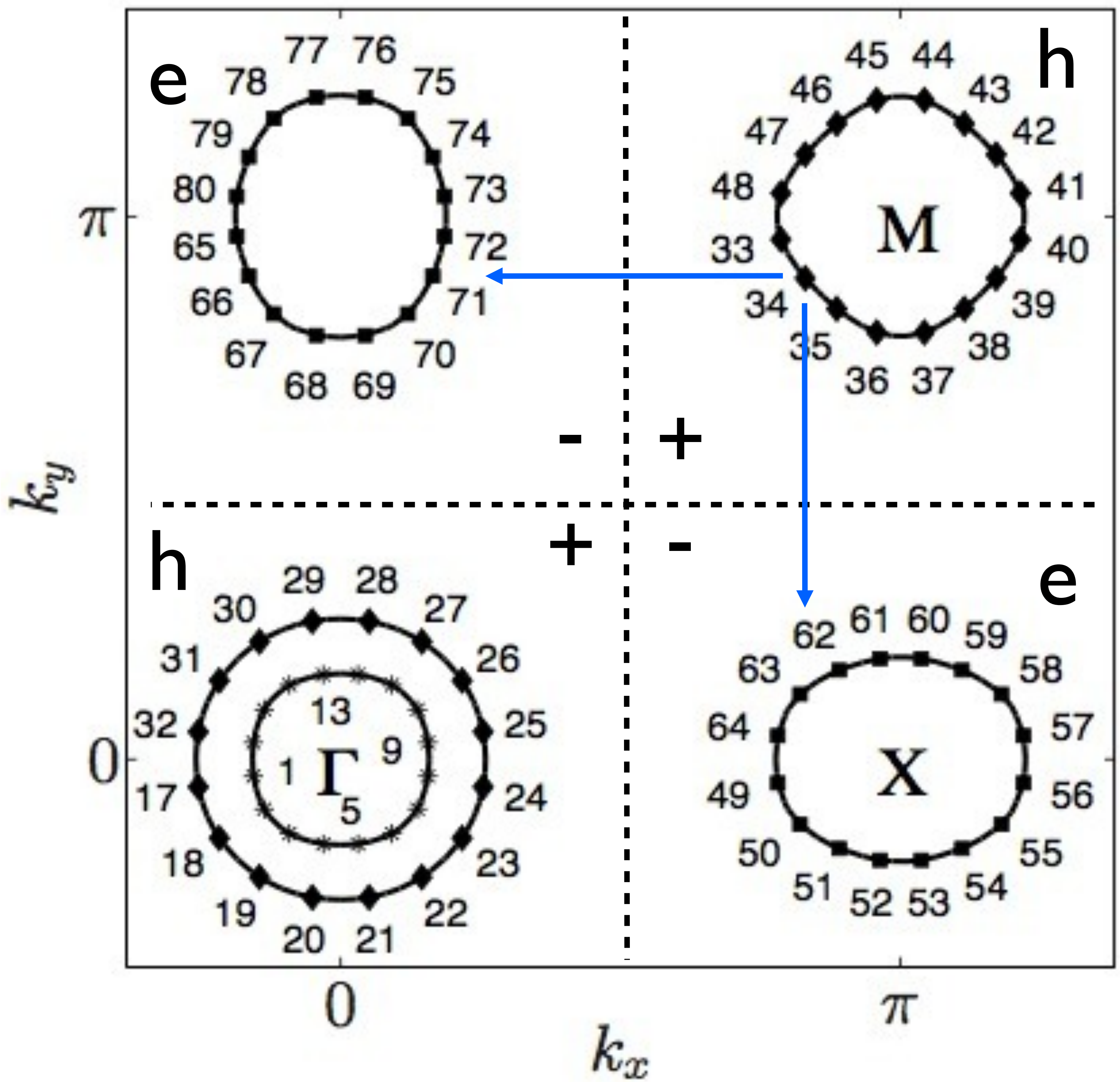
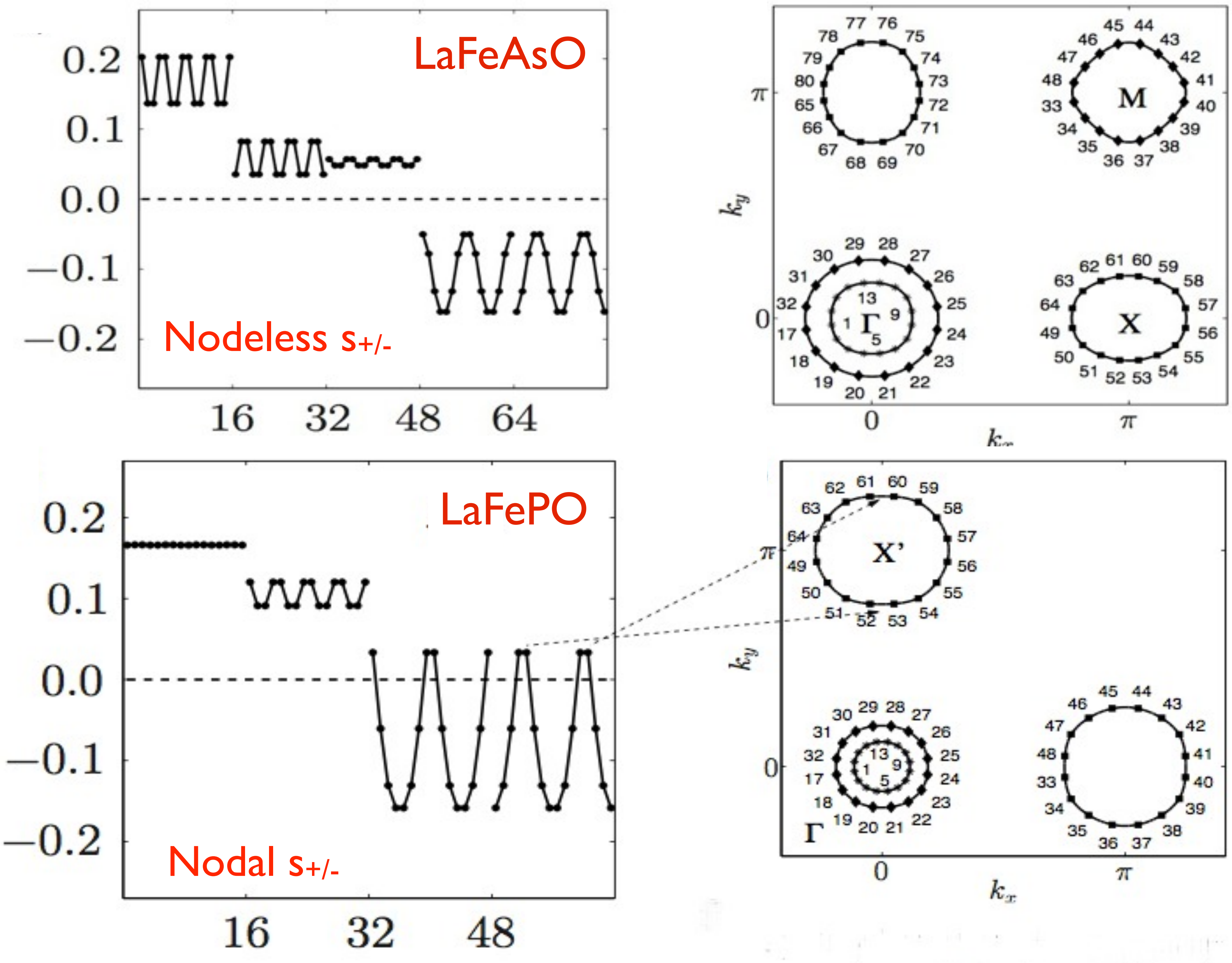


LaFeAsO vs. LaFePO: s-wave anisotropy

Thomale, Platt, Hanke, Bernevig, PRL 106, 187003 (2011)



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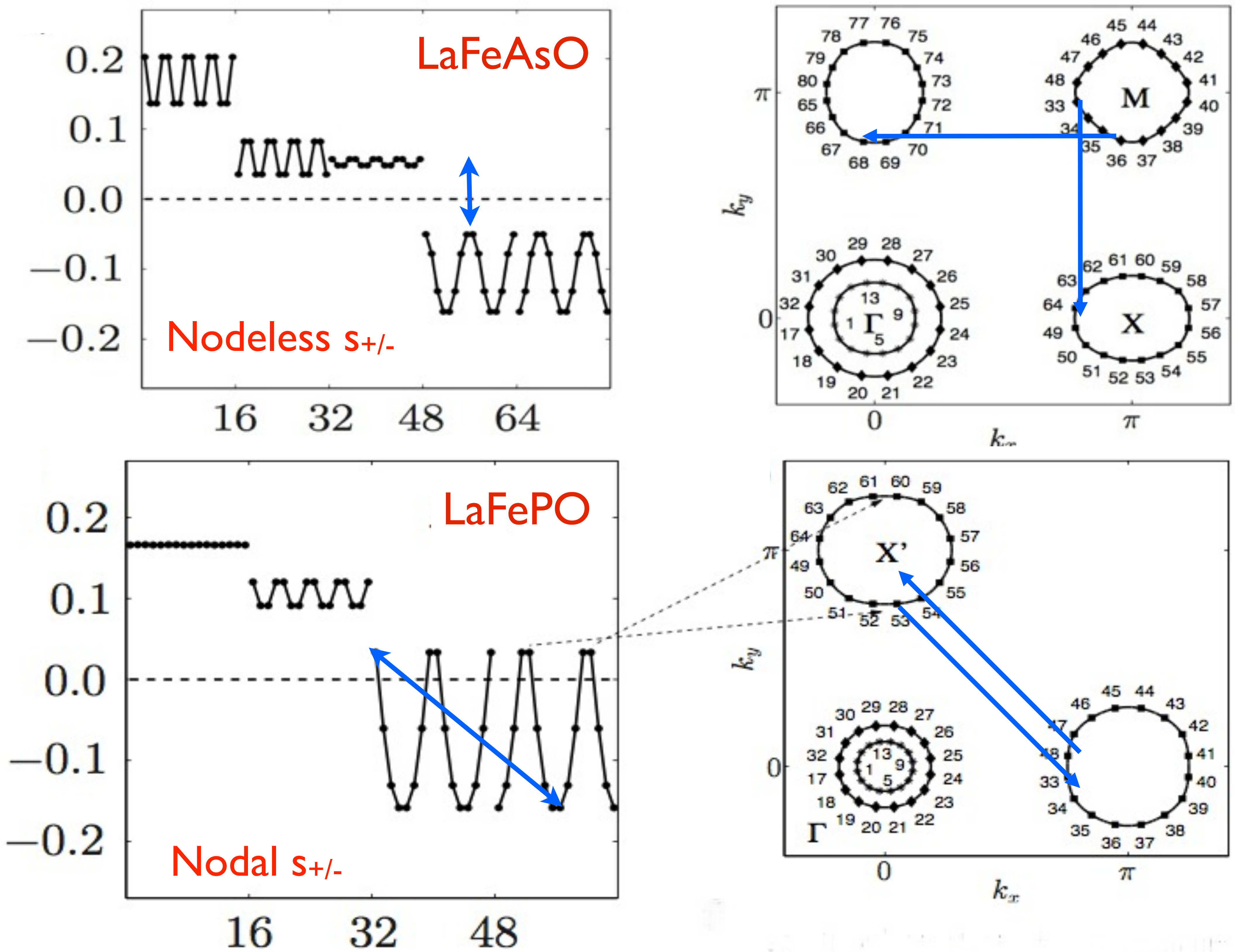

Prediction of extended d-wave in pnictides

RAPID COMMUNICATIONS

PHYSICAL REVIEW B **80**, 180505(R) (2009)

Functional renormalization-group study of the doping dependence of pairing symmetry in the iron pnictide superconductors

Ronny Thomale,[1] Christian Platt,[2] Jiangping Hu,[3] Carsten Honerkamp,[2] and B. Andrei Bernevig[4]
[1]*Institut für Theorie der Kondensierten Materie, Universität Karlsruhe, D 76128 Karlsruhe, Germany*
[2]*Theoretical Physics, University of Würzburg, D-97074 Würzburg, Germany*
[3]*Department of Physics, Purdue University, West Lafayette, Indiana 47907, USA*
[4]*Department of Physics, Princeton University, Princeton, New Jersey 08544, USA*
(Received 19 October 2009; published 13 November 2009)

We use the functional renormalization group to analyze the phase diagram of a four-band model for the iron pnictides subject to band interactions with certain A_{1g} momentum dependence. We determine the parameter regimes where an extended *s*-wave pairing instability with and without nodes emerges. For electron doping, the parameter regime in which a nodal gap appears is in correspondence to recent predictions [A. Chubukov *et al.*, arXiv:0903.5547 (unpublished)], however, at very low T_c. Upon hole doping, the *s*-wave gap never becomes nodal: above a critical strength of the intraband repulsion, the system favors an exotic extended *d*-wave instability on the enlarged hole pockets. At half filling, we find that a strong momentum dependence of

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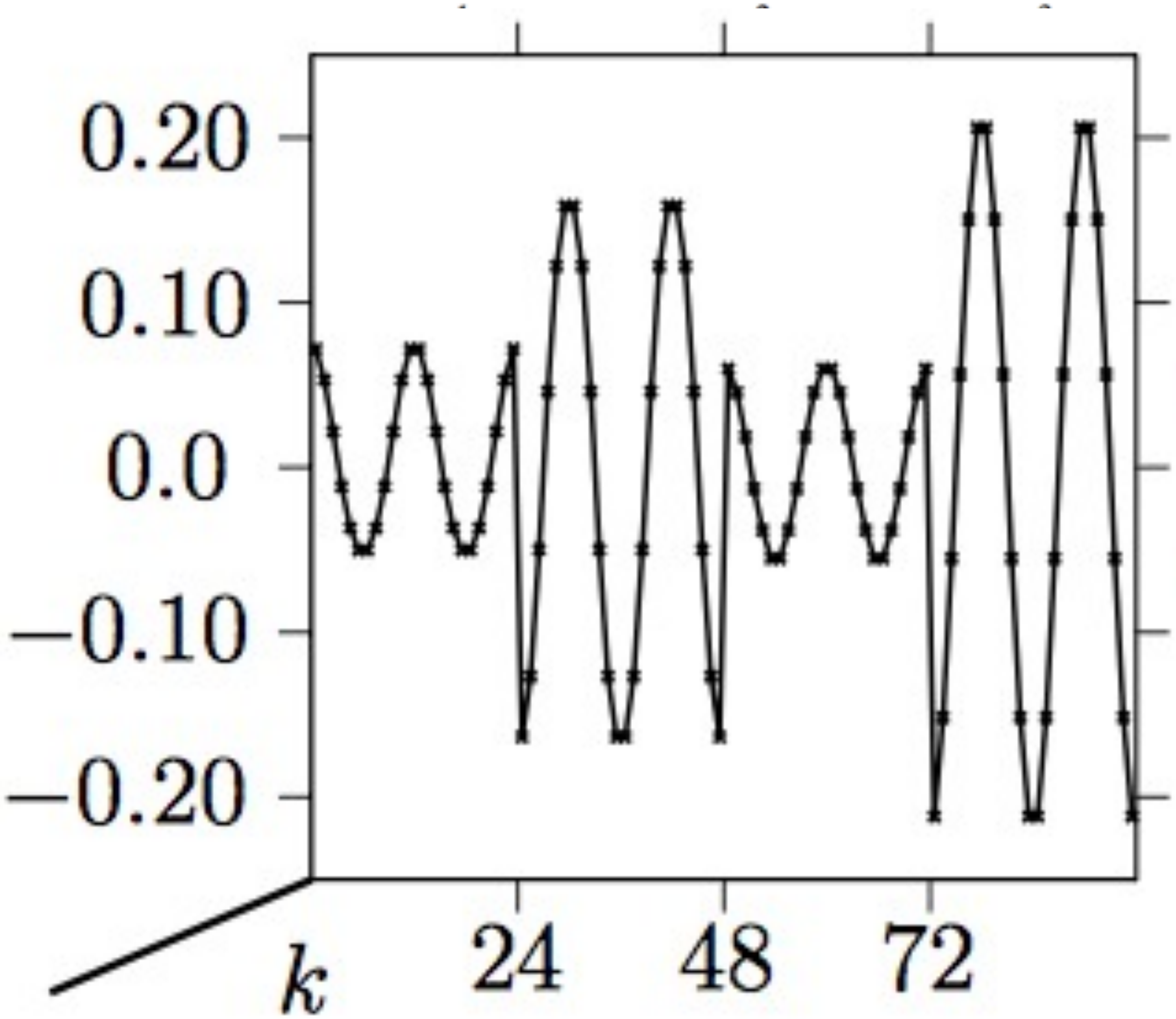
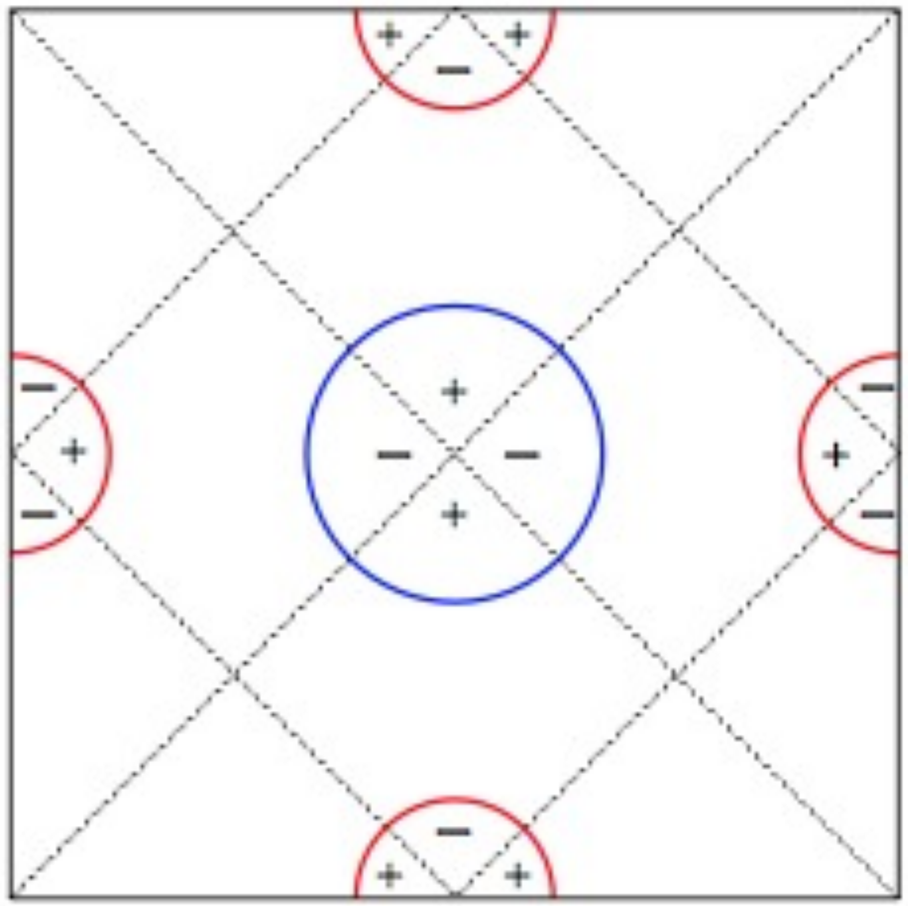
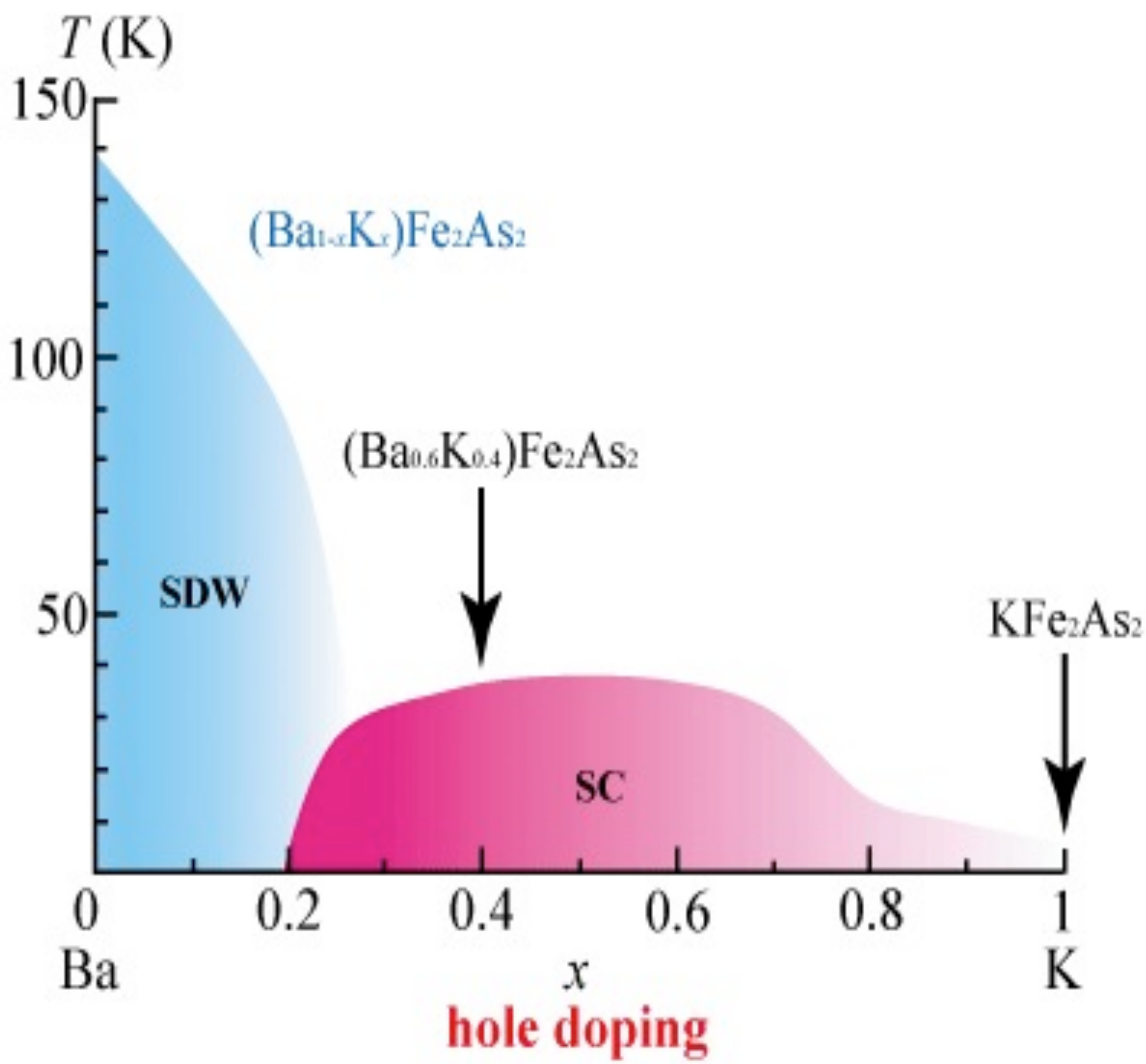


