Sudipfest

UCLA
April 4-6, 2019

Intertwined Charge, Nematic, Magnetic and Superconducting Order in Fe-Based Superconductors

Robert J. Birgeneau
UC Berkeley

1. **DYNAMICS OF THE DISSIPATIVE 2-STATE SYSTEM** By: LEGGETT, AJ; CHAKRAVARTY, S; DORSEY, AT; et al. REVIEWS OF MODERN PHYSICS Volume: 59 Issue: 1 Pages: 1-85 Published: JAN 1987	135	133	146	137	17	3540
2. **TWO-DIMENSIONAL QUANTUM HEISENBERG-ANTIFERROMAGNET AT LOW-TEMPERATURES** By: CHAKRAVARTY, S; HALPERIN, BI; NELSON, DR PHYSICAL REVIEW B Volume: 39 Issue: 4 Pages: 2344-2371 Published: FEB 1 1989	18	21	32	20	4	1207
3. **Hidden order in the cuprates** By: Chakravarty, S; Laughlin, RB; Morr, DK; et al. PHYSICAL REVIEW B Volume: 63 Issue: 9 Article Number: 094503 Published: MAR 1 2001	32	22	16	11	2	841
4. **WEAK LOCALIZATION - THE QUASI-CLASSICAL THEORY OF ELECTRONS IN A RANDOM POTENTIAL** By: CHAKRAVARTY, S; SCHMID, A PHYSICS REPORTS-REVIEW SECTION OF PHYSICS LETTERS Volume: 140 Issue: 4 Pages: 193-236 Published: JUL 1986	1	8	6	7	1	357
5. **QUANTUM FLUCTUATIONS IN THE TUNNELING BETWEEN SUPERCONDUCTORS** By: CHAKRAVARTY, S PHYSICAL REVIEW LETTERS Volume: 49 Issue: 9 Pages: 681-684 Published: 1982	3	7	1	4	2	335

Group Members

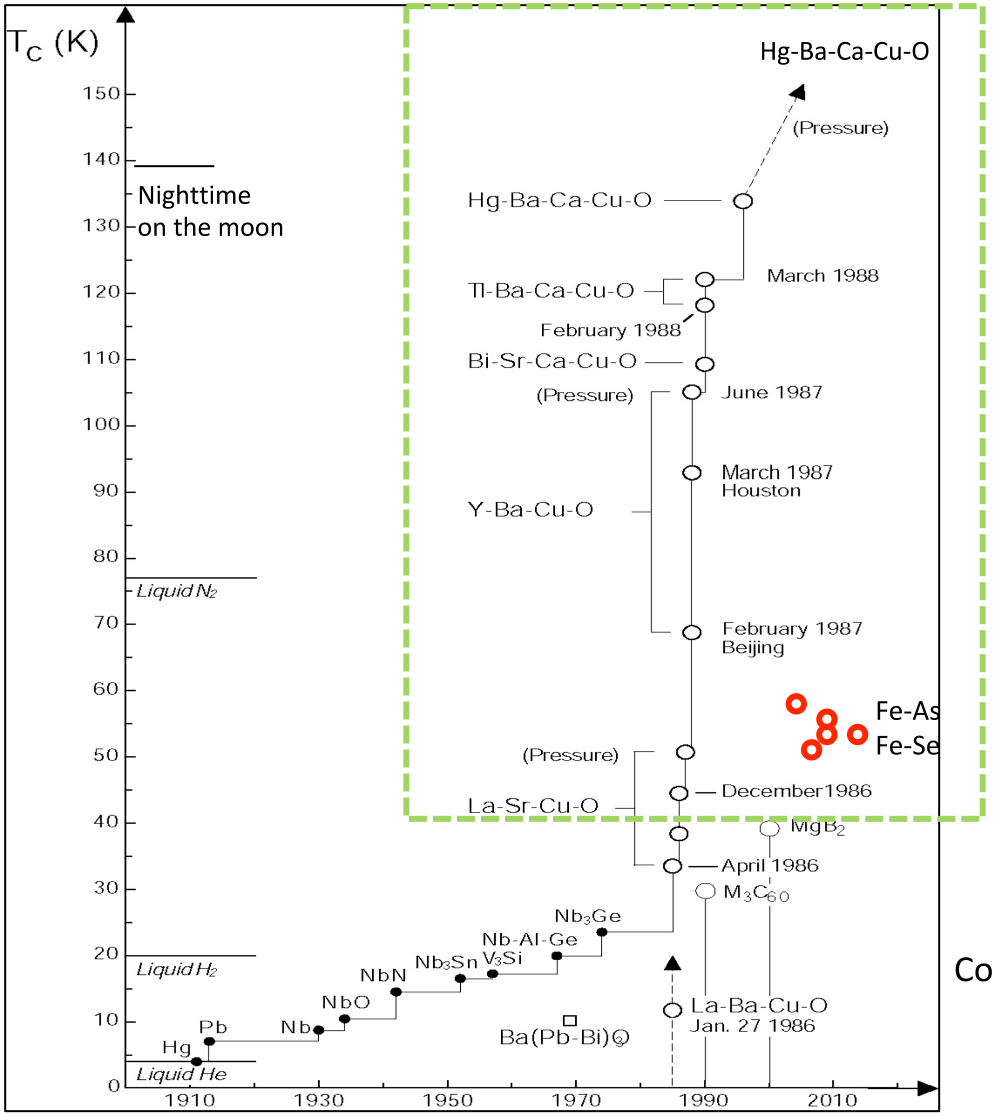
Xiang Chen
Ben Frandsen*
Alex Frano*
Yu He
Min Gyu Kim*
Yu Song
Meng Wang*
Shan Wu
Zhijun Xu*
Ming Yi*
Jun Zhao*

*Recent past members

Collaborators

Edith Bourret
Byron Freelon
Bernhard Keimer
Alessandra Lanzara
Dung Hai Lee
Z.-X. Shen
John Tranquada
Stephen Wilson

History of Superconductivity



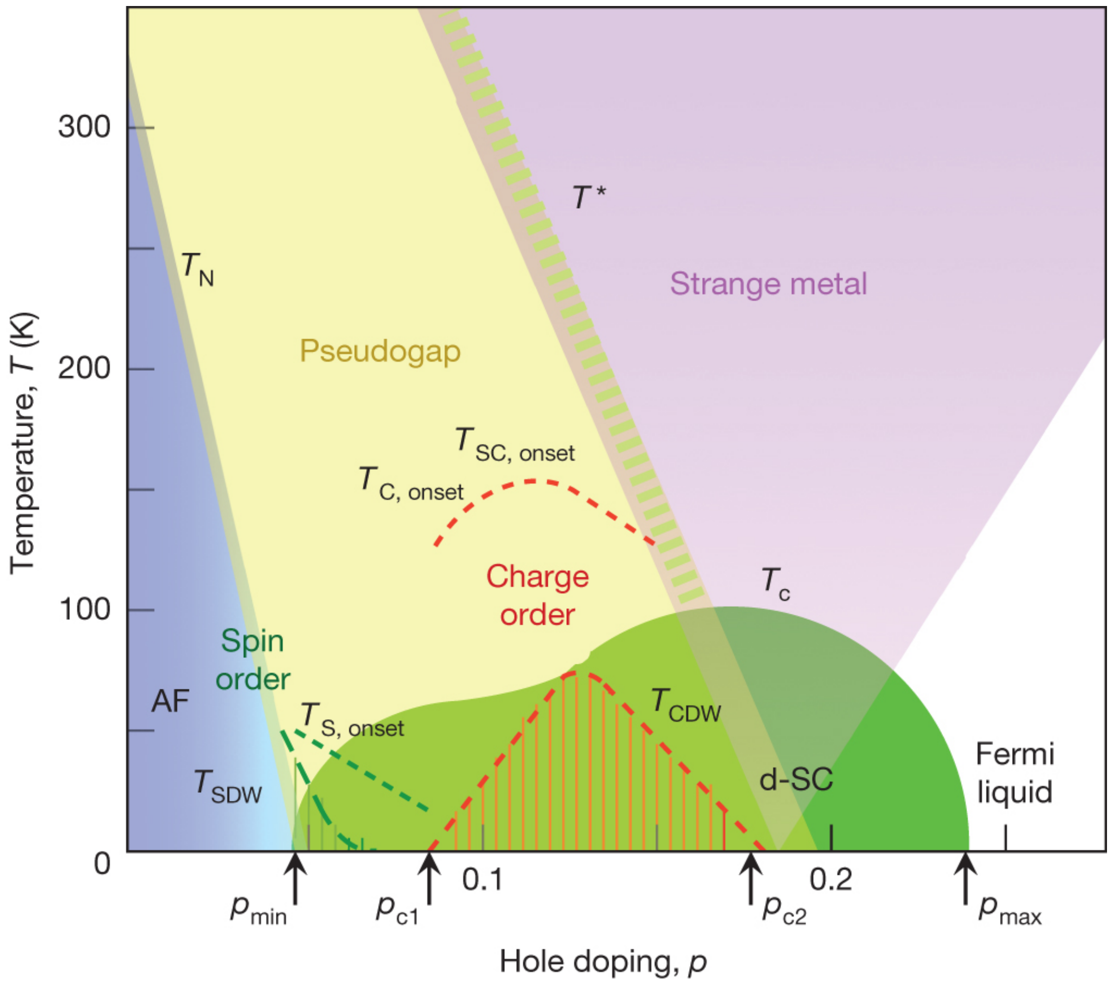
High Temperature Superconductors

Copper oxides

Iron based

Conventional superconductors

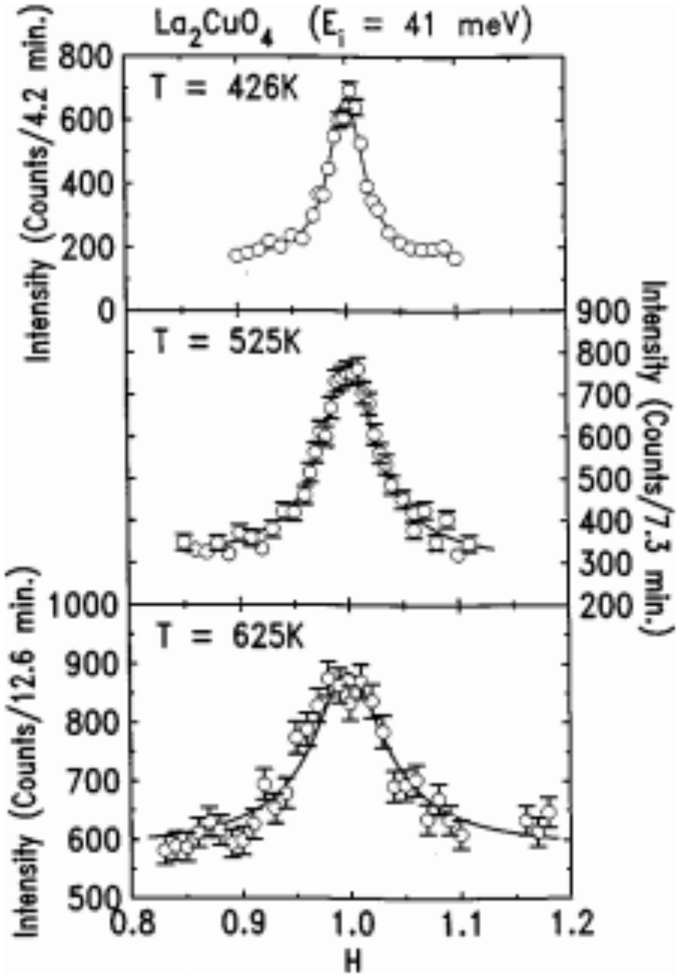
Phase diagram.

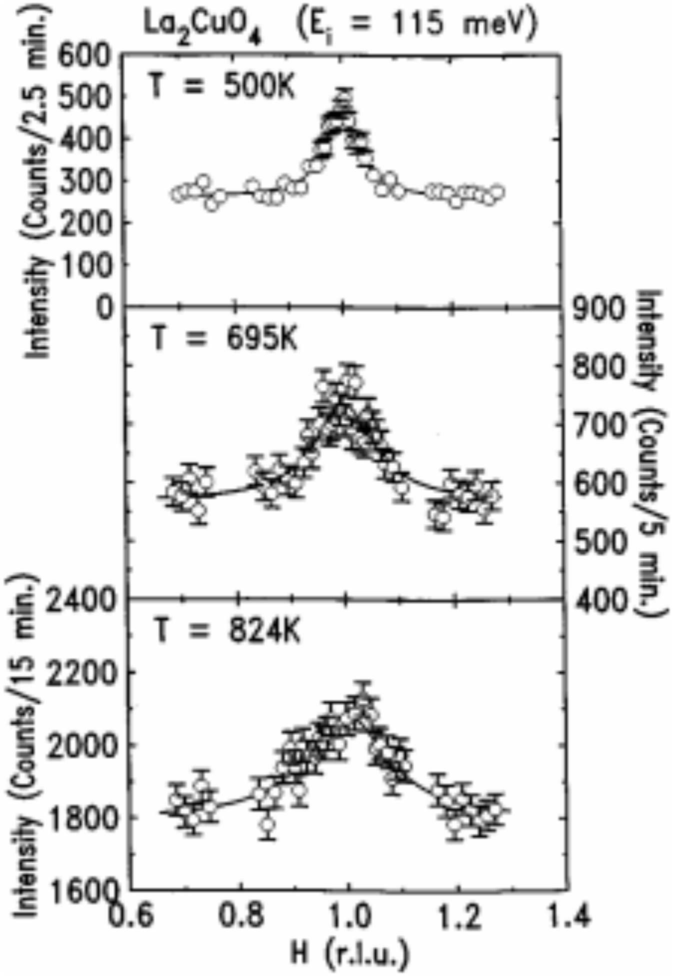


B Keimer *et al.* *Nature* **518**, 179-186 (2015) doi:10.1038/nature14165

Berkeley UNIVERSITY OF CALIFORNIA

nature


La2CuO4 (Ei = 41 meV)
Intensity (Counts/4.2 min.)
800
600
400
200
0
T = 426K
T = 525K
Intensity (Counts/7.3 min.)
900
800
700
600
500
400
300
200
T = 625K
Intensity (Counts/12.6 min.)
1000
900
800
700
600
500
0.8
0.9
1.0
1.1
1.2
H


La2CuO4 (Ei = 115 meV)
Intensity (Counts/2.5 min.)
600
500
400
300
200
100
0
T = 500K
T = 695K
Intensity (Counts/5 min.)
900
800
700
600
500
400
T = 824K
Intensity (Counts/15 min.)
2400
2200
2000
1800
1600
0.6
0.8
1.0
1.2
1.4
H (r.l.u.)

