TECHNISCHE UNIVERSITÄT DRESDEN

Peculiar magnetism of iron pnictides aside from superconductivity

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DRESDEN concept

Collaborators

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Neutron scattering: Yong Seung Kwon.

Université Paris-Sud, France

NMR measurements: J. Bobroff, Y. Texier, Y. Laplace.

Paus Scherrer Institute, Switzerland

μ*SR measurements:* R. Khasanov, K. Sedlak.

Laboratoire Léon Brillouin, Saclay, France

INS measurements: Ph. Bourges, Y. Sidis.

Institut Laue-Langevin, Grenoble, France

Instrument support: A. Ivanov.

FRM-II, Garching, Germany

Instrument support: T. Keller, J. T. Park.

Outline

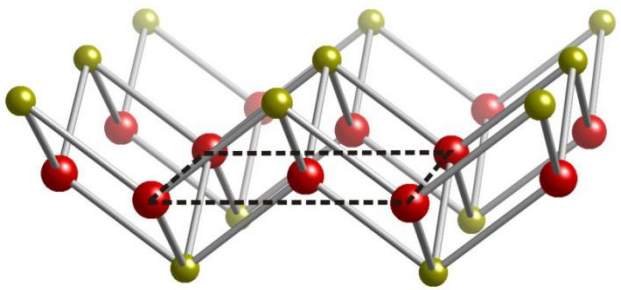
1. Spin waves in the iron-pnictide parent compounds.

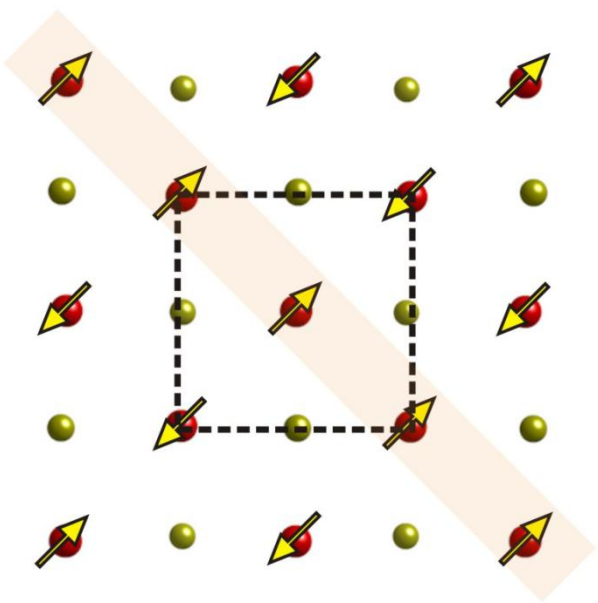
2. Zone-center gap, spin anisotropy, spin-nematic state.

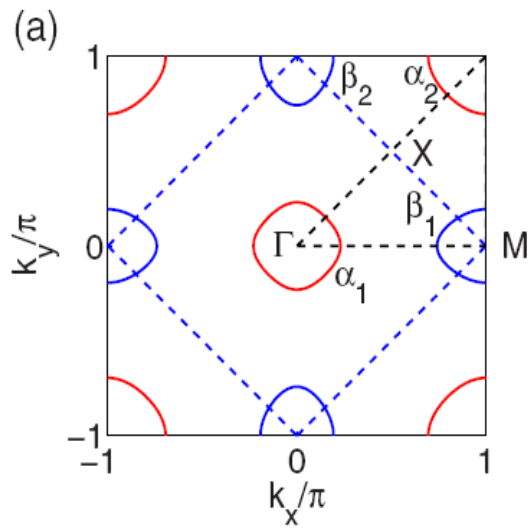
3. Comparing low-energy spin waves in $BaFe_2As_2$ and NaFeAs.

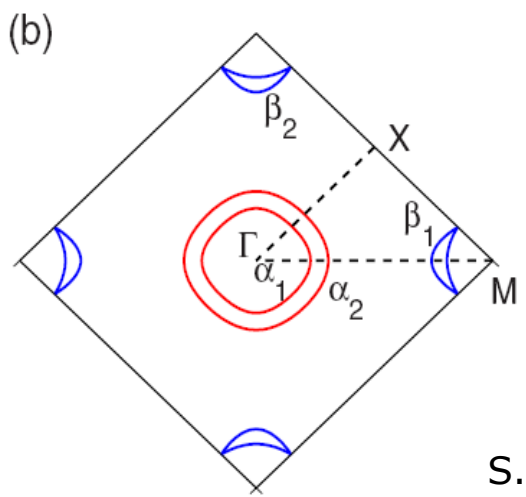
4. SDW transition in the presence of localized magnetic impurities: the case of $Ba(Fe_{1-x}Mn_x)_2As_2$.

Benefits of the unfolded Brillouin zone









more volume in reciprocal space: band intensities can be included

less volume in direct space (all atoms equivalent)

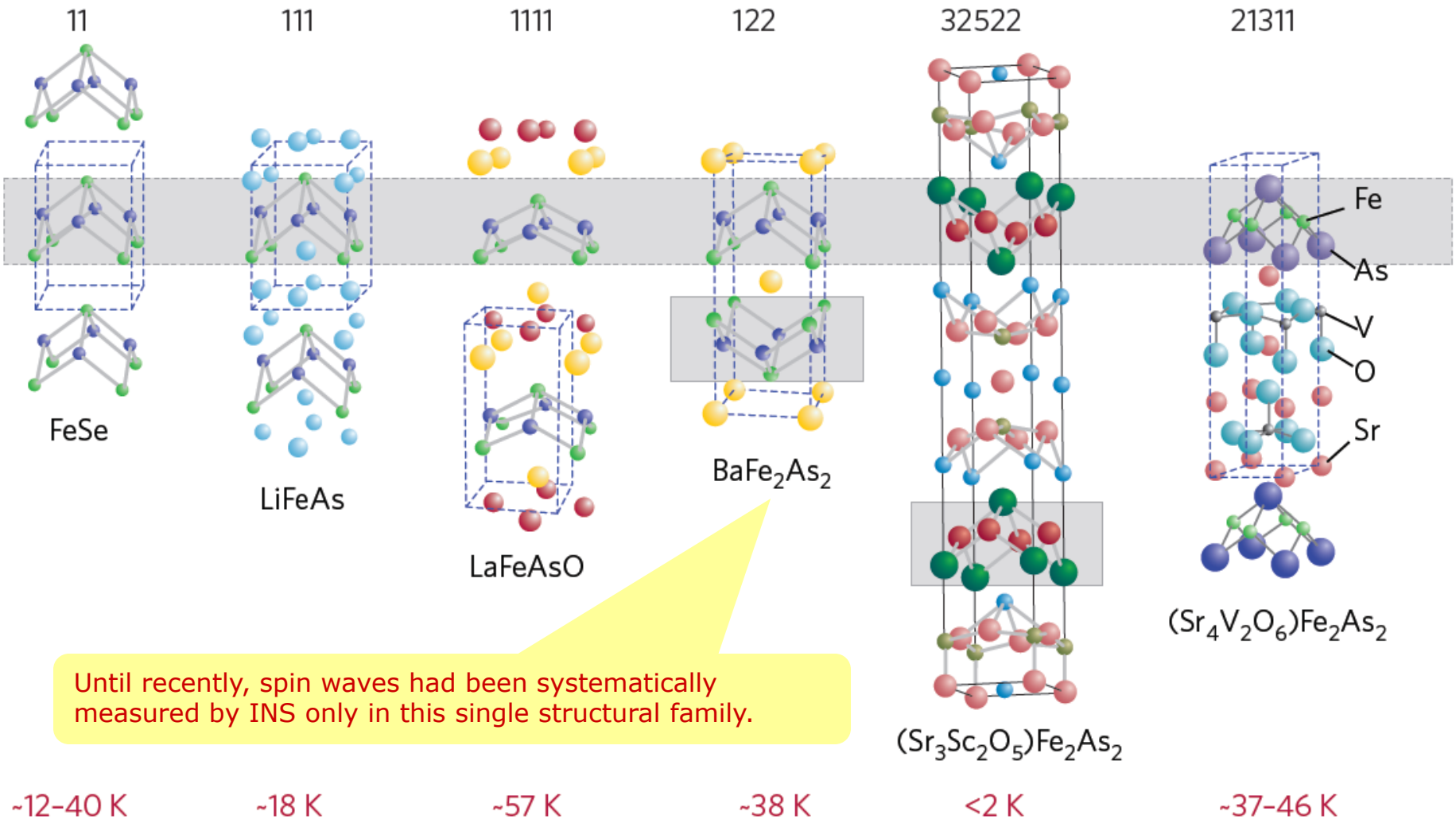
less volume in reciprocal space (equal intensities in all Brillouin zones)

more volume in direct space (nonequivalent atoms allowed)

J. Paglione & R. L. Greene, Nature Phys. **6**, 645 (2010)

S. Raghu *et al.*, PRB **77**, 220503 (2008)

The zoo of Fe-based superconductors

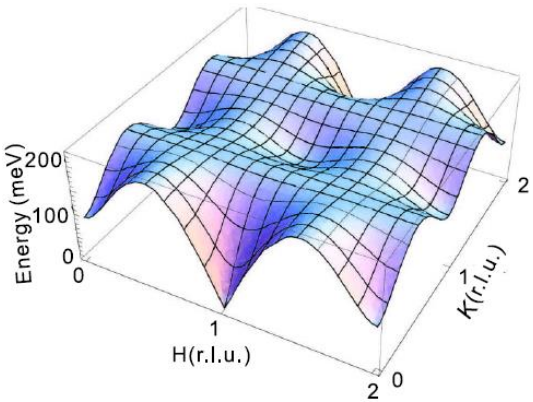


Until recently, spin waves had been systematically measured by INS only in this single structural family.

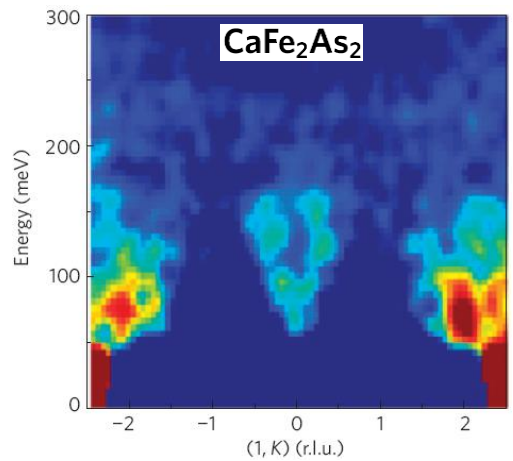
C. W. Chu, Nat. Phys. **5**, 787 (2009)

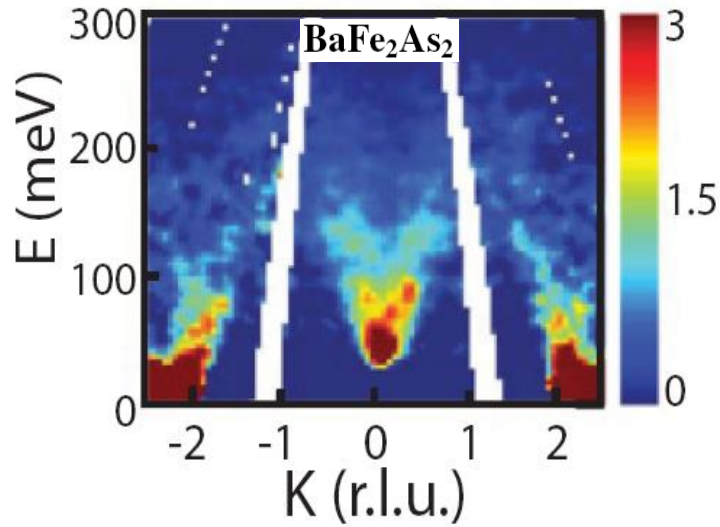
Spin waves in $SrFe_2As_2$, $CaFe_2As_2$ & $BaFe_2As_2$

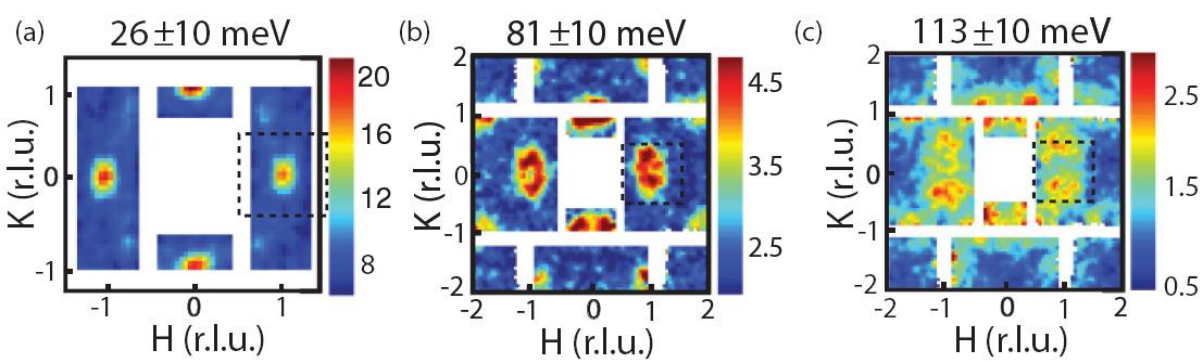
Expectation: $$H = J_{1a}\sum_{i,j}\mathbf{S}_i\cdot\mathbf{S}_j + J_{1b}\sum_{i,j}\mathbf{S}_i\cdot\mathbf{S}_j + J_2\sum_{i,j}\mathbf{S}_i\cdot\mathbf{S}_j + J_z\mathbf{S}_i\cdot\mathbf{S}_j - J_s(S_i^z)^2$$