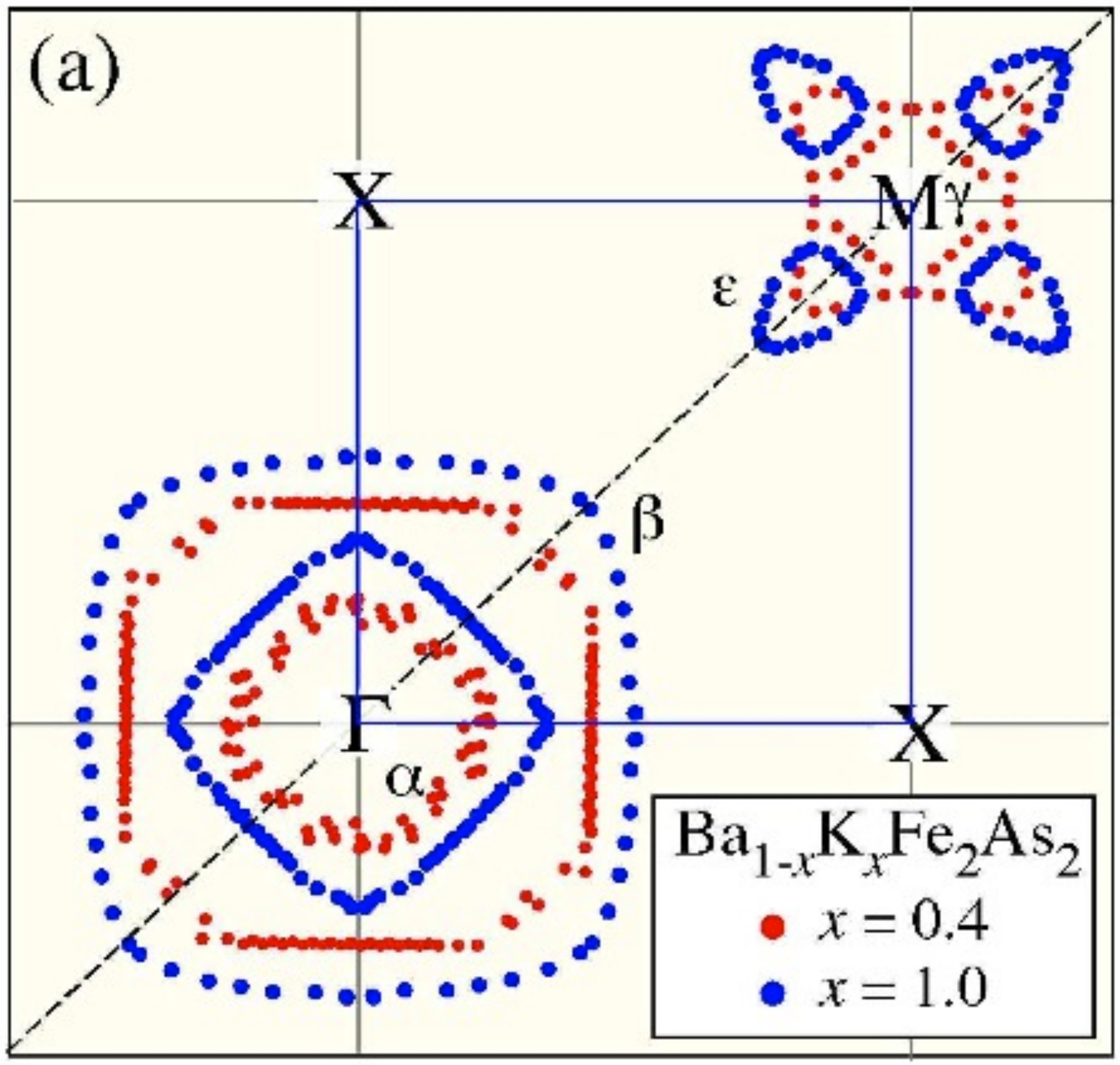


Present

D-wave in hole doped iron pnictides?

- moderate hole doping: electron and hole pockets
- strong hole doping: only hole pockets present





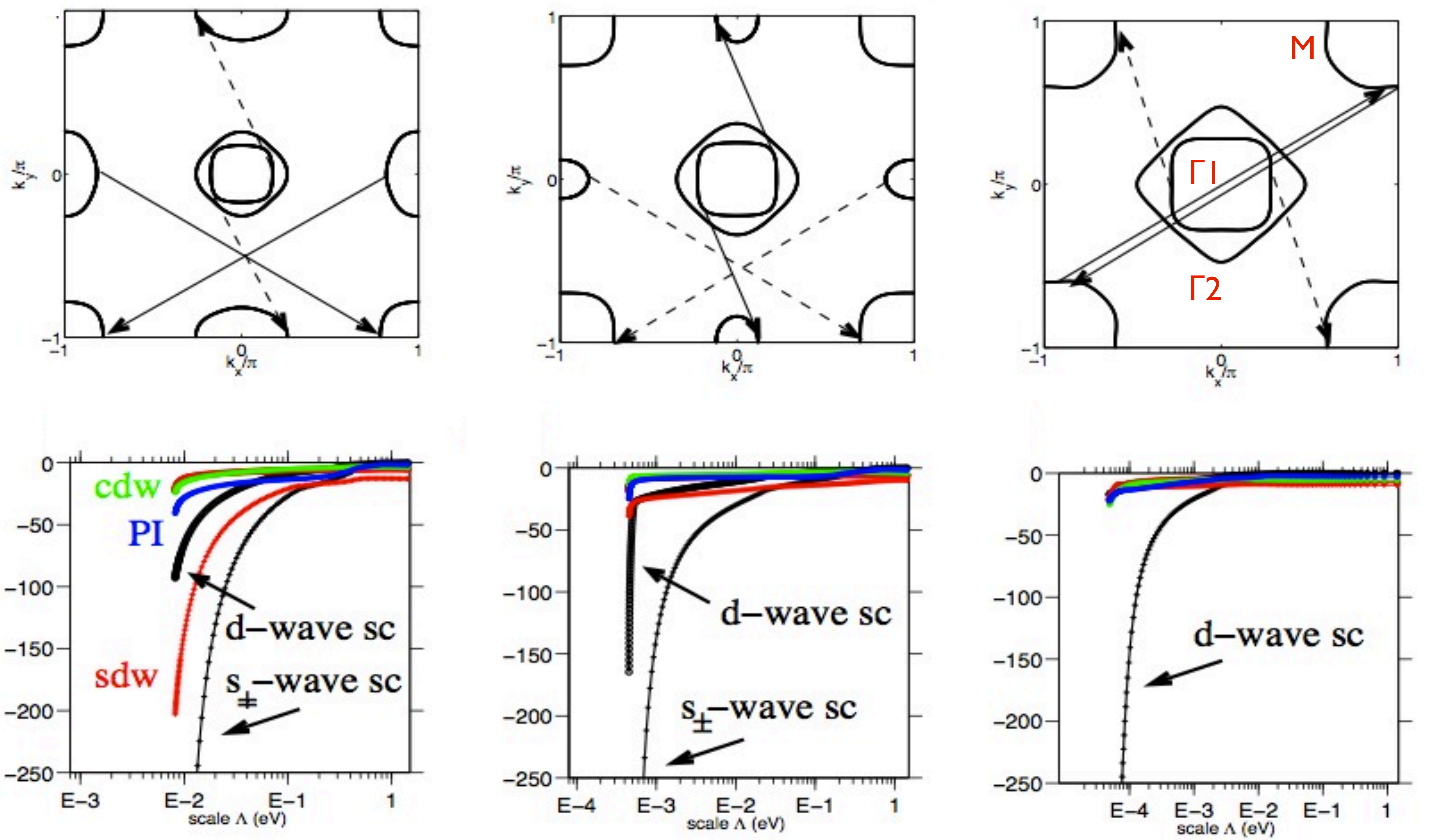
Ding group (China)

FRG: s to d-wave transition in K-doped Ba-122

Thomale, Platt, Hanke, Hu, Bernevig, PRL 107, 117001 (2011).

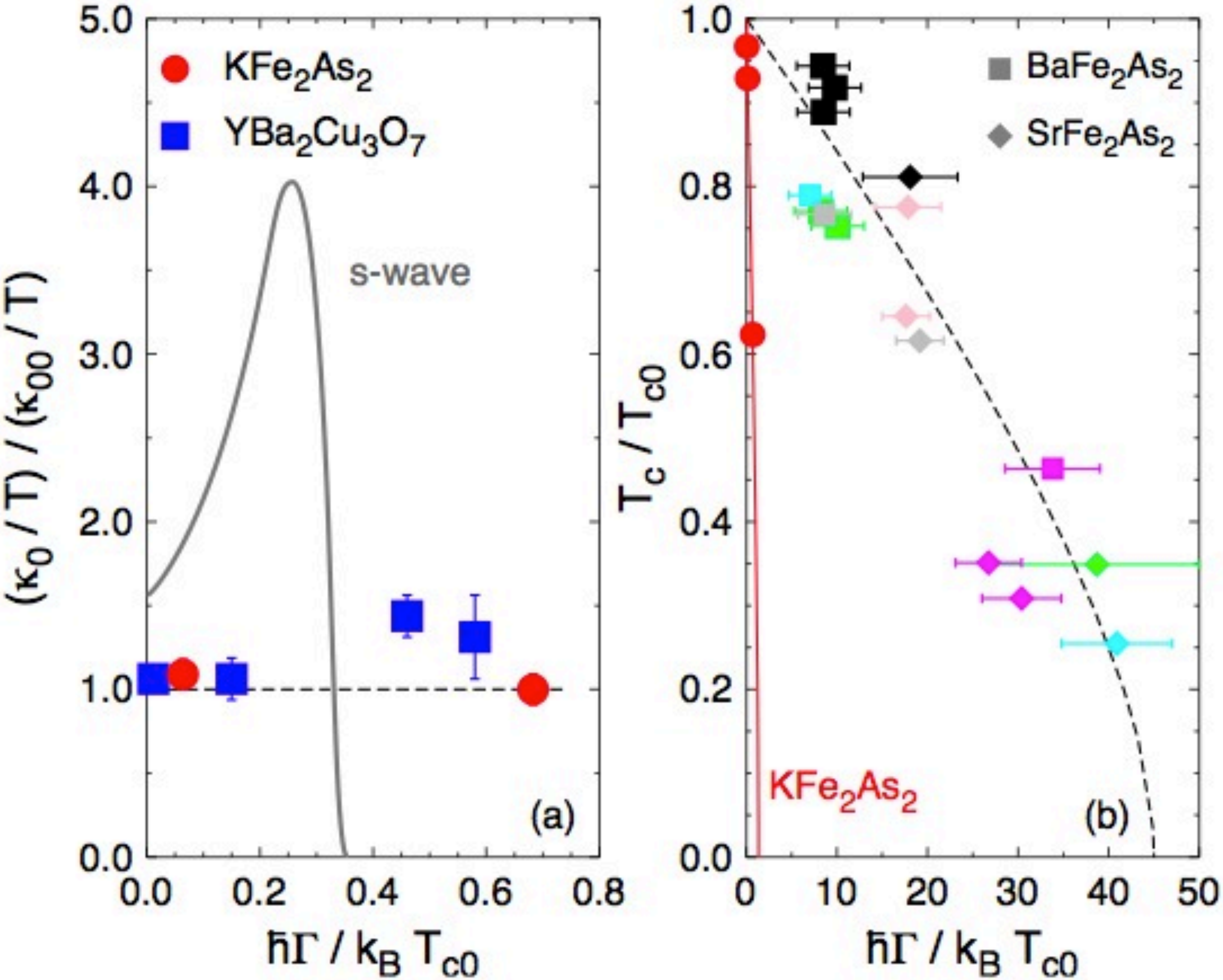
x=0.4

hole doping



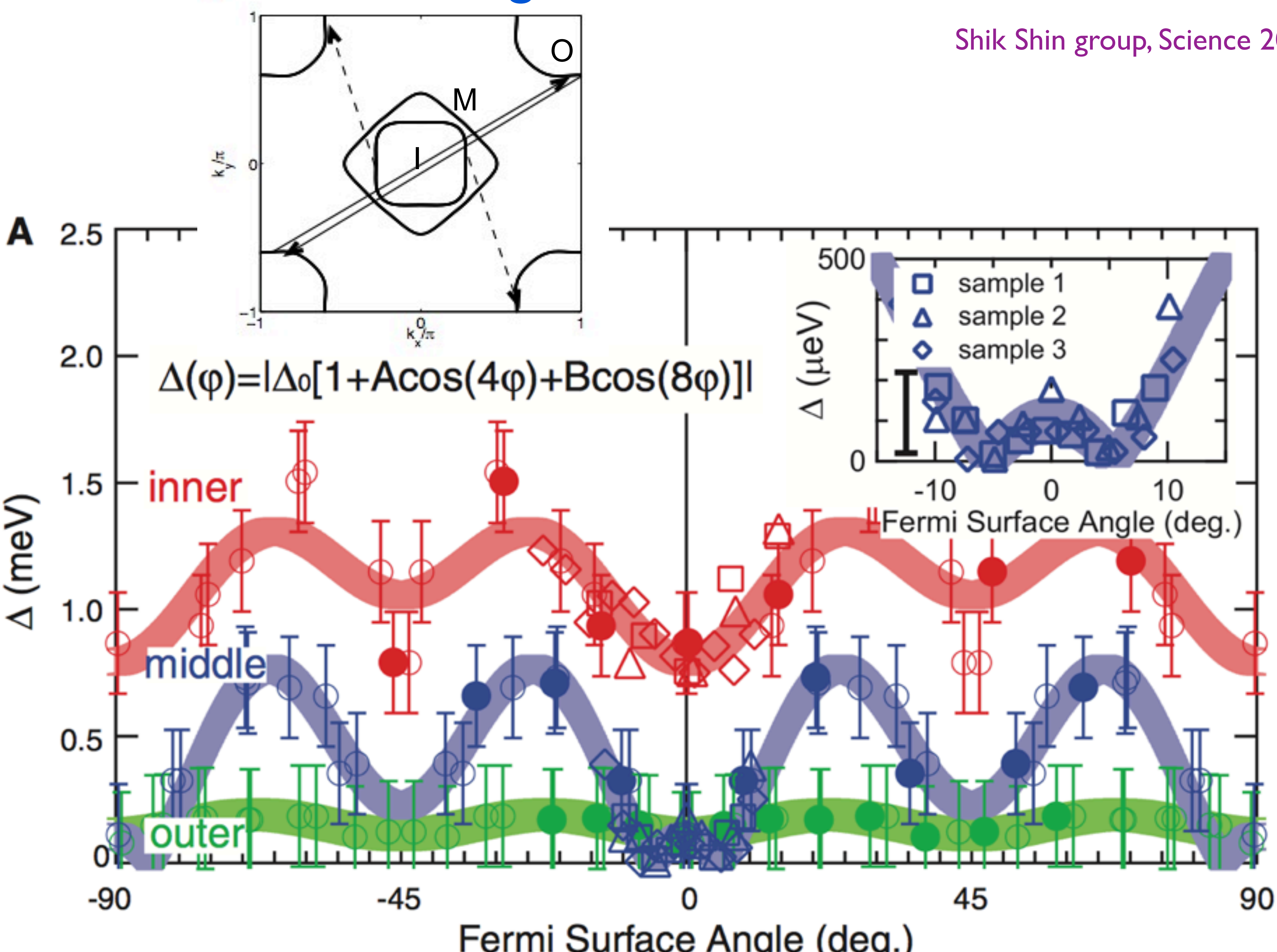
Evidence for d-wave: thermal transport

Taillefer group, Reid et al. PRL 2012



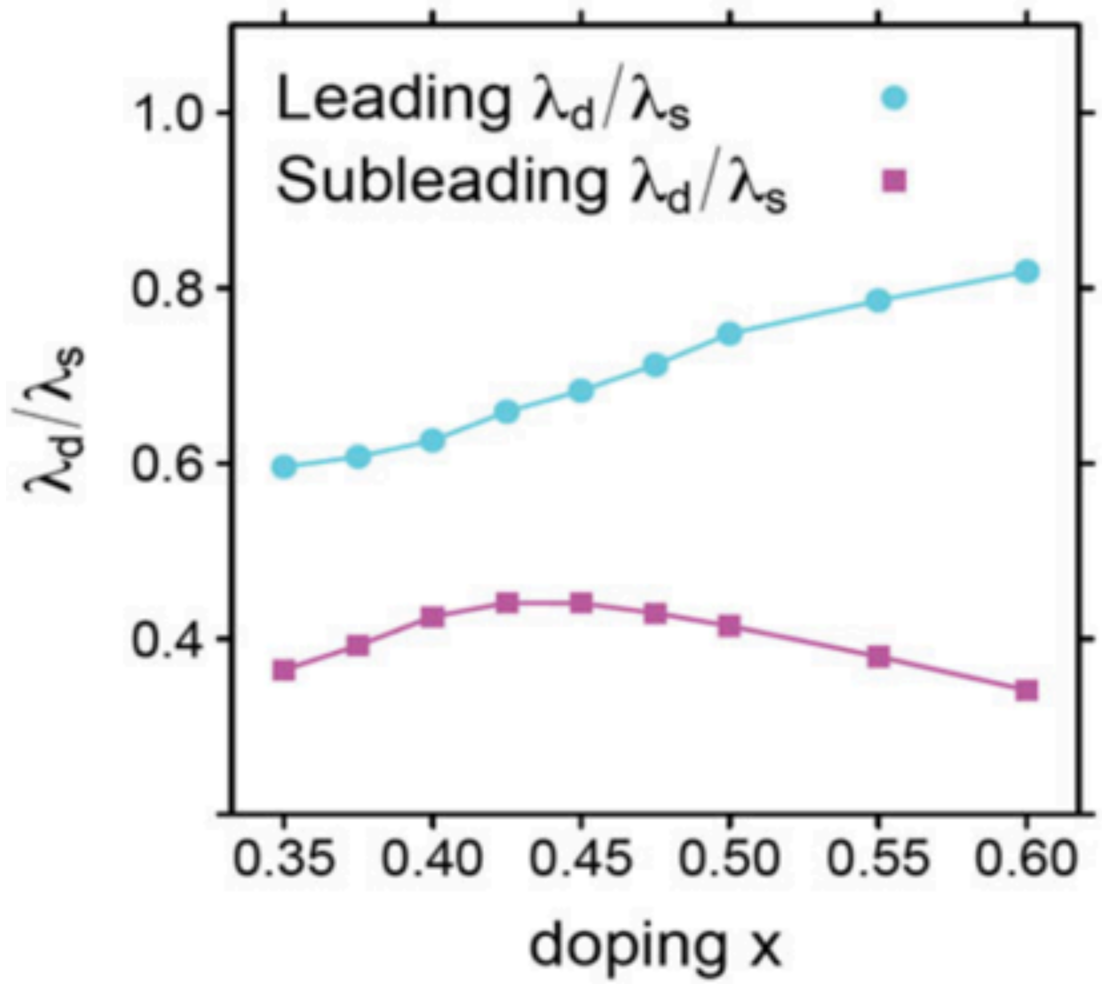
Evidence against d-wave: Laser ARPES

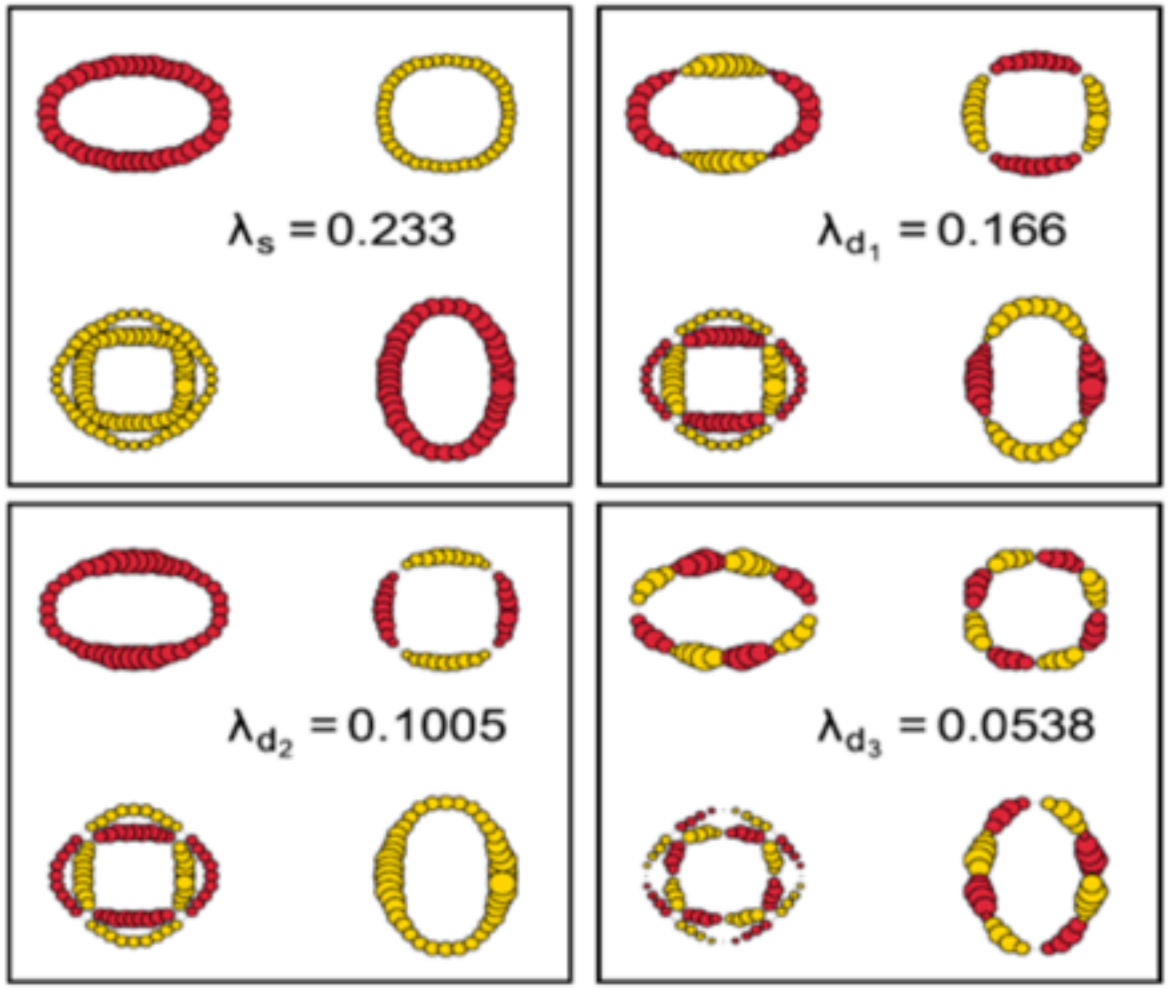
Shik Shin group, Science 2012



Raman: extended d-wave dominant subleading order

Maiti et al., PRL 117, 257001 (2016); Böhm et al., in preparation.