La_2CuO_4: A Model Two Dimensional S = ½ Heisenberg Antiferromagnet

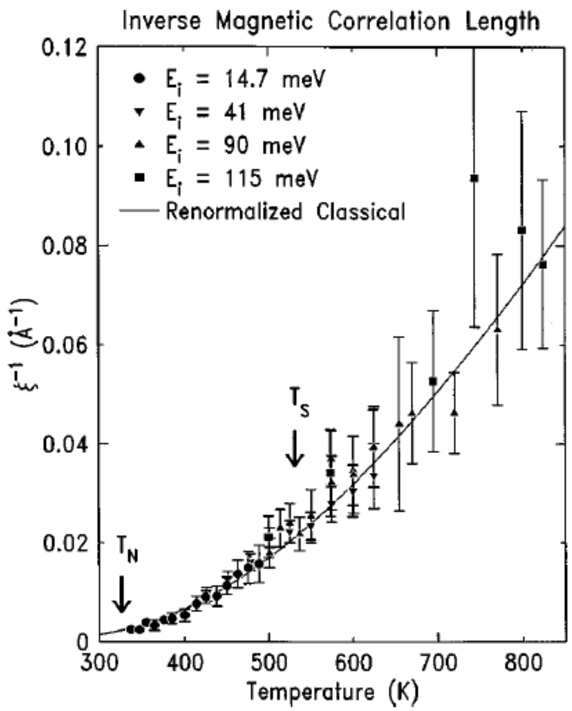
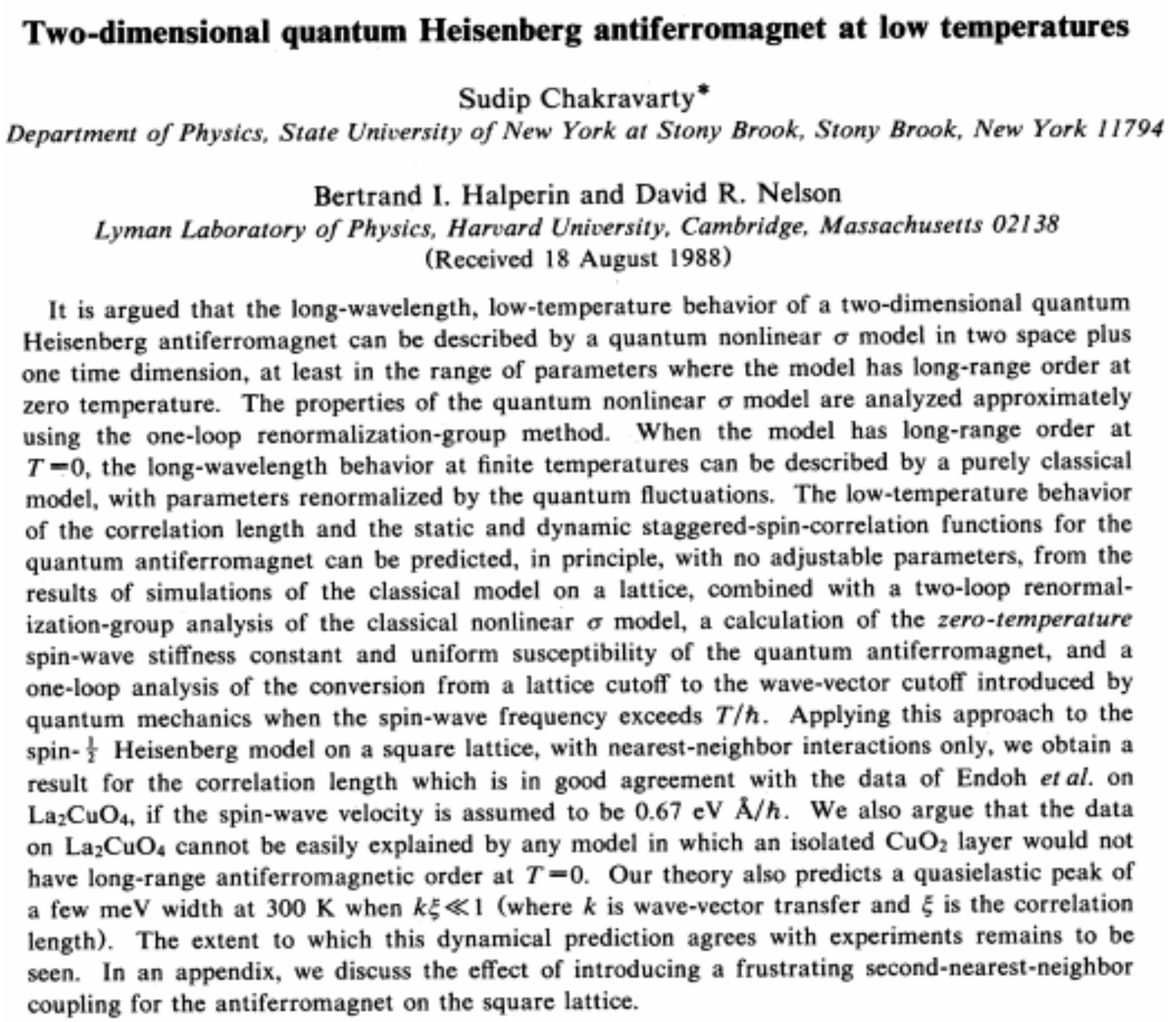


FIG. 5. Inverse magnetic correlation length of La_2CuO_4. The solid line is Eq. (6) with $J = 135$ meV. The Néel and structural transition temperatures are indicated by arrows.

$$\frac{\xi}{a} = \frac{e}{8}\,\frac{c/a}{2\pi\rho_s}\,e^{2\pi\rho_s/T}\left[1 - \frac{1}{2}\left(\frac{T}{2\pi\rho_s}\right) + \mathcal{O}\left(\frac{T}{2\pi\rho_s}\right)^2\right], \quad (6)$$

CHN: Phys. Rev. B 39, 2344, 198



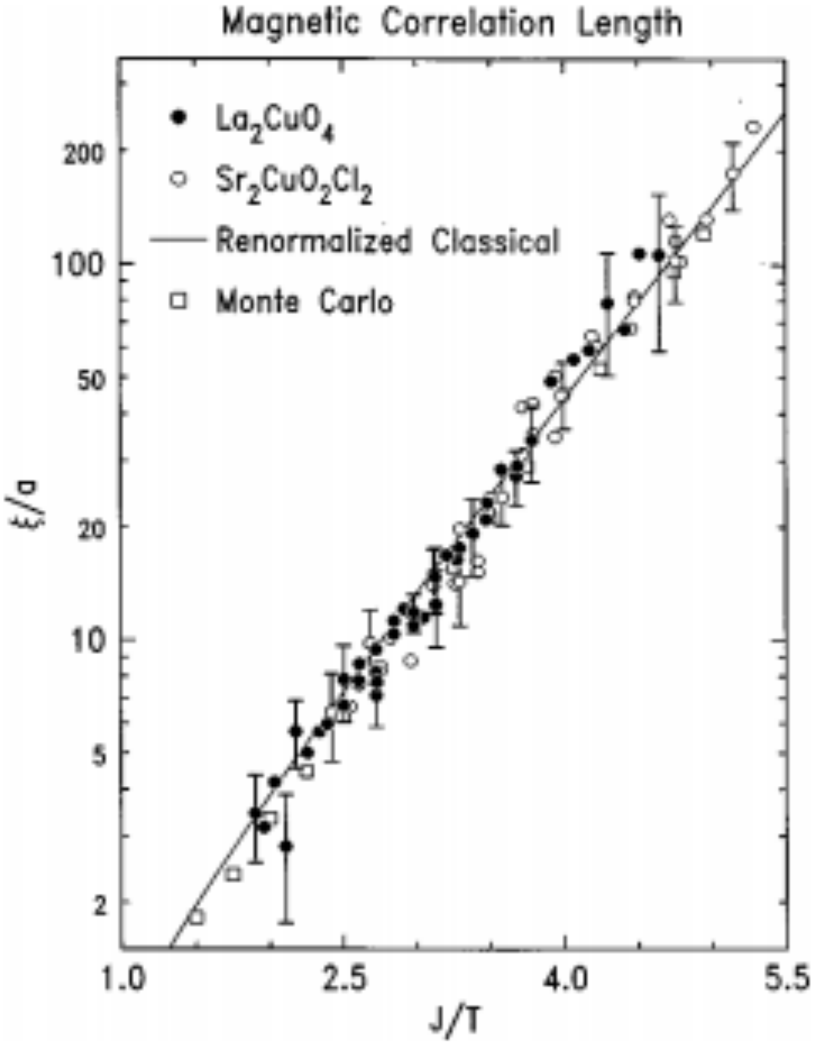
Two-dimensional quantum Heisenberg antiferromagnet at low temperatures

Sudip Chakravarty*
Department of Physics, State University of New York at Stony Brook, Stony Brook, New York 11794

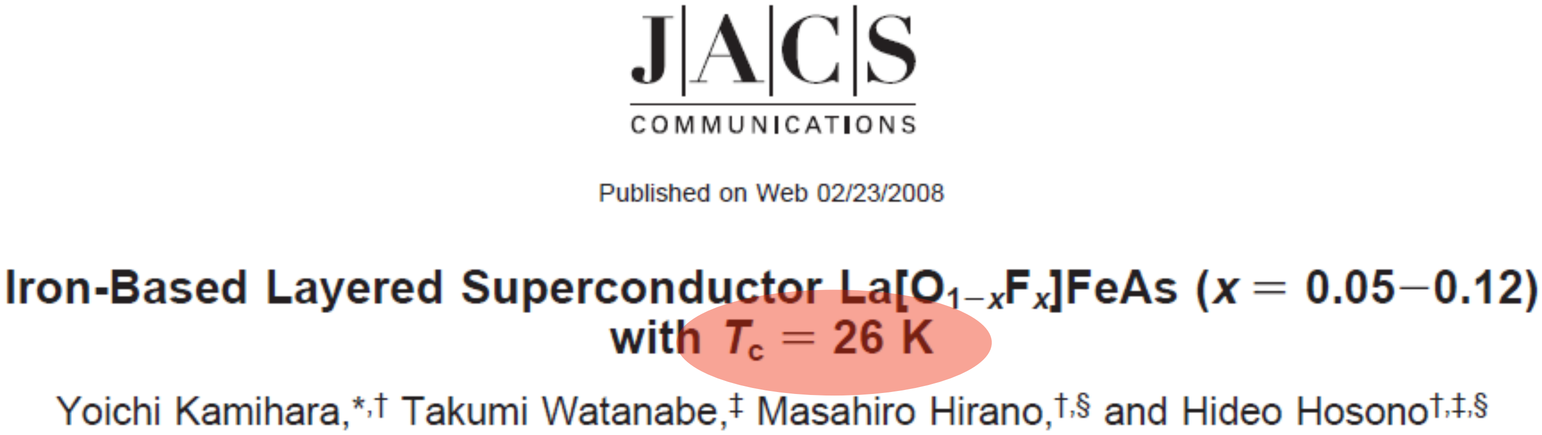
Bertrand I. Halperin and David R. Nelson
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

(Received 18 August 1988)

It is argued that the long-wavelength, low-temperature behavior of a two-dimensional quantum Heisenberg antiferromagnet can be described by a quantum nonlinear σ model in two space plus one time dimension, at least in the range of parameters where the model has long-range order at zero temperature. The properties of the quantum nonlinear σ model are analyzed approximately using the one-loop renormalization-group method. When the model has long-range order at $T=0$, the long-wavelength behavior at finite temperatures can be described by a purely classical model, with parameters renormalized by the quantum fluctuations. The low-temperature behavior of the correlation length and the static and dynamic staggered-spin-correlation functions for the quantum antiferromagnet can be predicted, in principle, with no adjustable parameters, from the results of simulations of the classical model on a lattice, combined with a two-loop renormalization-group analysis of the classical nonlinear σ model, a calculation of the *zero-temperature* spin-wave stiffness constant and uniform susceptibility of the quantum antiferromagnet, and a one-loop analysis of the conversion from a lattice cutoff to the wave-vector cutoff introduced by quantum mechanics when the spin-wave frequency exceeds $T/\hbar$. Applying this approach to the spin-$\frac{1}{2}$ Heisenberg model on a square lattice, with nearest-neighbor interactions only, we obtain a result for the correlation length which is in good agreement with the data of Endoh *et al.* on La_2CuO_4, if the spin-wave velocity is assumed to be 0.67 eV Å/$\hbar$. We also argue that the data on La_2CuO_4 cannot be easily explained by any model in which an isolated CuO_2 layer would not have long-range antiferromagnetic order at $T=0$. Our theory also predicts a quasielastic peak of a few meV width at 300 K when $k\xi \ll 1$ (where k is wave-vector transfer and ξ is the correlation length). The extent to which this dynamical prediction agrees with experiments remains to be seen. In an appendix, we discuss the effect of introducing a frustrating second-nearest-neighbor coupling for the antiferromagnet on the square lattice.