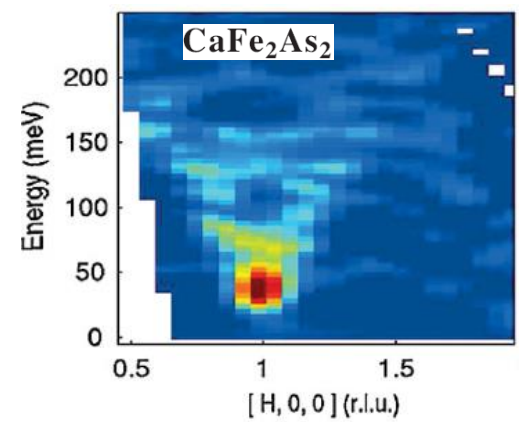


Reality:



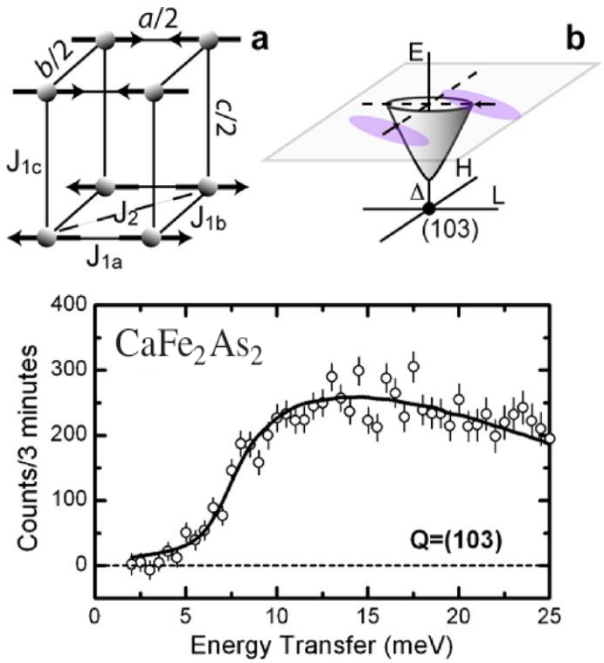




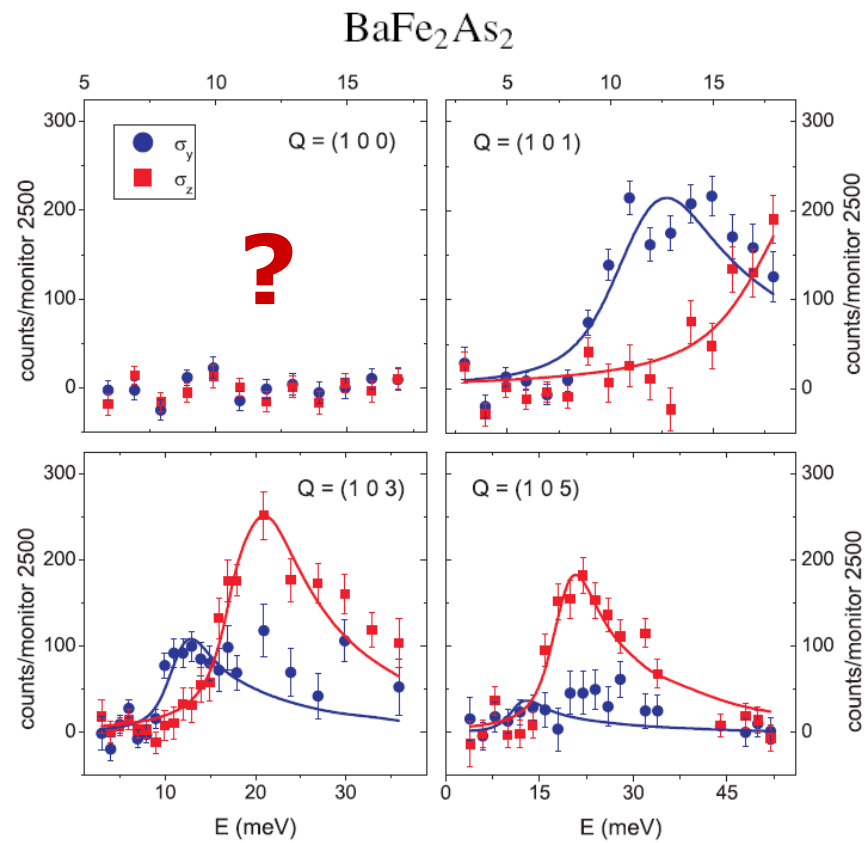


J. Zhao *et al.*, Nat. Phys. **5**, 555 (2009); L. W. Harriger *et al.*, PRB **84**, 054544 (2011); S. O. Diallo *et al.*, PRL **102**, 187206 (2009).

Spin anisotropy + zone-center gap



R. J. McQueeney *et al.*,
PRL **101**, 227205 (2008)



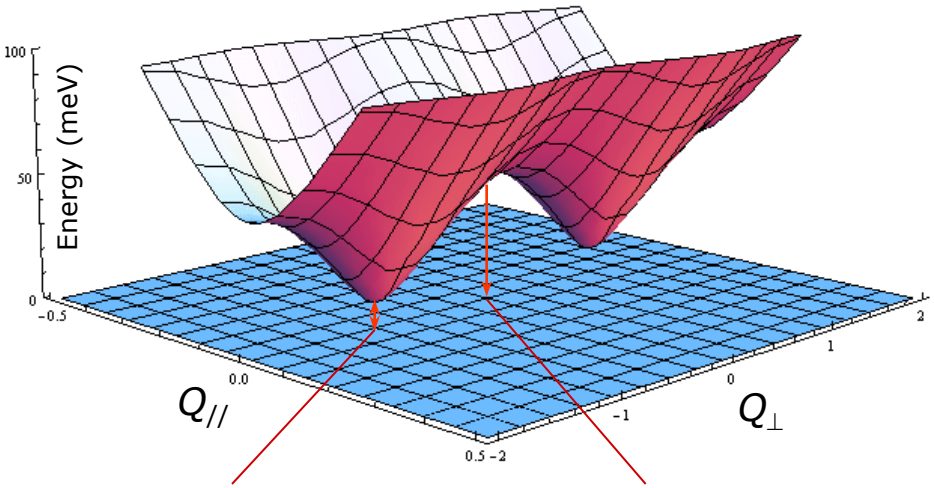
« The scan at Q=(1 0 0) does not indicate any magnetic scattering in agreement with the published magnon dispersion for $CaFe_2As_2$ (Refs. 21,22) and for $SrFe_2As_2$ (Refs. 23,24) indicating energies of the order of 100 meV for this **q** value. »

Neutron polarization analysis reveals 2 gaps:
11.6 meV (out-of-plane polarization)
18.9 meV (in-plane polarization)

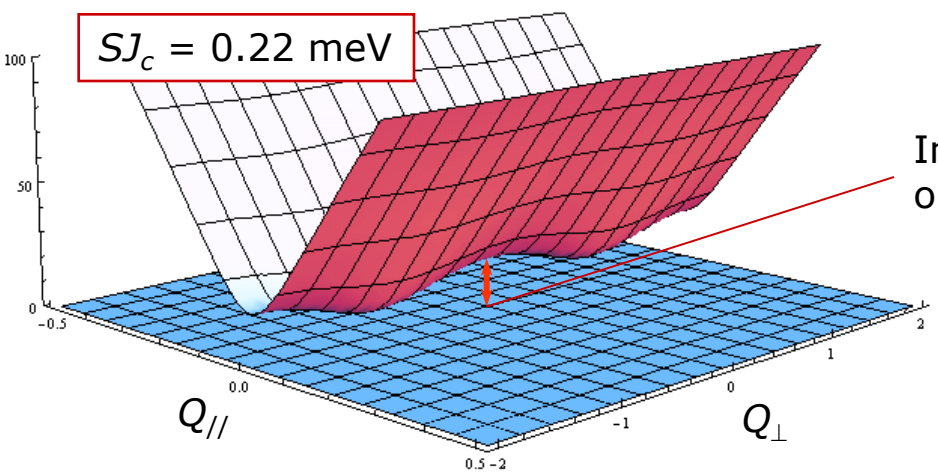
[N. Qureshi *et al.*, PRB **86**, 060410(R) (2012)]

How large is J_c in reality?

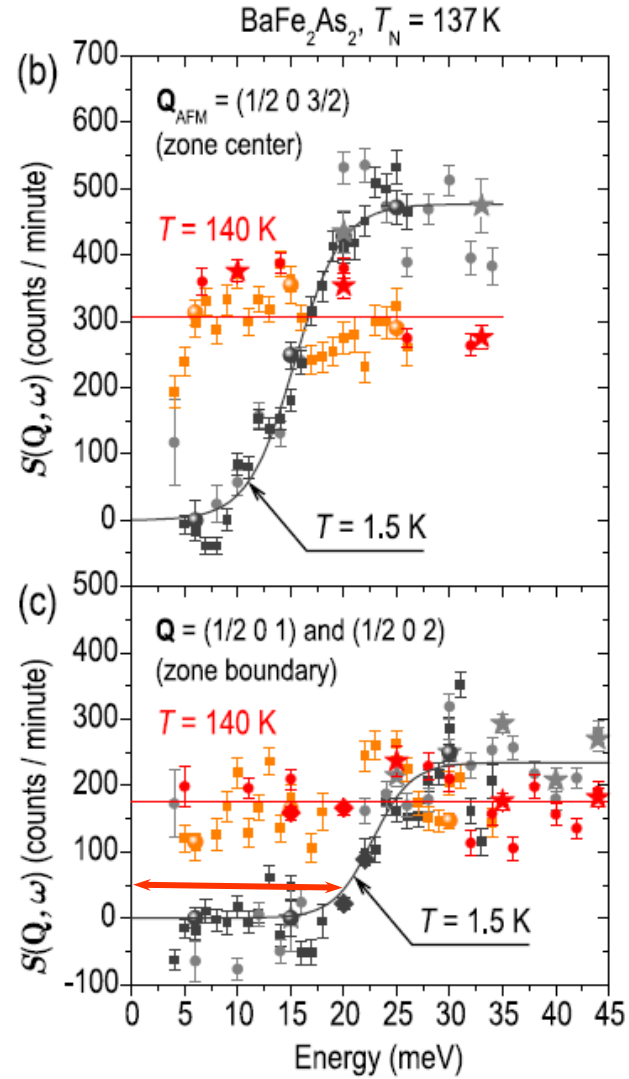
$BaFe_2As_2$ exchange parameters from Harriger *et al.* (SJ_c = 1.8 meV):