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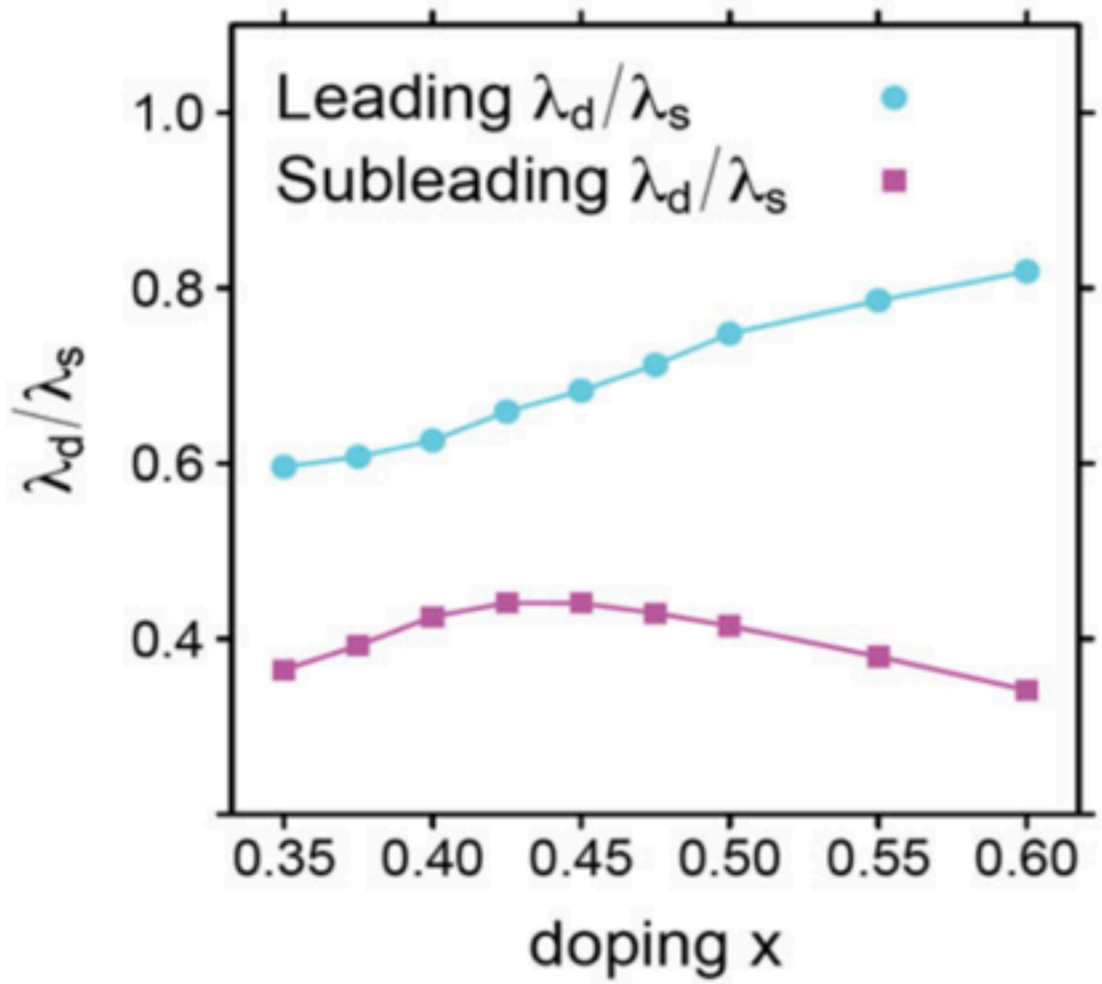

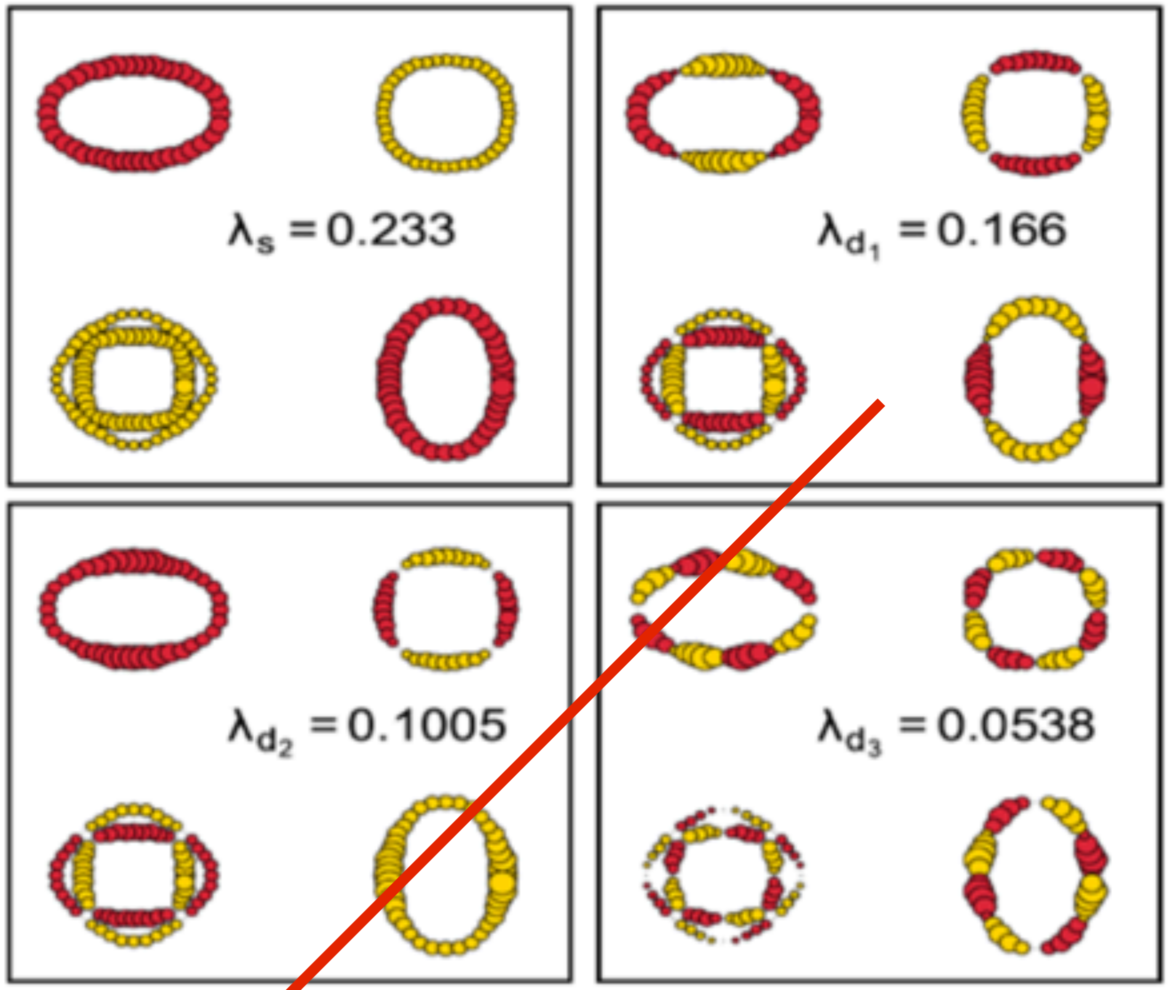

Extended d-wave!

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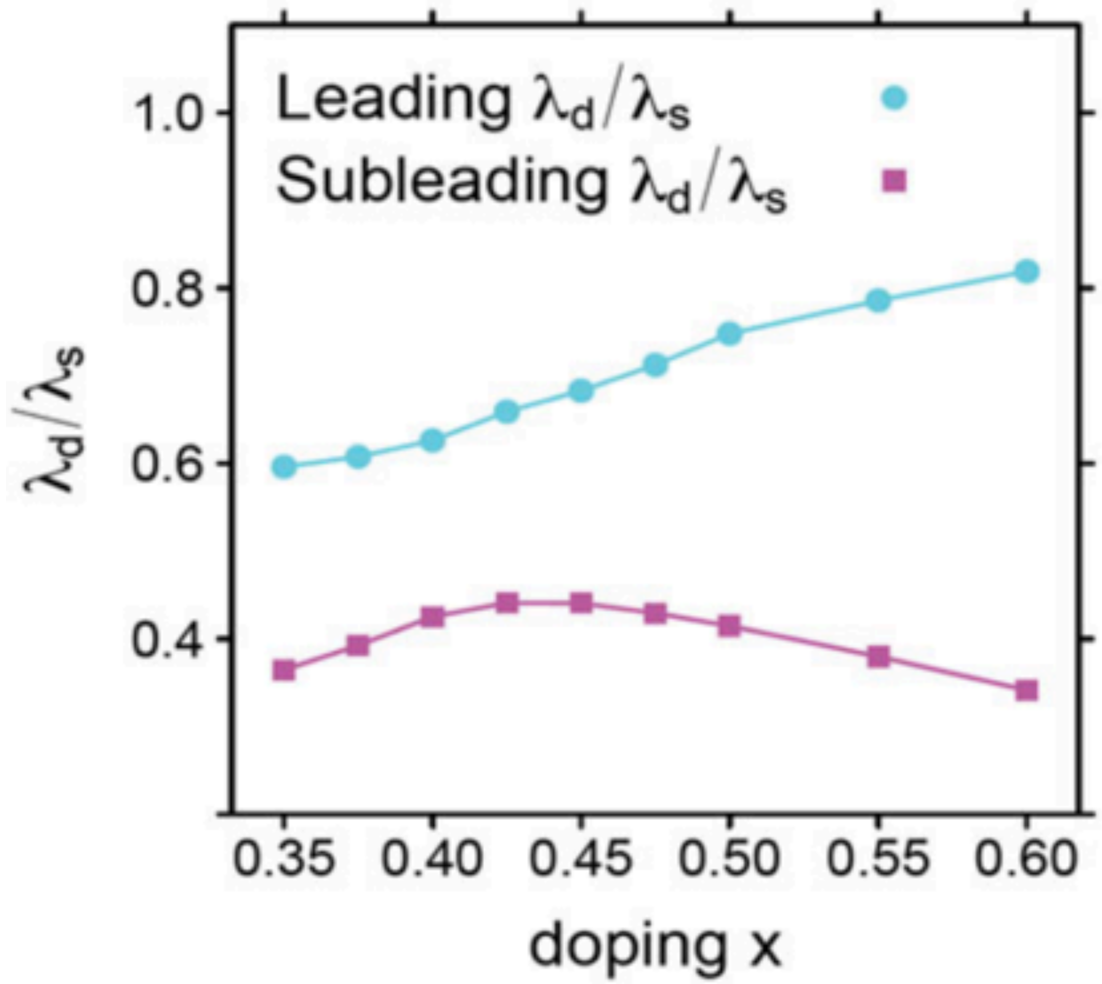
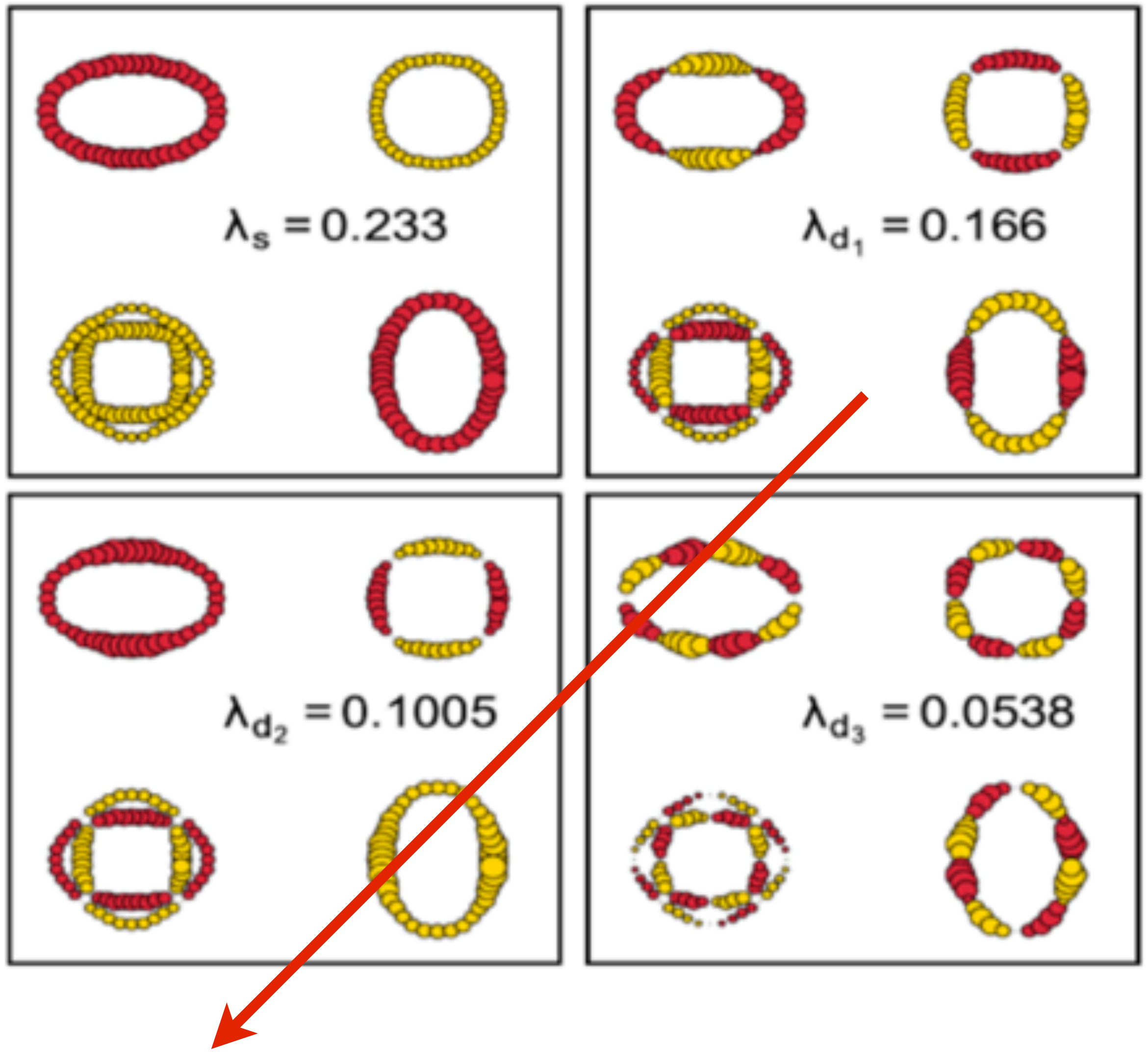
Maiti et al., PRL 117, 257001 (2016); Böhm et al., in preparation.





Extended d-wave!

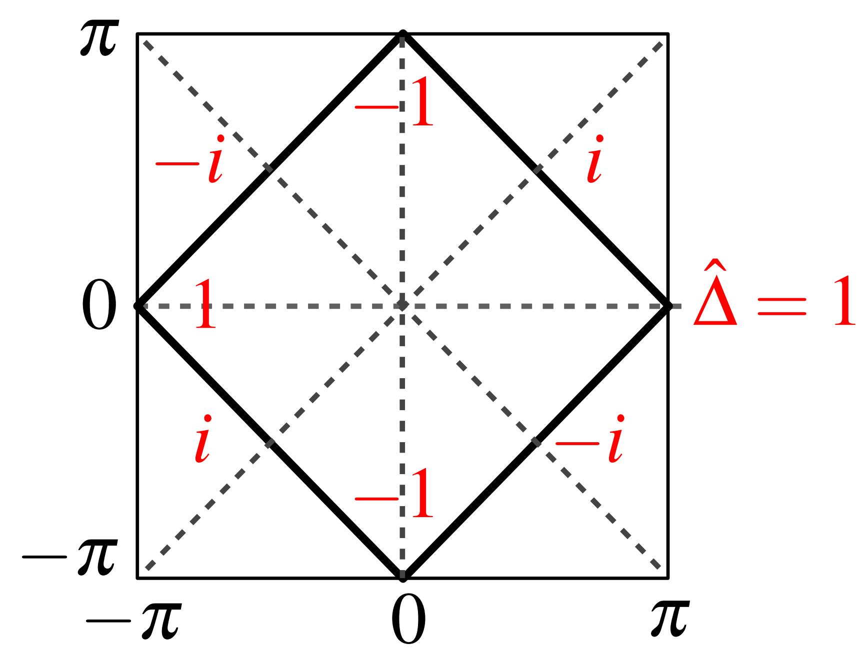
To be submitted: Raman scattering confirms the prediction of extended d-wave as the dominant subleading d-wave instability in K-doped Ba-122.

