# *Как «увидеть» скрытую квантовую критическую точку?*

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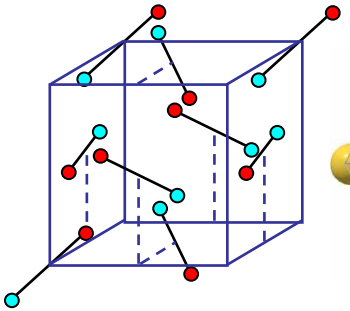
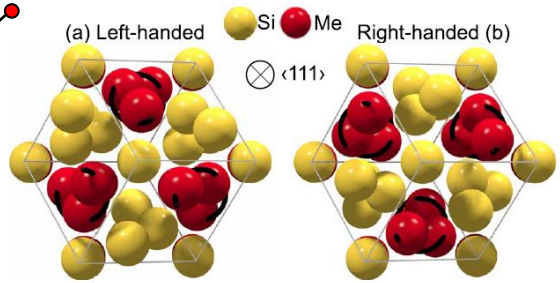
**49-я Школа ПИЯФ по физике конденсированного состояния**
**Санкт-Петербург, 16-21 марта 2015 г.**

# Quantum criticality in $Mn_{1-x}Fe_xSi$. Theoretical expectations.






a=0.456 nm

Mn, Fe
Si

B 20 structure

$Mn_{1-x}Fe_xSi$ substitutional solid solutions (x<0.3).

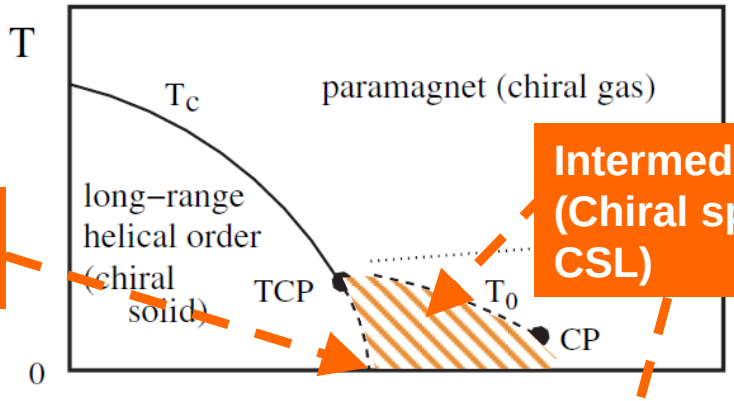
**Underlying QCP**

**Intermediate phase (Chiral spin liquid, CSL)**

L 96, 047207 (2006) PHYSICAL REVIEW LETTERS week ending 3 FEBRUARY 2006

**Blue Quantum Fog: Chiral Condensation in Quantum Helimagnets**

Sumanta Tewari,[1,2] D. Belitz,[1,3] and T. R. Kirkpatrick[1,2]




*Parameter controlling quantum criticality (pressure, concentration, etc.)*

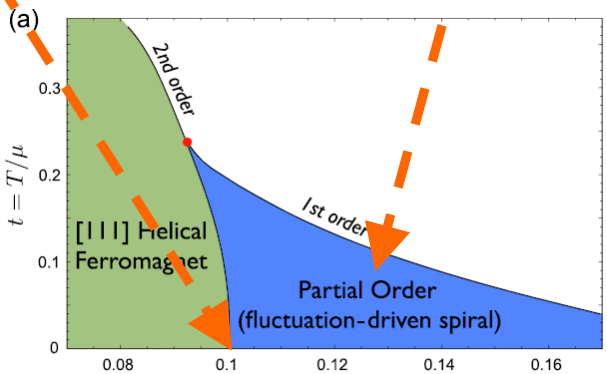
**After decay of the phase with long-range magnetic order an intermediate phase with short-range (fluctuation-driven) magnetic order should be formed. There is underlying QCP.**

**Intermediate phase may mask quantum critical anomalies like divergent magnetic susceptibility.**

PRL 108, 067003 (2012) PHYSICAL REVIEW LETTERS week ending 10 FEBRUARY 2012

**Quantum Order-by-Disorder Near Criticality and the Secret of Partial Order in MnSi**

Frank Krüger,[1] Una Karahasanovic,[1] and Andrew G. Green[2]



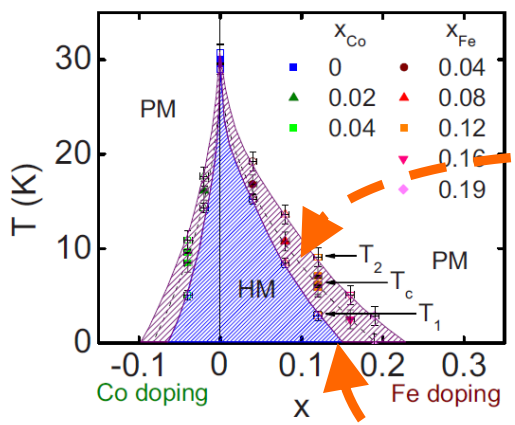

*Parameter controlling quantum criticality (pressure, concentration, etc.)*

# Quantum criticality in $Mn_{1-x}Fe_xSi$. Experimental situation.

PHYSICAL REVIEW B **82**, 064404 (2010)

**Quantum phase transitions in single-crystal $Mn_{1-x}Fe_xSi$ and $Mn_{1-x}Co_xSi$: Crystal growth, magnetization, ac susceptibility, and specific heat**