Magnetic Correlation Length
● La_2CuO_4
○ $Sr_2CuO_2Cl_2$
Renormalized Classical
□ Monte Carlo
ξ/a
200
100
50
20
10
5
2
1.0
2.5
4.0
5.5
J/T

Rise of the iron pnictides



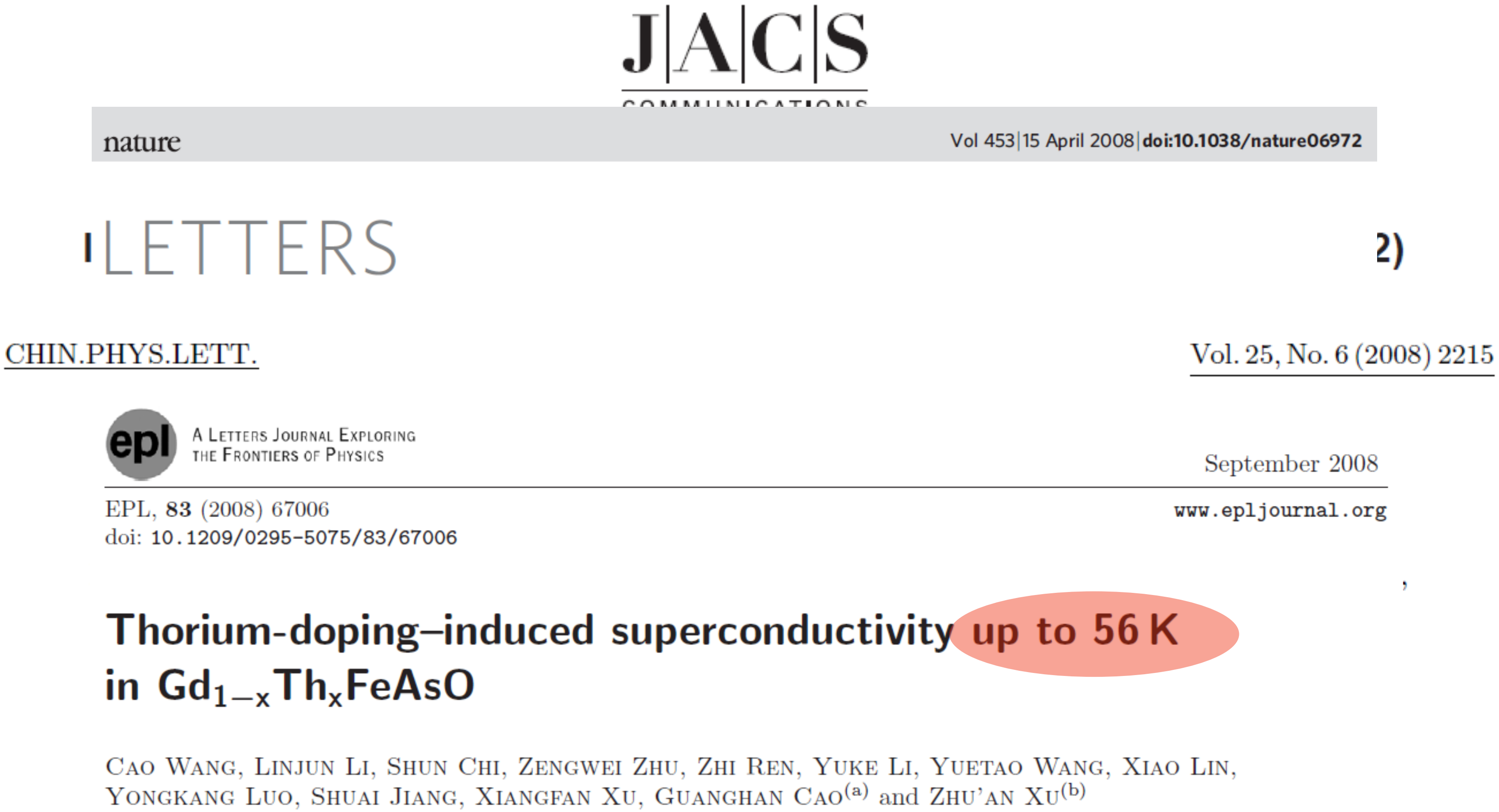
J|A|C|S
COMMUNICATIONS

Published on Web 02/23/2008

Iron-Based Layered Superconductor La[$O_{1-x}F_x$]FeAs ($x = 0.05-0.12$) with $T_c = 26$ K

Yoichi Kamihara,[*,†] Takumi Watanabe,[‡] Masahiro Hirano,[†,§] and Hideo Hosono[†,‡,§]

Rise of the iron pnictides



J|A|C|S

COMMUNICATIONS

nature

Vol 453 | 15 April 2008 | doi:10.1038/nature06972

LETTERS

2)

CHIN.PHYS.LETT.

Vol. 25, No. 6 (2008) 2215

epl

A Letters Journal Exploring the Frontiers of Physics

September 2008

EPL, **83** (2008) 67006

doi: 10.1209/0295-5075/83/67006

www.epljournal.org

Thorium-doping–induced superconductivity up to 56 K in $Gd_{1-x}Th_xFeAsO$

Cao Wang, Linjun Li, Shun Chi, Zengwei Zhu, Zhi Ren, Yuke Li, Yuetao Wang, Xiao Lin, Yongkang Luo, Shuai Jiang, Xiangfan Xu, Guanghan Cao(a) and Zhu'an Xu(b)

Rise of the iron pnictides

J|A|C|S

COMMUNICATIONS

nature Vol 453|15 April 2008|**doi:10.1038/nature06972**

LETTERS

2)

CHIN.PHYS.LETT. Vol. 25, No. 6 (2008) 2215

epl A LETTERS JOURNAL EXPLORING THE FRONTIERS OF PHYSICS

September 2008

EPL, **83** (2008) 67006
doi: 10.1209/0295-5075/83/67006

www.epljournal.org

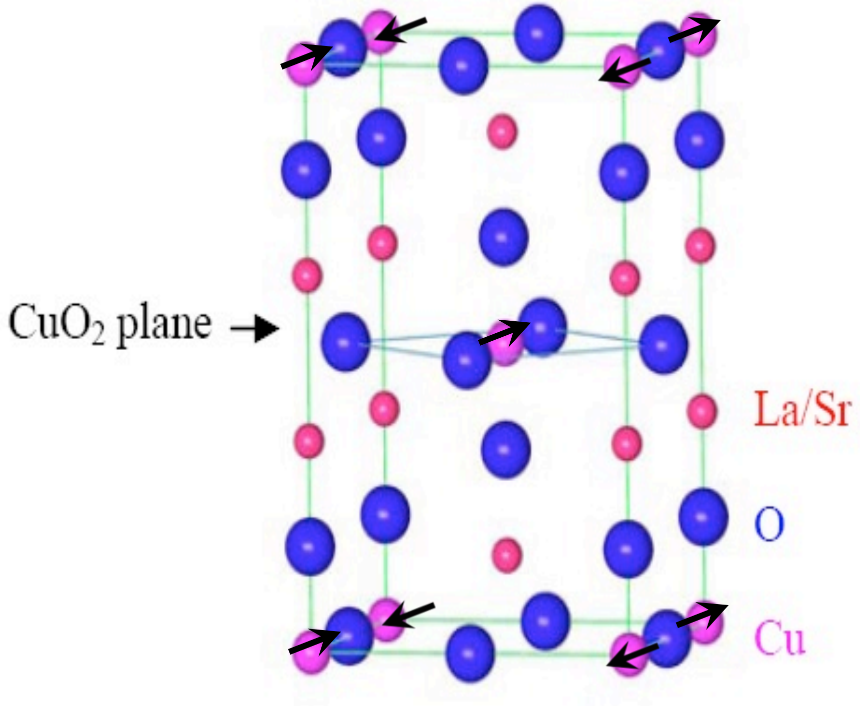
Superconductivity in single-layer films of FeSe with a transition temperature above 100 K

Jian-Feng Ge[1], Zhi-Long Liu[1], Canhua Liu[1]*, Chun-Lei Gao[1], Dong Qian[1], Qi-Kun Xue[2]*, Ying Liu[1,3], Jin-Feng Jia[1]*

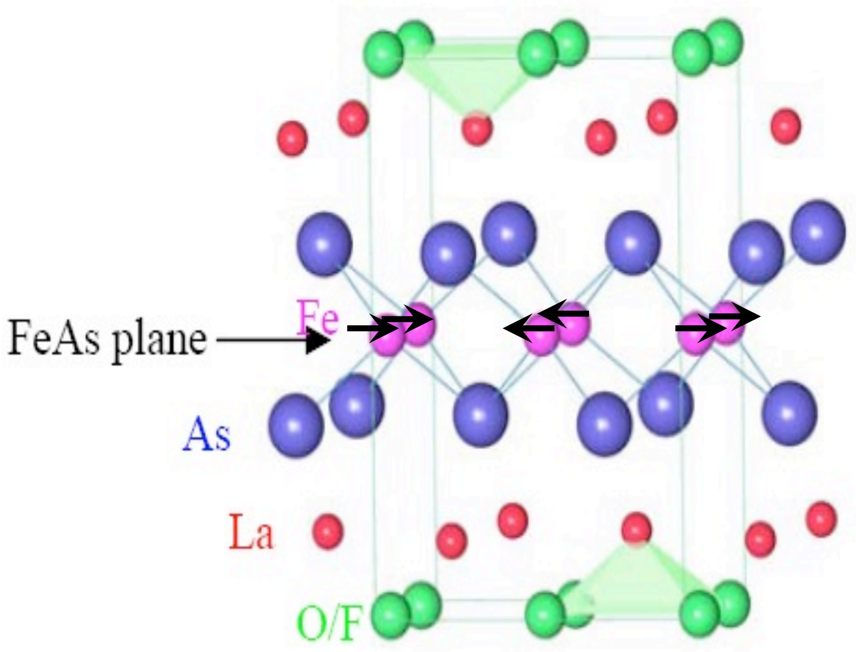
arxiv:1406.3435

Common features of high T_c superconductors

$La_{2-x}Sr_xCuO_4$



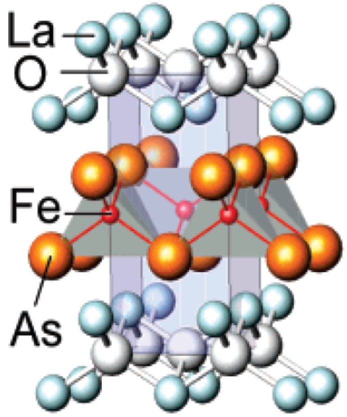
$LaFeAsO_{1-x}F_x$



New Iron Based Superconductors

ZrCuSiAs-type

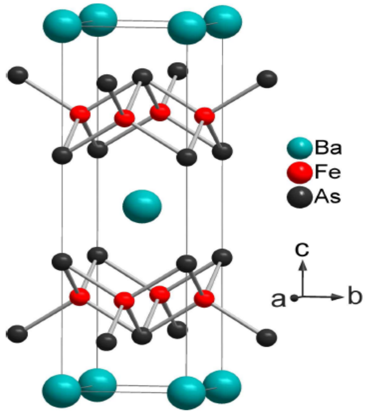
Kamihara et al., JACS (2008)



$(RE)FeAsO_{1-x}F_x$ $(T_c{\sim}55K)_{max}$

ThCr$_2$Si$_2$-type

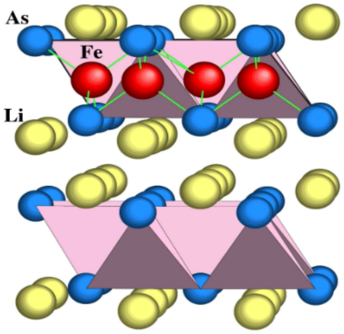
Rotter et al., PRL (2008)



$Ba_{1-x}K_xFe_2As_2$ $(T_c{\sim}38K)_{max}$

Cu$_2$Sb-type

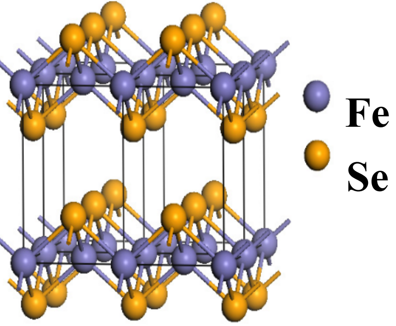
Nekrasov et al. JETP (2008)



$LiFeAs$ $(T_c{\sim}18K)_{max}$

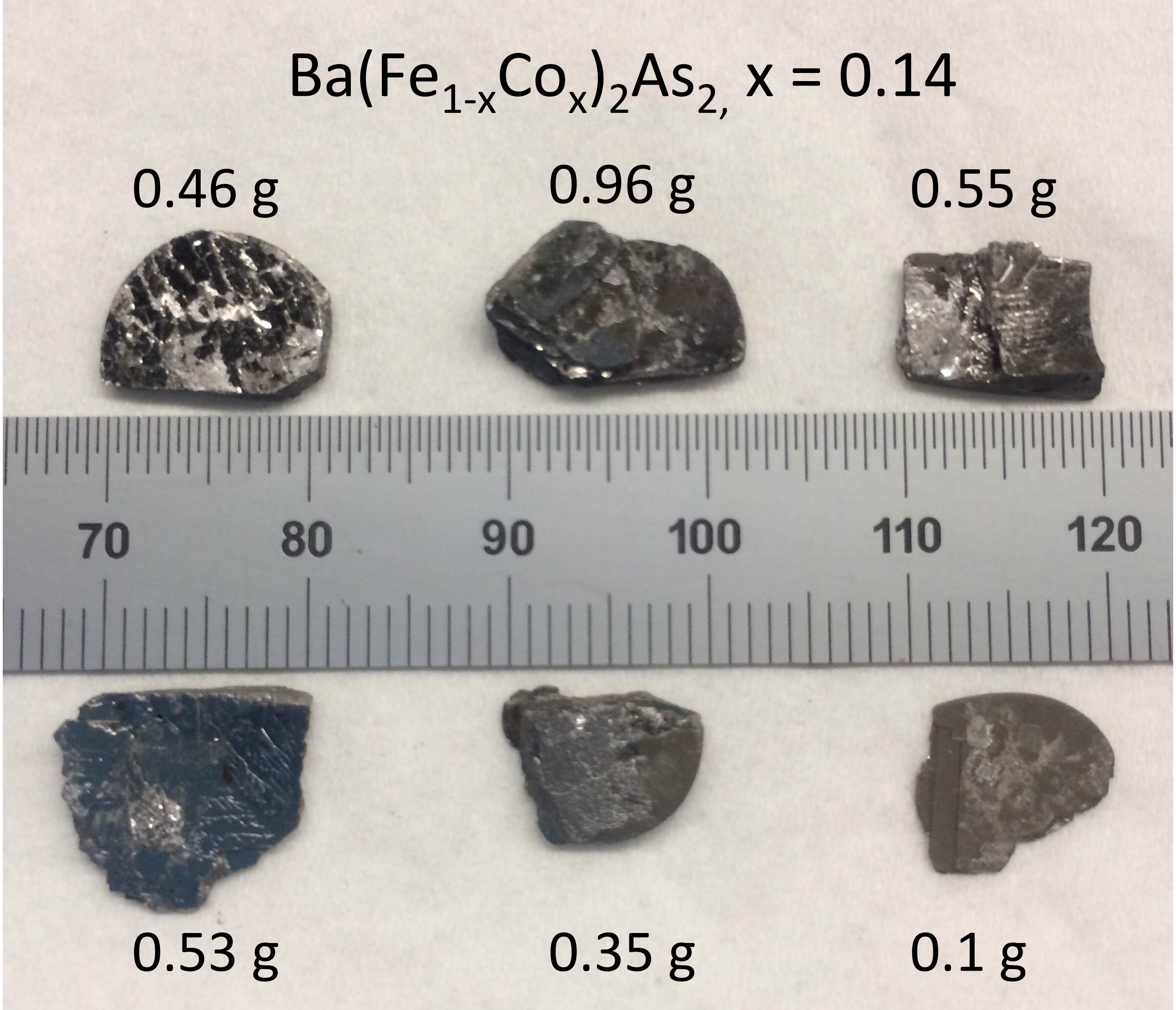
PbO-type

Hsu et al. ArxiV (2008)