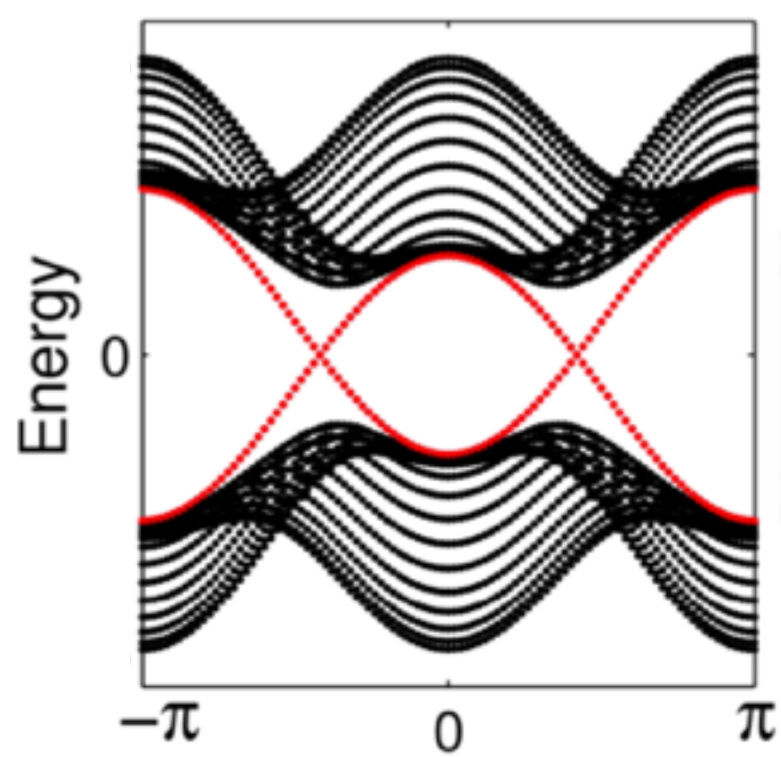
Chiral d-wave superconductivity

$$H_{d+id} = \sum_{\mathbf{k}} (c^\dagger_{\mathbf{k}\uparrow}, c_{-\mathbf{k}\downarrow}) \begin{pmatrix} \xi_{\mathbf{k}} & \Delta_{\mathbf{k}} \\ \Delta^*_{\mathbf{k}} & -\xi_{\mathbf{k}} \end{pmatrix} \begin{pmatrix} c_{\mathbf{k}\uparrow} \\ c^\dagger_{-\mathbf{k}\downarrow} \end{pmatrix}$$

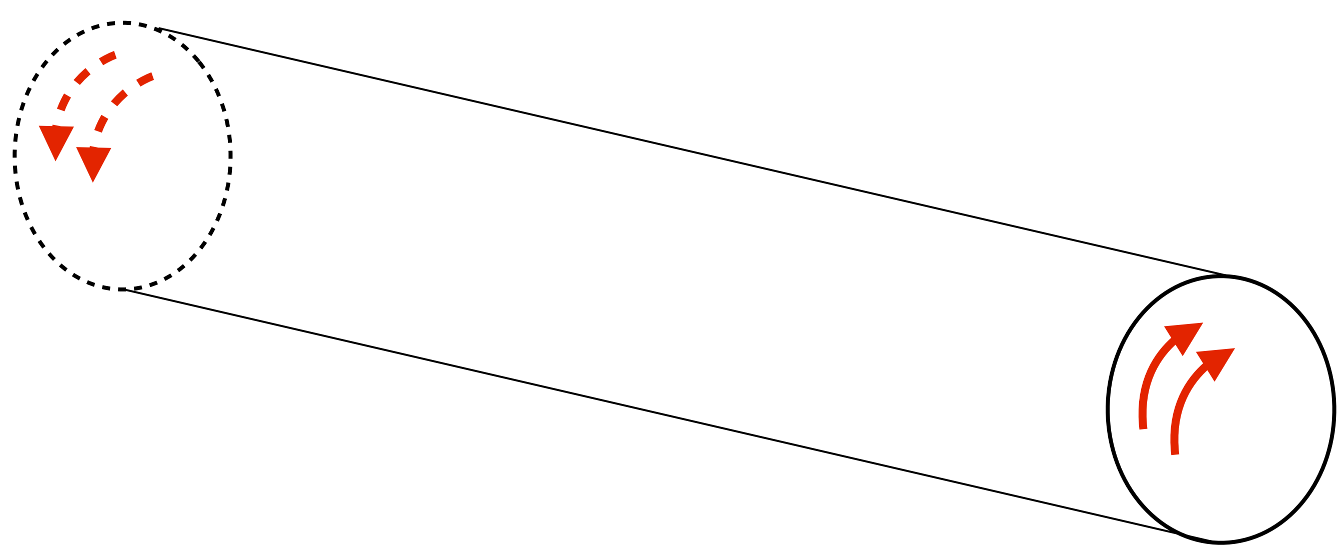
$$\Delta_{\mathbf{k}} = \cos(k_x) - \cos(k_y) + i\sin(k_x)\sin(k_y) = |\Delta_{\mathbf{k}}|e^{i\varphi_{\mathbf{k}}}$$

$$\xi_{\mathbf{k}} = \cos(k_x) + \cos(k_y)$$





$$C_{d\pm id} = \frac{1}{2\pi} \oint \nabla_{\mathbf{k}} \varphi_{\mathbf{k}} d\mathbf{k} = \pm 2$$

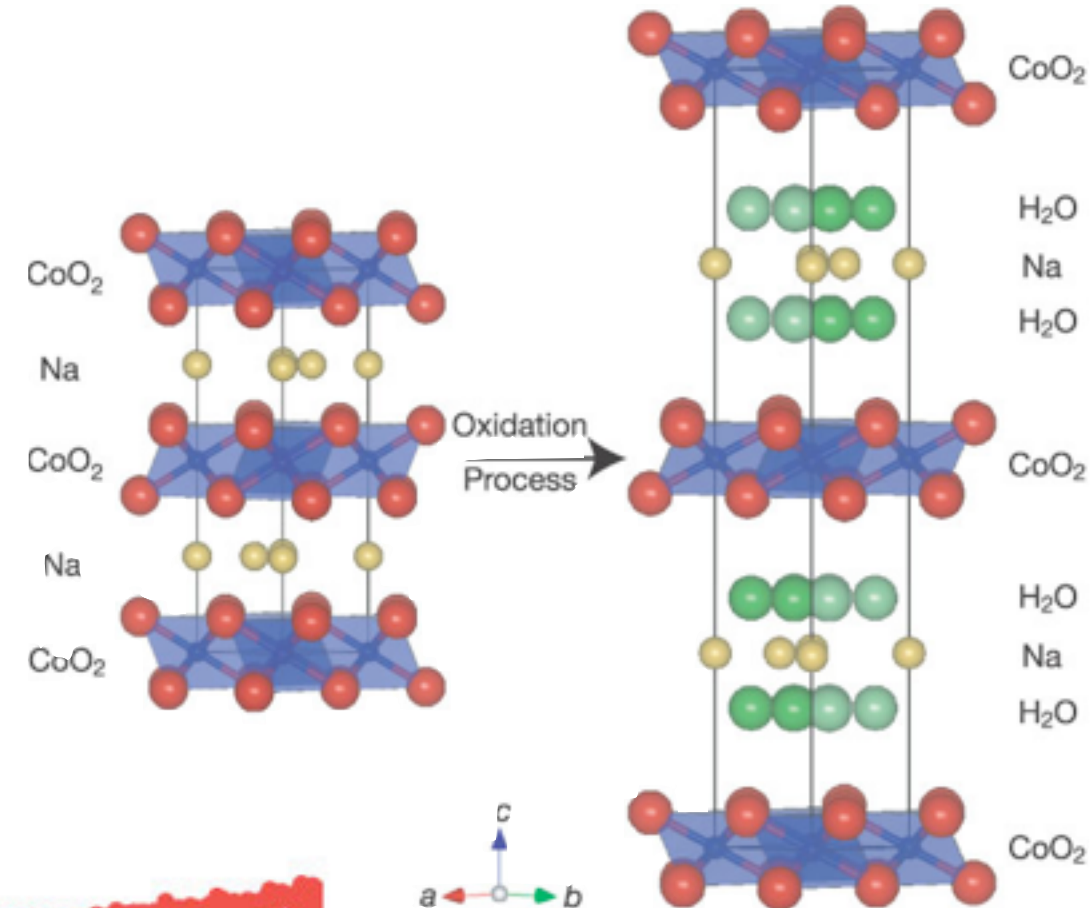


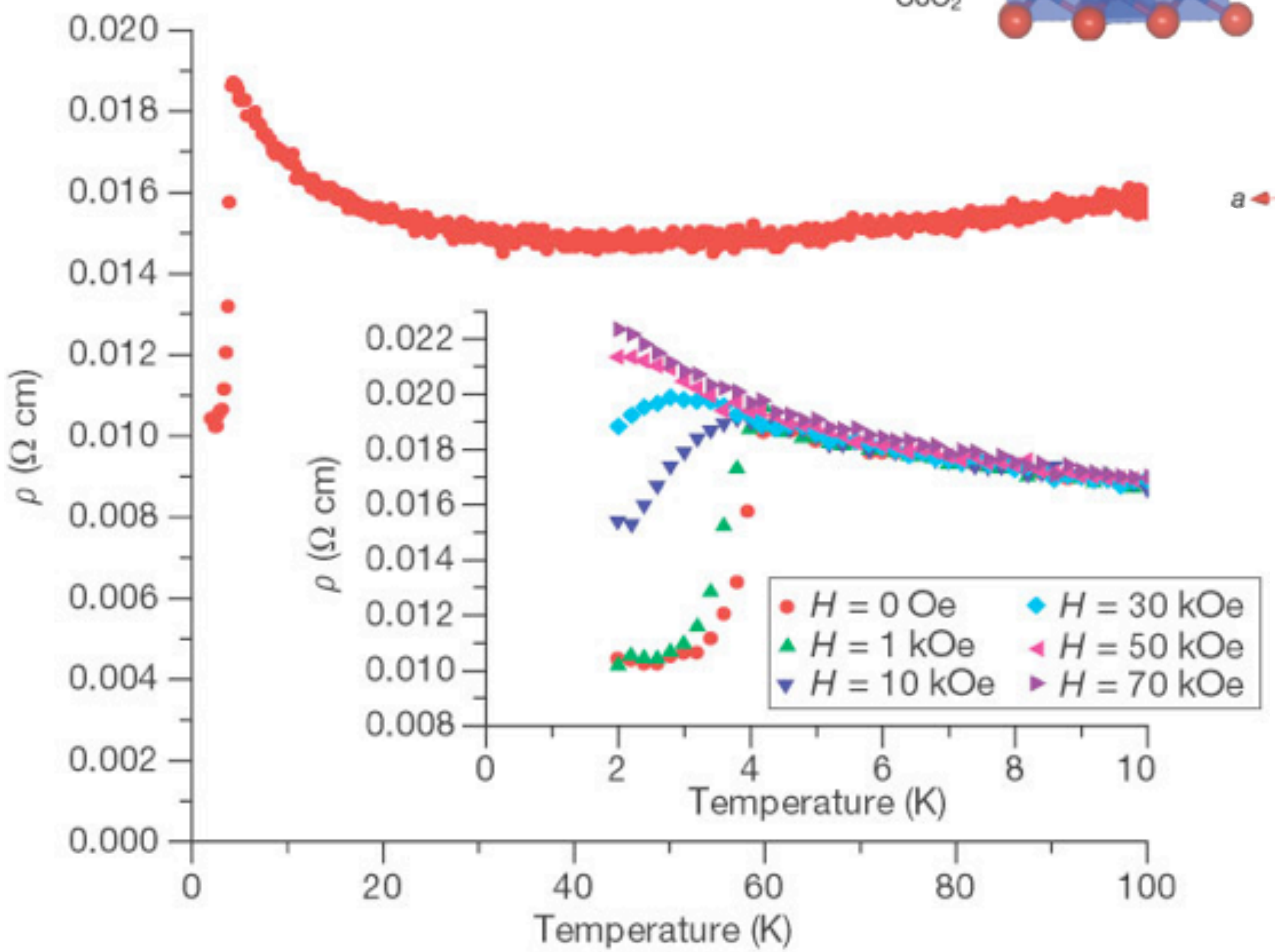
Takada et al., Nature 422, 53-55 (2003)

Superconductivity in two-dimensional CoO_2 layers

Kazunori Takada*‡, Hiroya Sakurai†, Eiji Takayama-Muromachi†, Fujio Izumi*, Ruben A. Dilanian* & Takayoshi Sasaki*‡

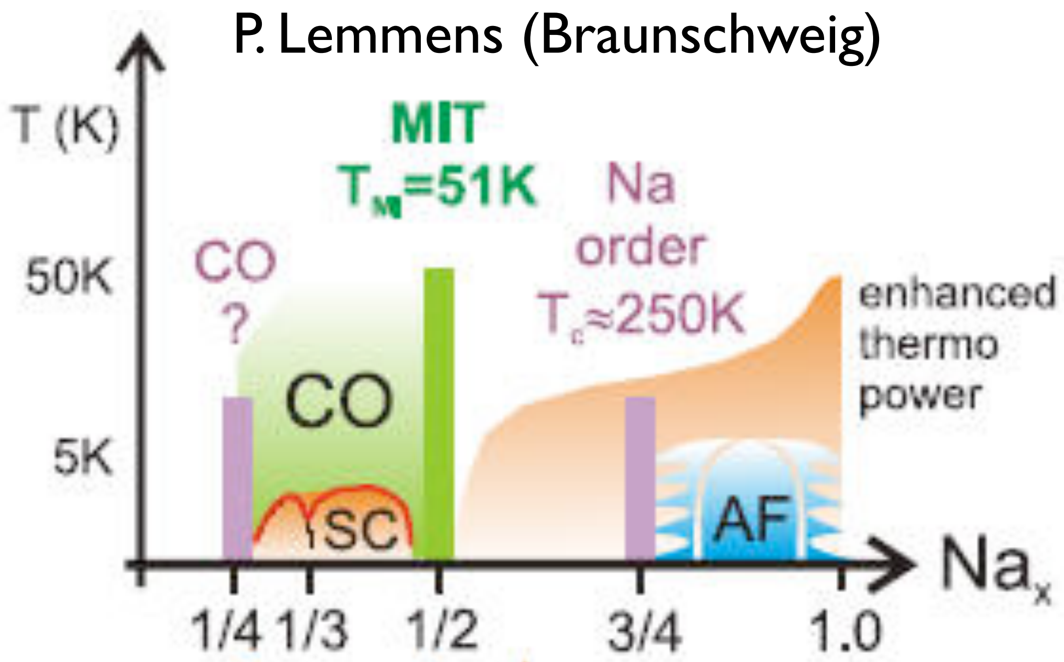
* *Advanced Materials Laboratory, National Institute for Materials Science, Tsukuba, Ibaraki 305-0044, Japan*
† *Superconducting Materials Center, National Institute for Materials Science, Tsukuba, Ibaraki 305-0044, Japan*
‡ *CREST, Japan Science and Technology Corporation*

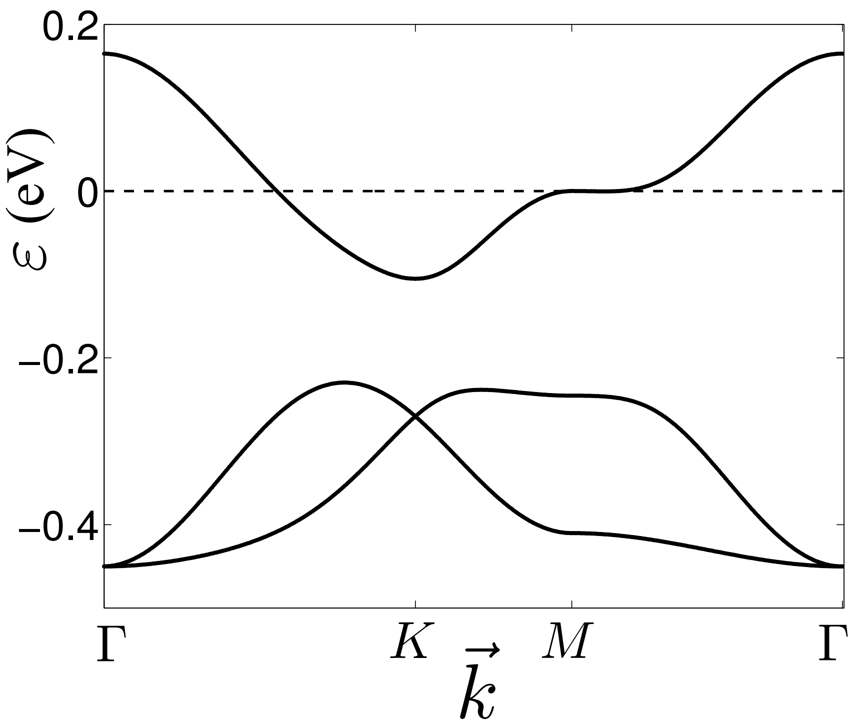


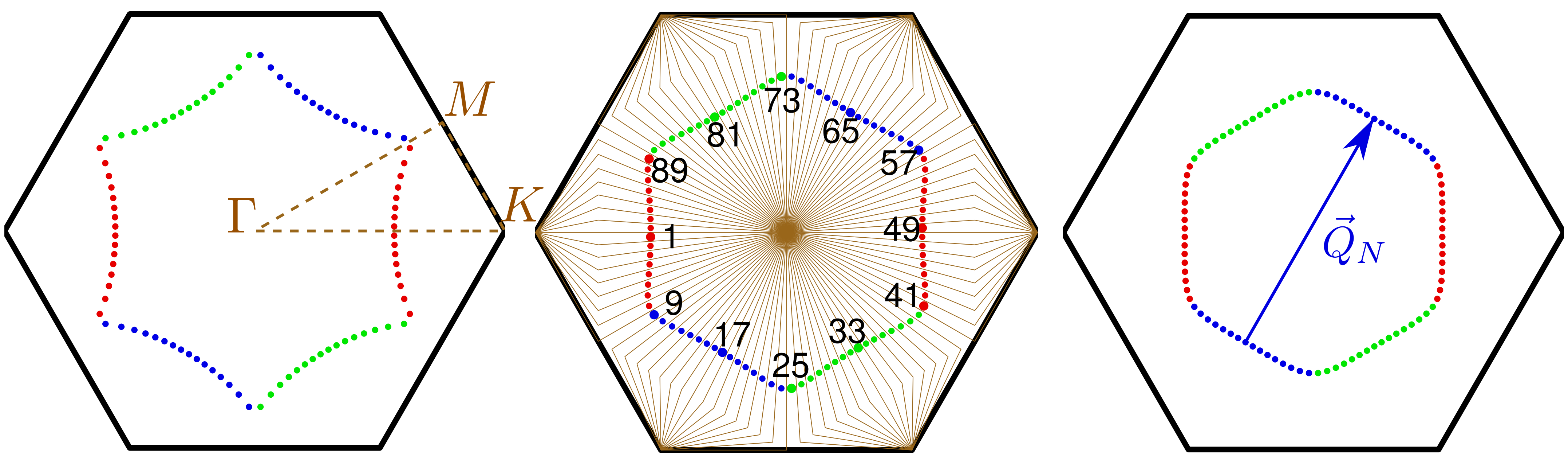


Cobaltate phase diagram

The phase diagram hosts a plethora of phases interpolating between the parent insulating compound (x=0) and Na-doped insulating limit (x=1)