Zone center gap: ~10 meV Zone boundary gap: ~50 meV

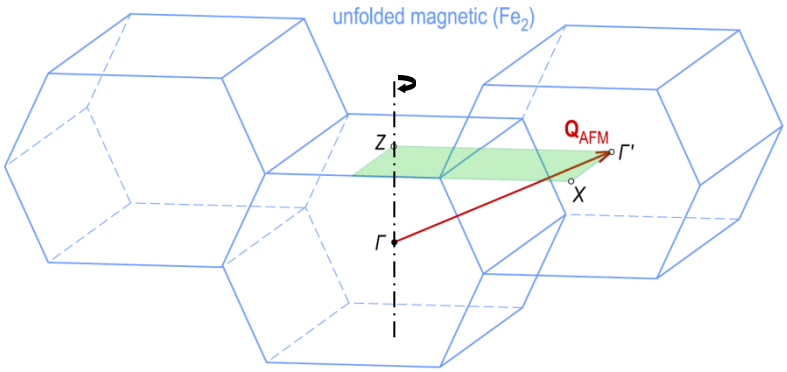


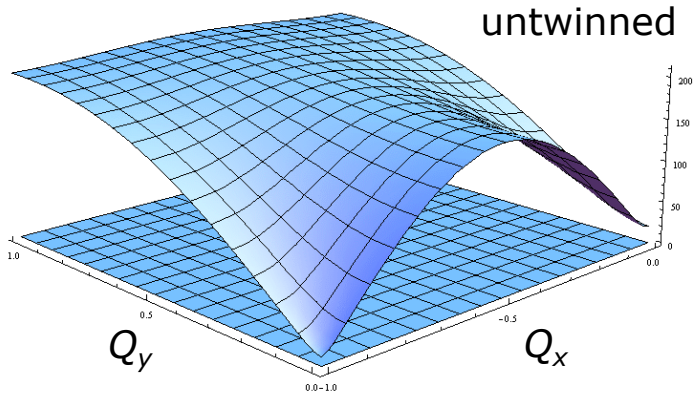
In reality:
only ~20 meV

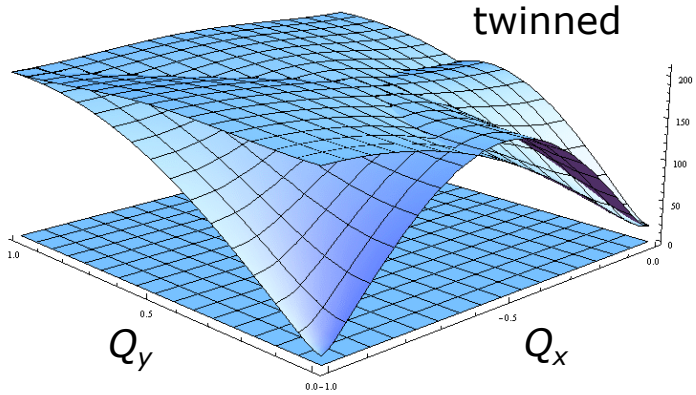


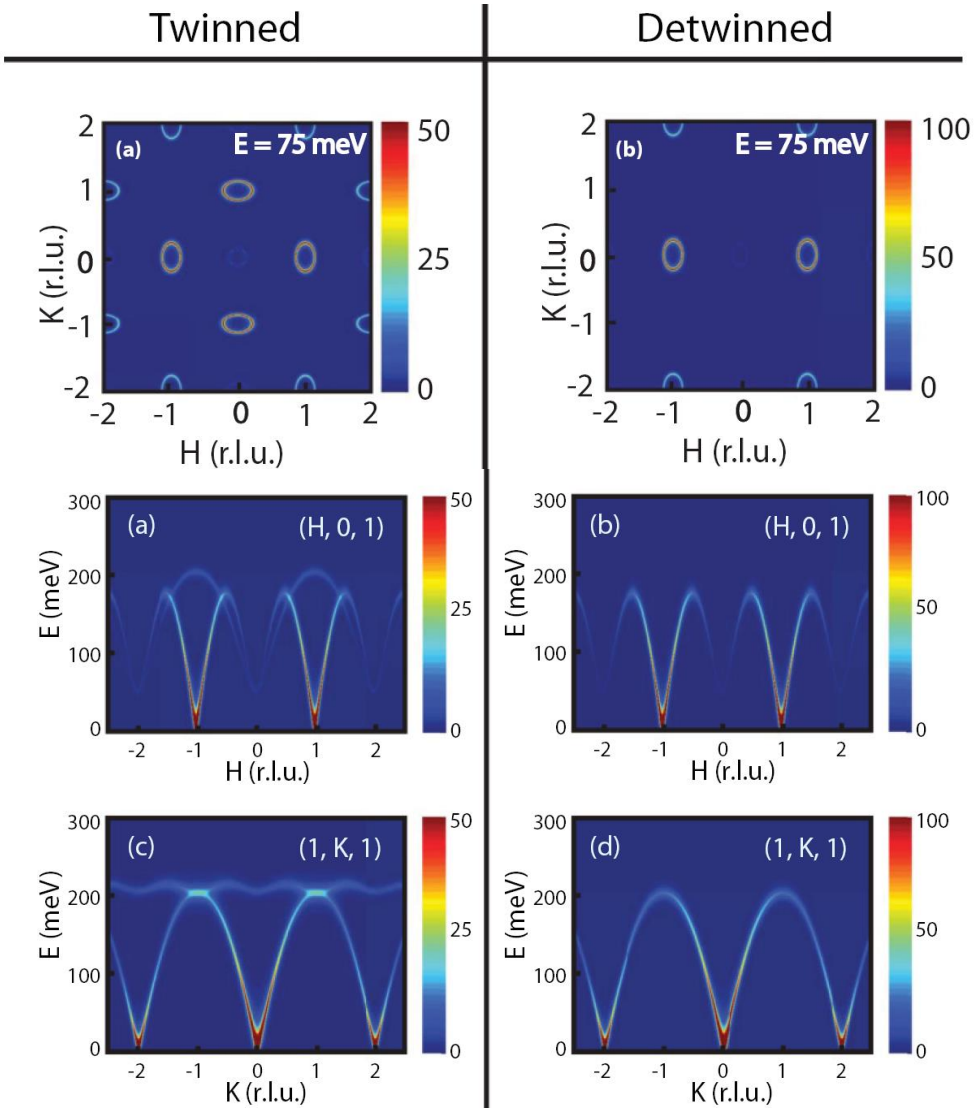
J. T. Park *et al.*, PRB **86**, 024437 (2012)

Effects of twinning



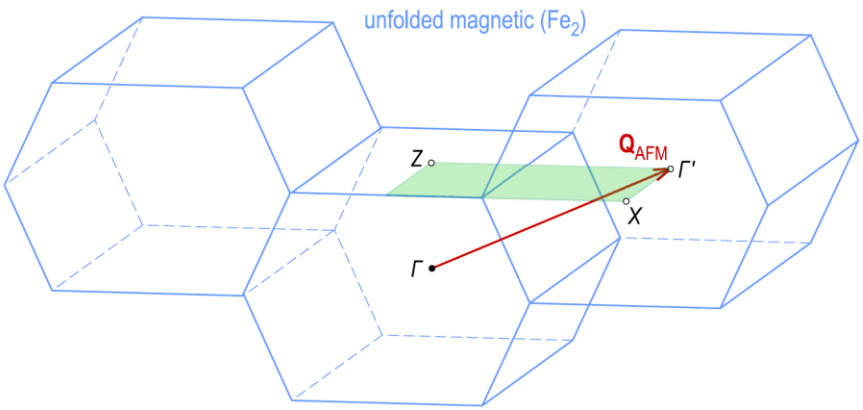




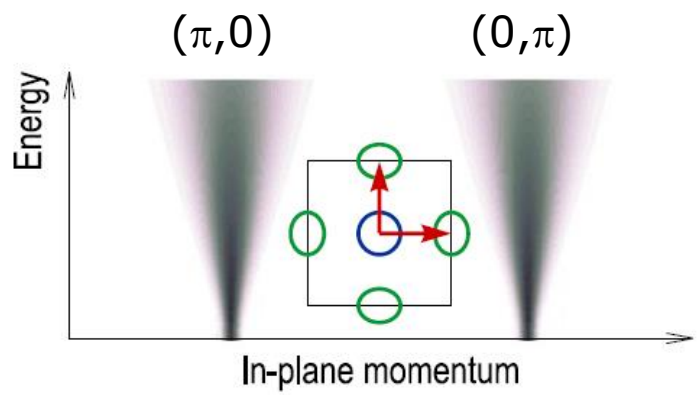


L. W. Harriger *et al.*, PRB **84**, 054544 (2011)

What happens across the transition?



Above T_N identical paramagnons at (π,0) and (0,π):

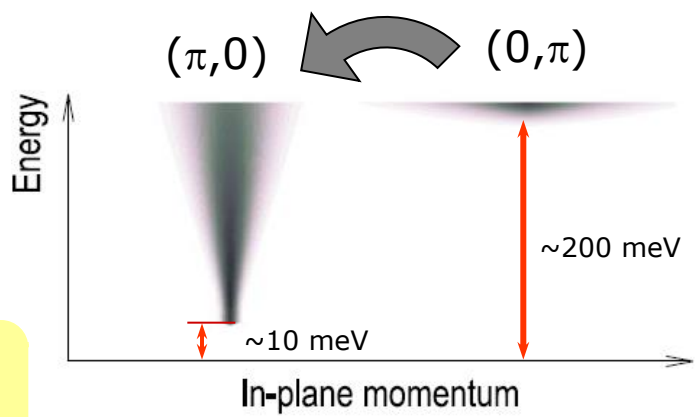


(with small modulation of intensity along $Q_\perp$)

Below T_N (in a detwinned crystal):

- At $\mathbf{Q}_{AFM}$ = (π,0,π) spin anisotropy gap (~10 meV) opens.
- At (0,π,π) the low-energy spectral disappears [is fully transferred to (π,0)].

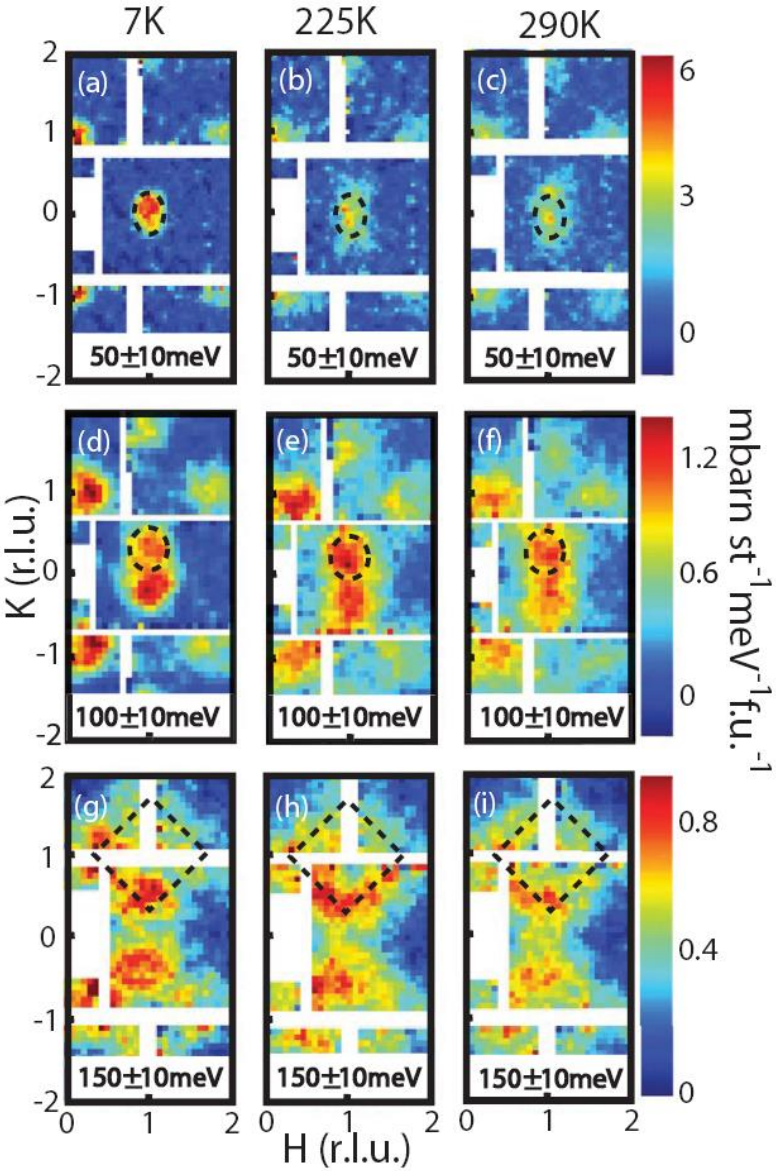
- At $\mathbf{Q}_{AFM}$ = (π,0,0) a gap of ~20 meV opens (given by a combination of anisotropy and J_c).

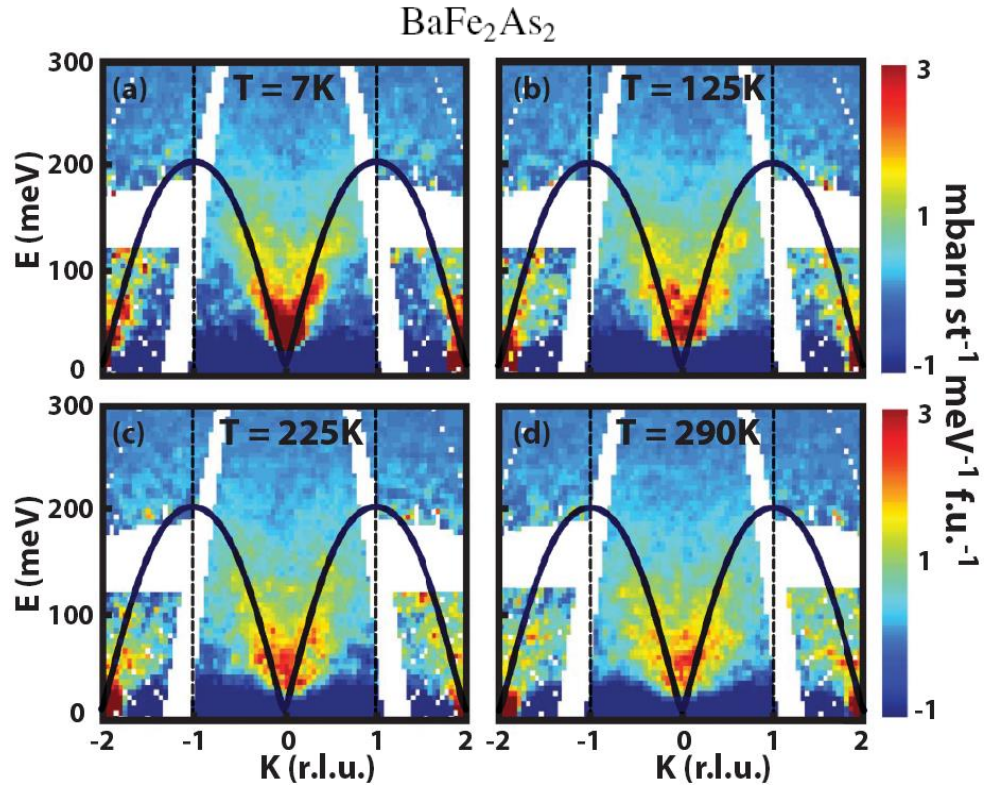


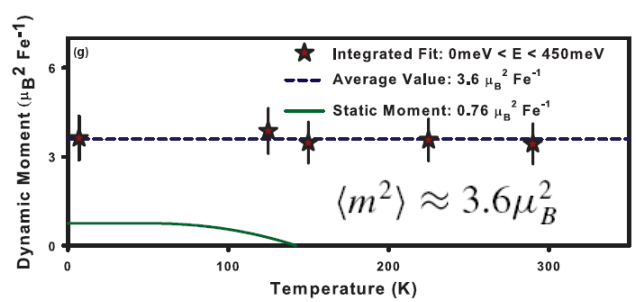
The opening of the anisotropy gap and its $\mathbf{Q}_z$-dispersion is the only experimentally observable effect across T_N on twinned single crystals!