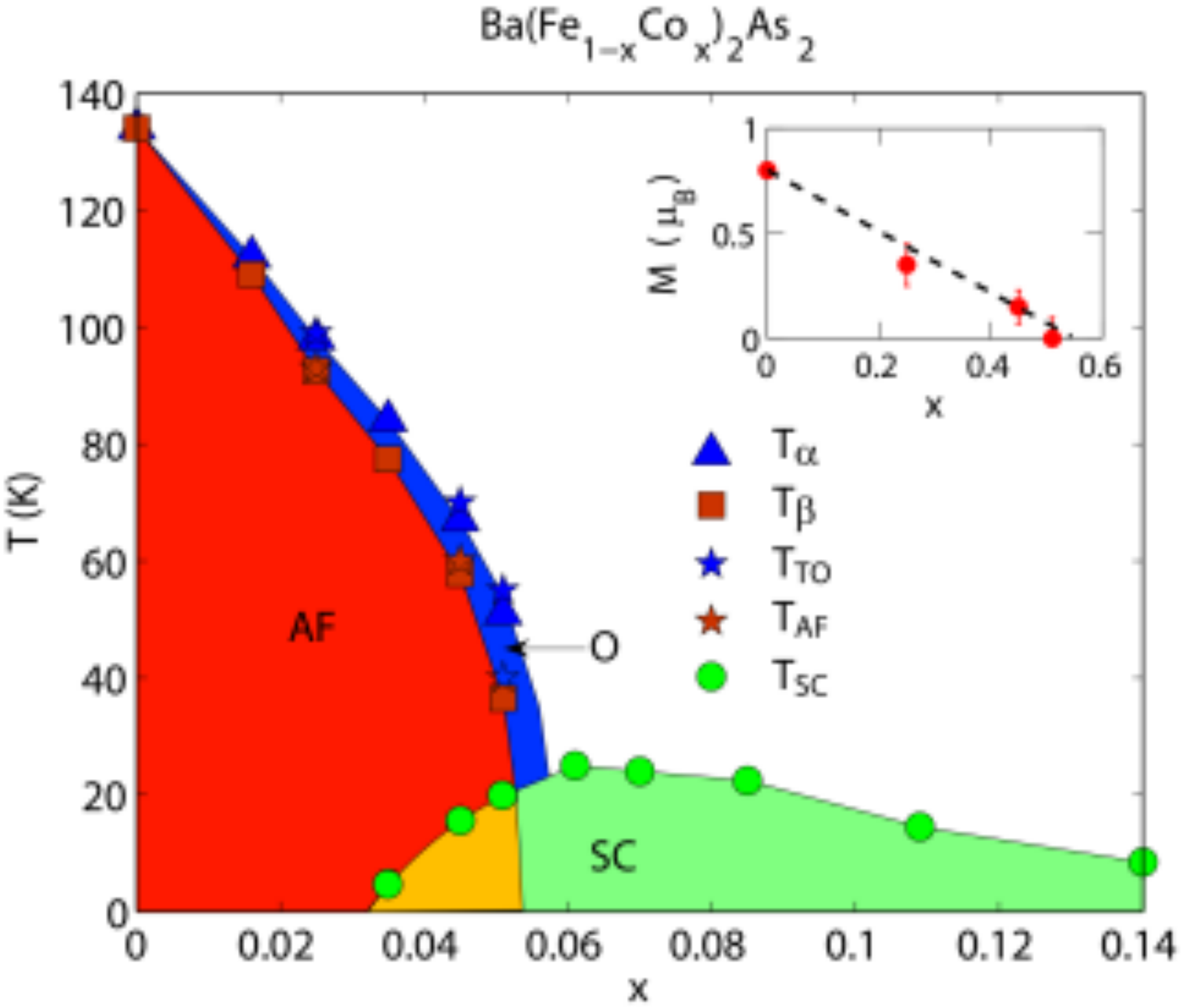


$FeSe_{1-x}Te_x$ $(T_c{\sim}15K)_{max}$

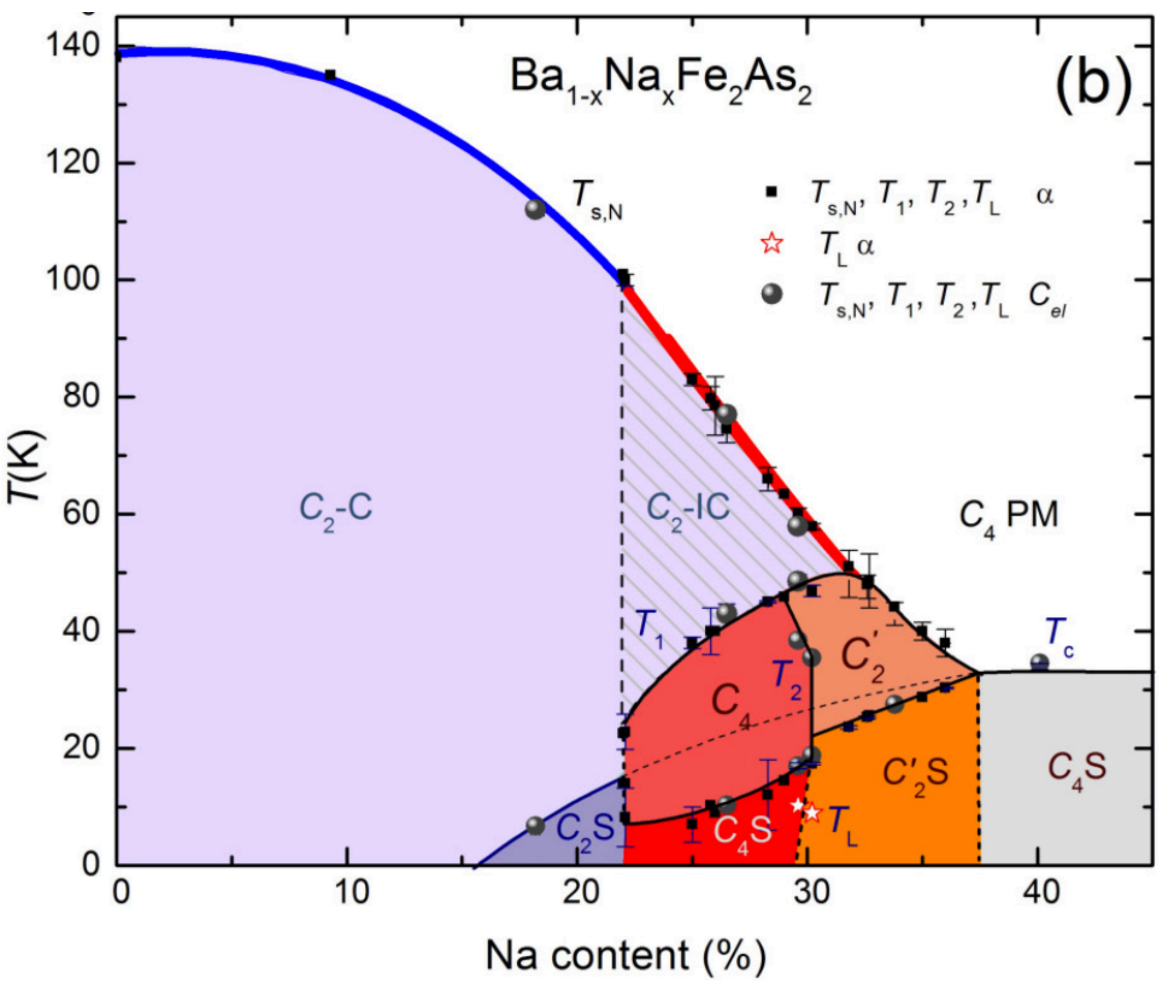
$Ba(Fe_{1-x}Co_x)_2As_2$, x = 0.14



Rb0.8Fe1.5SeS
3 grams
Grown with Bridgman furnace



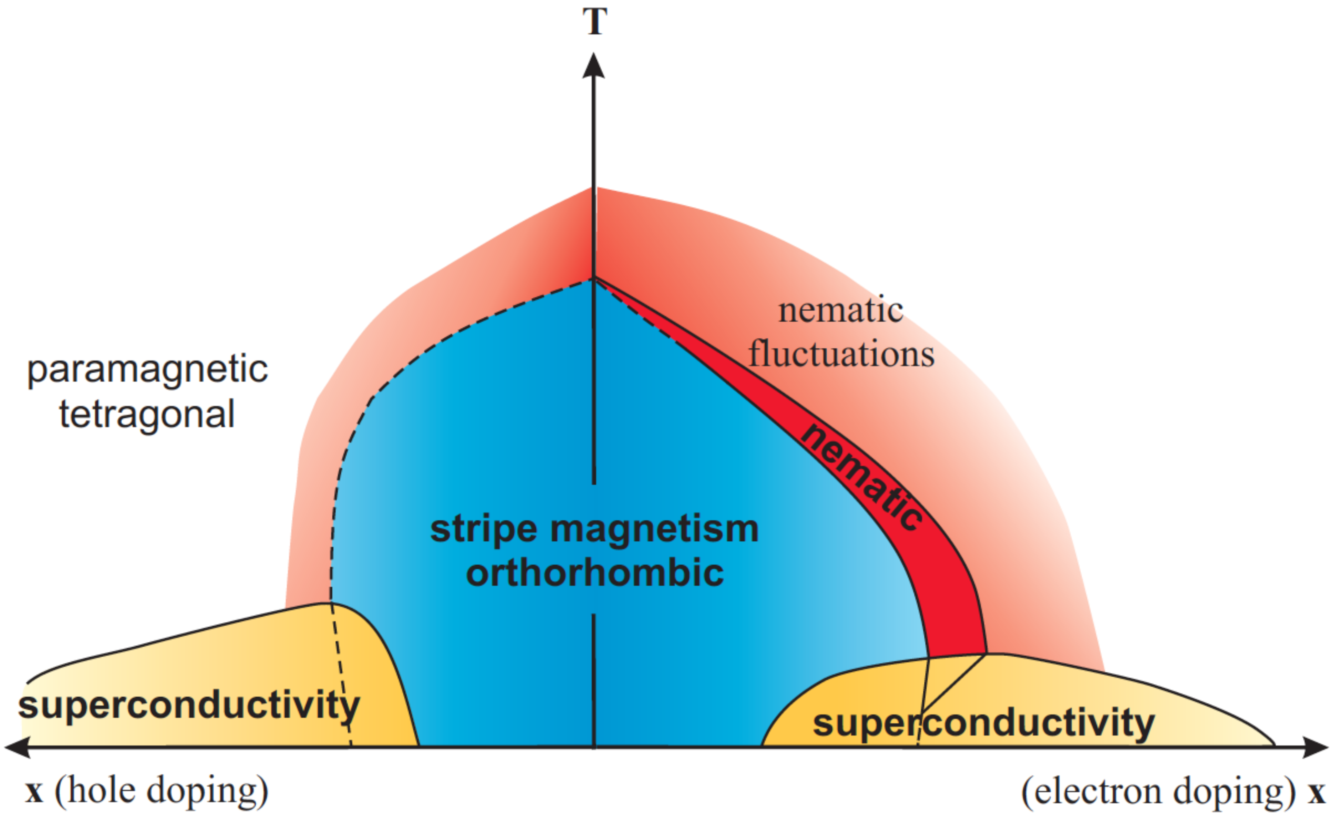
$Ba(Fe_{1-x}Co_x)_2As_2$



A. Bohmer *et al*. Nat. Comm. 6, 7911 (2015)
L. Wang *et al.* Phys. Rev. B 93, 014514 (2016)

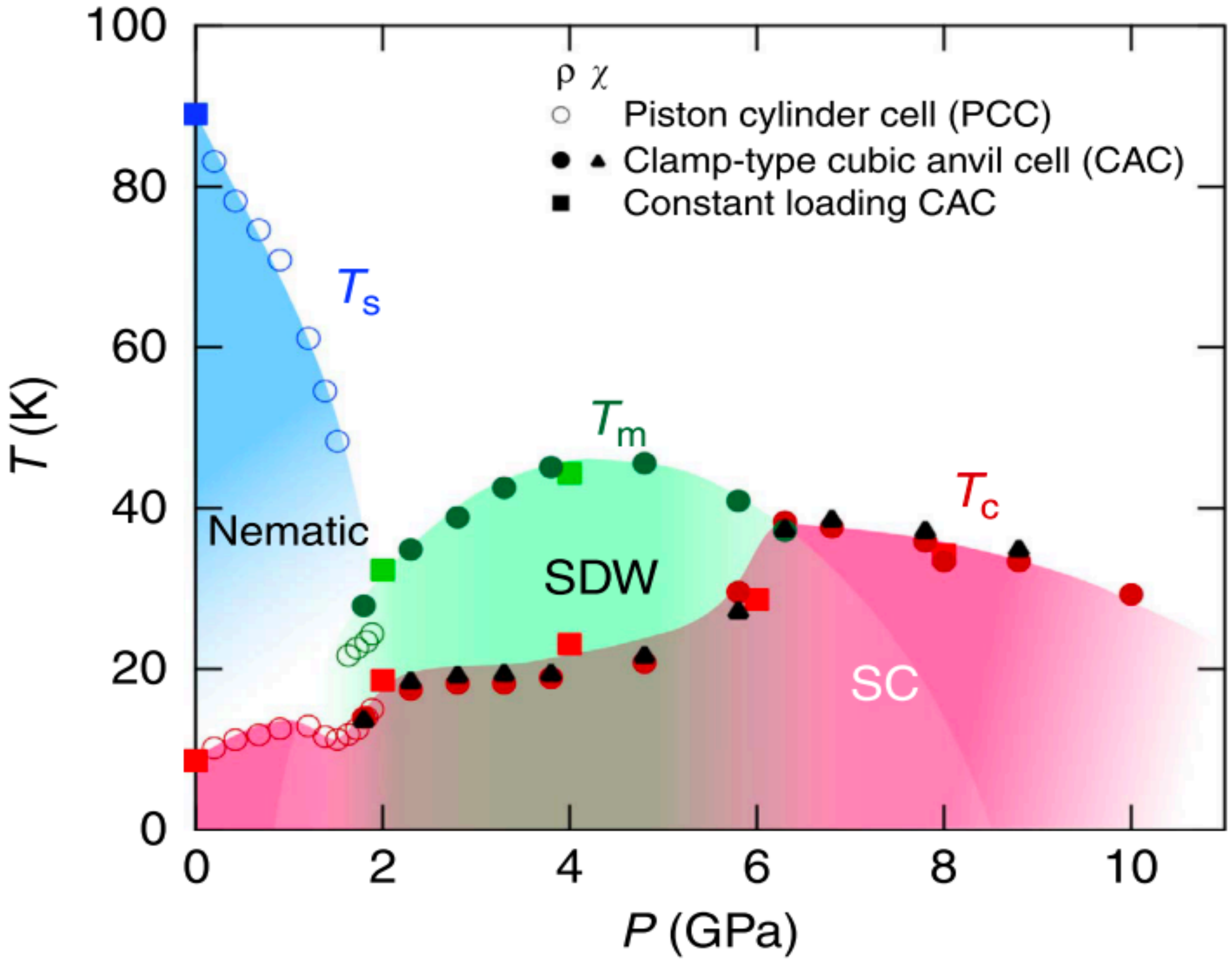
Schematic phase diagram of the iron pnictides

- what is the origin of the nematic instability?
- what is the importance of nematicity to superconductivity?