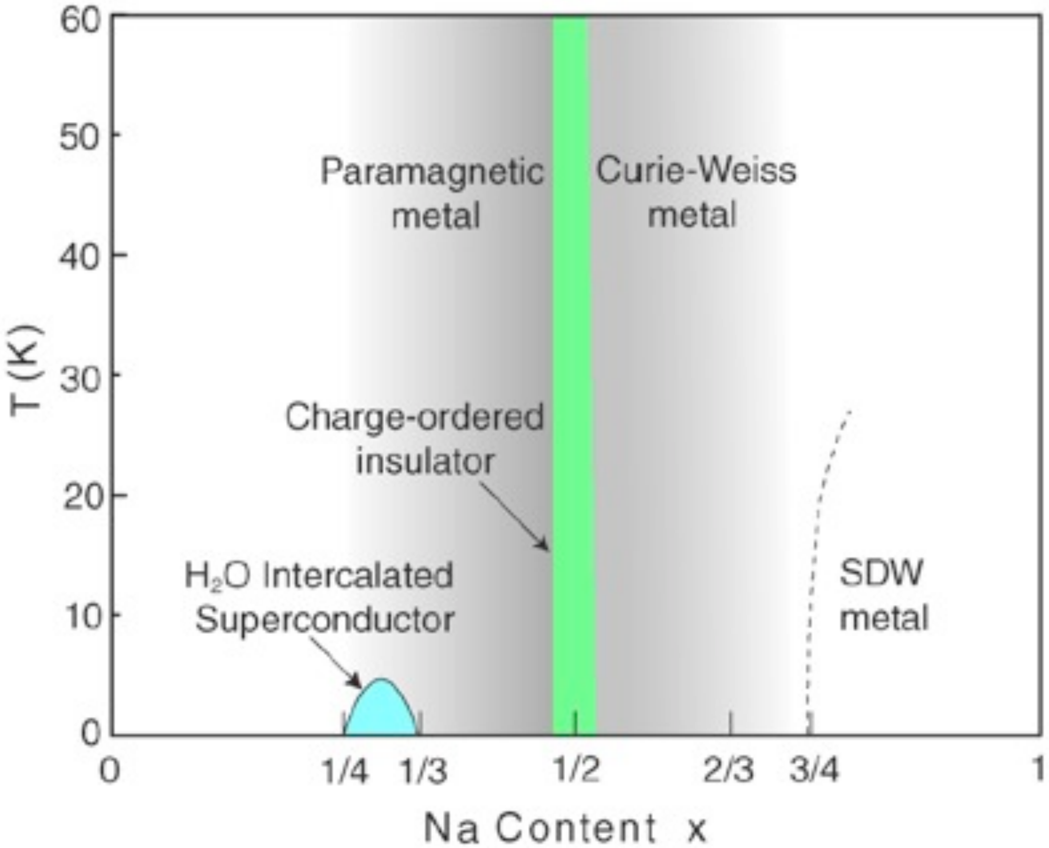


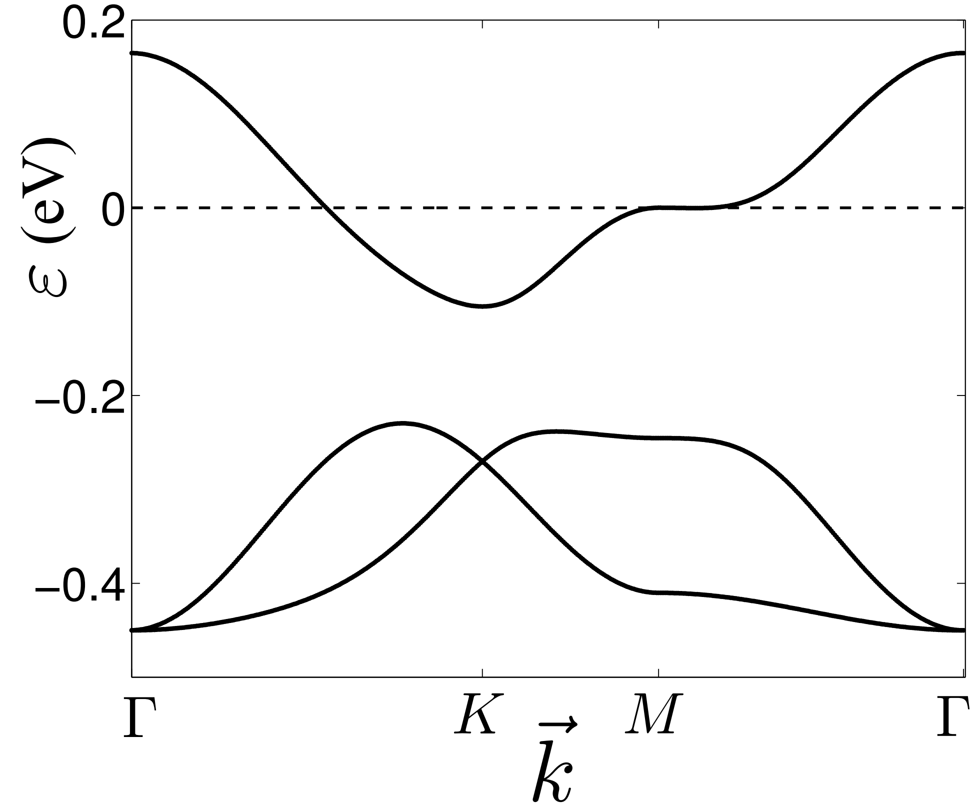


Cobaltate phase diagram

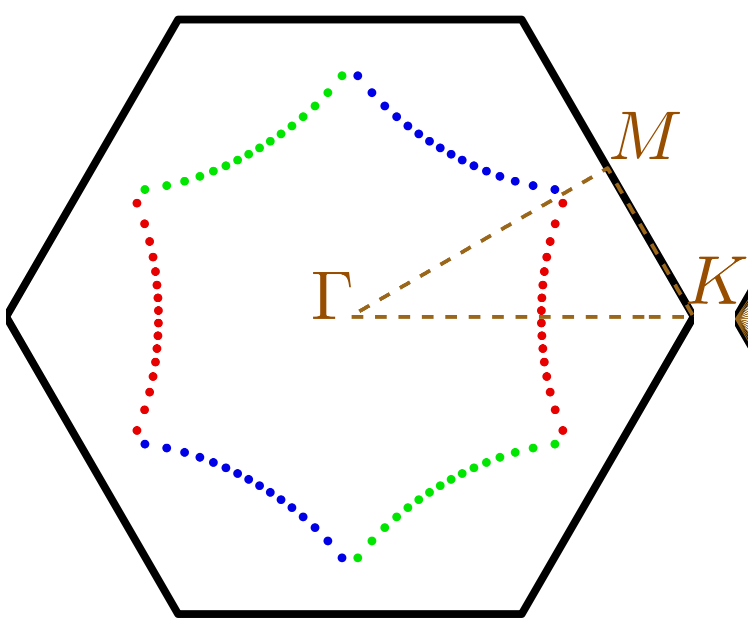
Ong group, PRB 2004

Aligia et al., PRL 2008

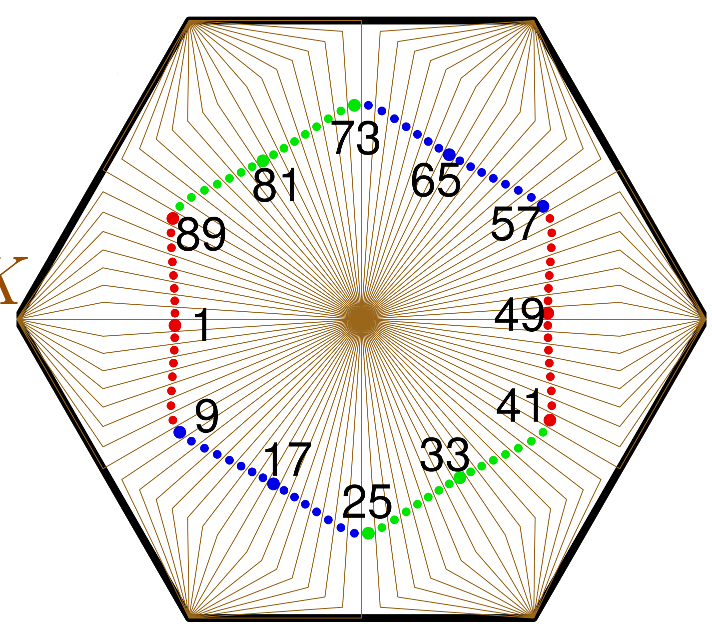




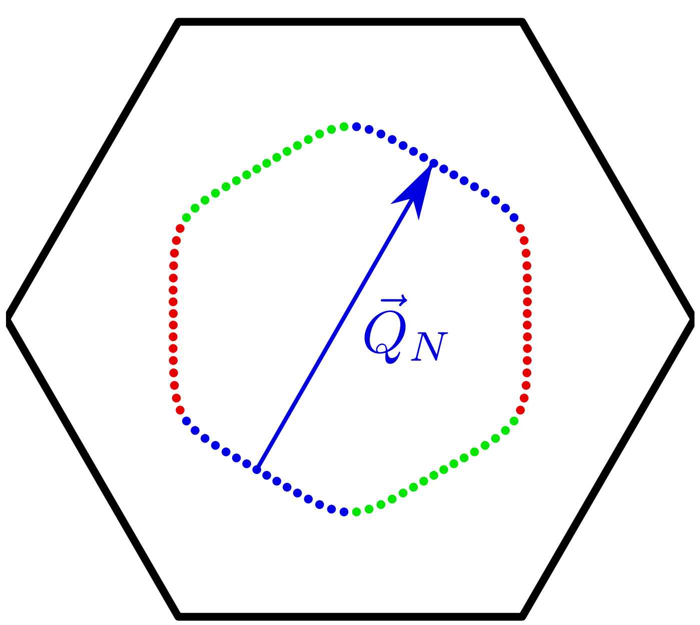
x=0.1



x=0.2



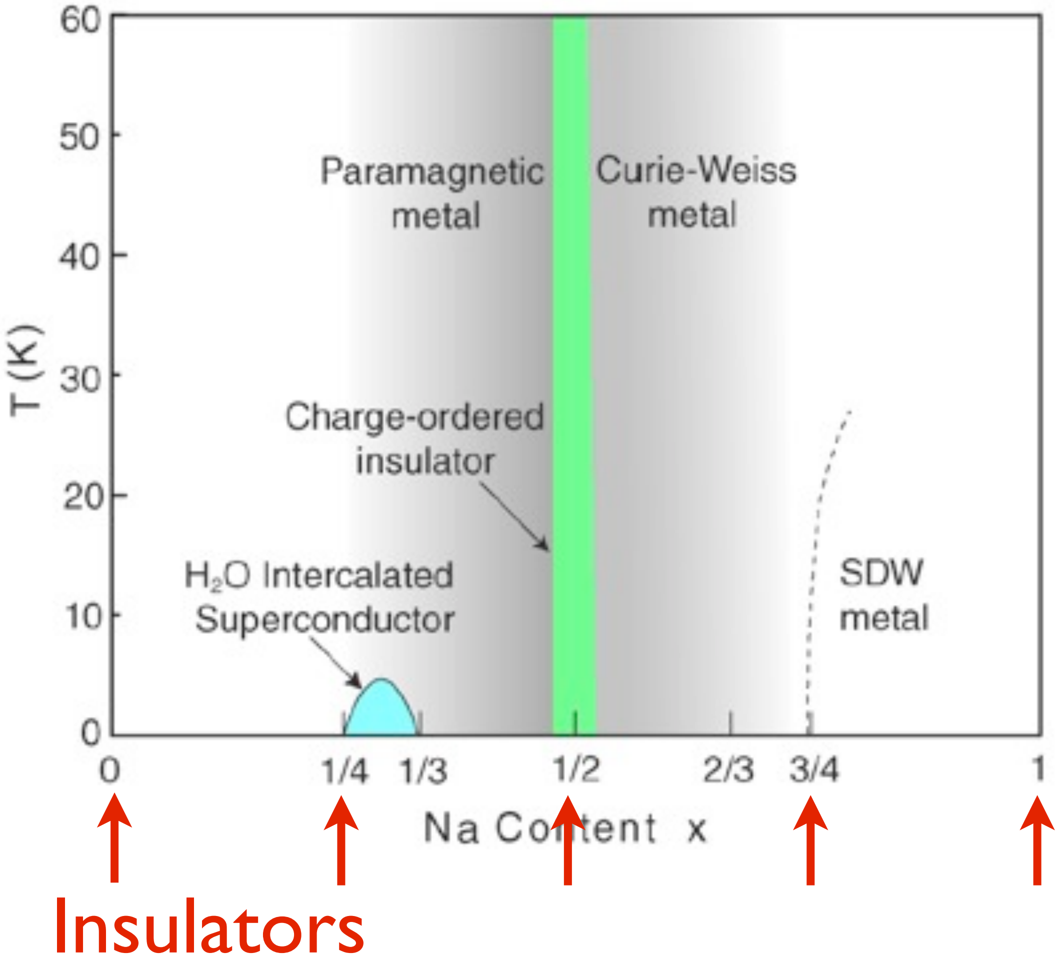
x=0.3

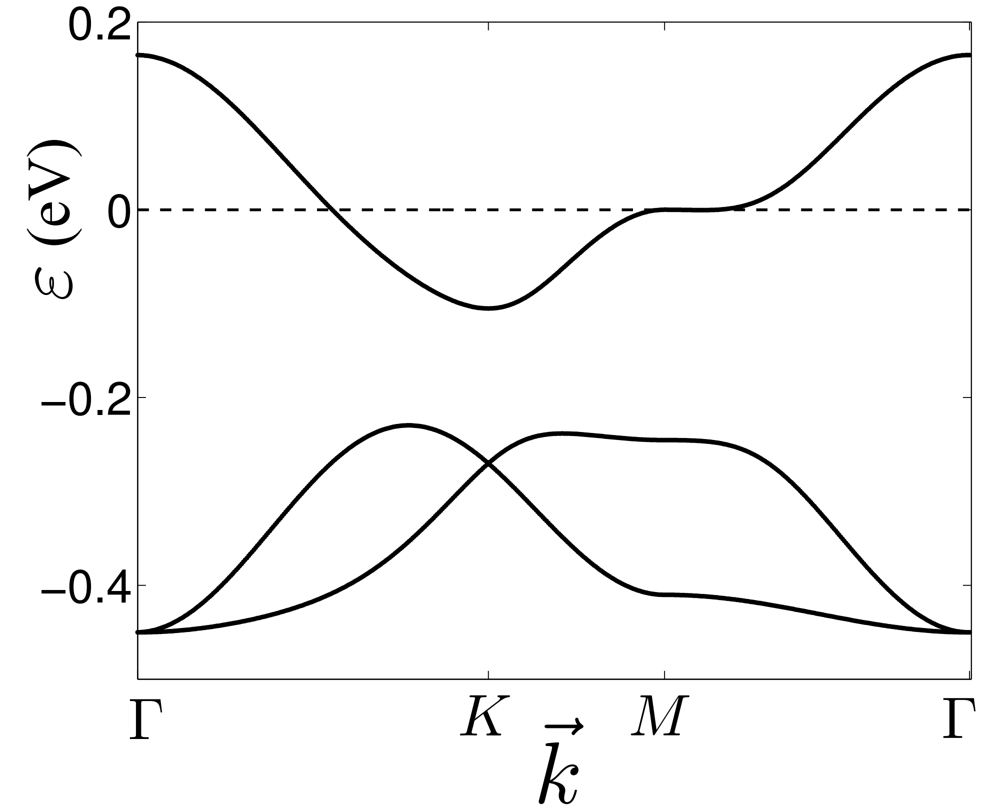


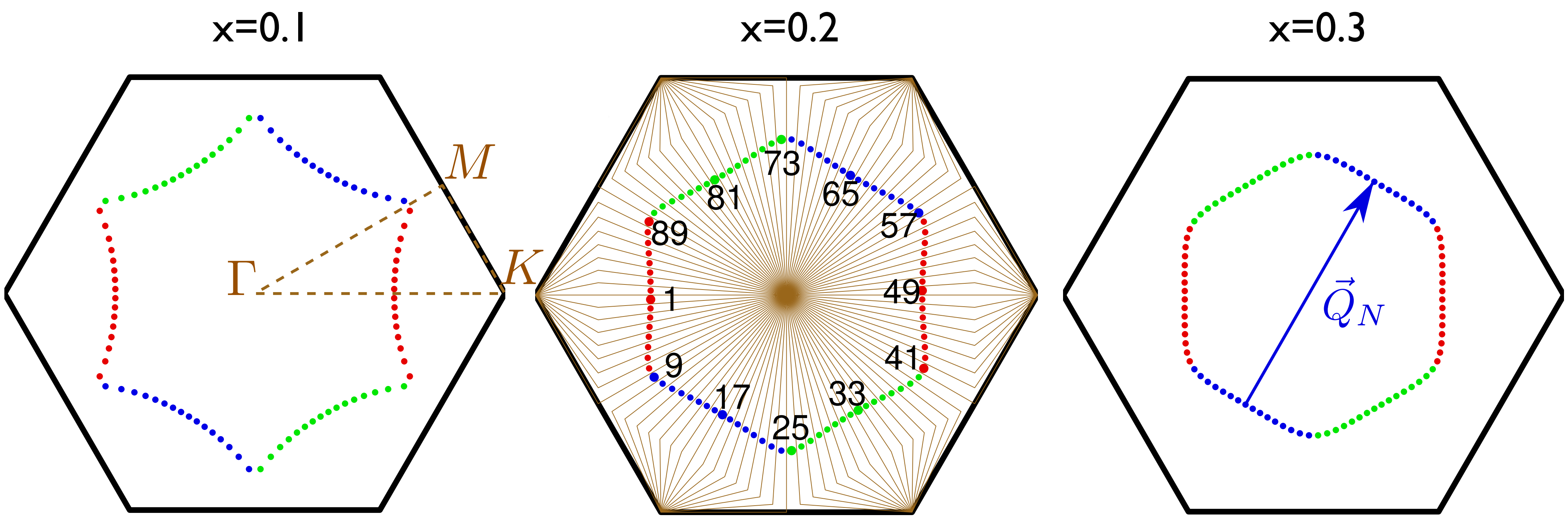
Cobaltate phase diagram

Ong group, PRB 2004

Aligia et al., PRL 2008

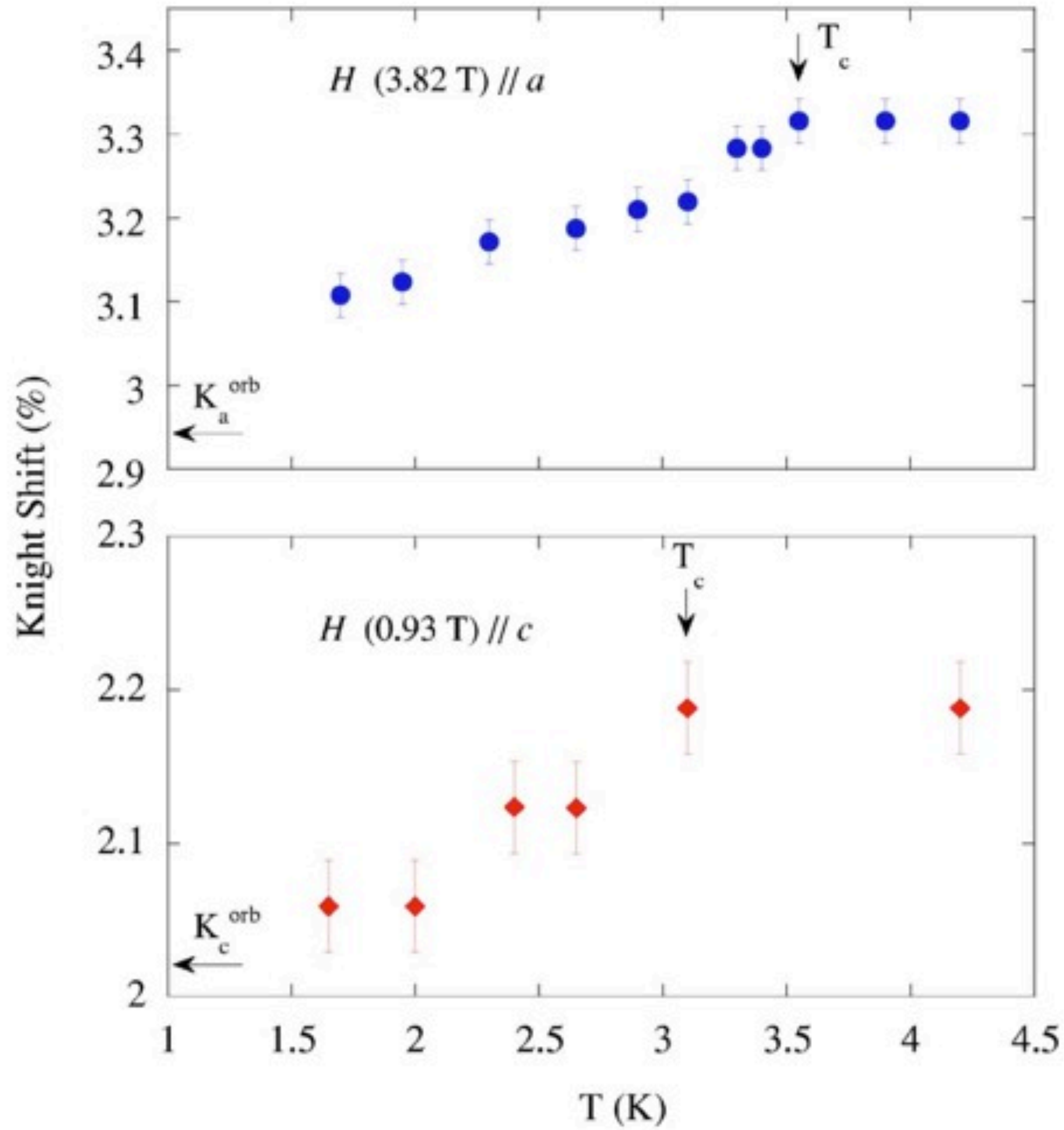




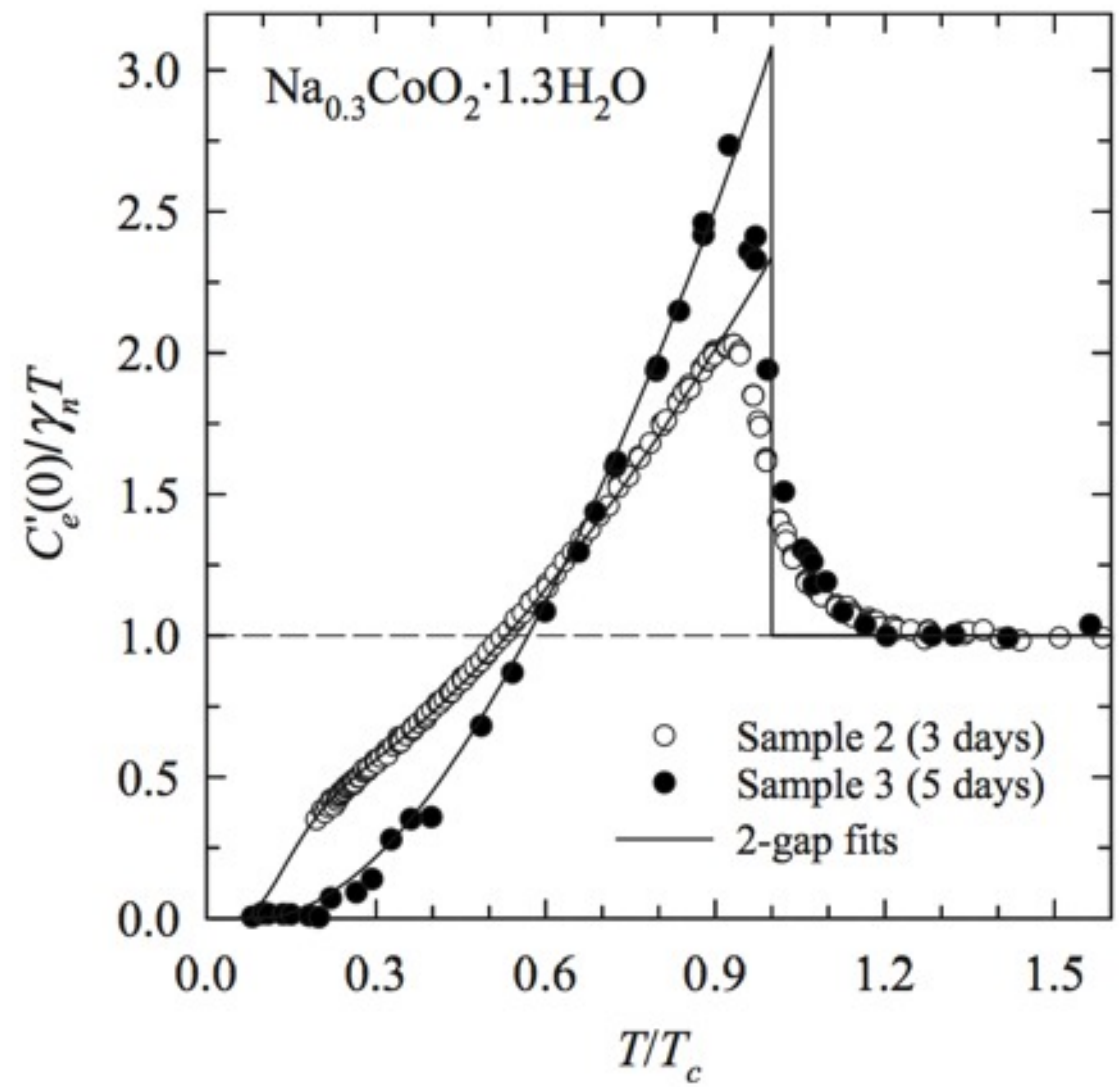


Evidence at x=0.3: Singlet, close-to-nodal superconductor

Knight shift: Lin group, PRB 2006



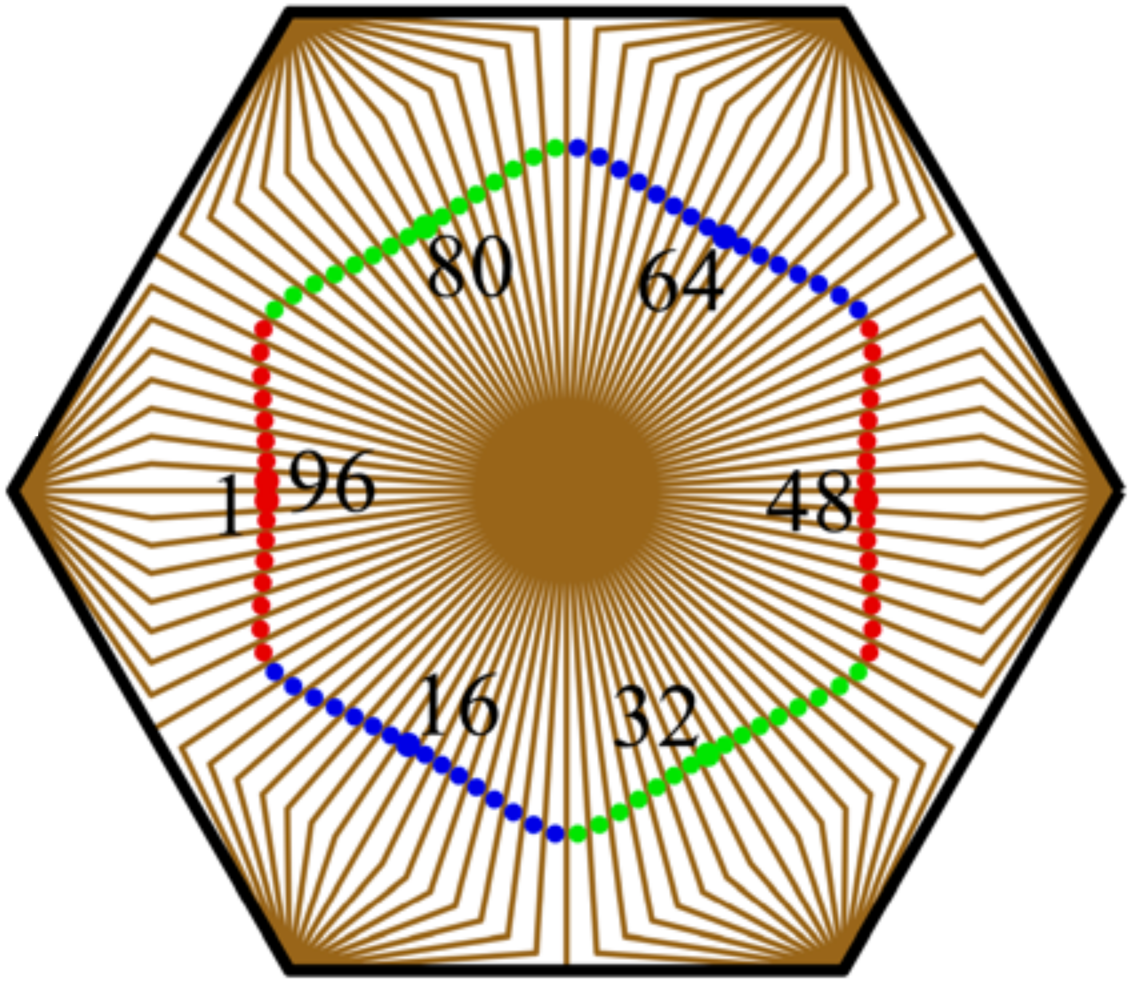
Specific heat: Cava group, PRB 2008



Hexagonal d-wave superconductivity

C_{6v}	E	C_2	$2C_3$	$2C_6$	$3\sigma_v$	$3\sigma_d$
A_1	1	1	1	1	1	1
A_2	1	1	1	1	-1	-1