A. Bauer,[1] A. Neubauer,[1] C. Franz,[1] W. Münzer,[1] M. Garst,[2,3] and C. Pfleiderer[1,*]



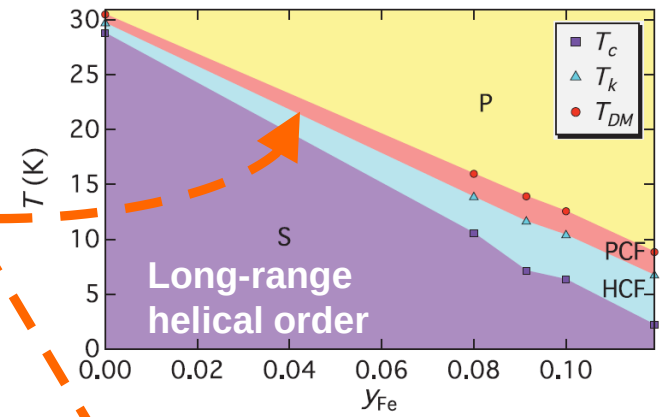

**Intermediate phase (Chiral spin liquid, CSL)**

**Underlying QCP**

PHYSICAL REVIEW B **83**, 224411 (2011)

**Chiral criticality in the doped helimagnets $Mn_{1-y}Fe_ySi$**

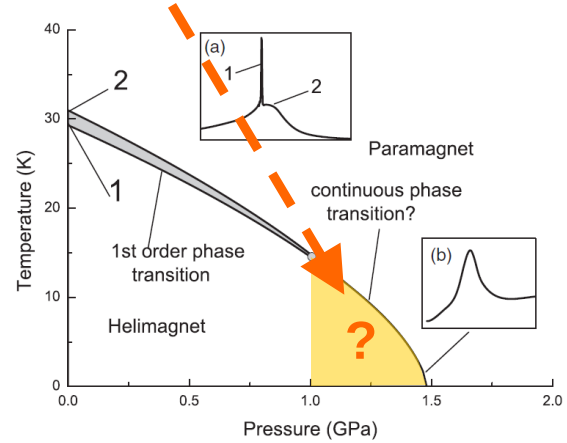
Sergey V. Grigoriev,[1] Evgeny V. Moskvin,[1] Vadim A. Dyadkin,[1] Daniel Lamago,[2,3] Thomas Wolf,[3] Helmut Eckerlebe,[4] and Sergey V. Maleyev[1]



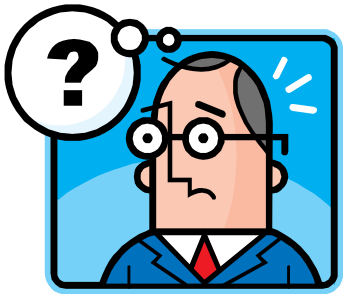

PHYSICAL REVIEW B **86**, 174407 (2012)

**Phase diagram of the itinerant helimagnet MnSi from high-pressure resistivity measurements and the quantum criticality problem**

Alla E. Petrova and Sergei M. Stishov*




Experimental magnetic phase diagrams differ from the theoretical ones.




What kind of QC points we have?

Is there any true QC anomalies?

How T-x phase diagram is constructed?

PHYSICAL REVIEW B **83**, 224411 (2011)

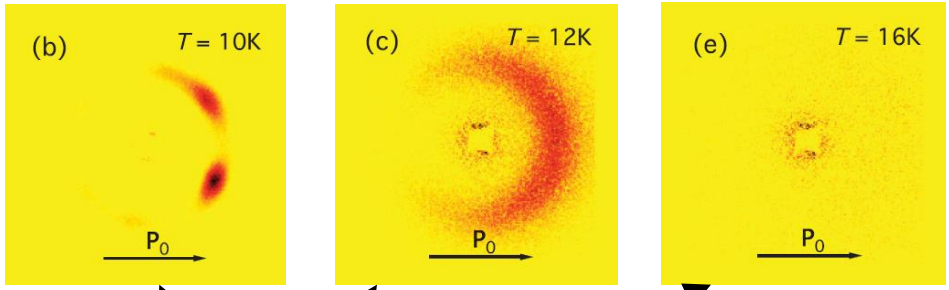
**Chiral criticality in the doped helimagnets $Mn_{1-y}Fe_ySi$**

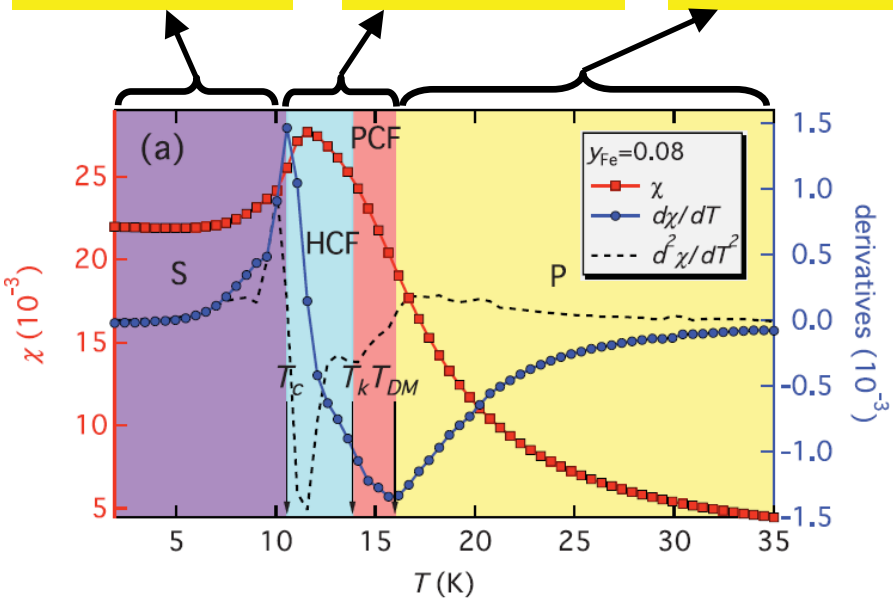
Sergey V. Grigoriev,[1] Evgeny V. Moskvin,[1] Vadim A. Dyadkin,[1] Daniel Lamago,[2,3] Thomas Wolf,[3] Helmut Eckerlebe,[4] and Sergey V. Maleyev[1]

**Long-range magnetic order (Chiral solid)**

**Short-range magnetic order (Chiral liquid)**

**Paramagnet (Chiral gas)**




**Correlation between magnetic susceptibility and polarized neutron scattering data is established in $Mn_{1-x}Fe_xSi$.**