Has not been observed due to twinning.

Real experiment on pure $BaFe_2As_2$

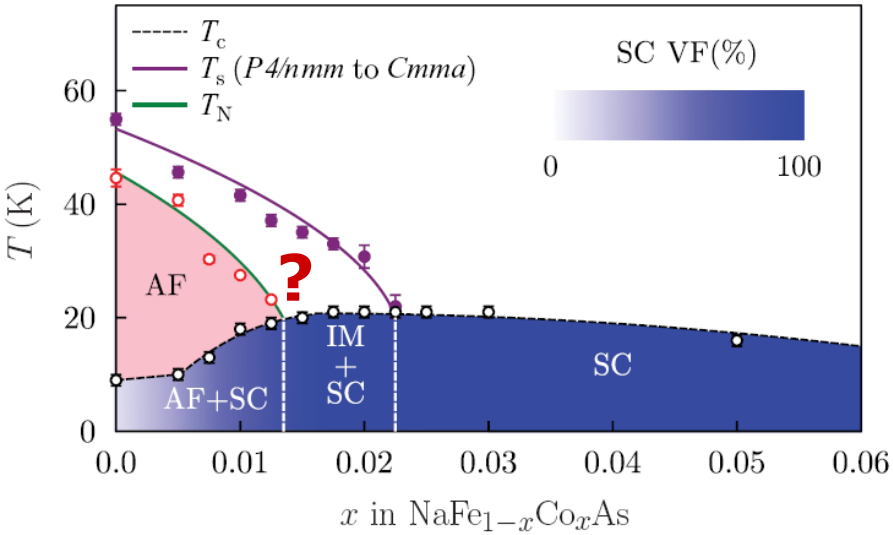




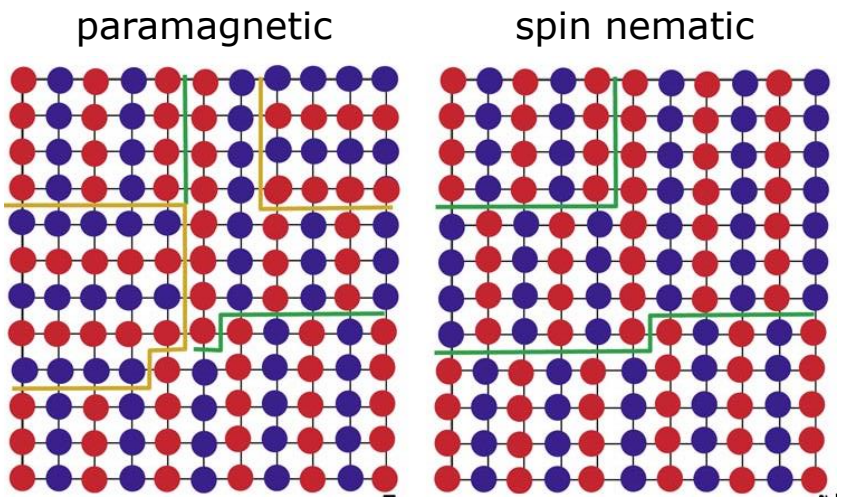


L. Harriger *et al.*, PRB **86**, 140403(R) (2012)

"Nematicity"

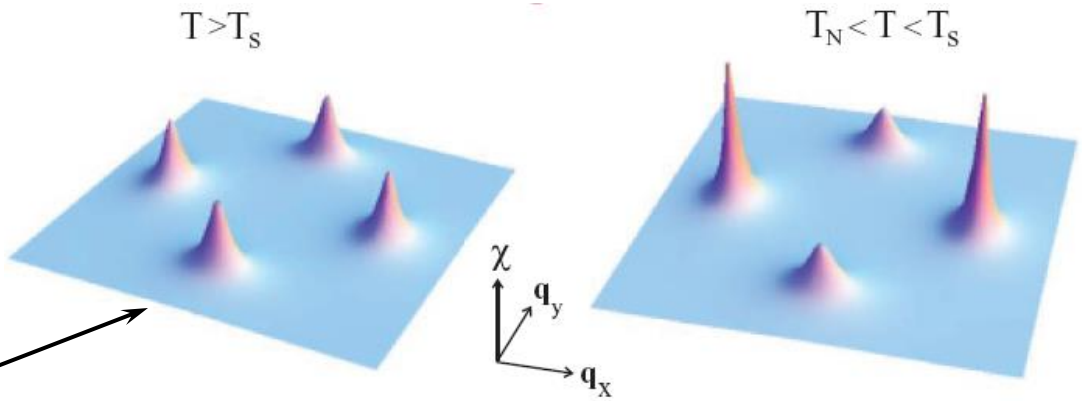


J. D. Wright *et al.*, PRB **85**, 054503 (2012)



Mazin & Johannes, Nat. Phys. **5**, 141 (2009)

- Is there magnetic anisotropy in the nematic phase?
- How does the spin excitation spectrum look like?
- What is the driving force of the structural transition?

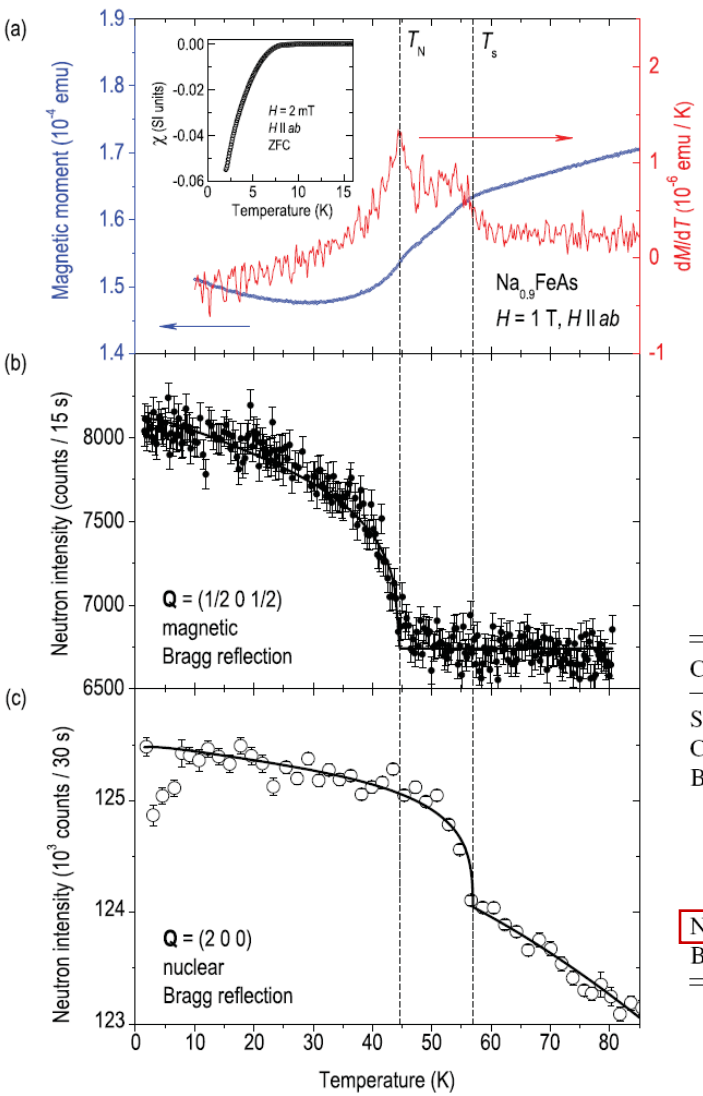


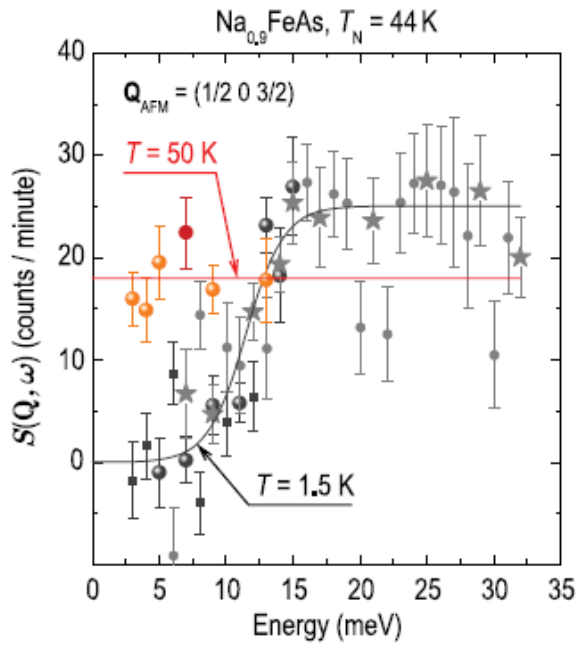
Spin anisotropy not taken into account (gapless excitations)

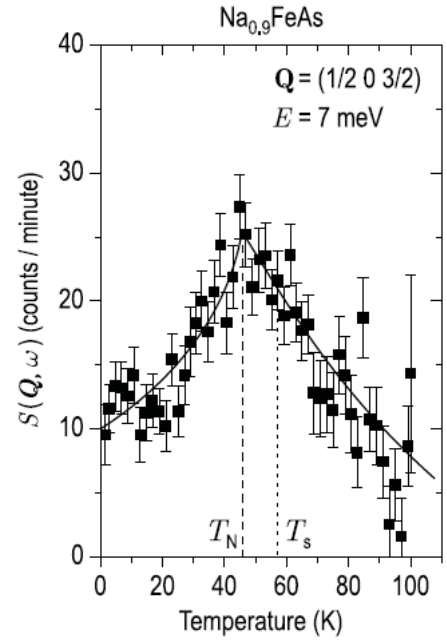
R. M. Fernandes *et al.*, PRB **85**, 024534 (2012)

Zone-center gap in $Na_{1-\delta}FeAs$

Transitions are well separated:



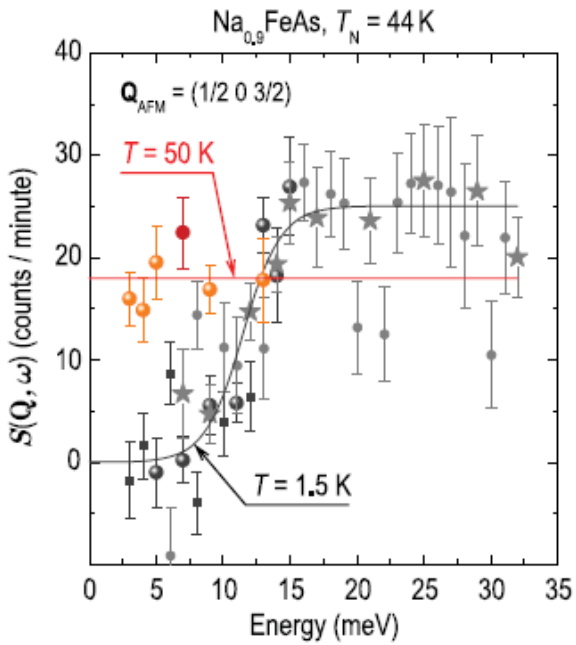




Compound	T_N (K)	μ_{Fe}/μ_B	$\Delta_{Q_{AFM}}$ (meV)	Ref.
$SrFe_2As_2$	205	1.0 (Ref. 32)	6.5	8
$CaFe_2As_2$	172	0.8 (Ref. 33)	6.9(2)	9,10
$BaFe_2As_2$	137	0.9 (Refs. 22,34)	7.7(2)	7
			9.8(4)	11
			10.1 (out-of-plane)	12
			16.4 (in-plane)	12
			10(1)	our work
$Na_{1-\delta}FeAs$	45	0.1 (Refs. 19,21)	10(2)	our work
$BaFe_{1.96}Ni_{0.04}As_2$	91		~2	30

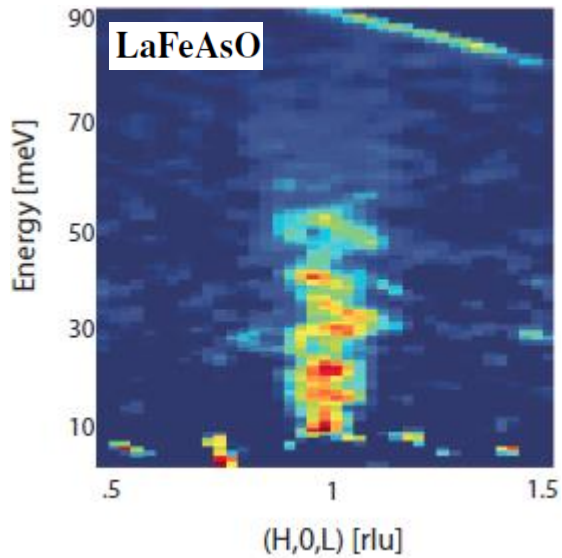
J. T. Park, D. Inosov *et al.*, Phys. Rev. B **86**, 024437 (2012)