B_1	1	-1	1	-1	1	-1
B_2	1	-1	1	-1	-1	1
E_1	2	-2	-1	1	0	0
E_2	2	2	-1	-1	0	0

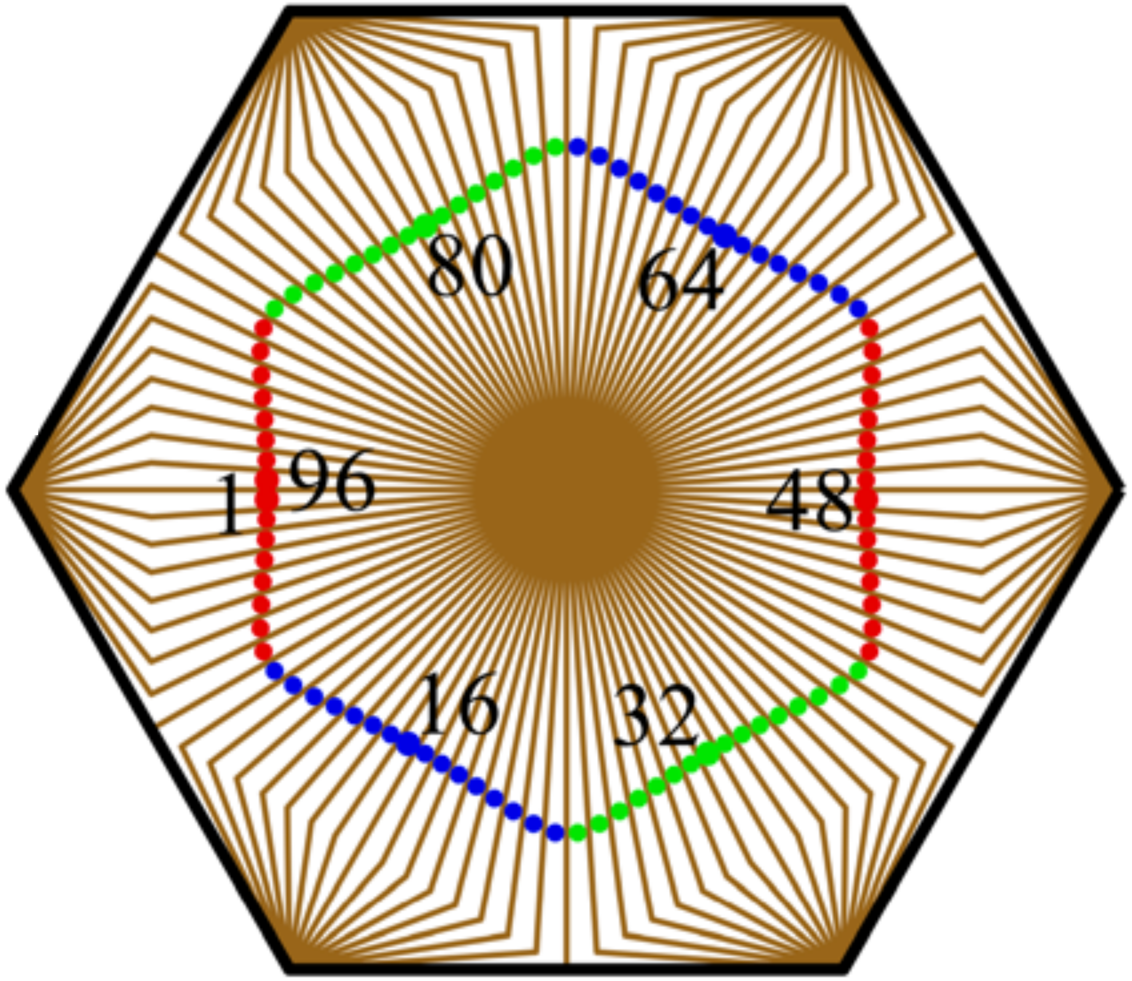
d_{x2-y2}/d_{xy}



Hexagonal d-wave superconductivity

C_{6v}	E	C_2	$2C_3$	$2C_6$	$3\sigma_v$	$3\sigma_d$
A_1	1	1	1	1	1	1
A_2	1	1	1	1	-1	-1
B_1	1	-1	1	-1	1	-1
B_2	1	-1	1	-1	-1	1
E_1	2	-2	-1	1	0	0
E_2	2	2	-1	-1	0	0

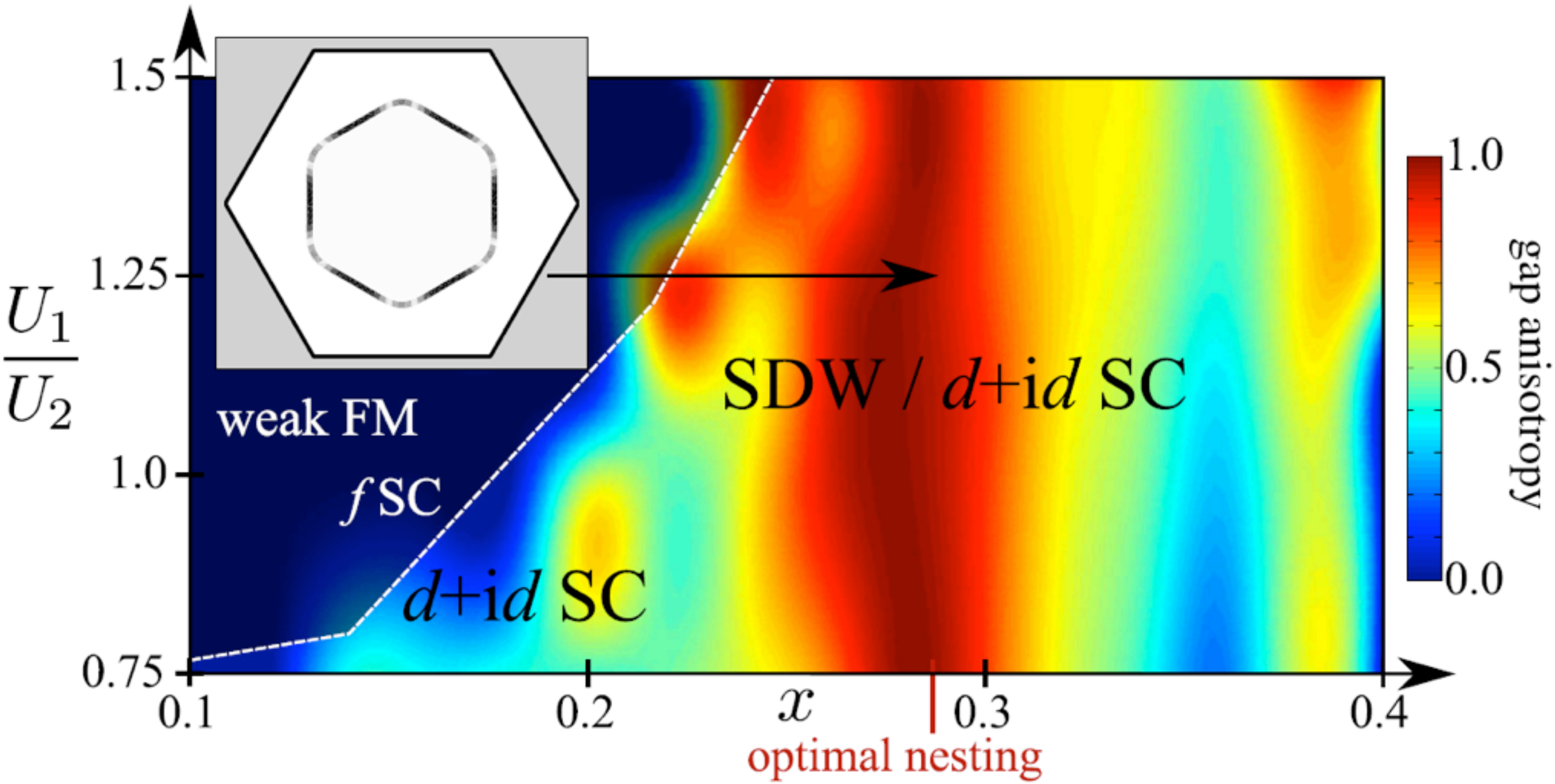
d_{x2-y2}/d_{xy}



The d-wave hexagonal point group representation is two-dimensional, implying a degeneracy at the instability level.

FRG analysis: anisotropic d+id phase

The multi-orbital Hubbard model at x ~ 0.3 yields a d+id-wave superconductor with a strongly anisotropic gap function.



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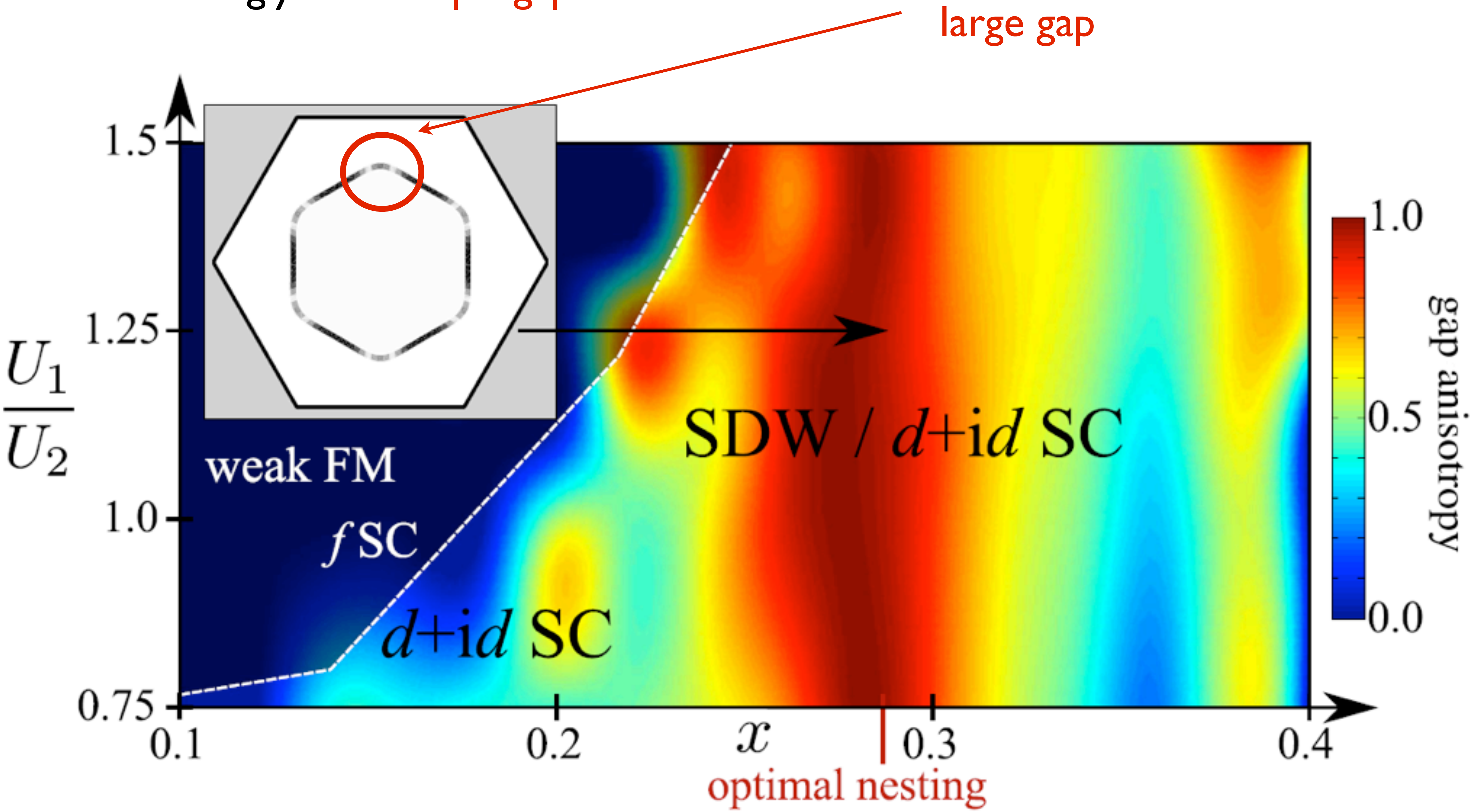

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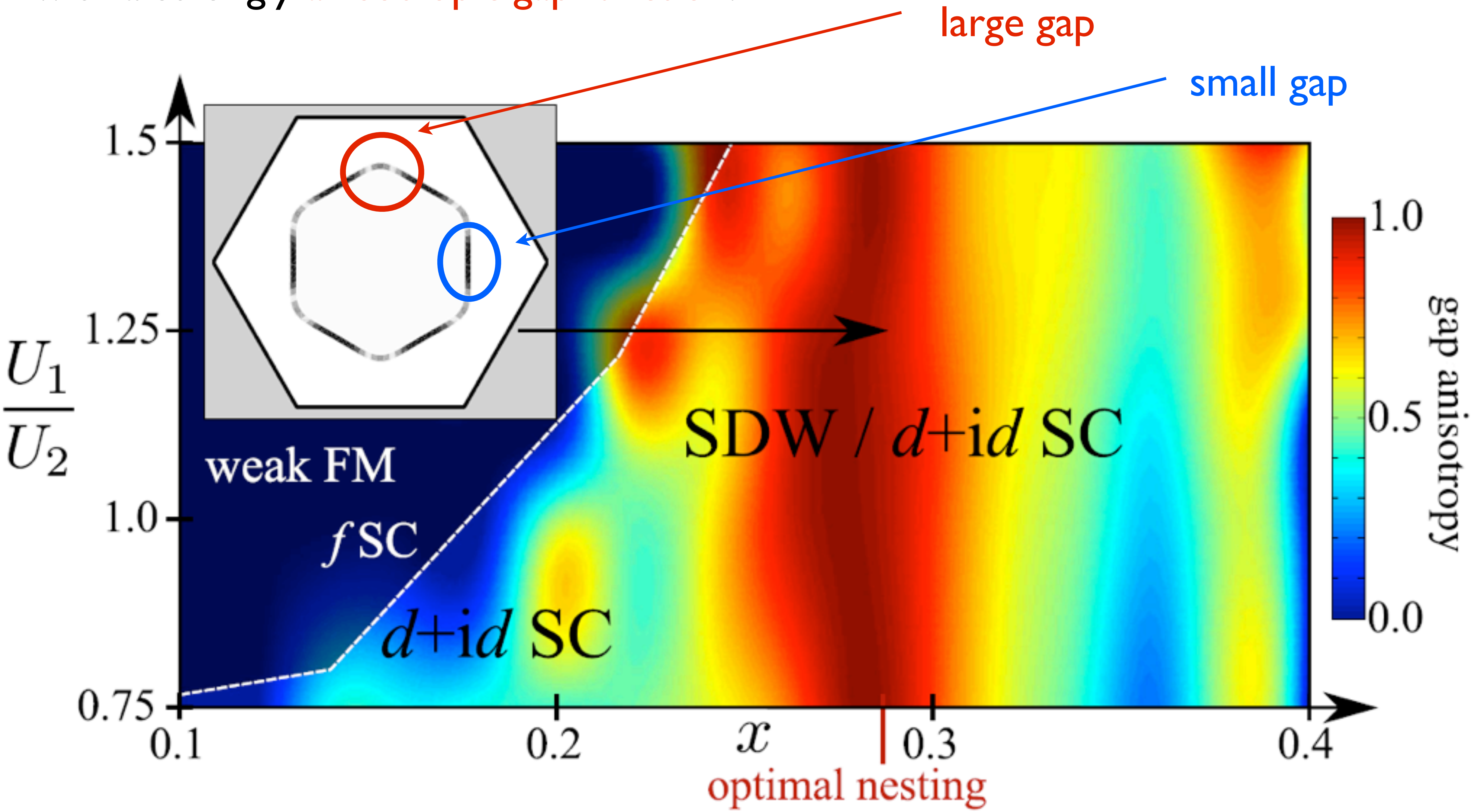
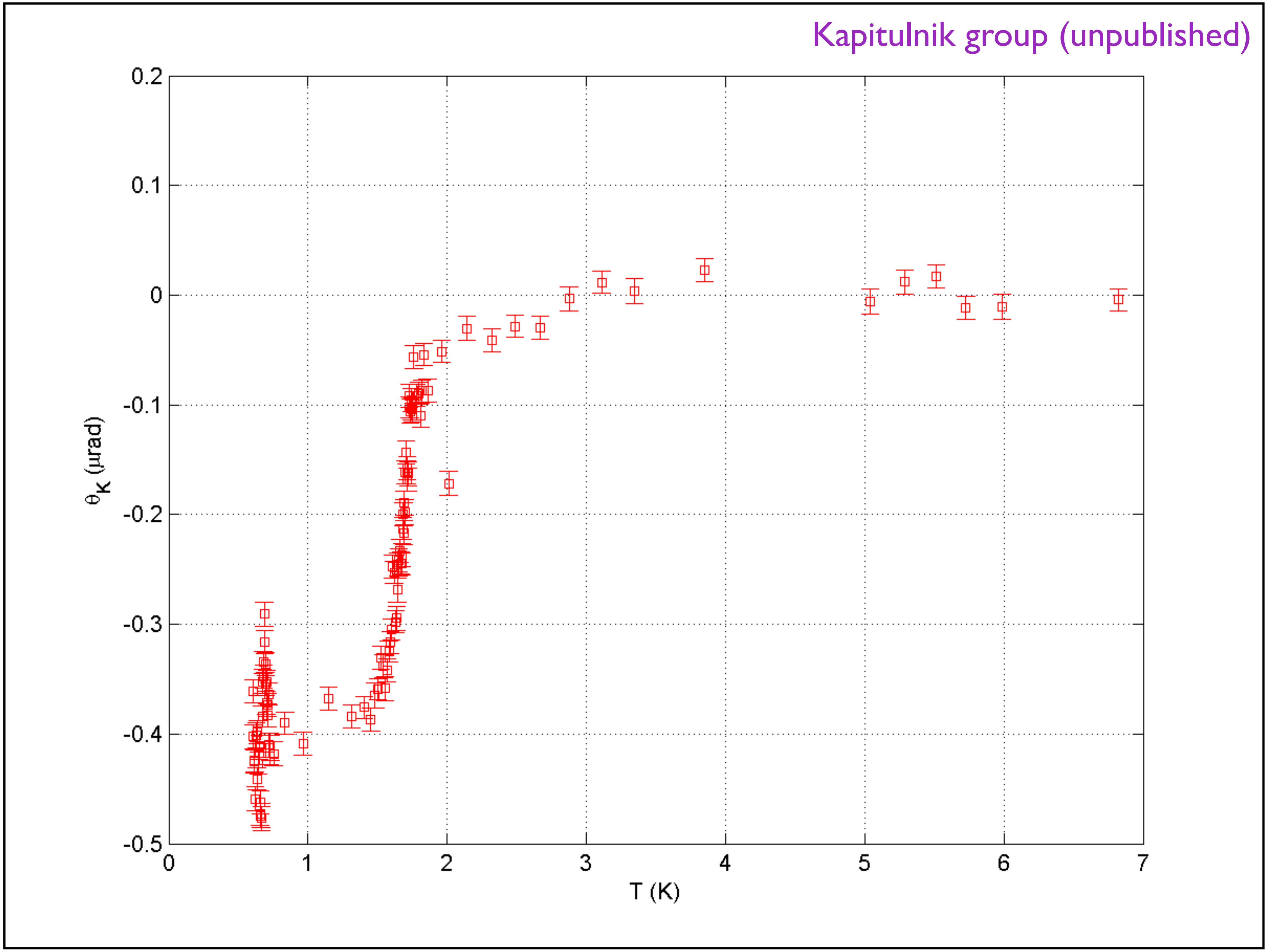