**The extrema of the $\partial\chi/\partial T$ derivative may be used for identification of the magnetic phases with long-range and short-range magnetic order.**

PHYSICAL REVIEW B **82**, 064404 (2010)

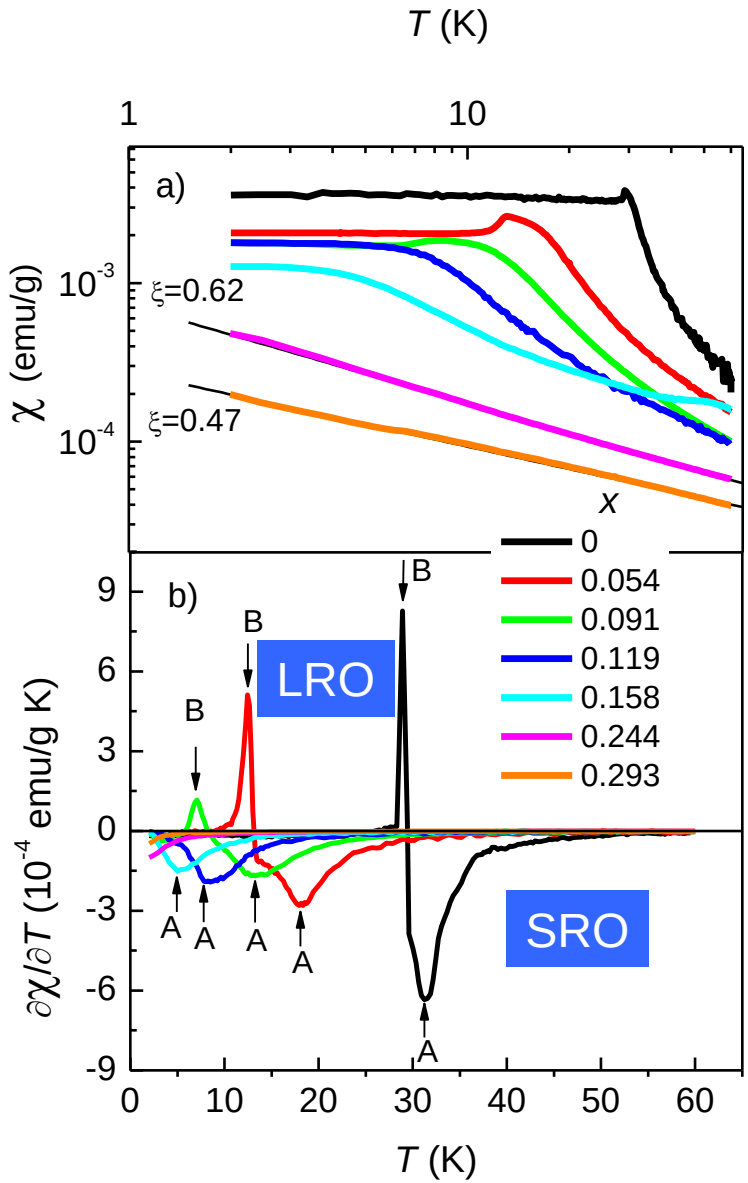
**Quantum phase transitions in single-crystal $Mn_{1-x}Fe_xSi$ and $Mn_{1-x}Co_xSi$: Crystal growth, magnetization, ac susceptibility, and specific heat**