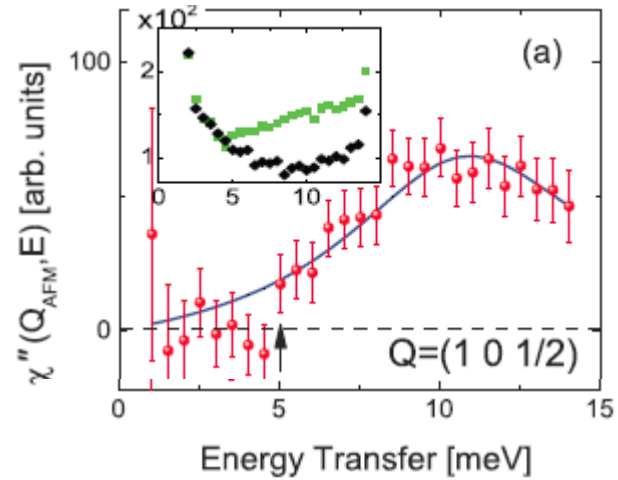
“Universality” of the anisotropy gap



J. T. Park *et al.*, PRB (2012)

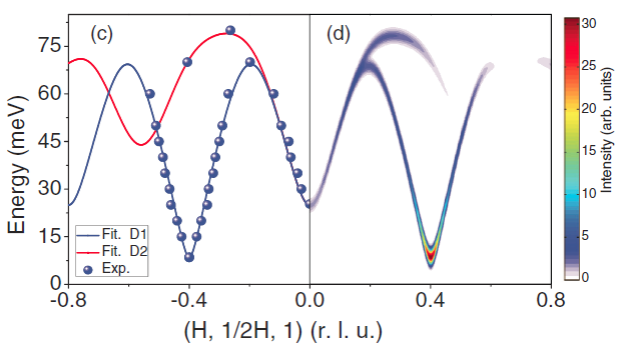
First INS data on single-crystalline 1111 compound:

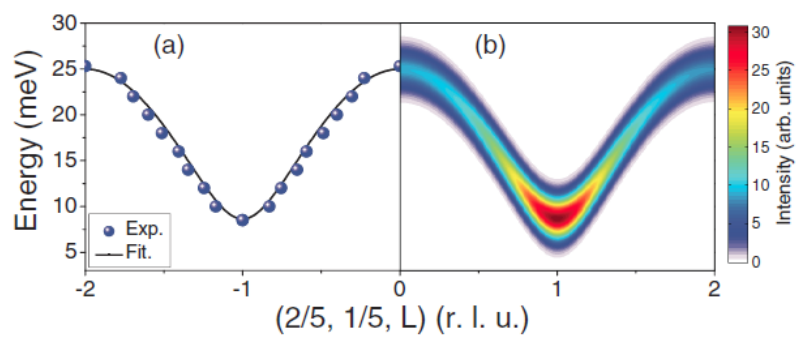




M. Ramazanoglu, R. J. McQueeney *et al.*, PRB **87**, 140509(R) (2013)

Zone-center gap in $K_2Fe_4Se_5$:

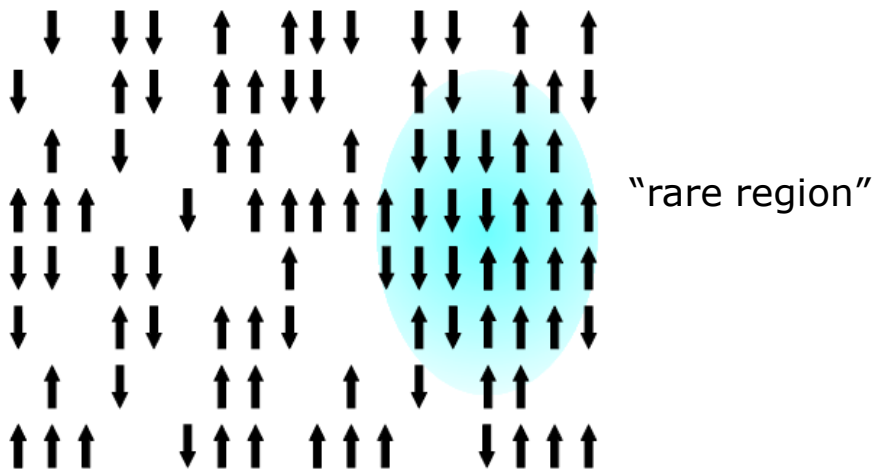




Y. Xiao, Th. Brückel *et al.*, PRB **87**, 140408(R) (2013)

Effects of localized magnetic impurities on the SDW transition in $Ba(Fe_{1-x}Mn_x)_2As_2$

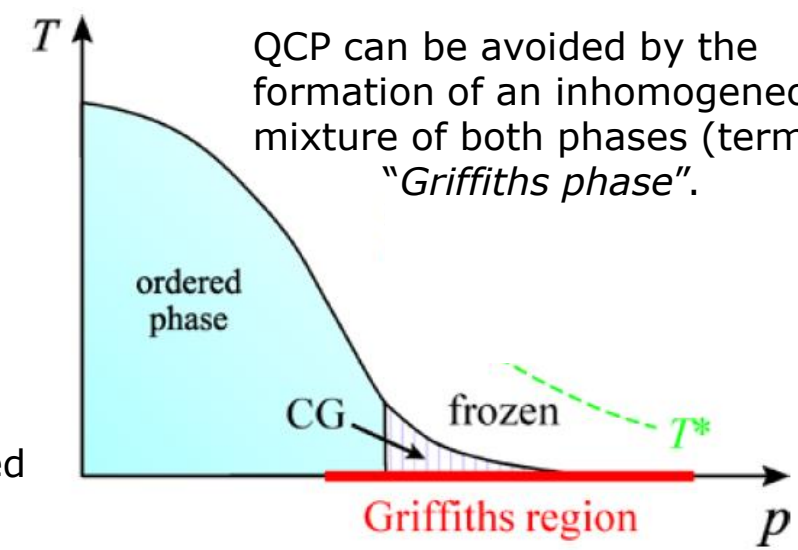
Phase transitions in the presence of disorder



Specifics for metals: long-range RKKY interactions can align rare regions over long distances (so-called cluster glass (CG) phase.

- Will the phase transition remain sharp in the presence of disorder?

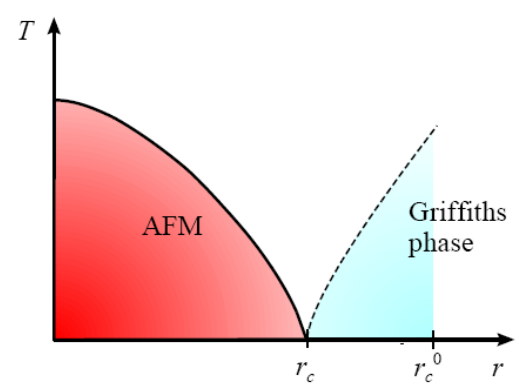
QCP can be avoided by the formation of an inhomogeneous mixture of both phases (termed "*Griffiths phase*".



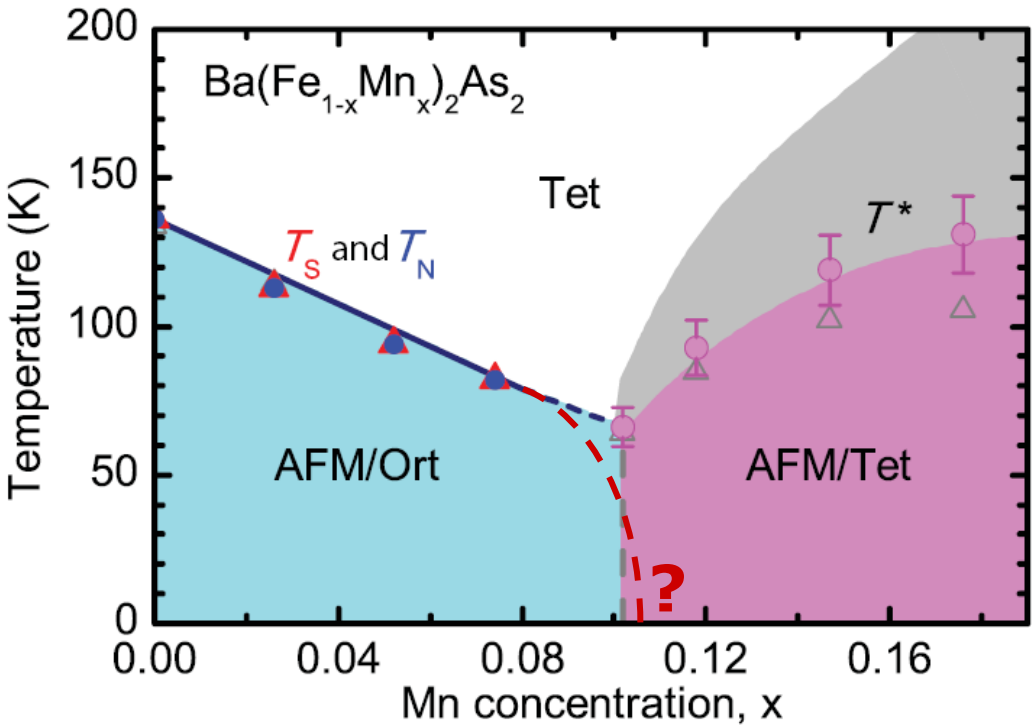
[T. Vojta, J. Phys. A: Math. Gen. **39**, R143 (2006); J. Low Temp. Phys. **161**, 299 (2010)]

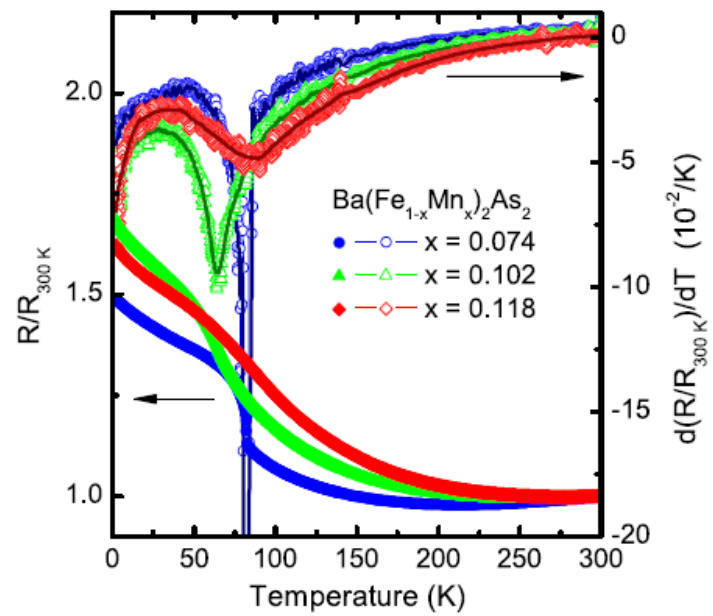
« Let us now turn to experiment. Unfortunately and somewhat ironically, all clear-cut experimental observations of quantum Griffiths phases are in itinerant ferromagnets rather than in antiferromagnets. »

[D. Nozadze & T. Vojta, EPL **95**, 57010 (2011)]



The phase diagram of $Ba(Fe_{1-x}Mn_x)_2As_2$

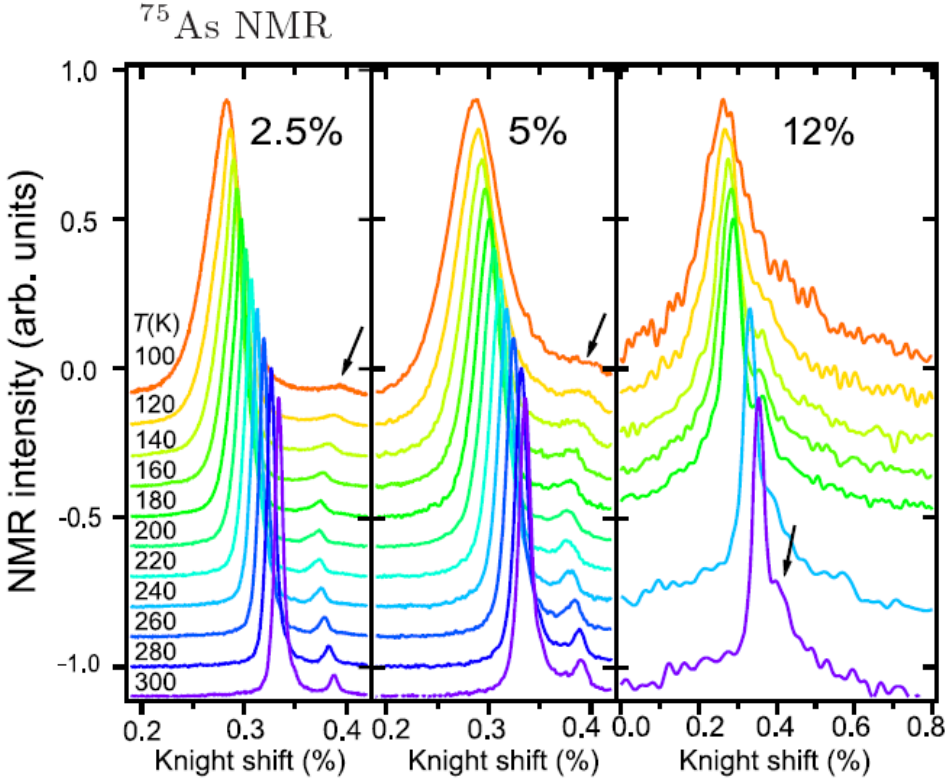


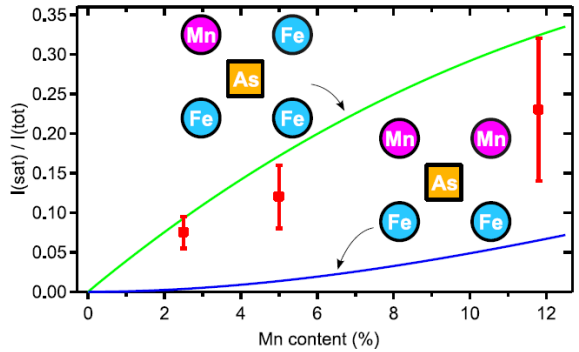


- Broadened transition above x_c = 10%;
- Nonmonotonic behavior of T_N;
- Absence of orthorhombic distortion for $x > x_c$.