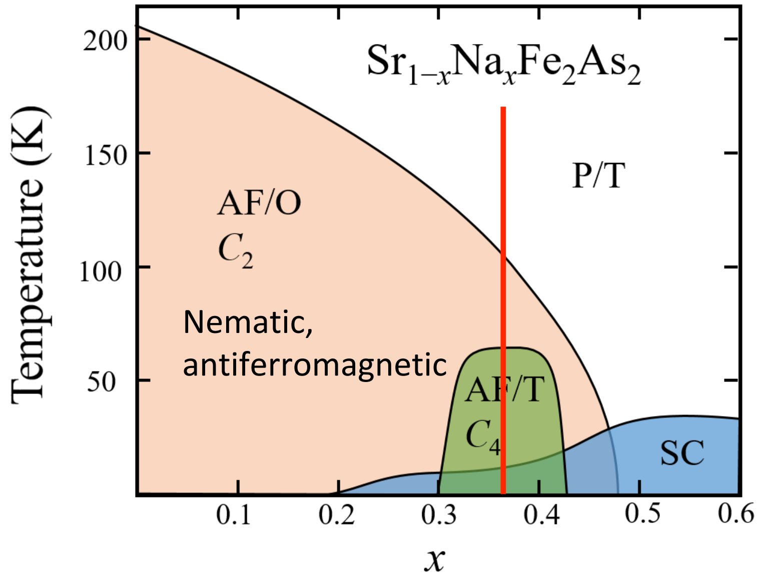
nematic transition = tetragonal-to-orthorhombic transition

FeSe phase diagram: temperature vs pressure

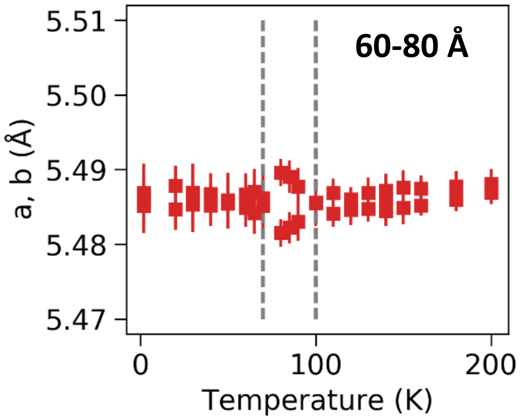


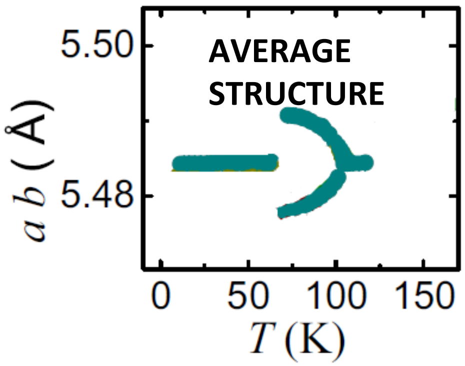
J. Sun *et al*. Nat. Comm. 7 12146 (2016)

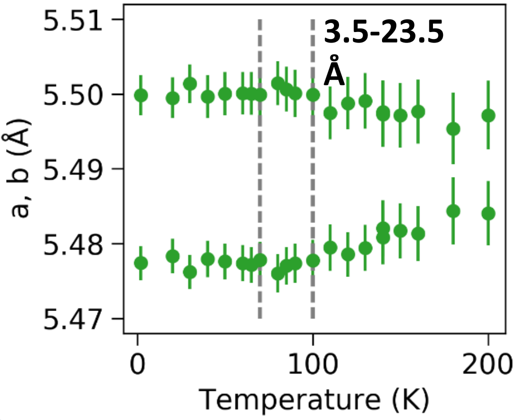
Structure of $Sr_{1-x}Na_xFe_2As_2$: x = 0.34 (with magnetic C_4 phase)

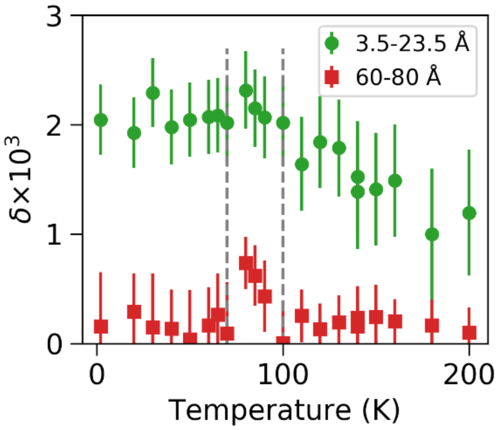


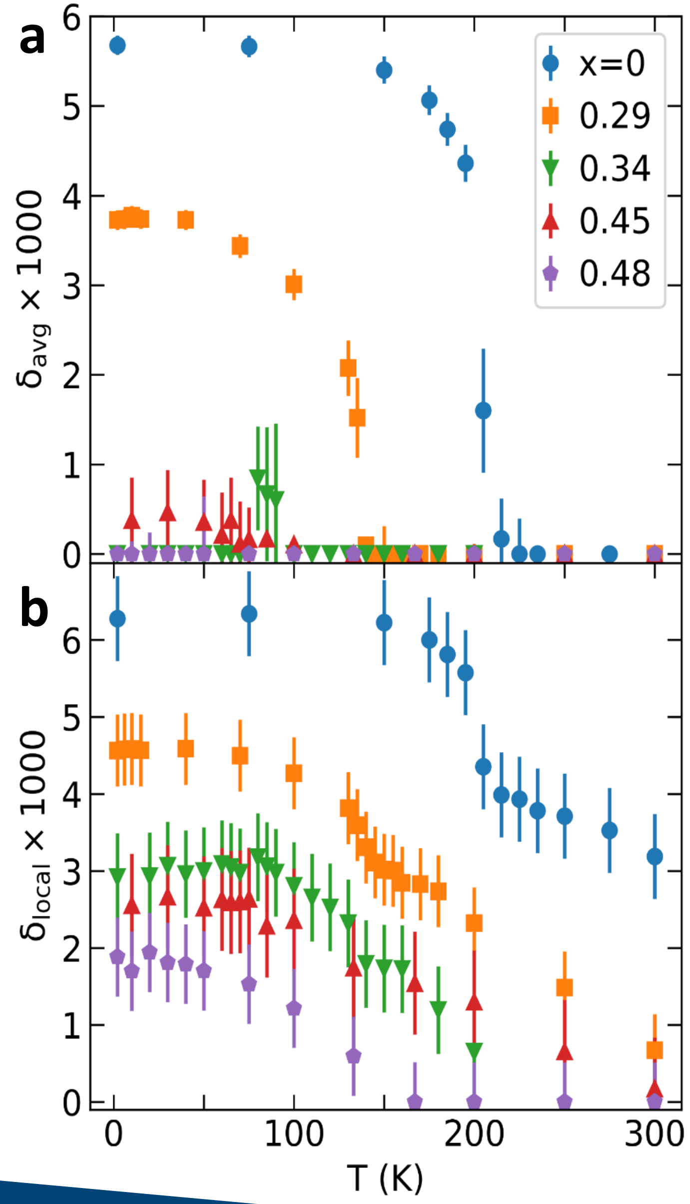
Frandsen et al, PRL **119**, 187001 (2017)