A. Bauer,[1] A. Neubauer,[1] C. Franz,[1] W. Münzer,[1] M. Garst,[2,3] and C. Pfleiderer[1,*]

**Classical ferromagnetic equation of state is applicable for $Mn_{1-x}Fe_xSi$.**

**Belov-Arrott analysis is possible**

# Experimental results. Magnetic susceptibility.



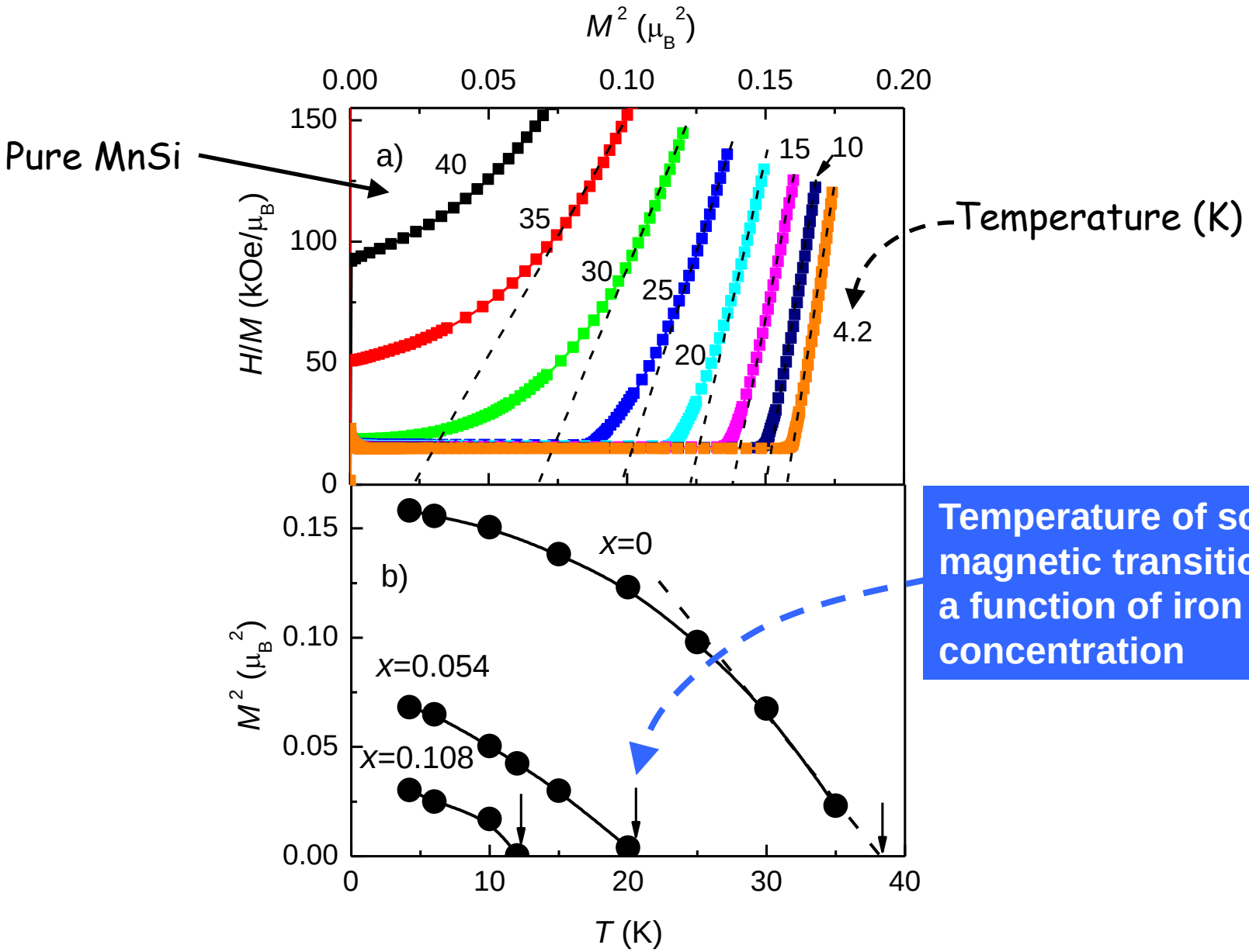

**Griffiths-type QC anomaly for *x* >0.24**

$$\chi \sim \frac{1}{T^{\xi}} \qquad \xi \sim 0.5 - 0.6$$

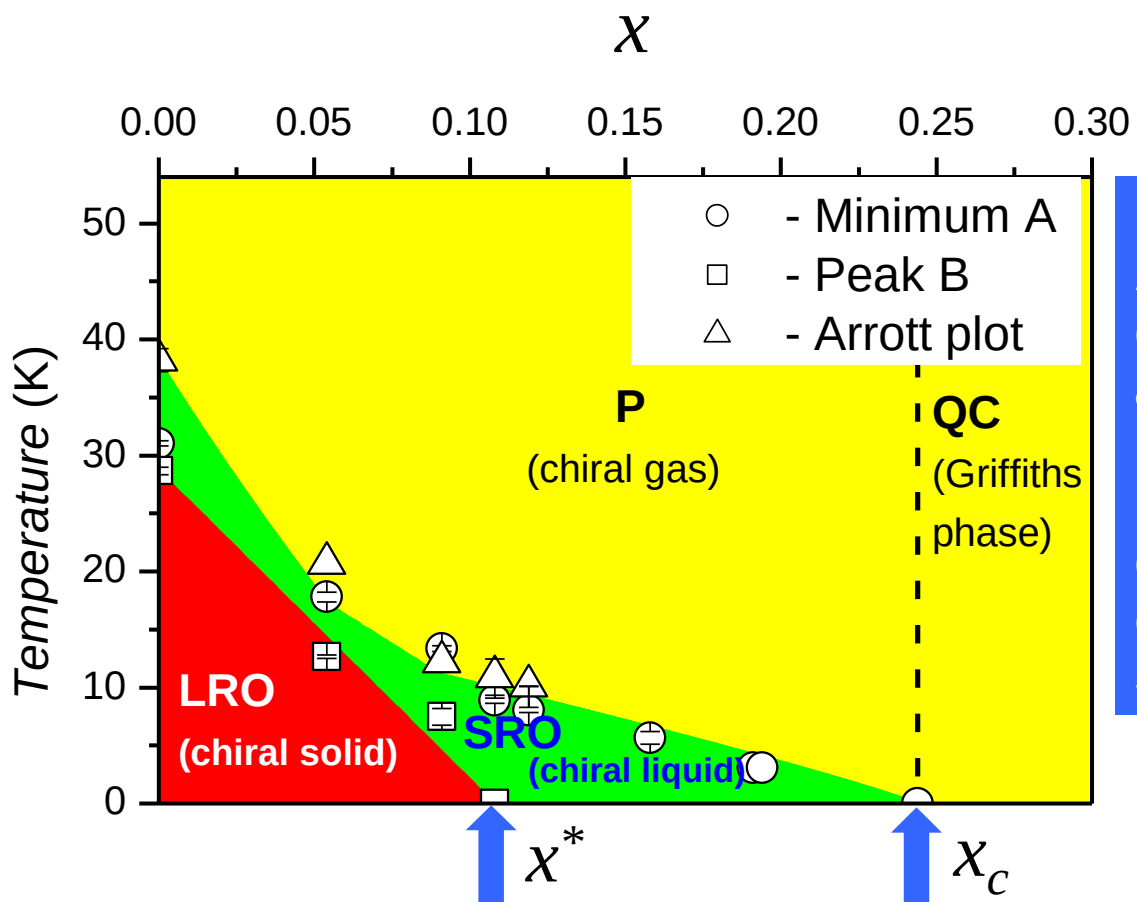
**Peak B is a marker of long-range magnetic order (LRO).**

**Minimum A is a marker of short-range magnetic order (SRO).**

# Experimental results. Belov-Arrott analysis of magnetization.




**Temperature of some magnetic transition as a function of iron concentration**




**Both susceptibility and Arrott analysis give characteristic temperatures above transition into the magnetic phase with spiral LRO. These temperatures corresponds to formation of the magnetic phase with SRO (chiral spin liquid).**