T violation probed by Kerr angle



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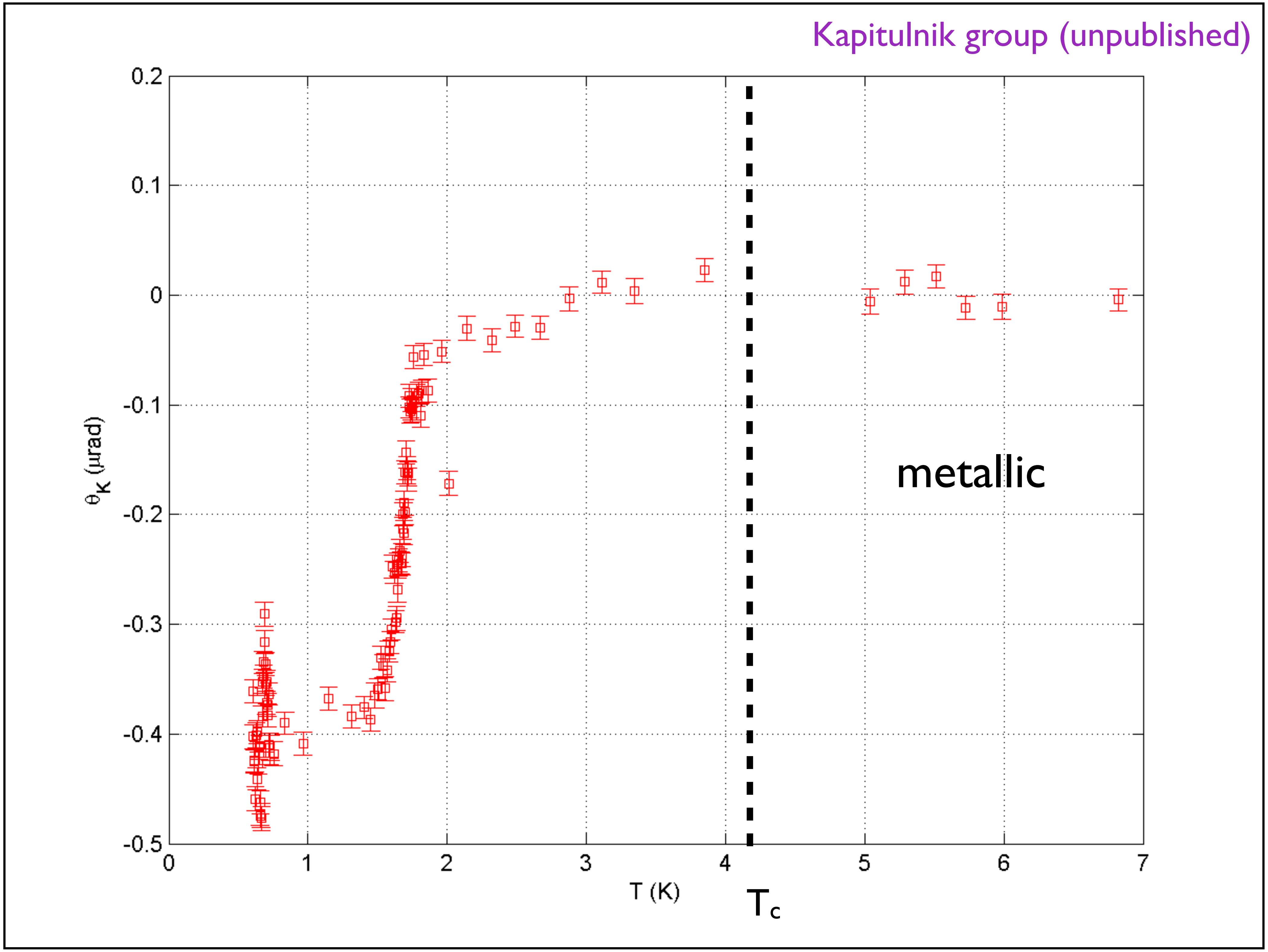
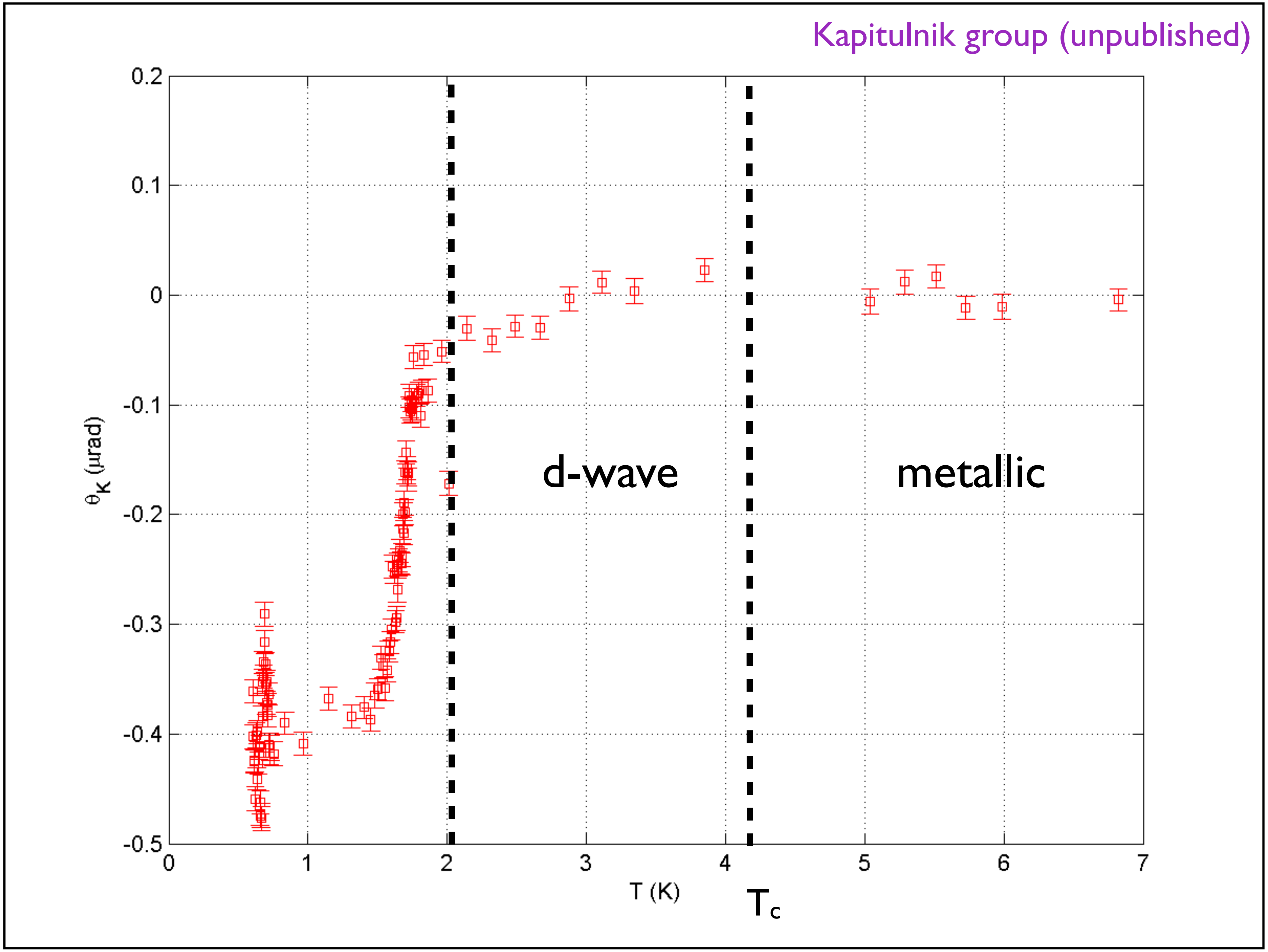


T violation probed by Kerr angle



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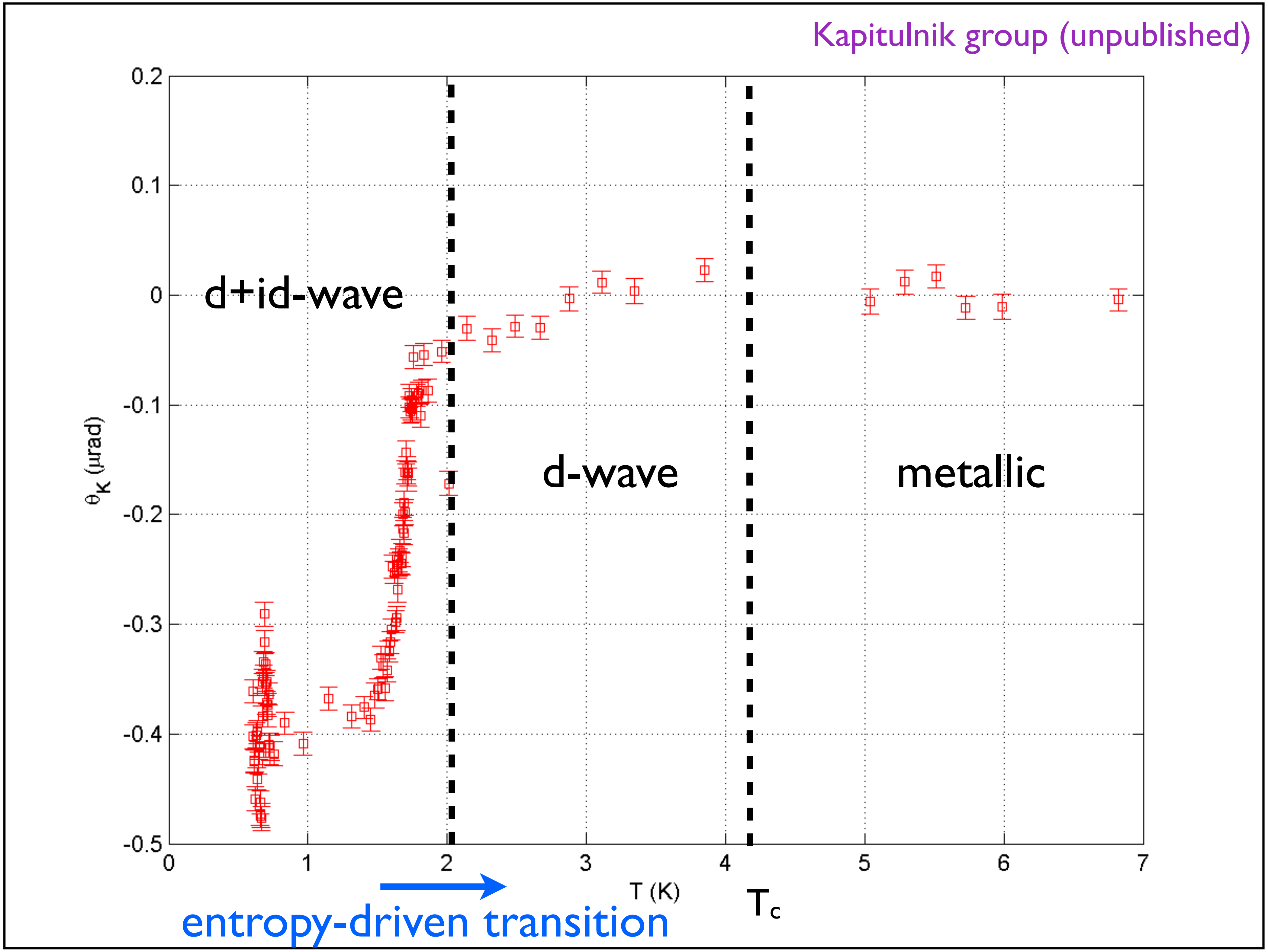


Future

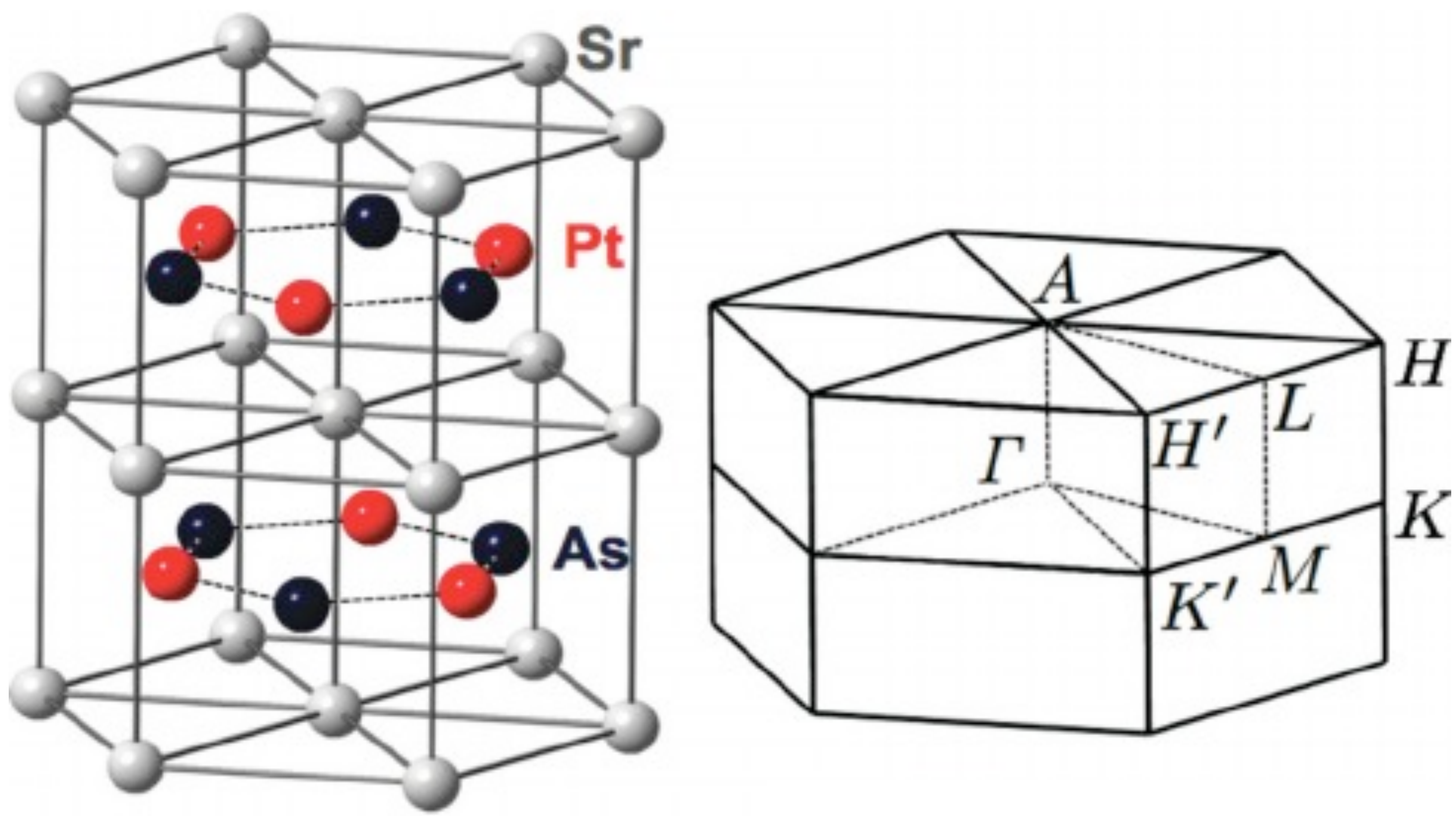
SrPtAs - a Weyl superconductor?

RAPID COMMUNICATIONS

PHYSICAL REVIEW B **89**, 020509(R) (2014)

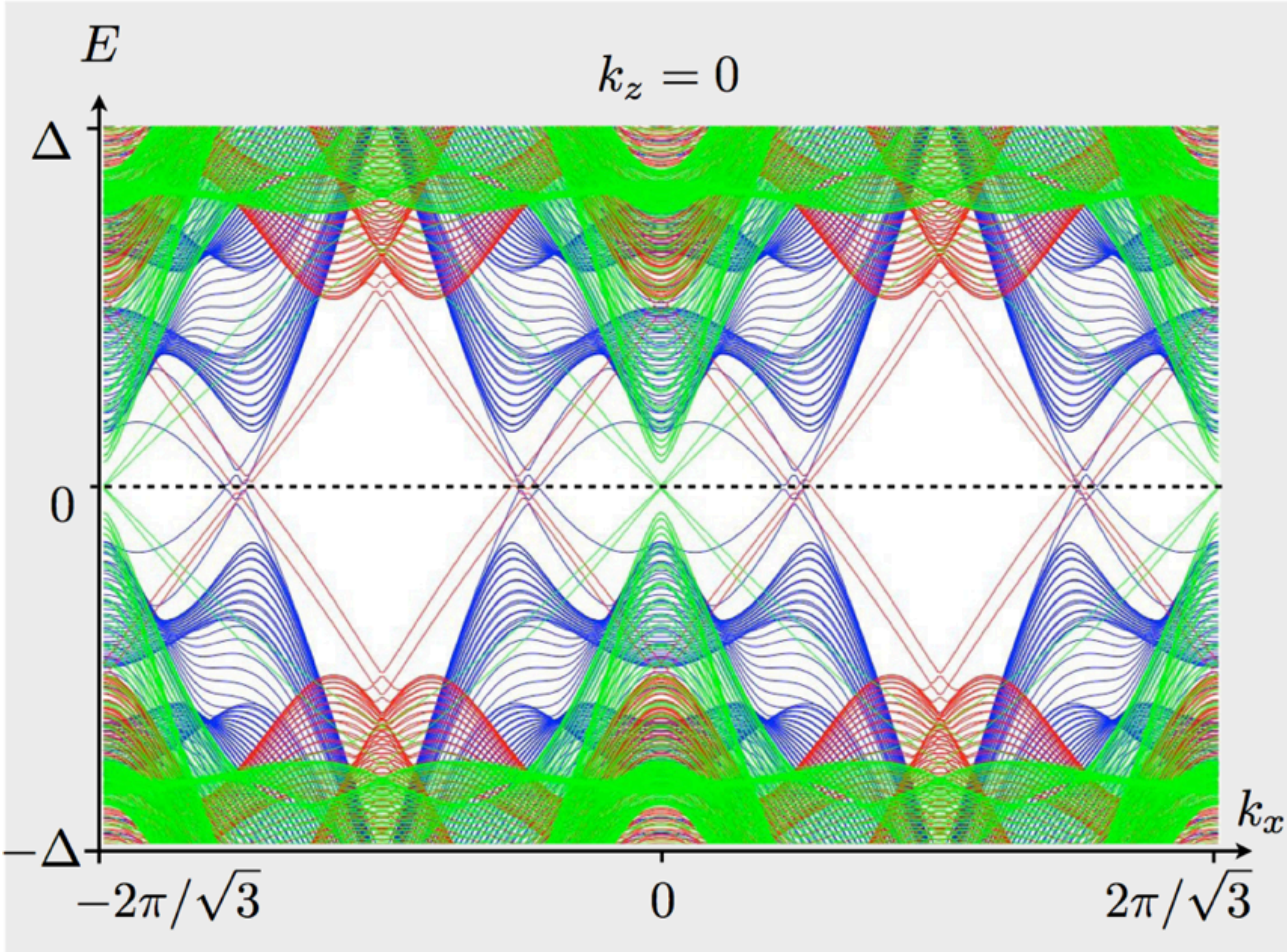
Chiral *d*-wave superconductivity in SrPtAs

Mark H. Fischer,[1,2] Titus Neupert,[3,4] Christian Platt,[5] Andreas P. Schnyder,[6] Werner Hanke,[5] Jun Goryo,[7] Ronny Thomale,[5] and Manfred Sigrist[4]