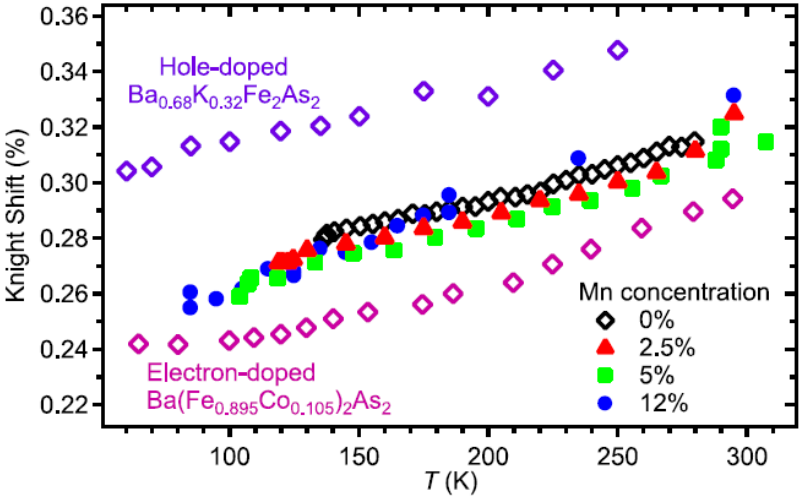
M. G. Kim *et al.*, PRB **82**, 220503 (2010); *ibid.* **83**, 054514 (2011)

Absence of doping and localized Mn moments

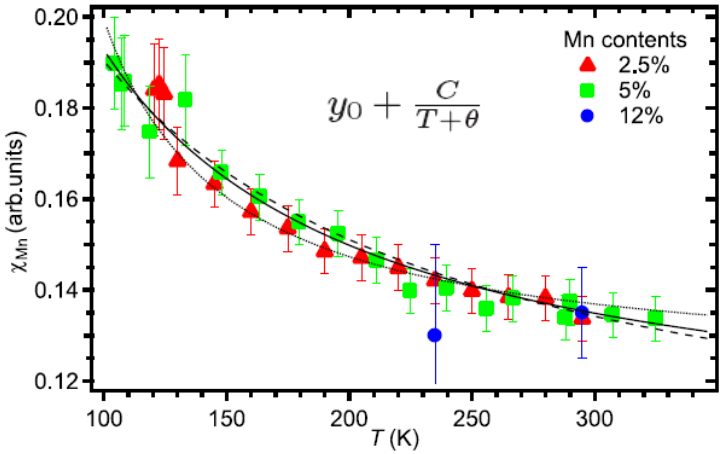




Absence of hole doping:

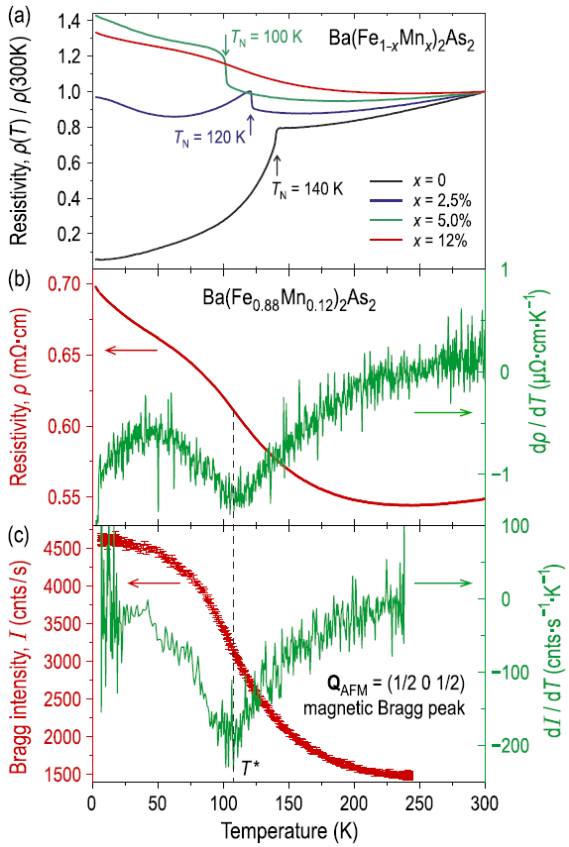


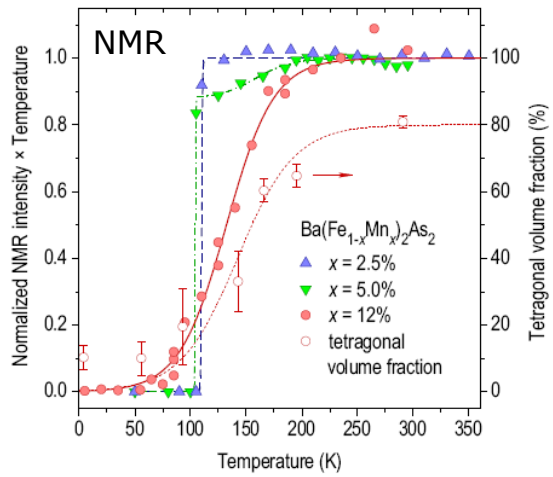
Mn susceptibility ⟶ Curie-Weiss model

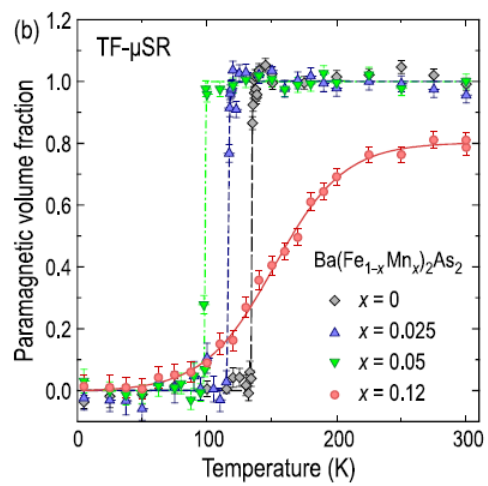


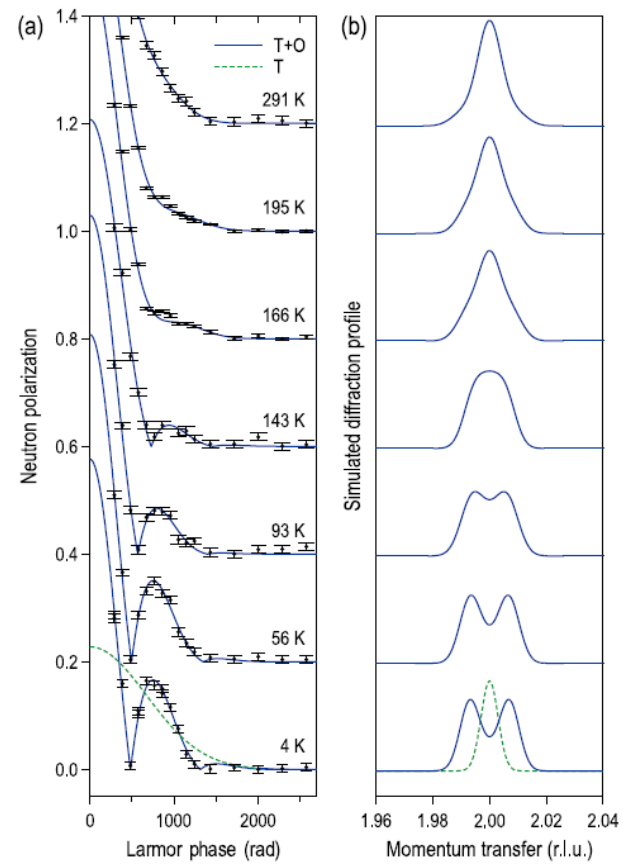
Y. Texier *et al.*, EPL **99**, 17002 (2012)