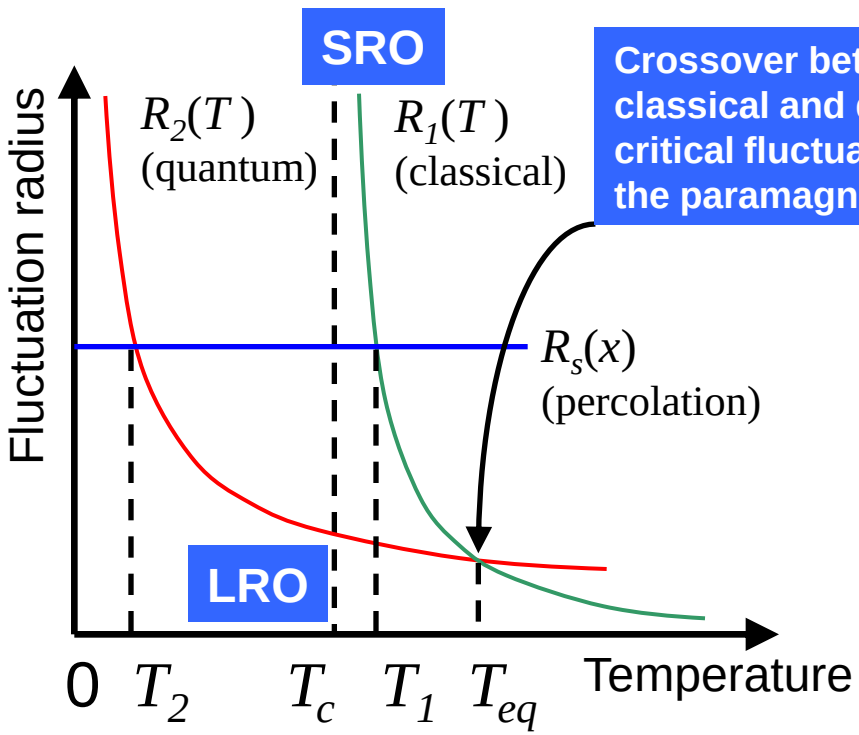
**There are two quantum critical points, $x^*$ and $x_c$. The first QC point $x^* \sim 0.11$ corresponds to disappearance of LRO and is an underlying one, which is hidden inside the SRO phase. The second QC point $x_c \sim 0.24$ is a "true" one and marks suppression of the magnetic phase with SRO (chiral spin liquid).**

Quantum bicriticality in $Mn_{1-x}Fe_xSi$ solid solutions.

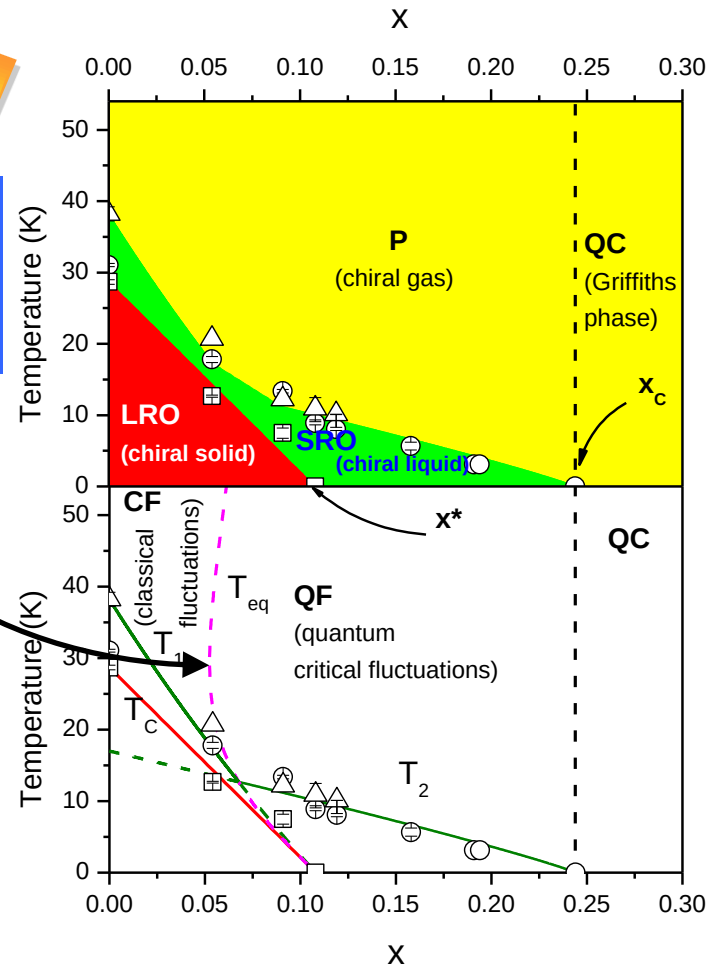
Pis'ma v ZhETF, vol. 98, iss. 12, pp. 933 – 937 © 2013 December 25

Quantum bicriticality in $Mn_{1-x}Fe_xSi$ solid solutions: exchange and percolation effects

S. V. Demishev[+1)], I. I. Lobanova[+*], V. V. Glushkov[+*], T. V. Ischenko[+], N. E. Sluchanko[+], V. A. Dyadkin, N. M. Potapova, S. V. Grigoriev




**Crossover between classical and quantum critical fluctuations in the paramagnetic phase**




**Presence of both classical and quantum critical fluctuations.**

**Phase with short-range order is formed when fluctuations slow down and freeze.**

**Fluctuations freeze when their radius reaches critical value controlled by disorder (or defects) in the system.**

# The model. Calculation details.

Classical fluctuations (CF): $R_1 = \dfrac{a_1}{[T/T_c(x)-1]^{\delta}}$; $\delta \sim 1/2$

Quantum critical fluctuations (QF): $R_2 = a_2 \dfrac{T_0}{T}$

Defects and disorder (percolation):

$R_s = R_c = \dfrac{l}{(1-x/x_c)^{\nu}}$; $\nu \sim 0.9$, $x_c$ - percolation threshold

$R_{1,2} = R_s \Rightarrow T_{1,2}(x)$ Freezing condition

$R_1 = R_2 \Rightarrow T_{eq}(x)$ Crossover between CF and QF

**There is only one fitting parameter $T_2(0)$ (measure of the quantum critical fluctuations strength).**

Transition into LRO phase

$T_c(x) = T_c(0)(1-x/x^*)$

Transition into SRO phase:

$T(x) = \max\{T_1(x), T_2(x)\}$

$$T_1 = T_c(x)\left\{1 + \frac{\delta T(0)}{T_c(0)}\left(1 - \frac{x}{x_c}\right)^{\nu/\delta}\right\}$$

$$T_2 = T_2(0)\left(1 - \frac{x}{x_c}\right)^{\nu}$$

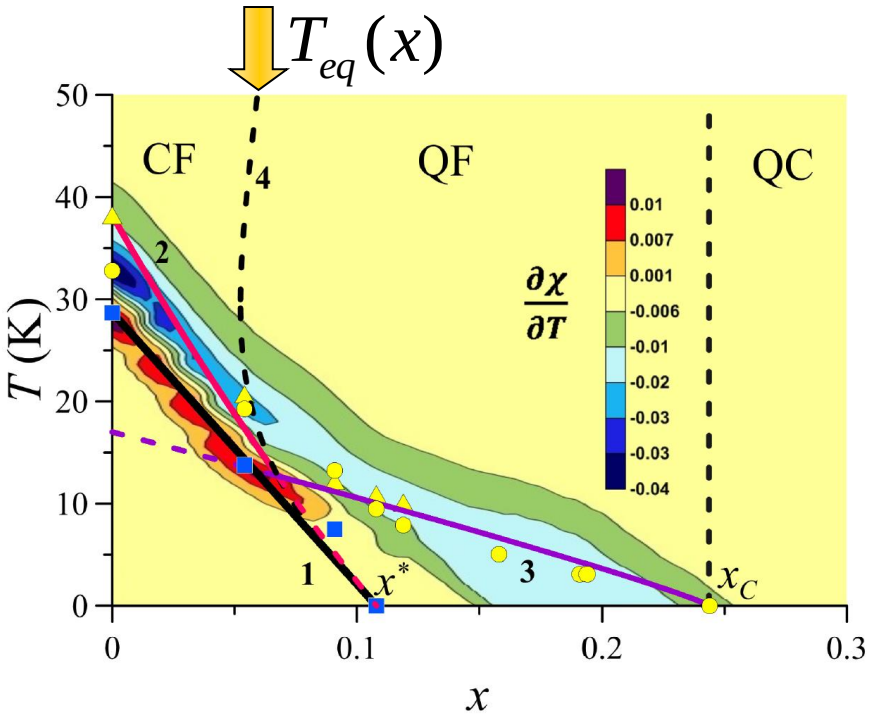
$$\delta T(0) = T_c(0)\left(\frac{a_1}{l}\right)^{1/\delta}; T_2(0) = T_0 \frac{a_2}{l}$$

CF - QF crossover temperature for model choice $\delta = 1/2$

$$A = \frac{z^2}{z-1} \Rightarrow T_{eq}(x)$$

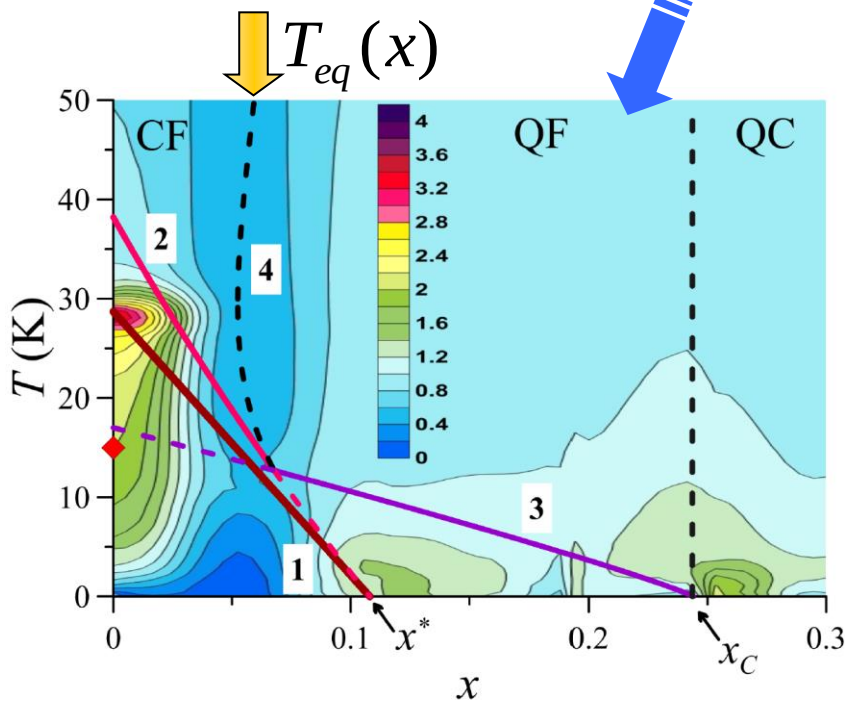
$$z = \frac{T_{eq}}{T_c(x)}; \quad A = \frac{T_2(0)^2 T_c(0)}{\Delta T(0) T_c(x)^2}$$

**No $T_{eq}(x)$ in the $\partial\chi/\partial T$ data!**




**Analysis of the resistivity data:**

$$\rho(T) = \rho_0 + A \cdot T^{\alpha} \Rightarrow \alpha(x,T)$$




**The predicted crossover line is observed in the resistivity data due to scattering on magnetic fluctuations (Yosida mechanism).**

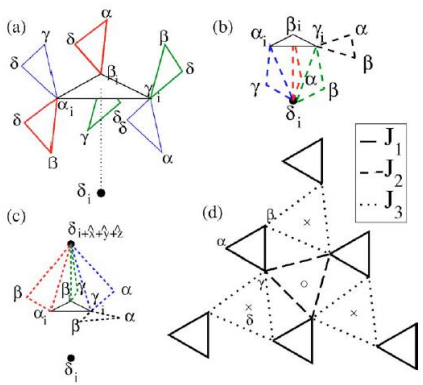
**In the case of static susceptibility these fluctuations are averaged and don't affect $\chi(T)$ data.**

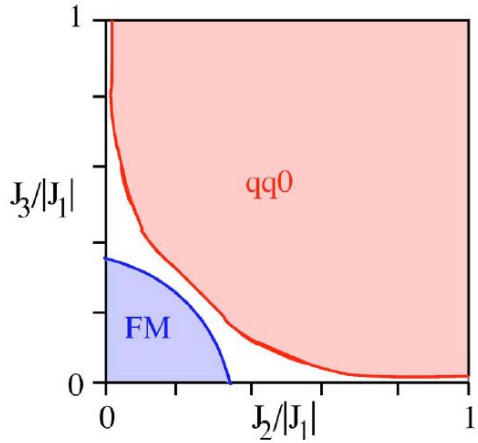
## Why intermediate phase is formed? Why LRO phase is supressed?