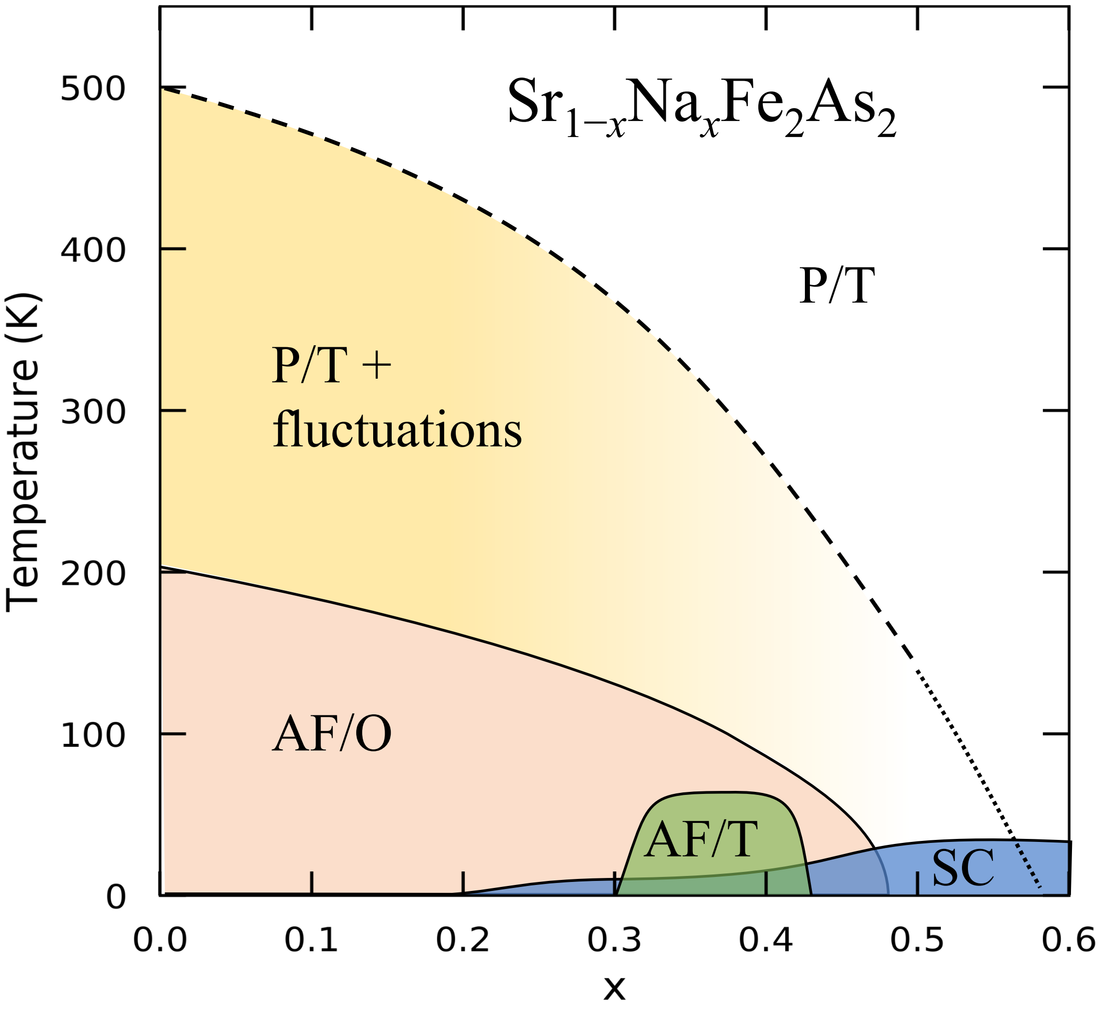








Berkeley
UNIVERSITY OF CALIFORNIA

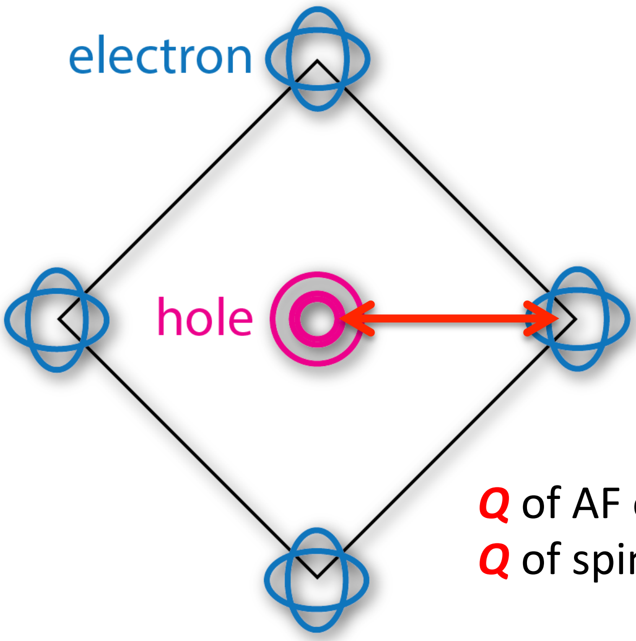


Note:
Disorder acts as a random nematic field

→ The physics of the 3D random field Ising Model

The curious case of doped iron chalcogenide superconductors

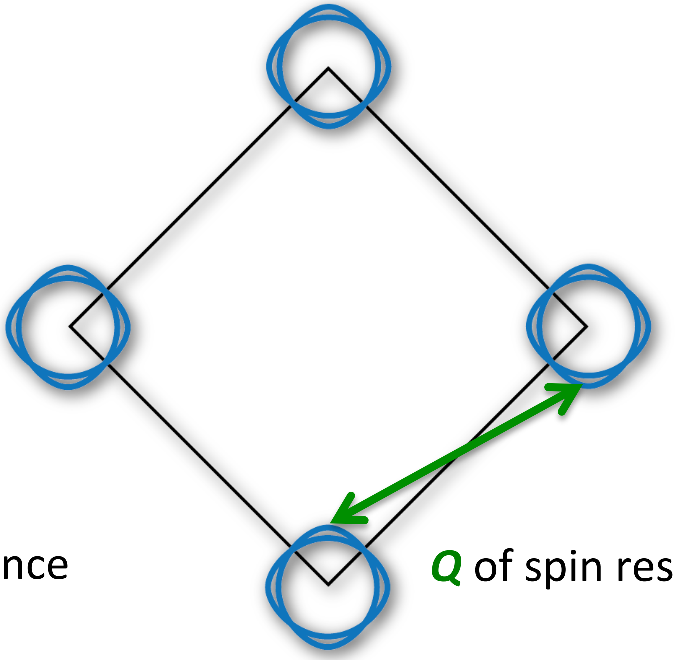
Iron-pnictides



Q of AF order
Q of spin resonance

Spin fluctuations at the Fermi surface nesting vector (π , π)

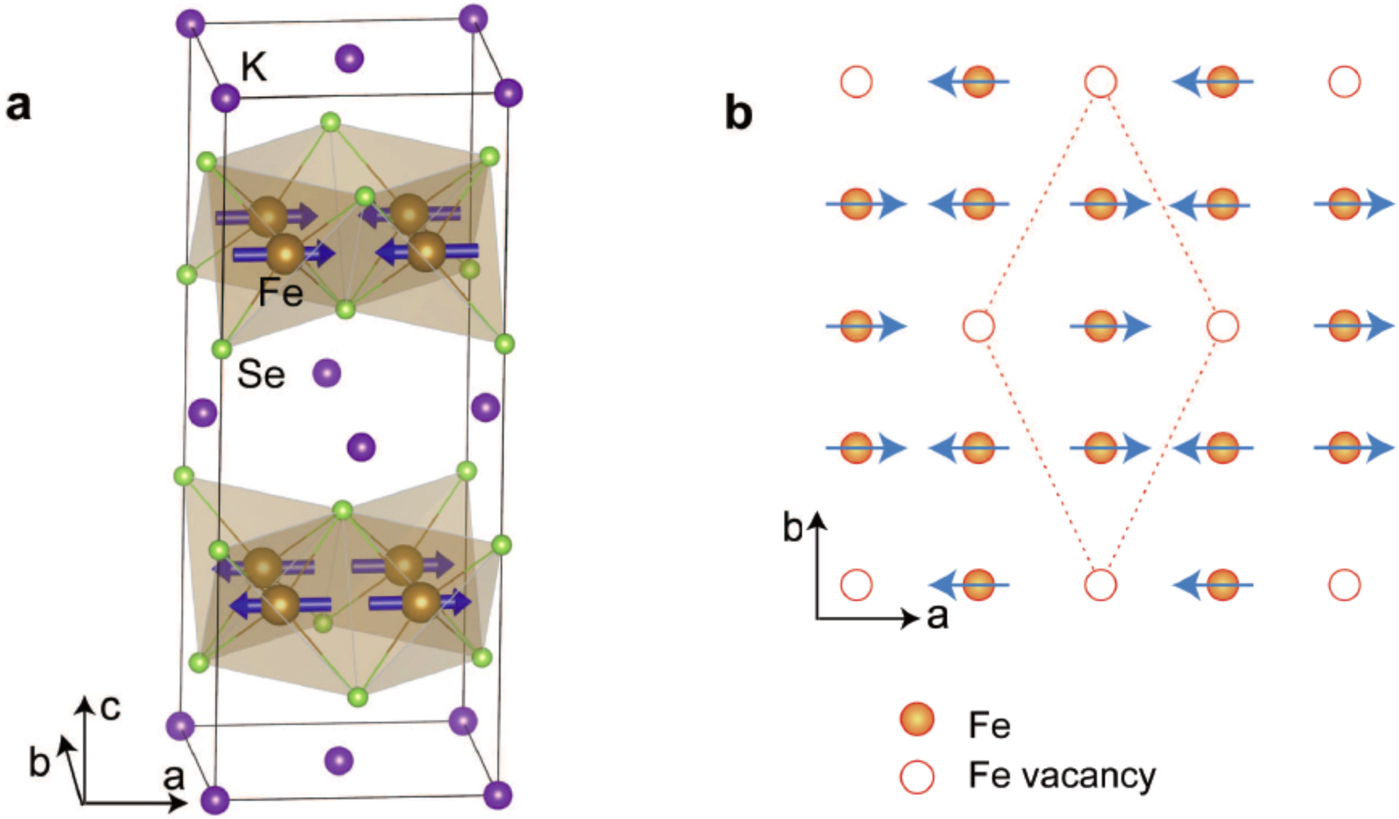
Doped Iron-chalcogenides



Q of spin resonance

Lack of electron and hole Fermi surface nesting conditions

Stripe type AF order and rhombus iron vacancy order of semiconducting $K_{0.85}Fe_{1.54}Se_2$



J. Zhao et al. arXiv:1205.5992 (2012)

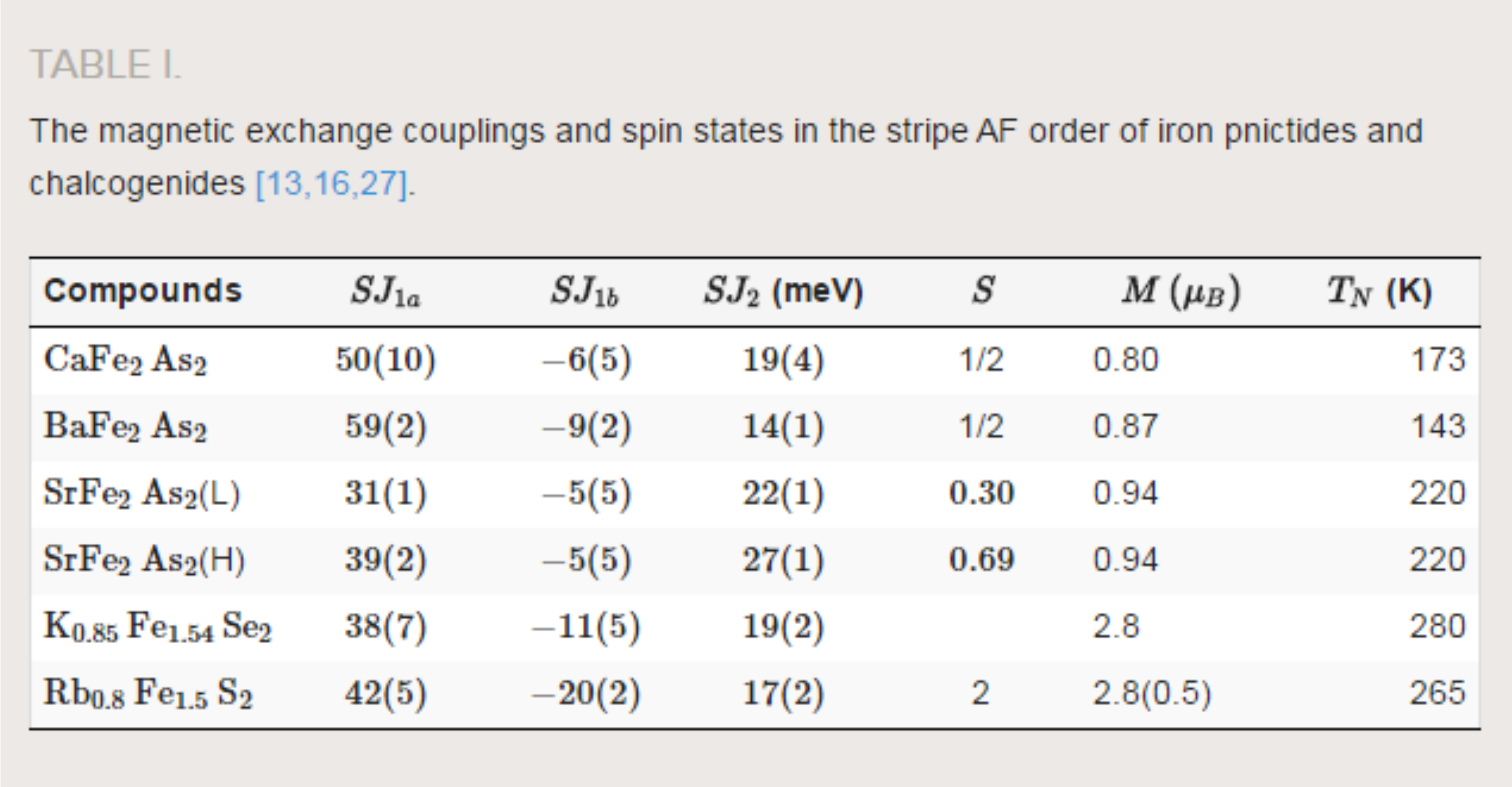
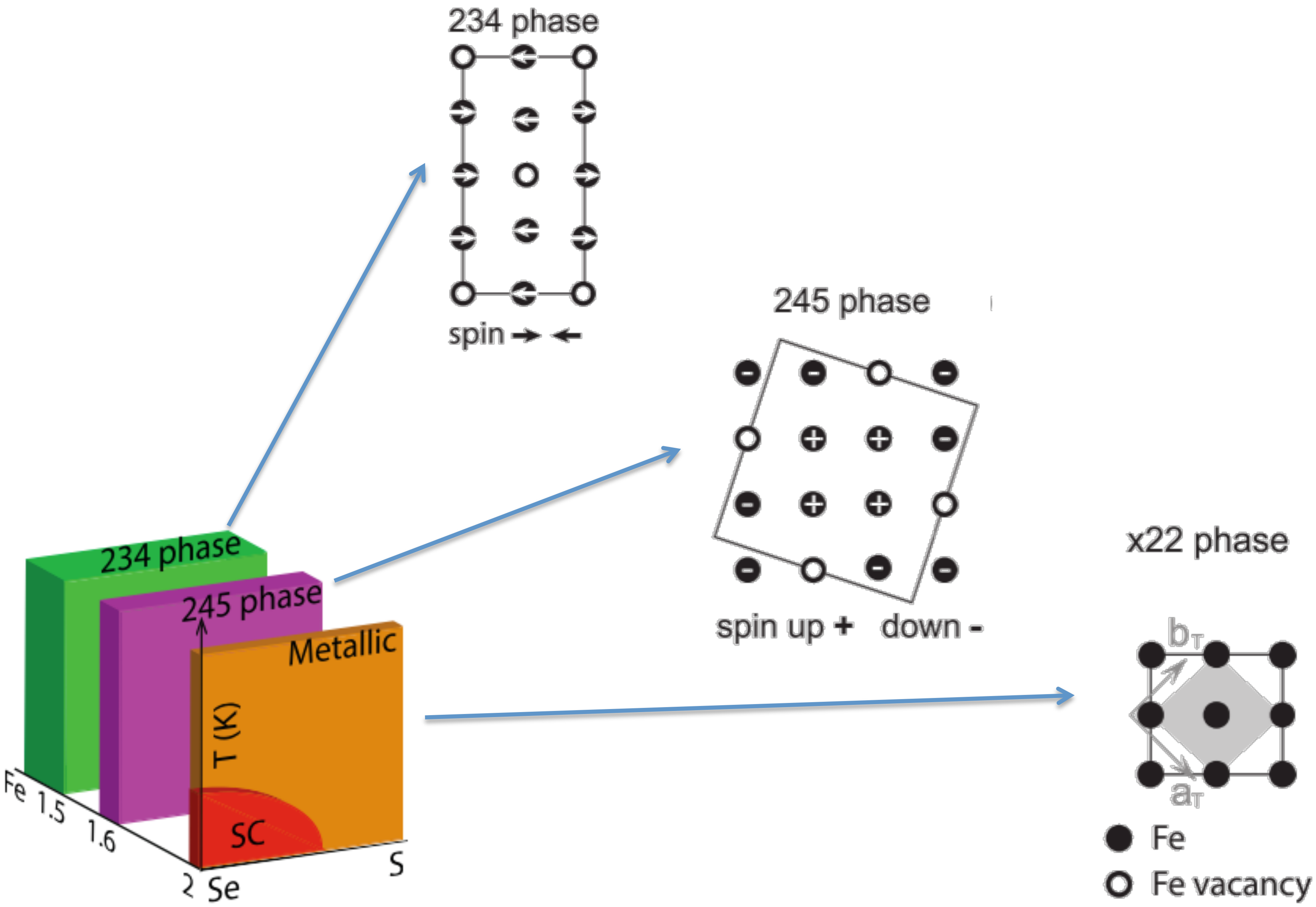


TABLE I.