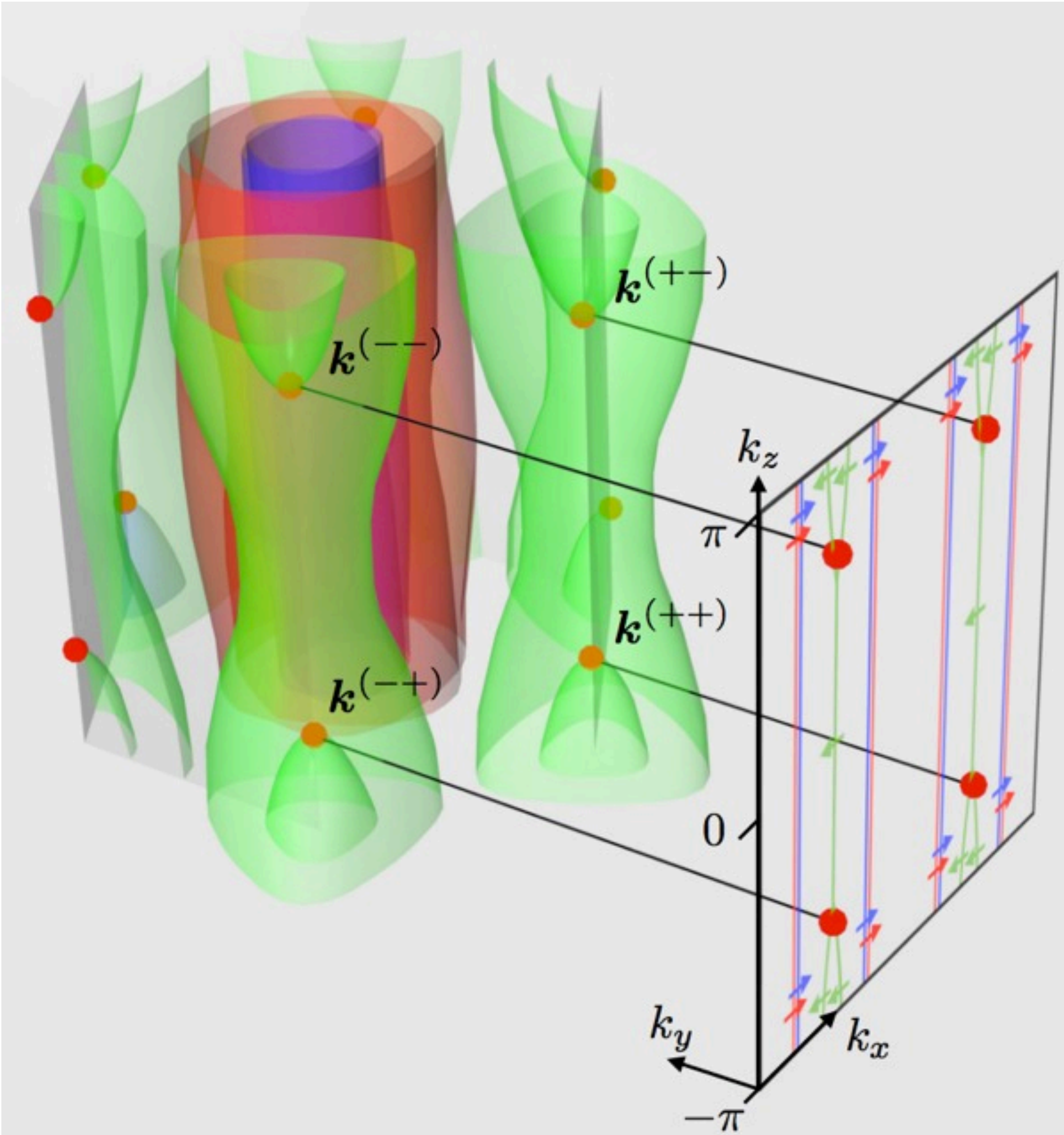


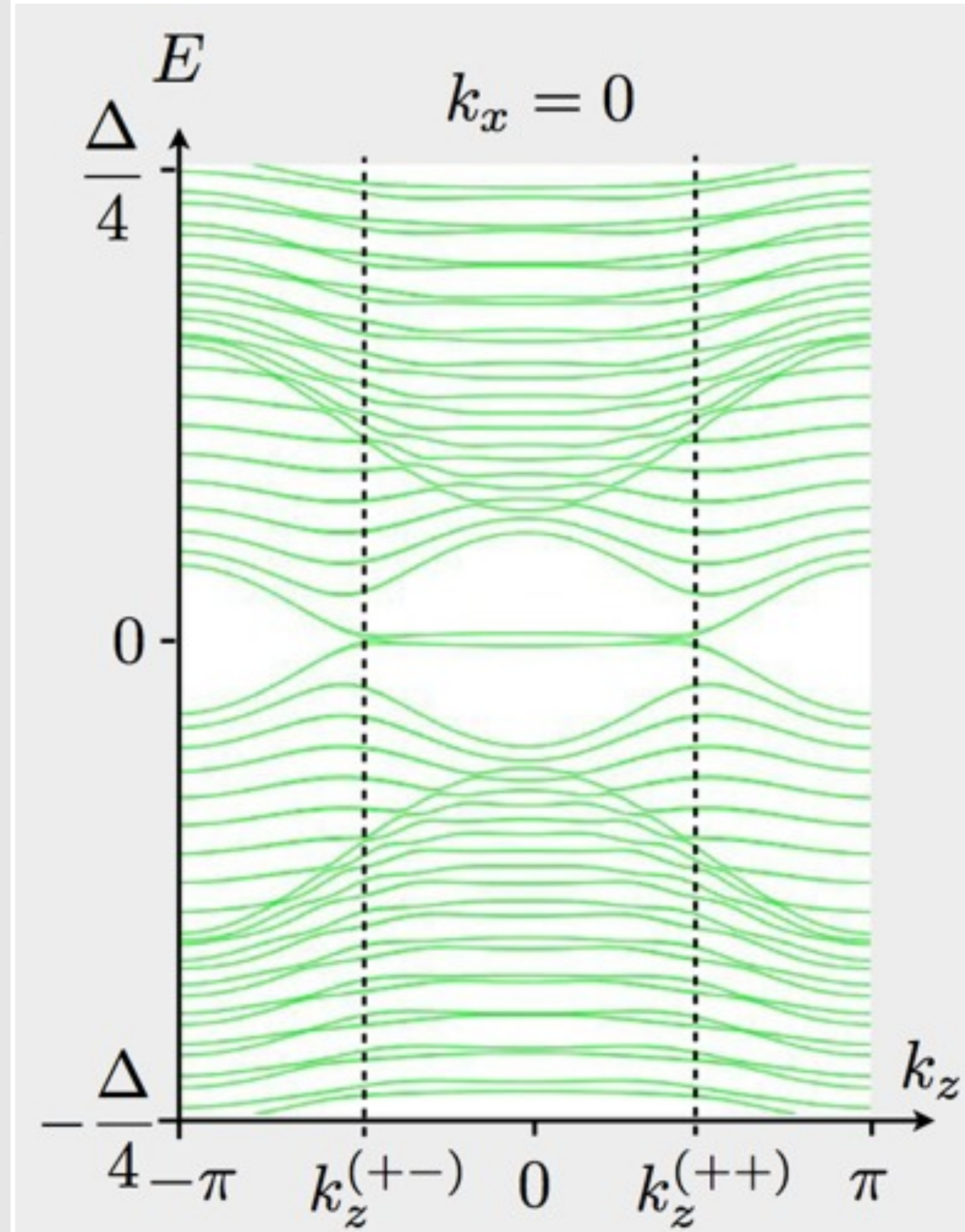
(a)

Bogoliubov spectrum

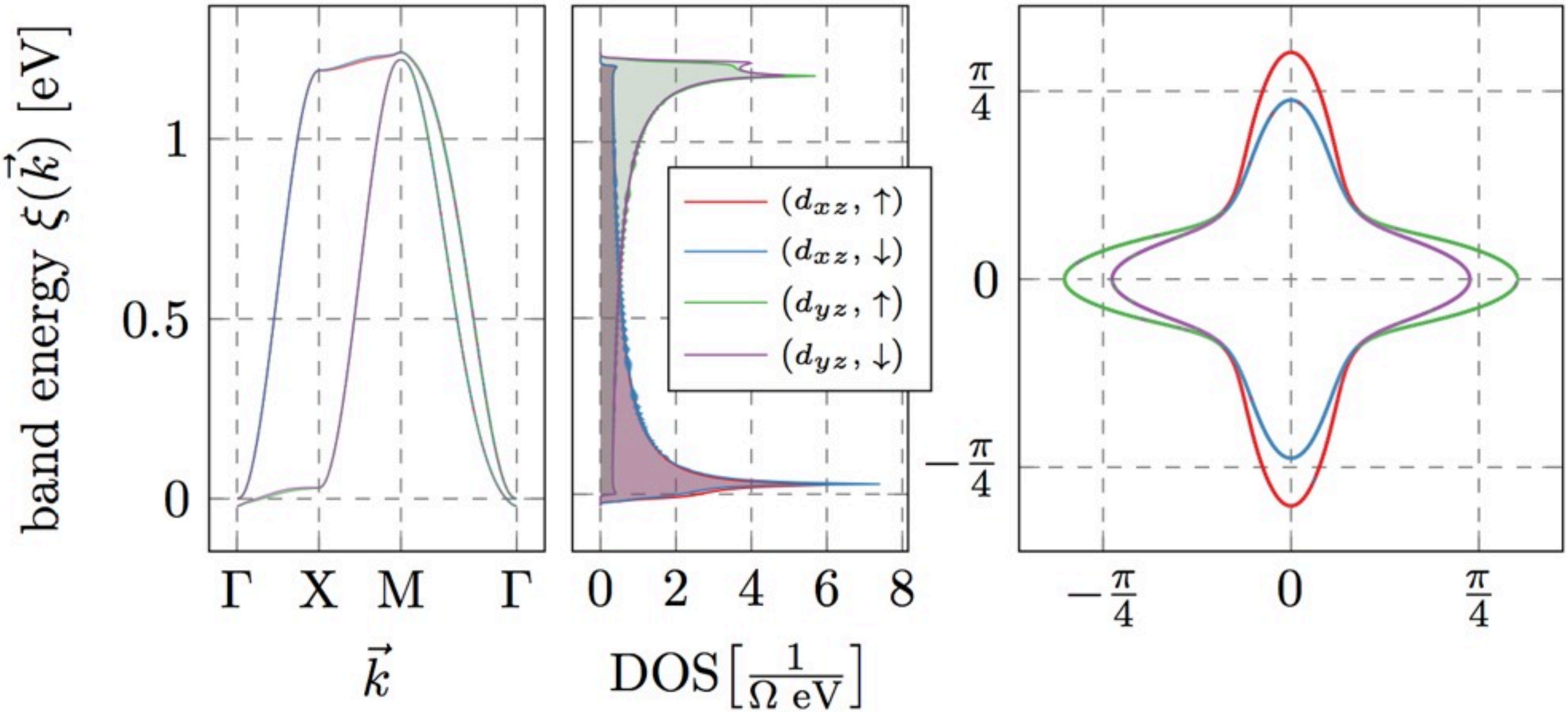


SrPtAs: First prediction of a Weyl superconductor

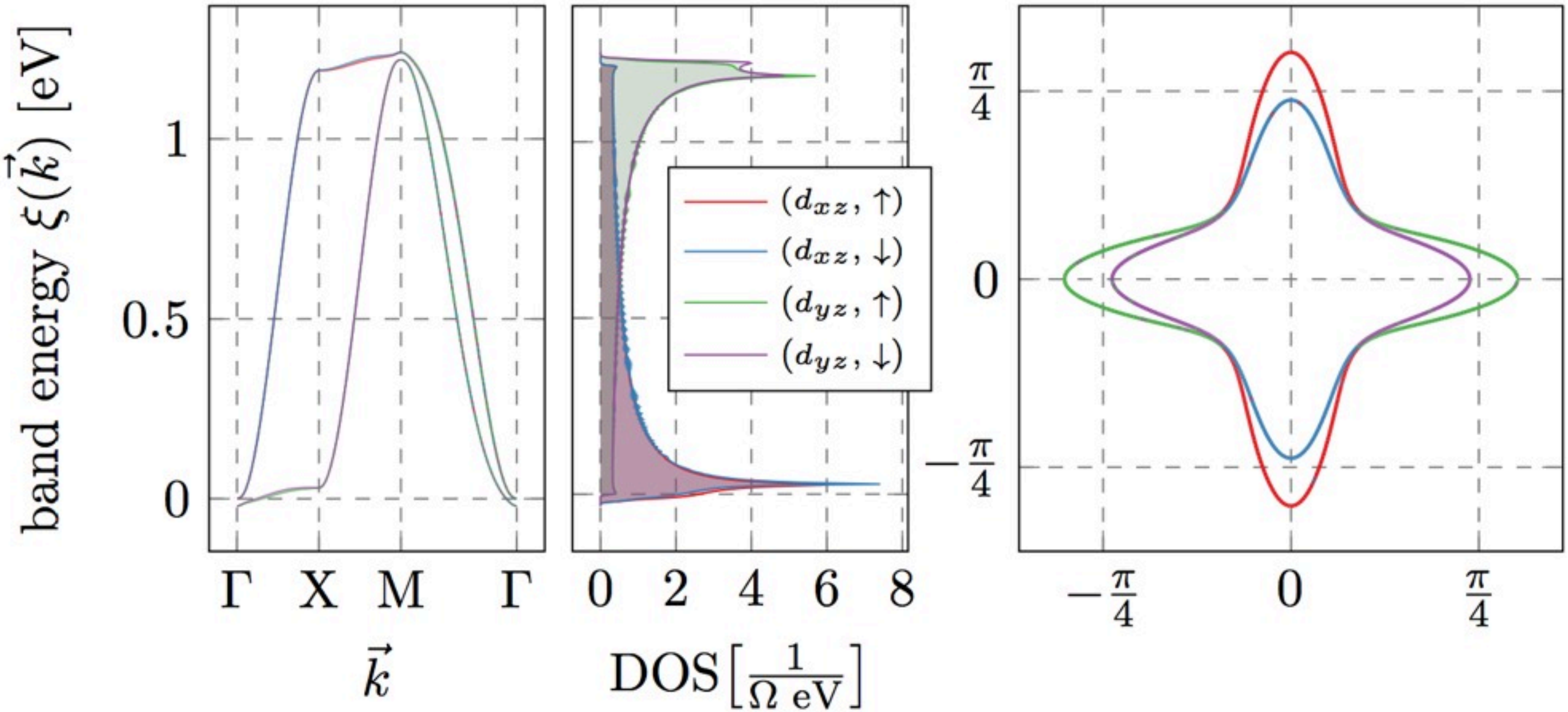




LAO/STO - tight binding setup

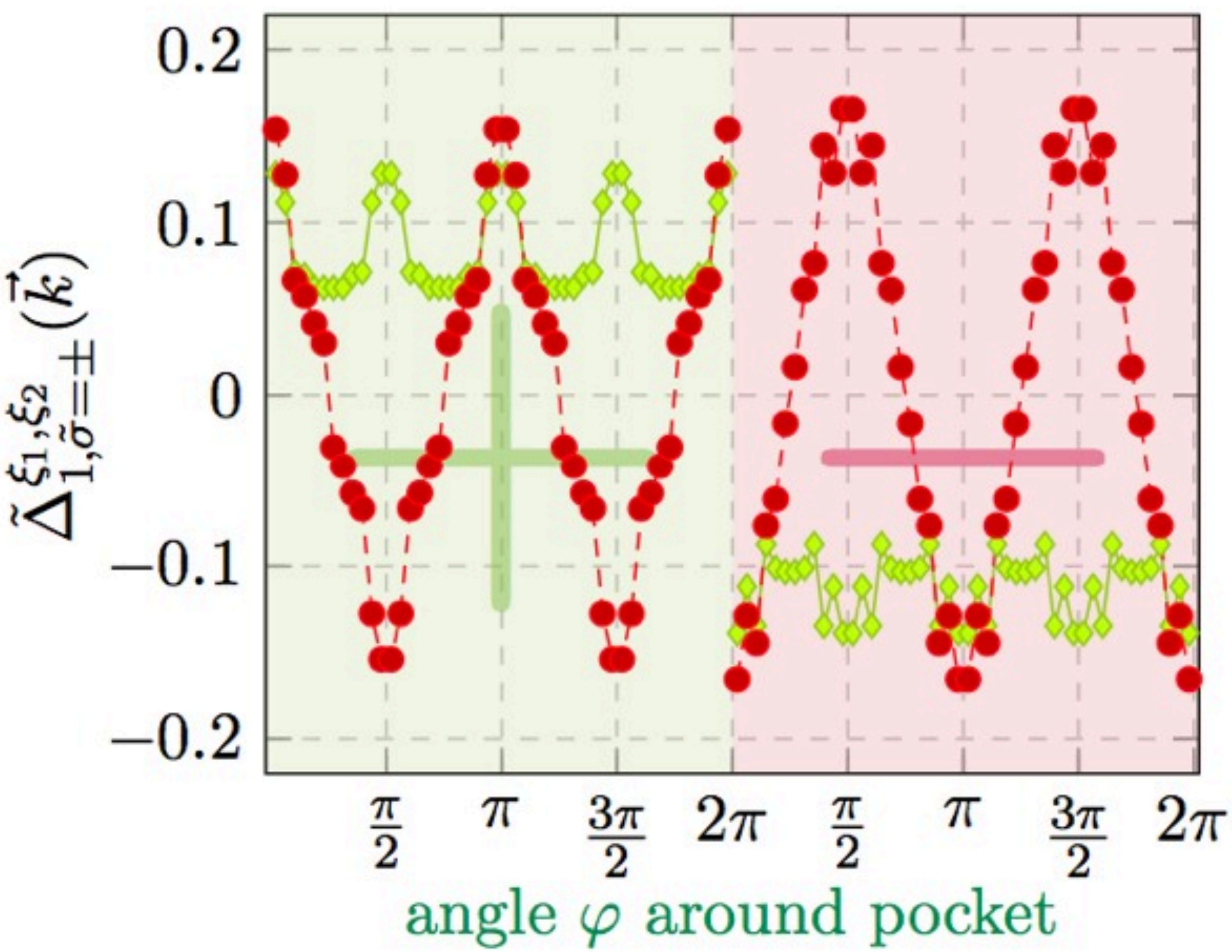


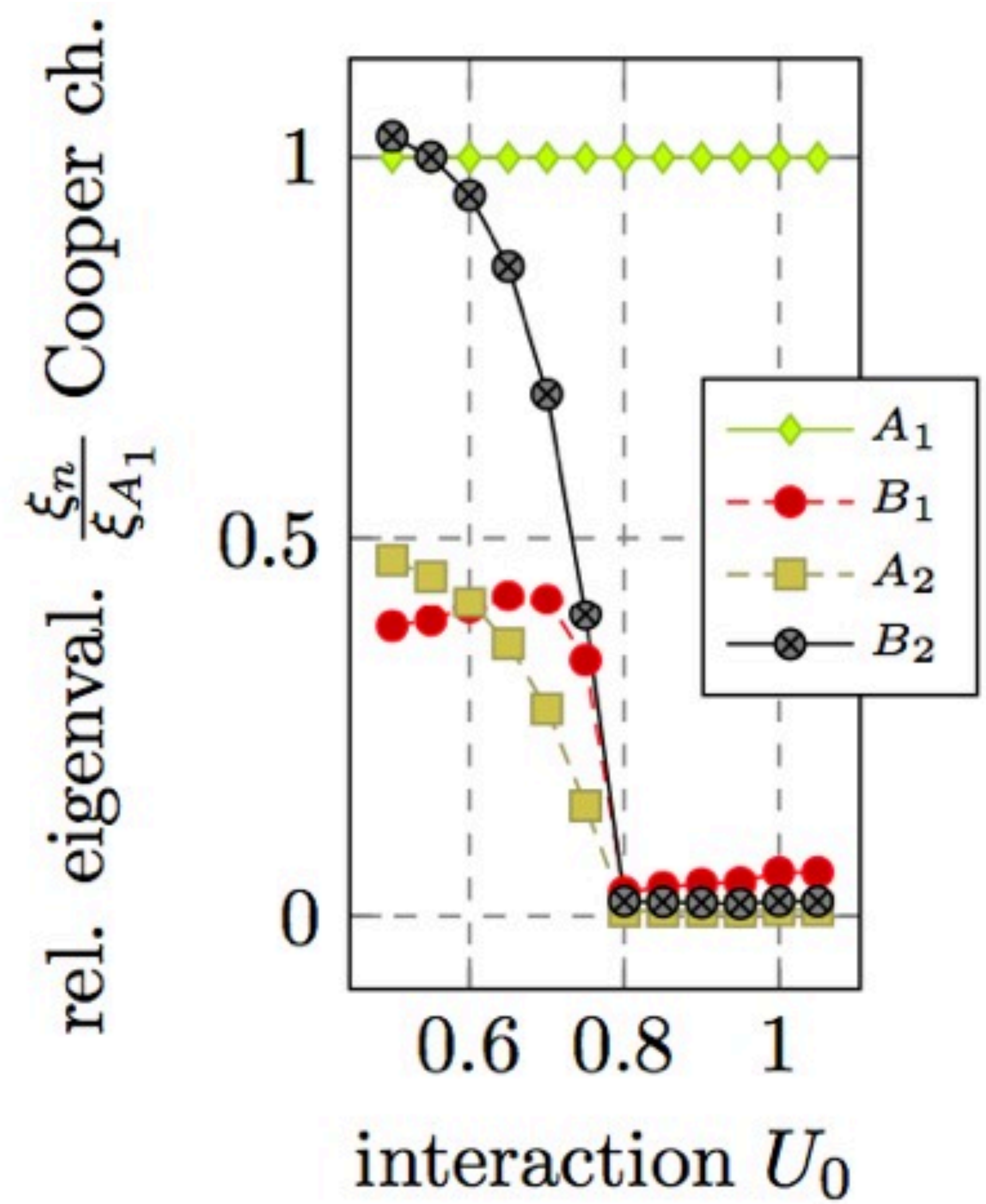
LAO/STO - tight binding setup



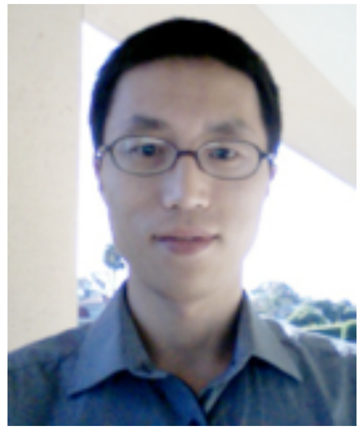
New methodological step: Spin-orbit FRG with complete double group implementation.

LAO/STO - s-wave vs. d-wave





Research team

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UNIVERSITÄT
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