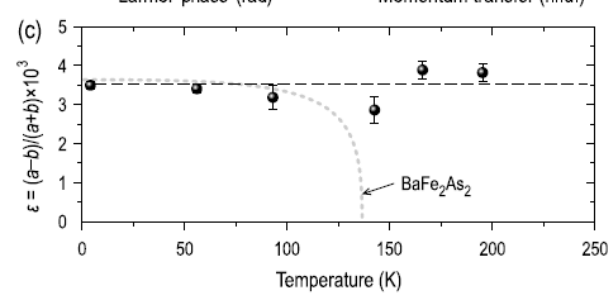
Evidence for phase coexistence





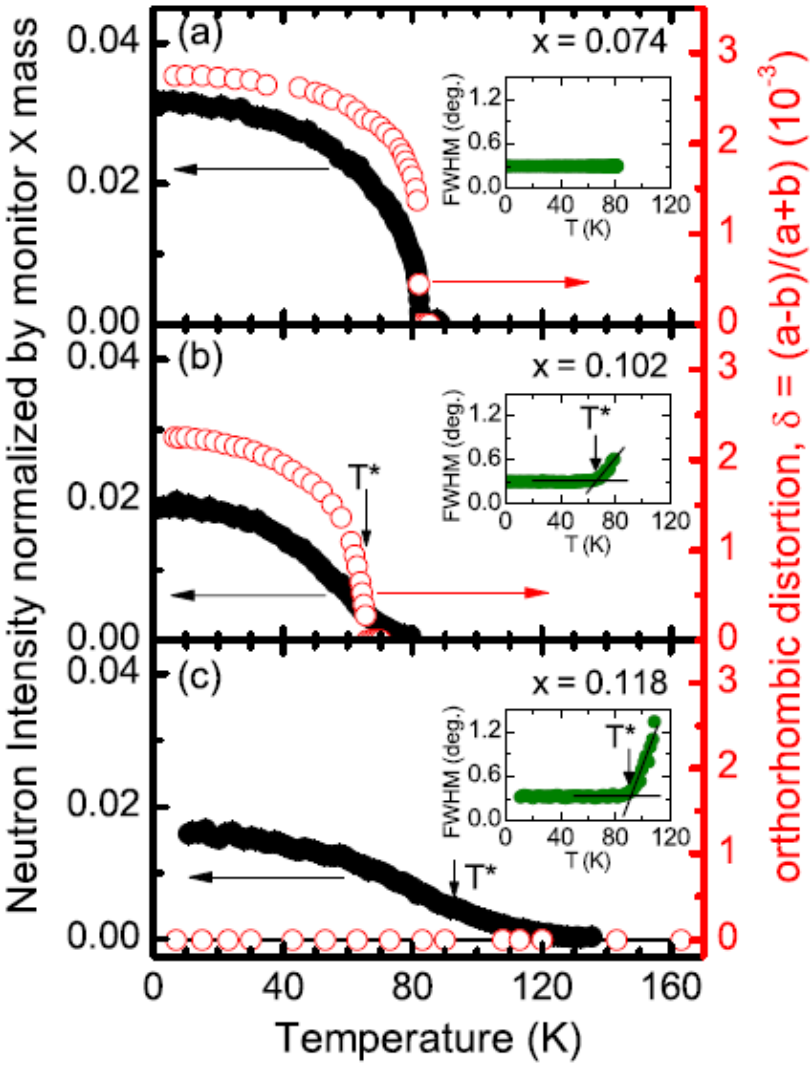




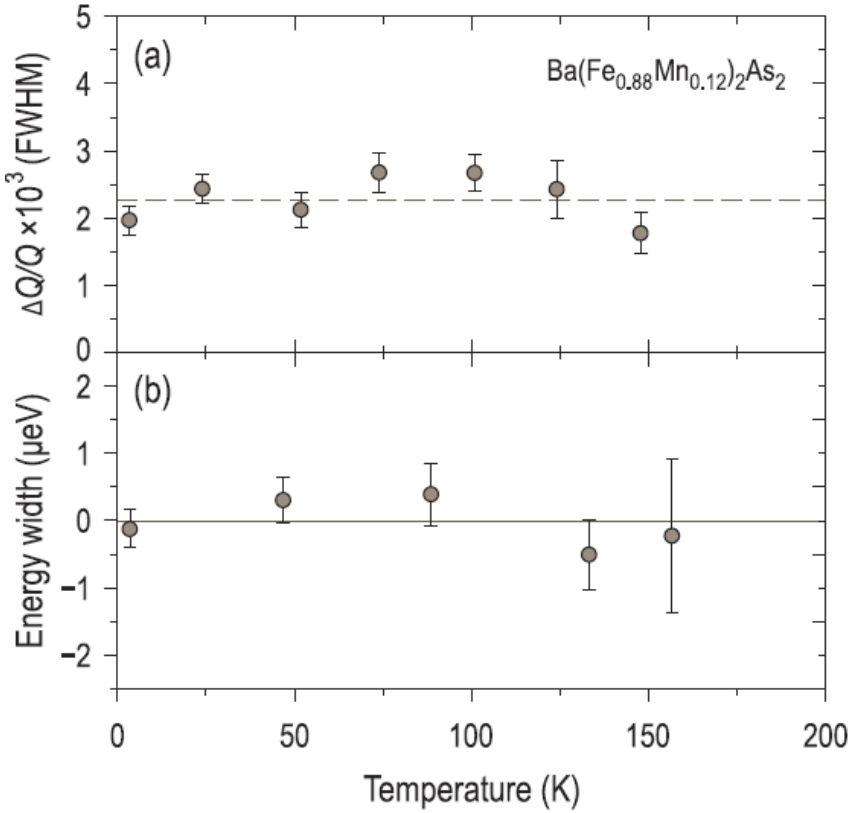


D. Inosov *et al.*, Phys. Rev. B **87**, 224425 (2013)

Momentum- and energy width of the Bragg peak



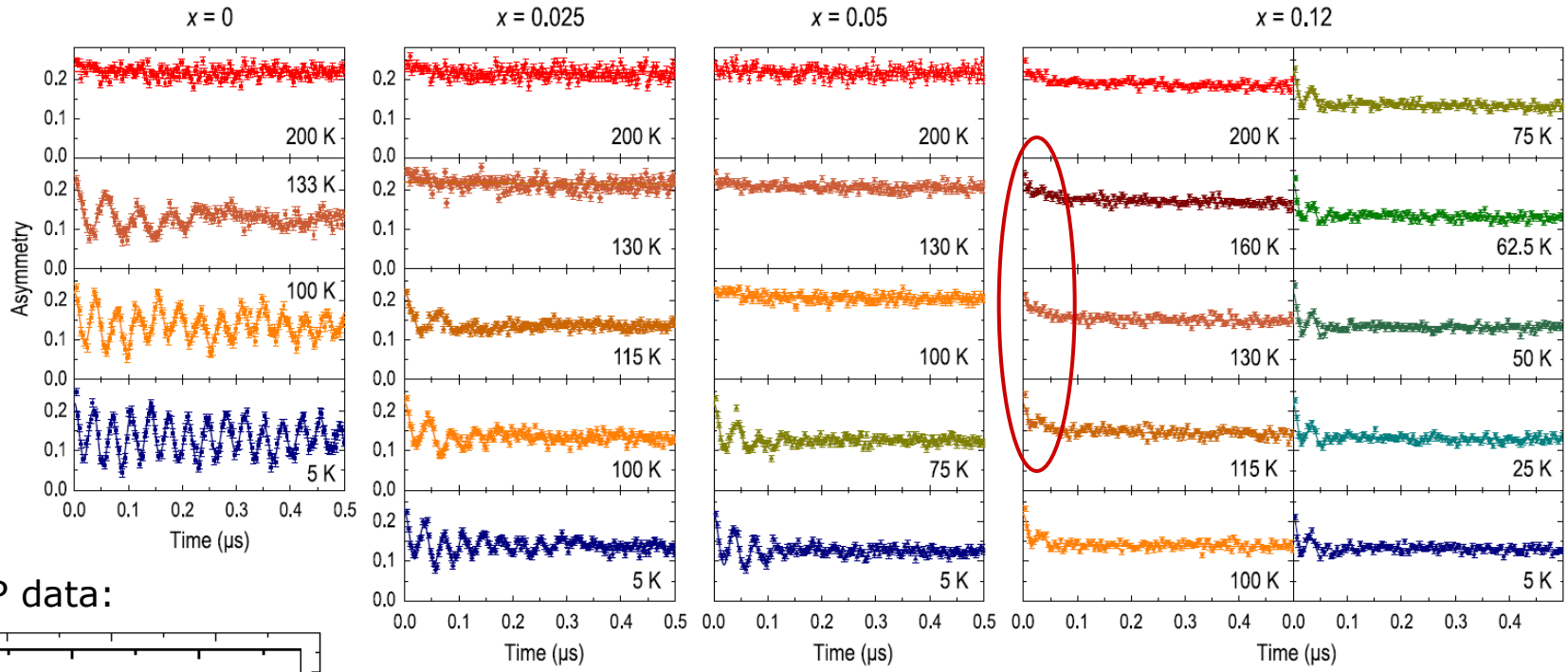
TRISP data (neutron Larmor diffraction and spin-echo spectroscopy):



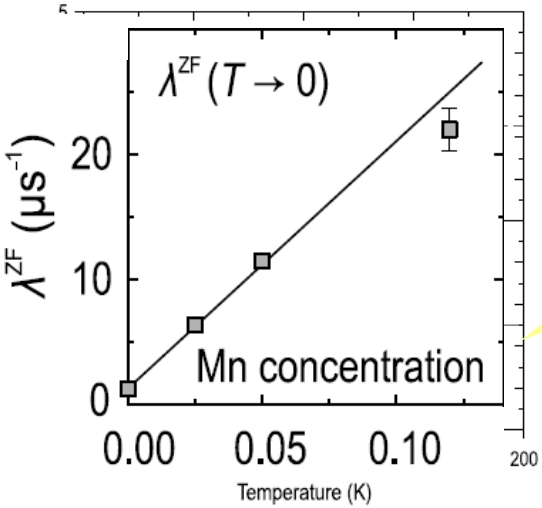
D. Inosov *et al.*, PRB **87**, 224425 (2013)

M. G. Kim, A. I. Goldman *et al.*, PRB **82**, 220503 (2010)

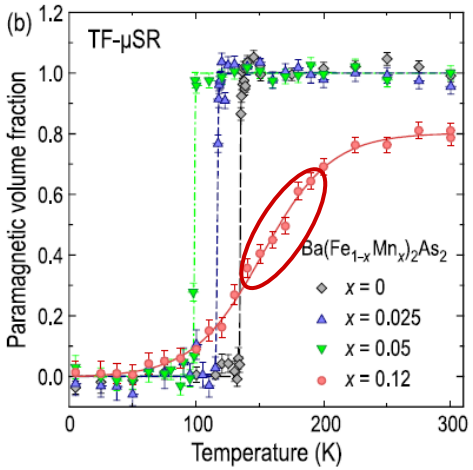
Static long-range magnetic order



TRISP data:

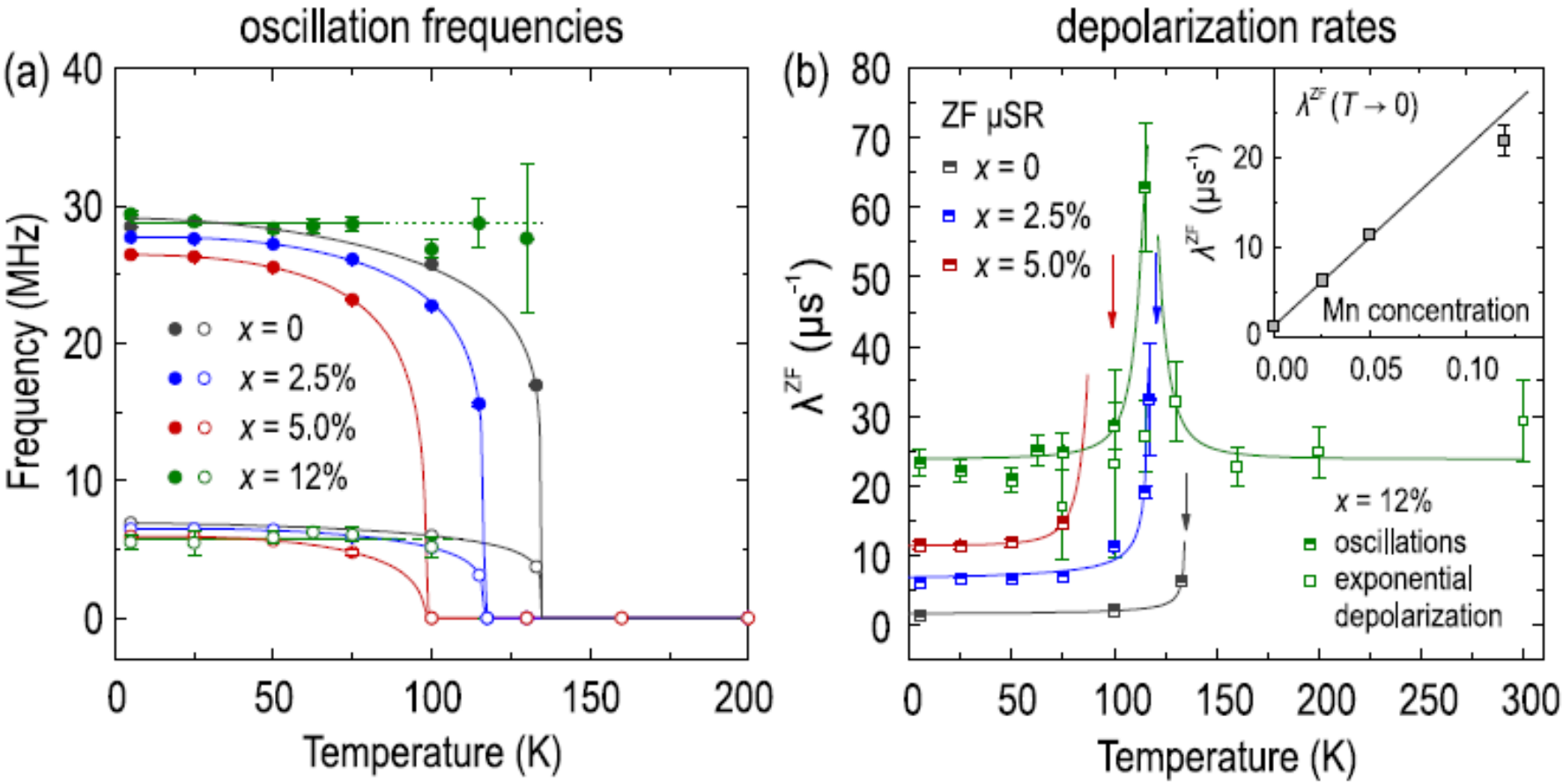


Long-range AFM correlations between static magnetic nanosize clusters



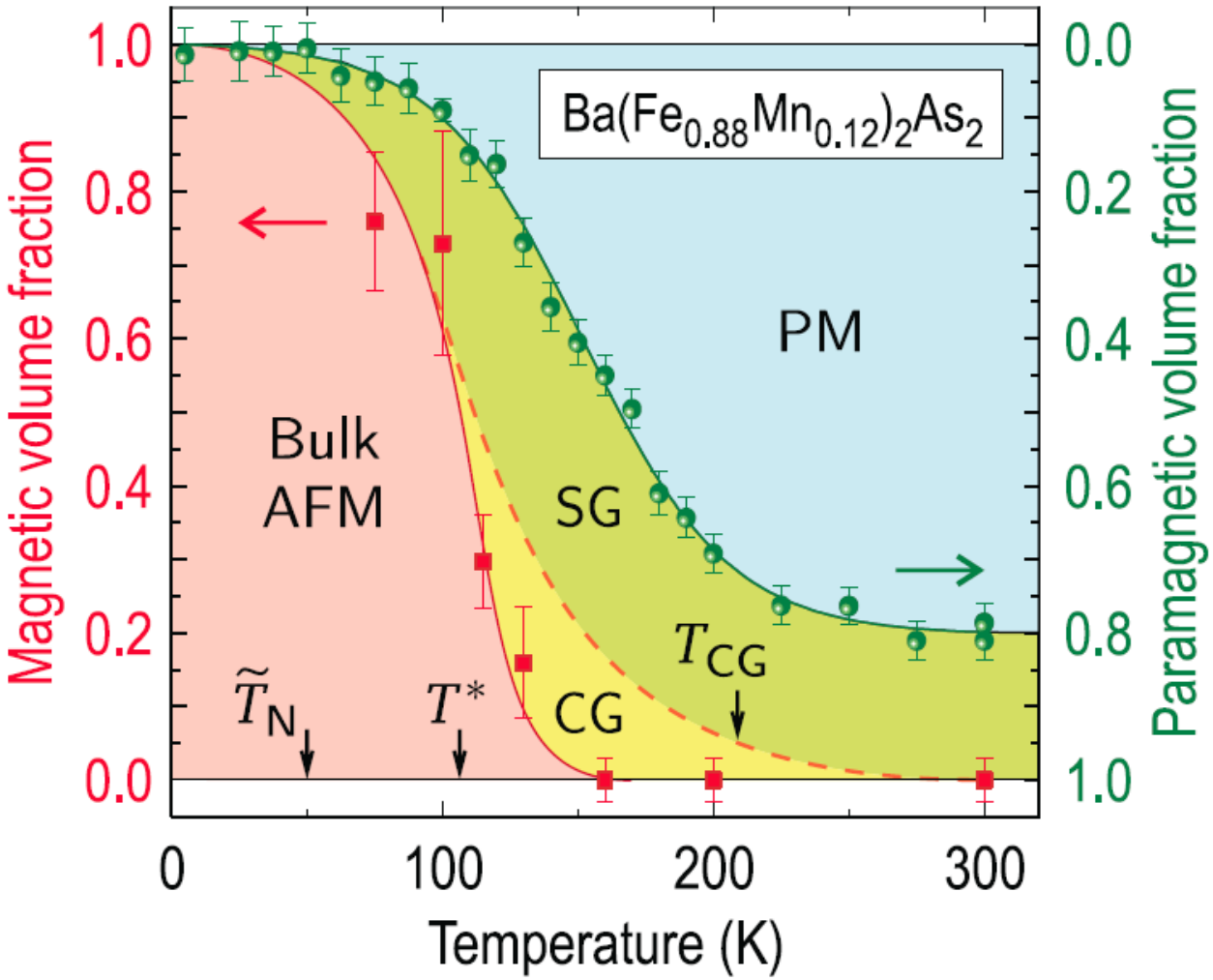
Momentum and energy width of the magnetic Bragg peak