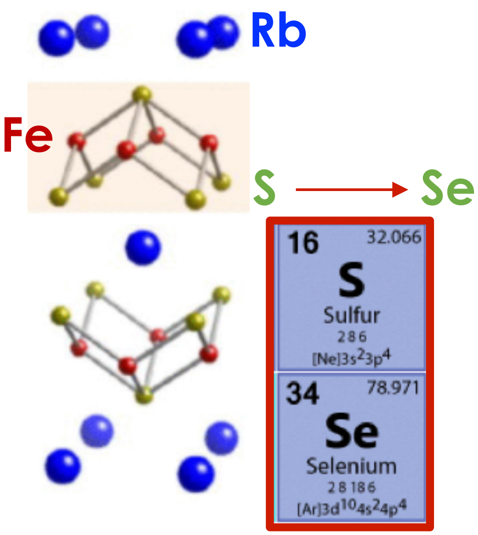
The magnetic exchange couplings and spin states in the stripe AF order of iron pnictides and chalcogenides [13,16,27].

Compounds	SJ_{1a}	SJ_{1b}	SJ_2 (meV)	S	M (μ_B)	T_N (K)
$CaFe_2As_2$	50(10)	−6(5)	19(4)	1/2	0.80	173
$BaFe_2As_2$	59(2)	−9(2)	14(1)	1/2	0.87	143
$SrFe_2As_2$(L)	31(1)	−5(5)	22(1)	0.30	0.94	220
$SrFe_2As_2$(H)	39(2)	−5(5)	27(1)	0.69	0.94	220
$K_{0.85}Fe_{1.54}Se_2$	38(7)	−11(5)	19(2)		2.8	280
$Rb_{0.8}Fe_{1.5}S_2$	42(5)	−20(2)	17(2)	2	2.8(0.5)	265

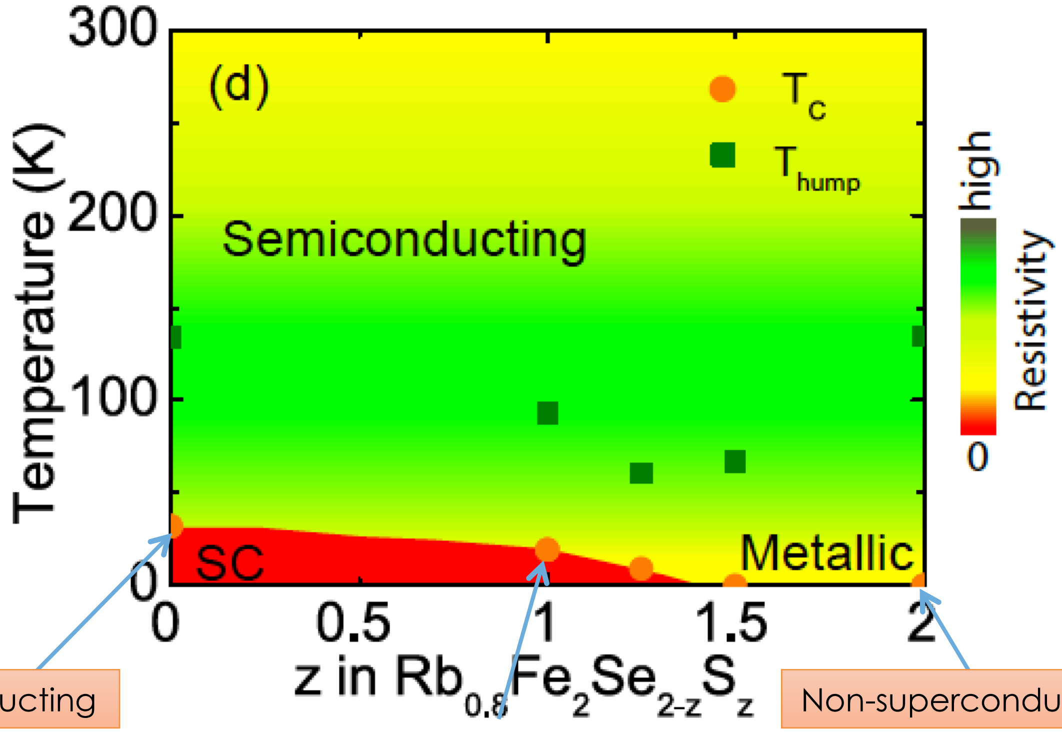
Different phases in $Rb_xFe_ySe_{2-z}S_z$



Correlation-tuned superconductivity in $Rb_xFe_2(Se,S)_2$



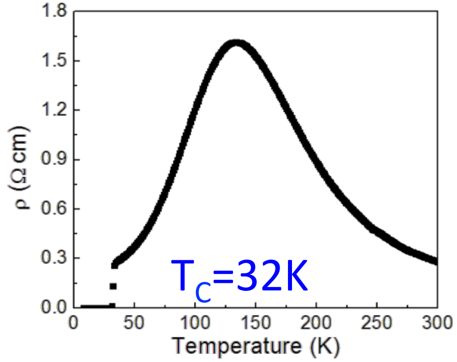
No charge carrier doping



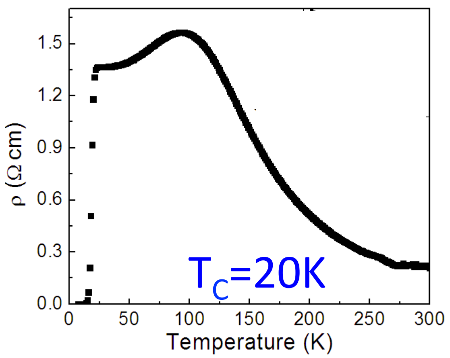
Superconducting

Non-superconducting

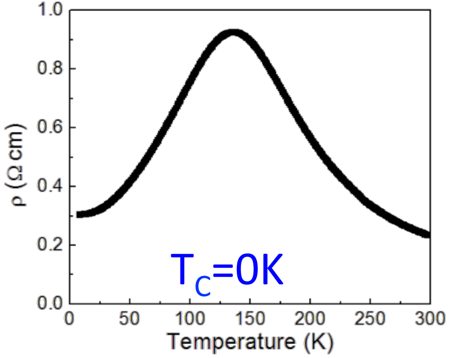
$Rb_{0.8}Fe_2Se_2$



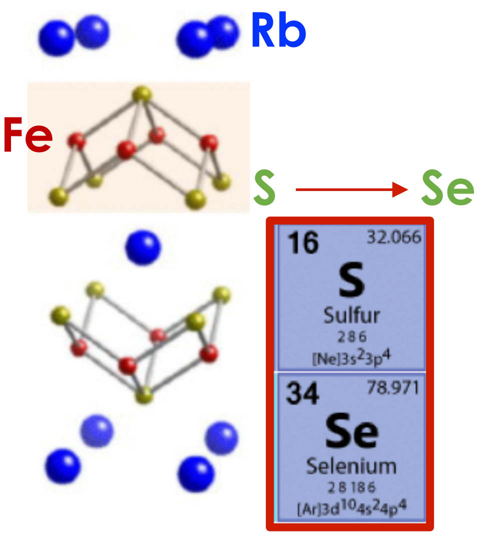
$Rb_{0.8}Fe_2SeS$



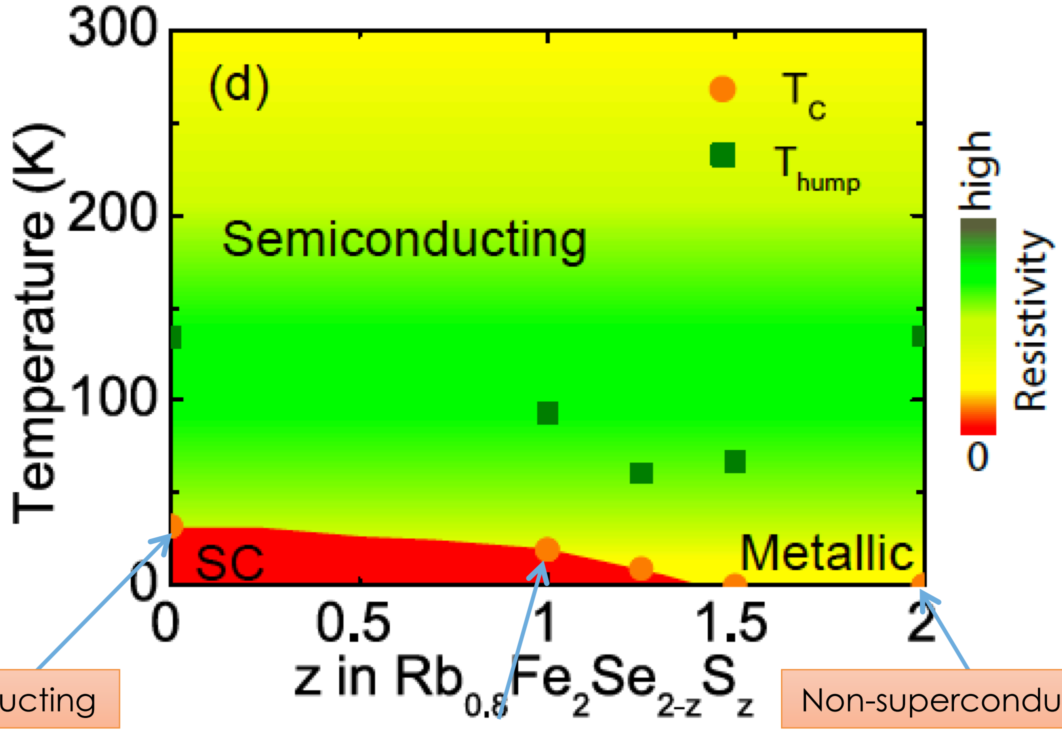
$Rb_{0.8}Fe_2S_2$



Correlation-tuned superconductivity in Rb$_x$Fe$_2$(Se,S)$_2$

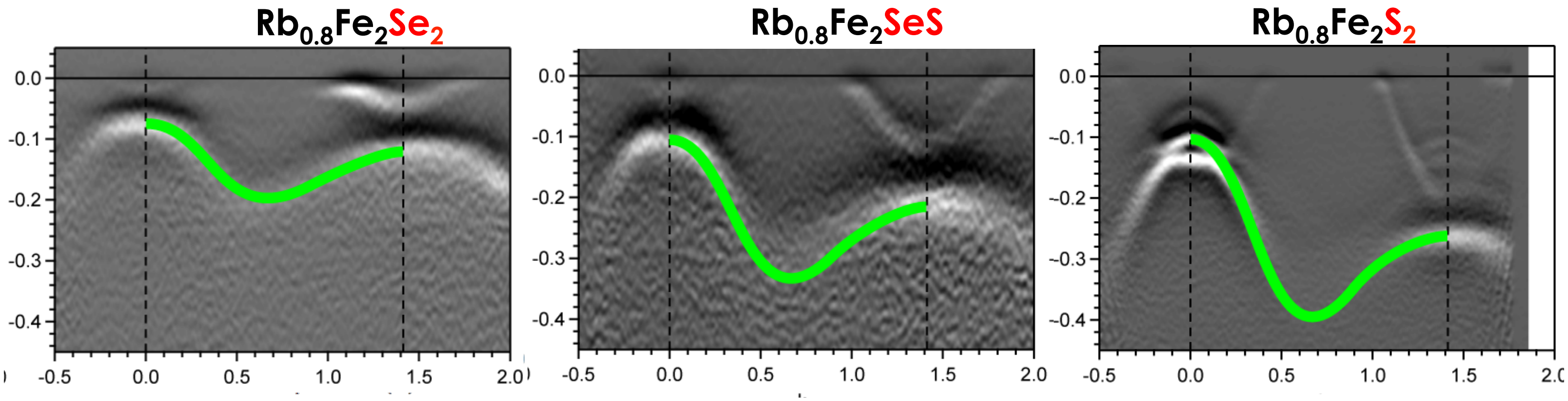


No charge carrier doping



Superconducting

Non-superconducting



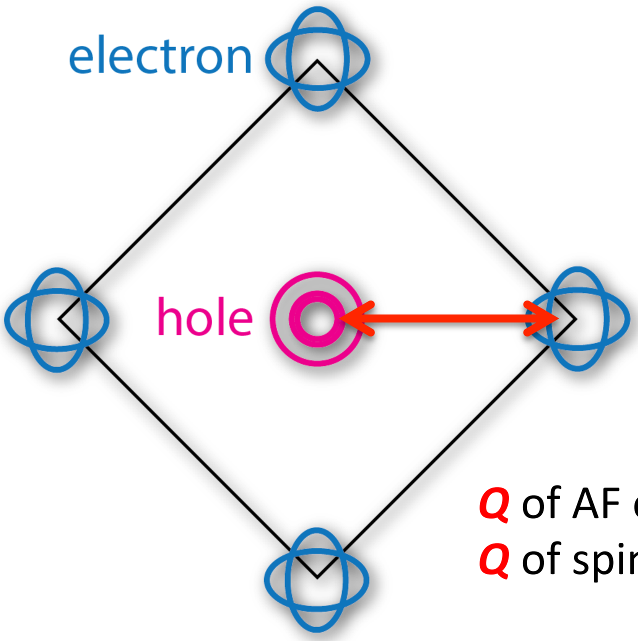
slower electrons
– strong correlations

band slope ~ electron velocity

faster electrons
– weak correlations

The curious case of doped iron chalcogenide superconductors

Iron-pnictides

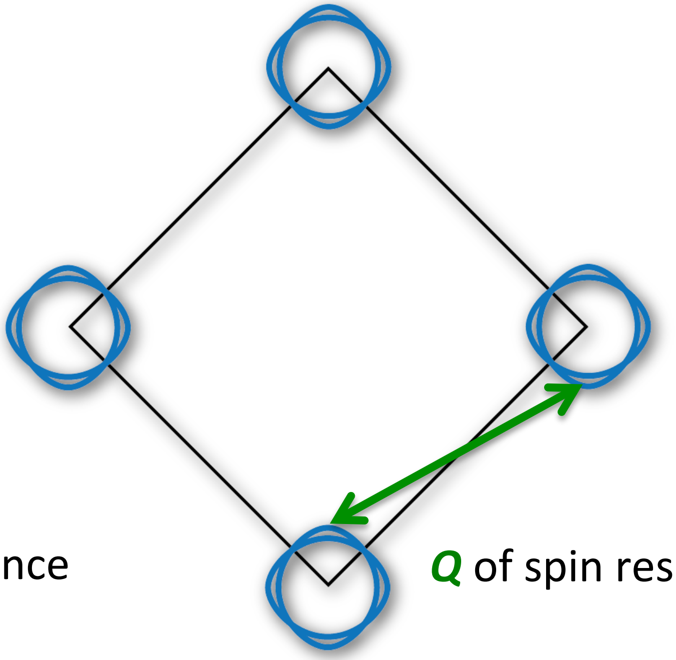


Q of AF order

Q of spin resonance

Spin fluctuations at the Fermi surface nesting vector (π , π)