PHYSICAL REVIEW B **75**, 064430 (2007)

**Microscopic model for spiral ordering along (110) on the MnSi lattice**

John M. Hopkinson* and Hae-Young Kee†




$J_1$ – nn (FM) exchange

$J_2$ – next nn (AFM) exchange

$J_3$ – third nn (AFM) exchange

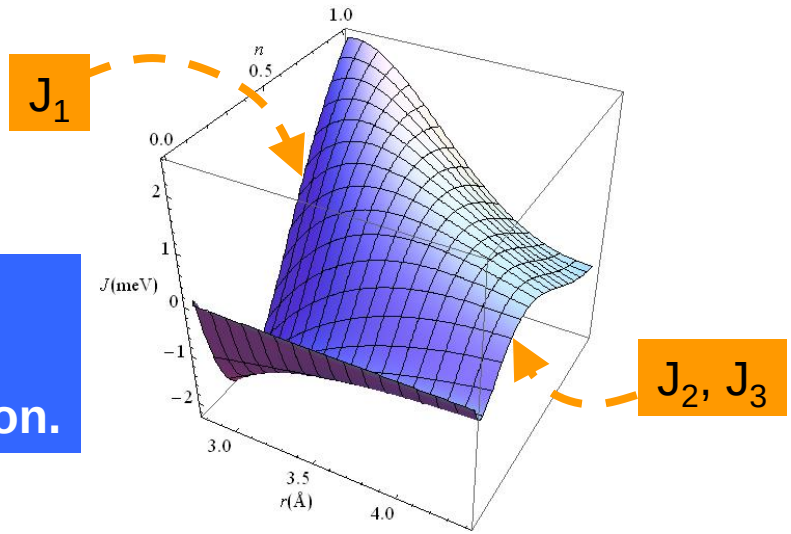
$J_2 \cong J_3$

$$|J_2 / J_1|_{cr} \sim 0.21 - 0.32$$

**Frustration try to align spirals along (110).**

**DM interaction try to align spirals along (111)**

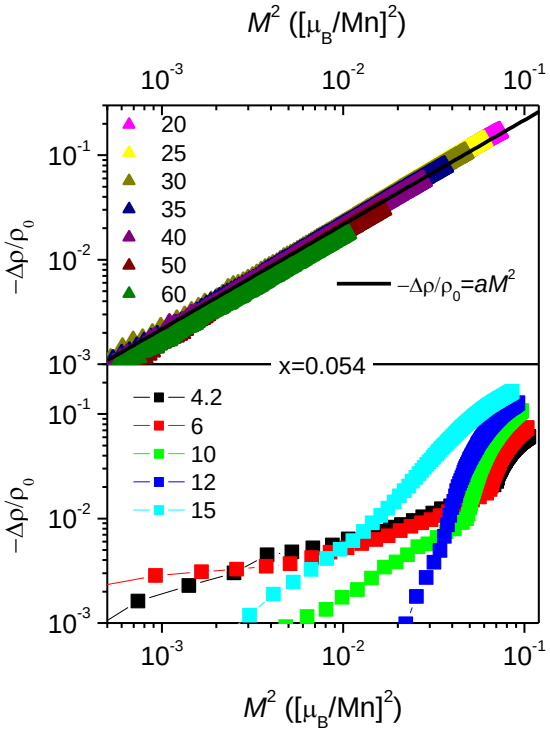
**Competition between two interactions may lead to loosing of the long-range order and formation of the chiral liquid state.**



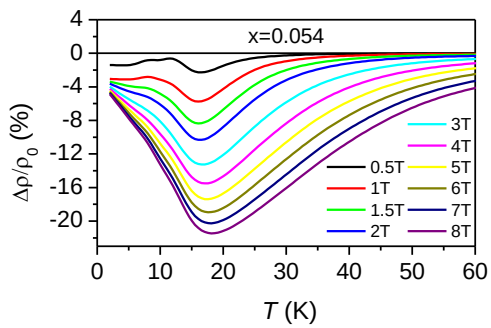

**In Heisenberg paradigm RKKY exchange defines $J_1$, $J_2$, $J_3$ parameters, which may be tuned by variation of the electron concentration.**

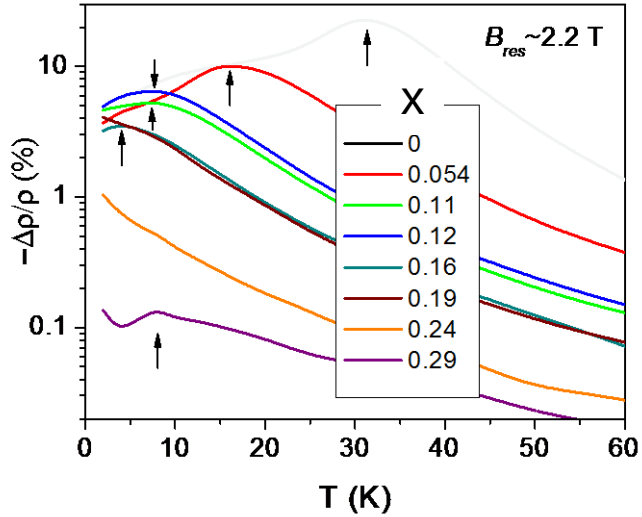
# QC points and ESR. Phase diagram of $Mn_{1-x}Fe_xSi$ for $B=B_{res}$.