Magnetic moment and the amount of disorder



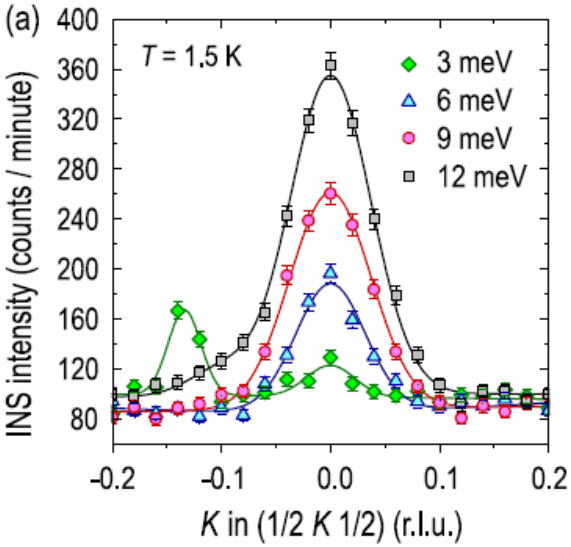
D. Inosov *et al.*, Phys. Rev. B **87**, 224425 (2013)

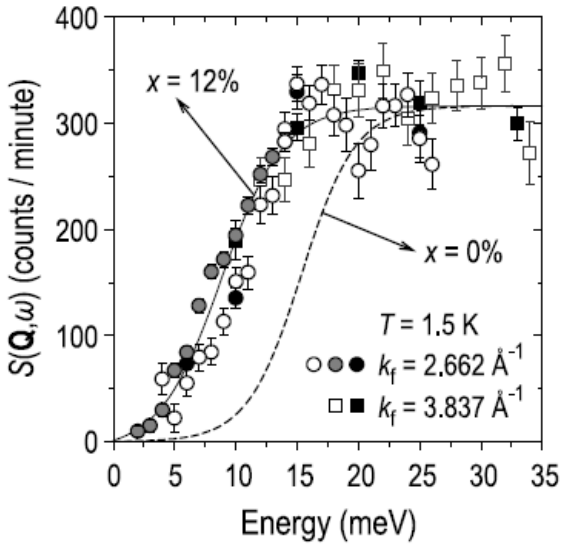
Summary of the μSR results

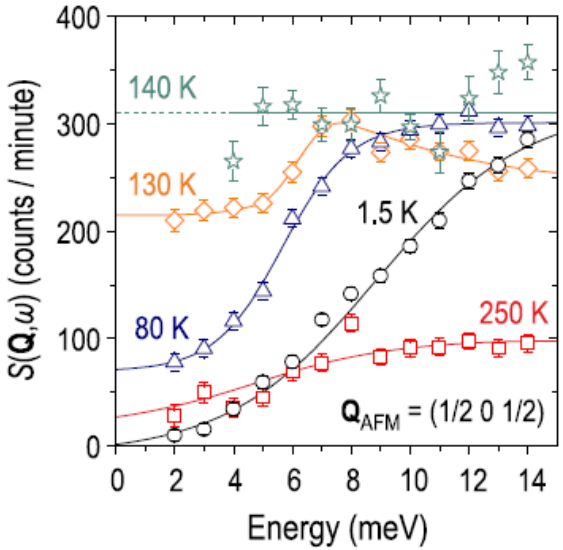


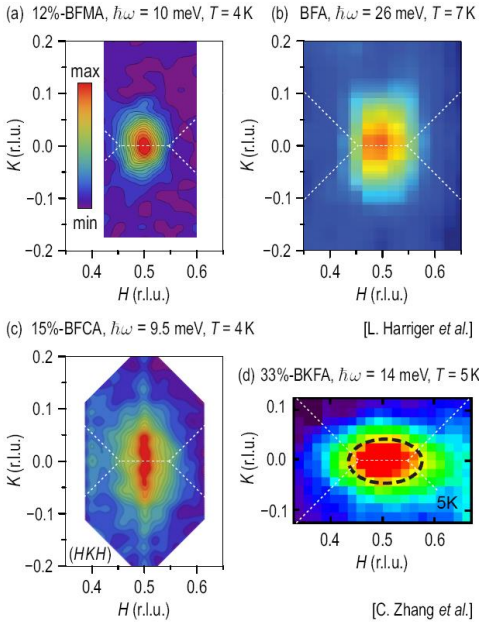
D. Inosov *et al.*, Phys. Rev. B **87**, 224425 (2013)

Effect on magnetic fluctuations

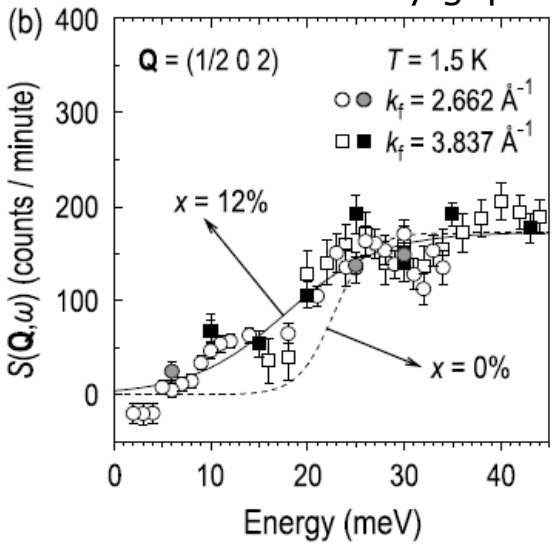


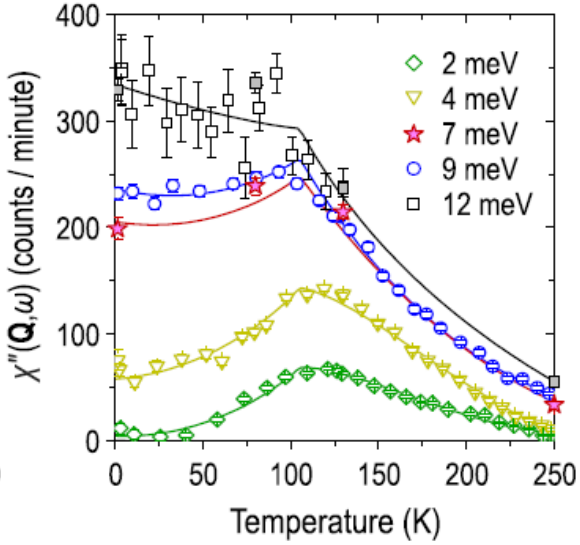




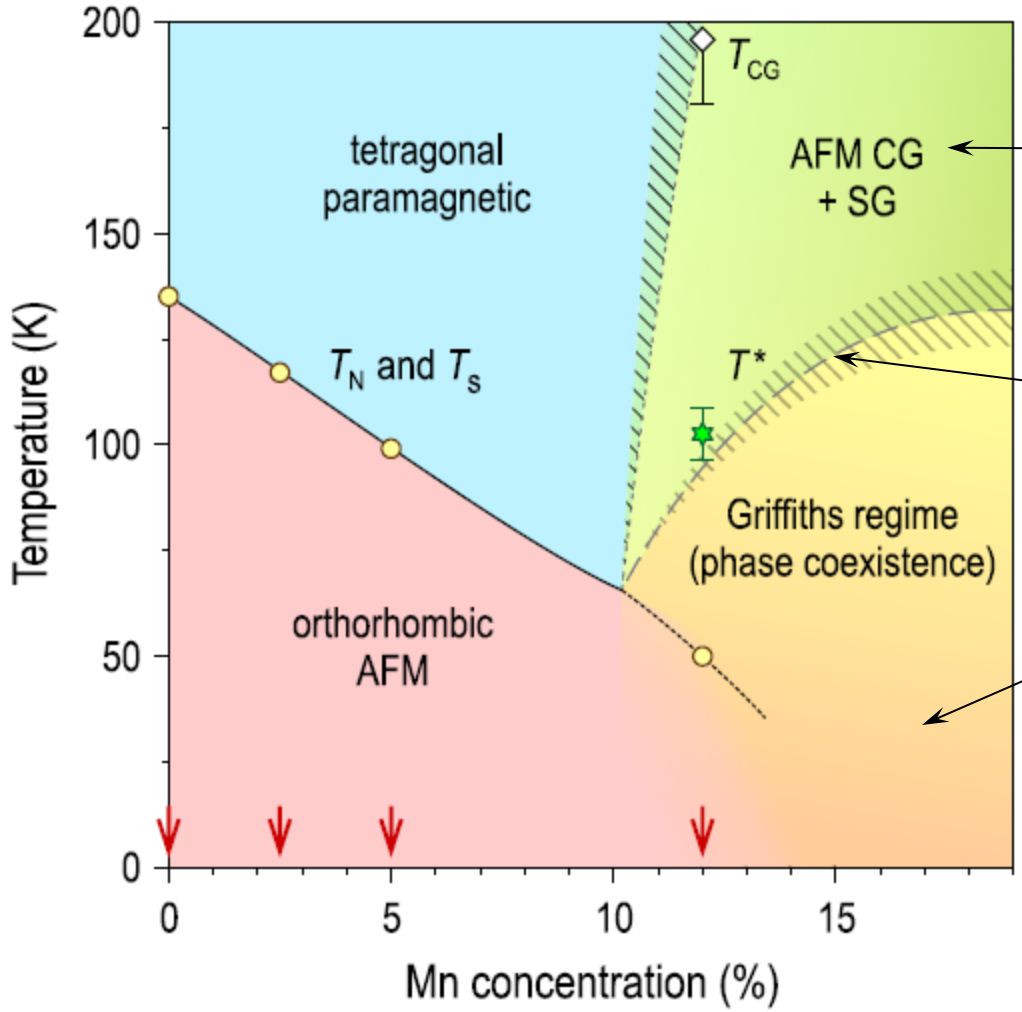


zone-boundary gap





New version of the phase diagram



Static long-range order between nanometer-sized disconnected AFM clusters correlated over long distances (possibly via RKKY exchange).

percolation crossover region

Large connected AFM domains with inclusions of the paramagnetic phase; tetragonal and orthorhombic phases coexist microscopically.

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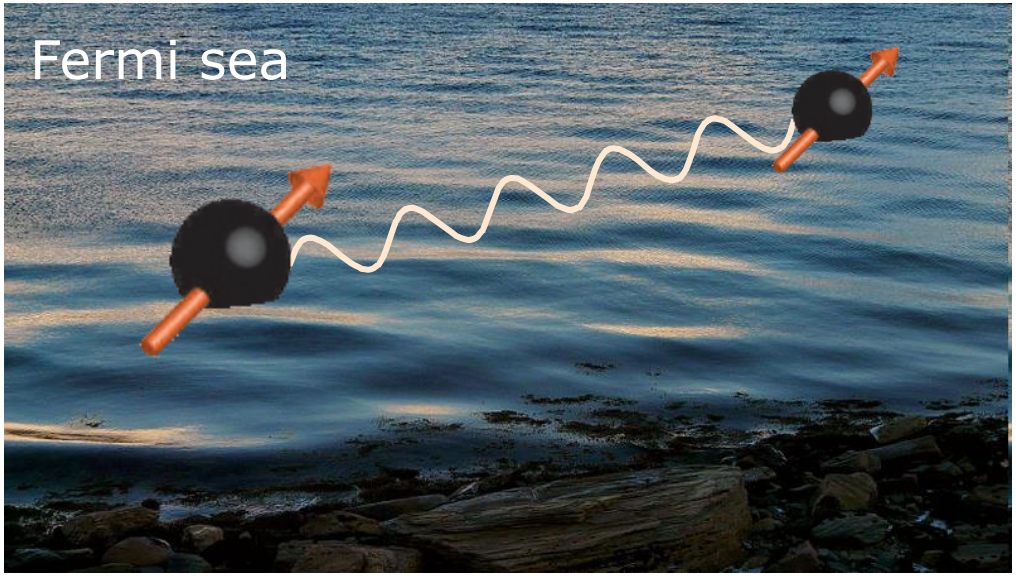
Why is this interesting?

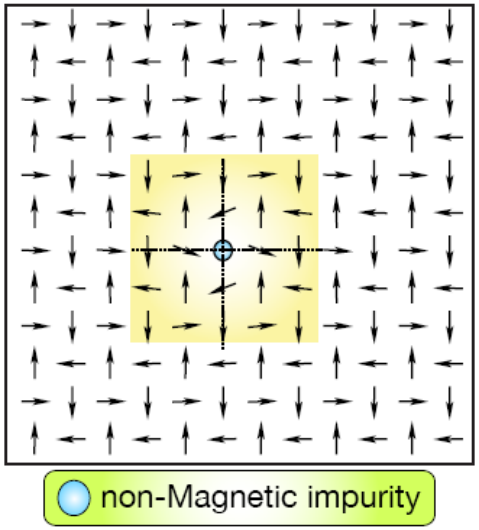
- A perfect example of a system with local moments embedded in a strongly nested metal.



Remarkably, long-range AFM order can be stabilized while most of the sample volume remains paramagnetic!

Useful testing ground for theories of disordered magnetism.

noncollinear magnetism?



PHYSICAL REVIEW B **84**, 134513 (2011)

RKKY interaction in the spin-density-wave phase of iron-based superconductors

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C. Weber & F. Mila, PRB **86**, 184432 (2012)

Thank you for your attention

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Andrew Walters

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Julien Bobroff *et al.* (NMR)
Alexander Yaresko (theoretical support)