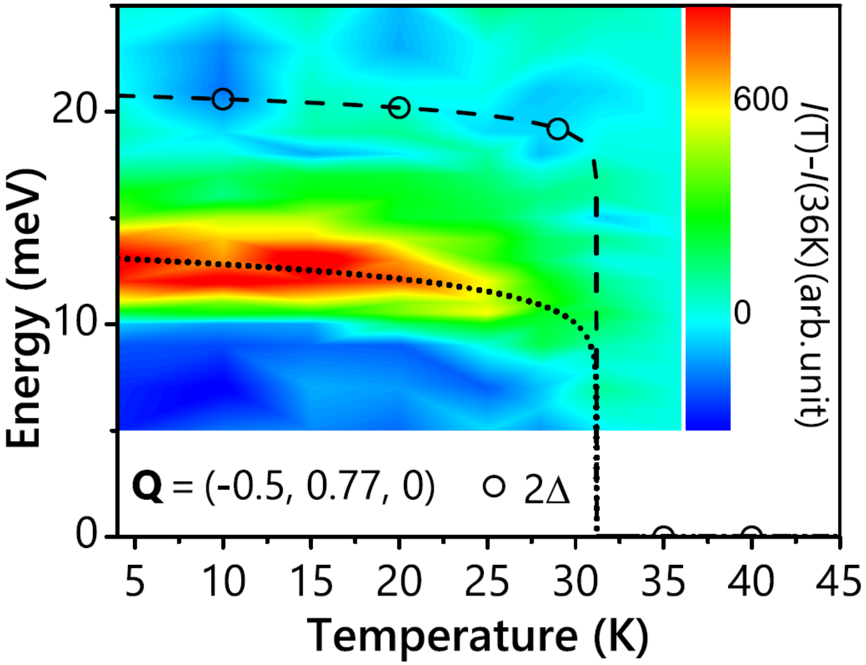
Doped Iron-chalcogenides



Q of spin resonance

Lack of electron and hole Fermi surface nesting conditions

Spin resonant mode in $K_xFe_{2-y}Se_2$



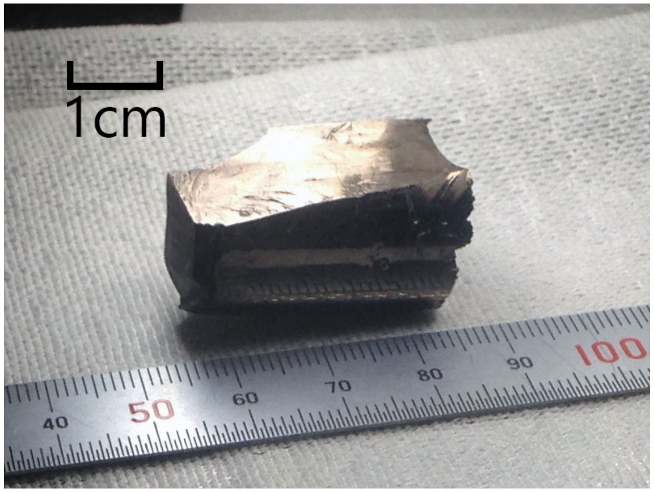


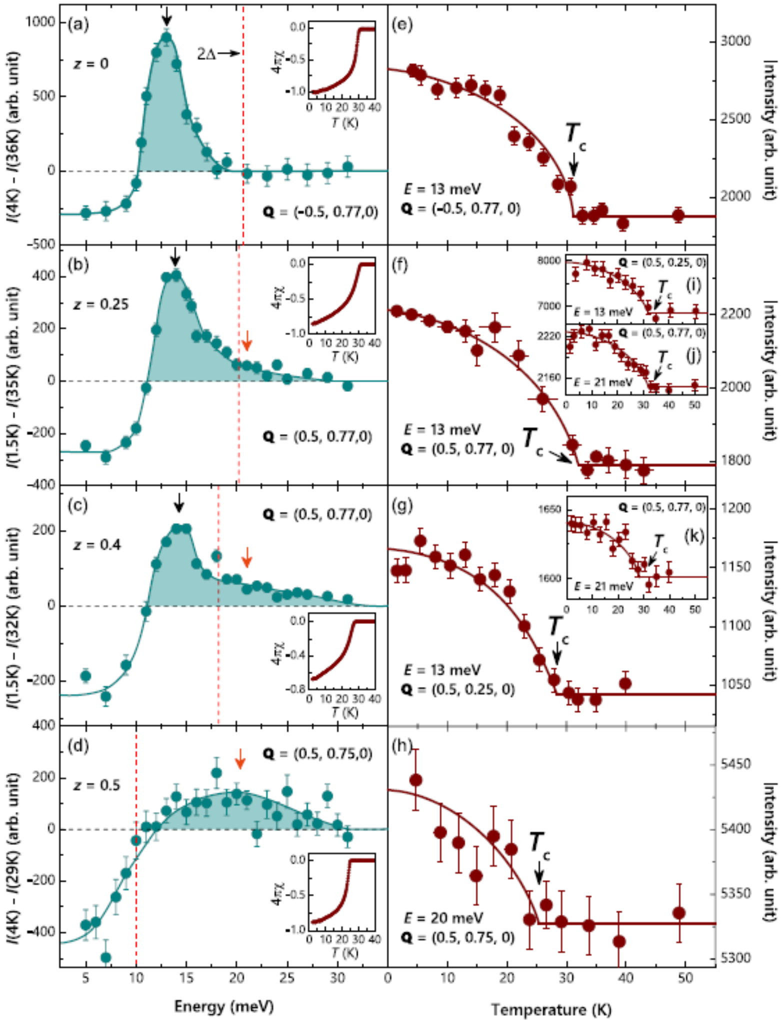
Photo of a KFe2-ySe2 single crystal used for the INS measurement

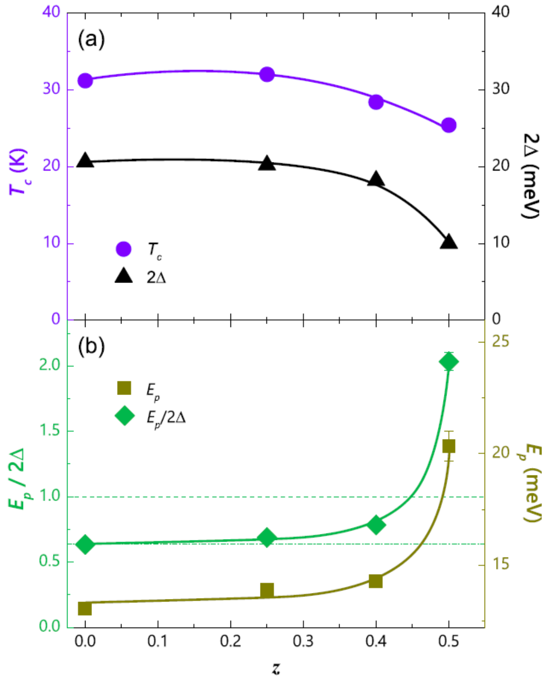
Evidence for **sign-reversed** pairing symmetry in in $K_xFe_{2-y}Se_2$

Spin resonant mode below 2Δ in the superconducting state

Q. Wang *et al., Phys. Rev. Lett.* **116,** 197004 (2016).

Transition from sign-reversed to sign-preserved Cooper pairing in $K_xFe_{2-y}(Se_{1-z}S_z)_2$

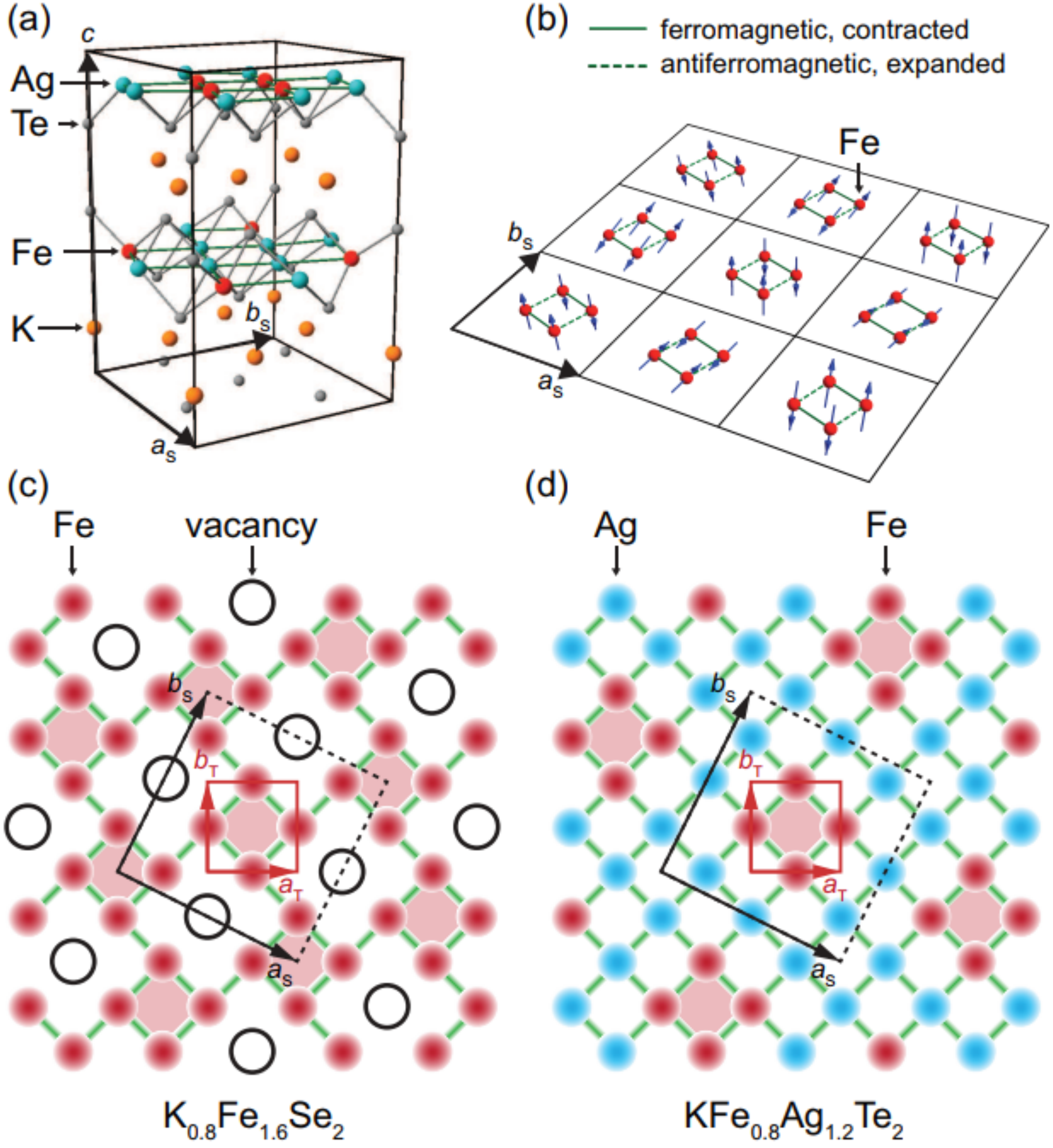




sign-reversed (z=0) to sign-preserved (z=0.5) pairing

Multiple pairing channels are required to understand the superconductivity in this system

Q. Wang *et al., Phys. Rev. Lett.* **116,** 197004 (2016).


(a)
c
Ag
Te
Fe
K
b_s
a_s
(b)
ferromagnetic, contracted
antiferromagnetic, expanded
Fe
b_s
a_s
(c)
Fe
vacancy
b_s
b_T
a_T
a_s
$K_{0.8}Fe_{1.6}Se_2$
(d)
Ag
Fe
b_s
b_T
a_T
a_s
$KFe_{0.8}Ag_{1.2}Te_2$

Iron Pnictides and Chalcogenides

- Parent Materials are antiferromagnetic semi-metals or narrow band gap semiconductors.
- Magnetic and structural transitions are intimately connected. The structural (aka nematic) transition lifts the degeneracy of the dxz and dyz orbitals.
- Local orthorhombicity (a.k.a. nematicity) persists to temperatures far above the magnetic and superconducting transition temperatures.
- In the parent materials at low temperatures the magnetic exchange interactions appear to be universal.
- Antiferromagnetism and superconductivity compete.
- Phase diagrams have a remarkable similarity to those of the copper oxides.

Question: Is there a universal model?

Lessons

- The most interesting developments in solid state physics, including especially superconductivity, have originated either from the discovery of new materials or the discovery of new properties of old materials.

- These materials require experimental studies with many different probes plus sophisticated theory. So far there has been no silver bullet.