**Yosida mechanism holds in $Mn_{1-x}Fe_xSi$.**

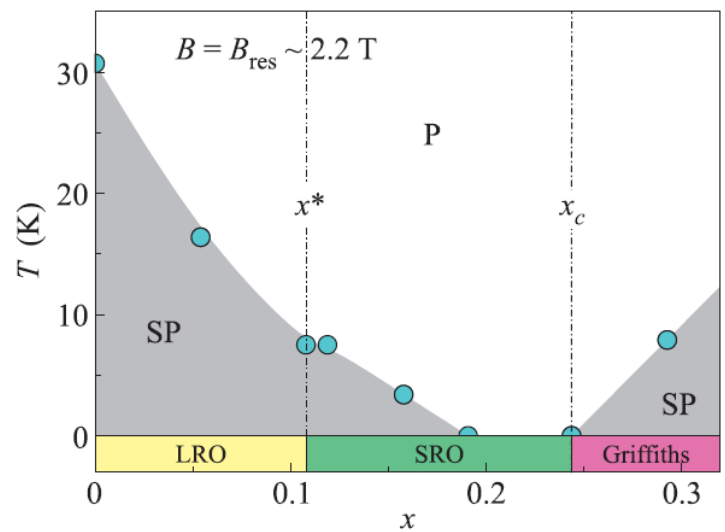



**Magnetoresistance maximum evolution with iron concentration.**




**Phase diagram in magnetic field corresponding to magnetic resonance**




Pis'ma v ZhETF, vol. 100, iss. 1, pp. 30 – 33

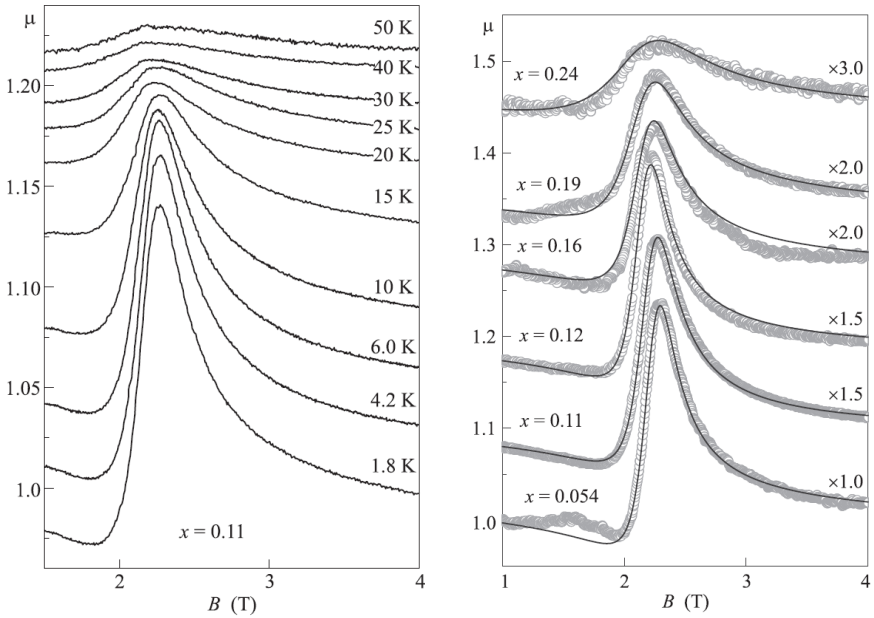


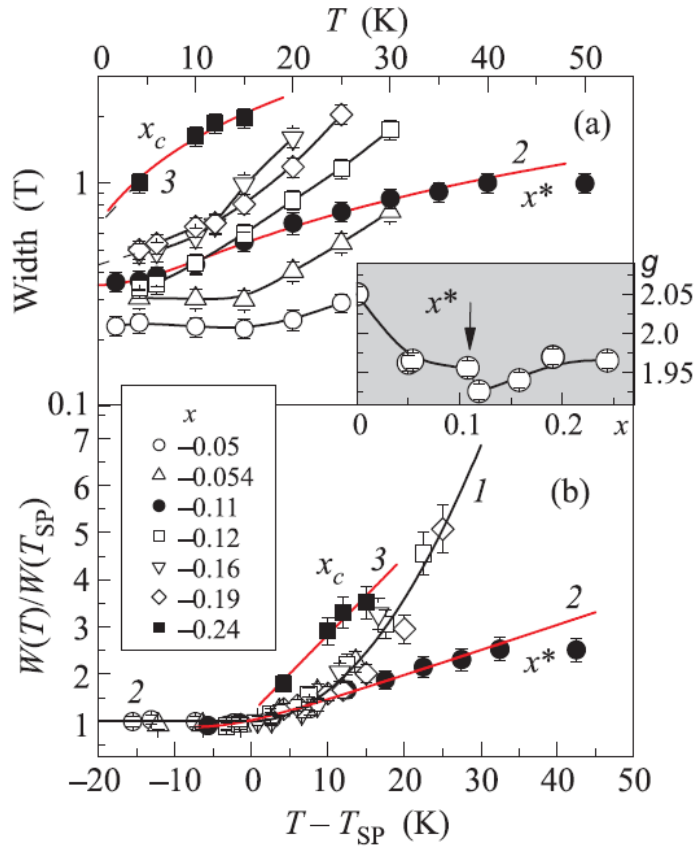
Anomalous spin relaxation and quantum criticality in $Mn_{1-x}Fe_xSi$ solid solutions[1)]

S. V. Demishev+*2), A. N. Samarin+*, V. V. Glushkov+*, M. I. Gilmanov+*, I. I. Lobanova+*, N. A. Samarin+, A. V. Semeno+, N. E. Sluchanko+, N. M. Chubova×, V. A. Dyadkin×, S. V. Grigoriev×

# ESR in $Mn_{1-x}Fe_xSi$. Results.

## 60 GHz ESR spectra




**Strong broadening of the line width (enhancement of spin fluctuations) with iron concentration.**

**Universal scaling $W(T)/W(T_{SP})=1+a(T-T_{SP})^2$ for all concentrations except quantum critical points x* and $x_c$.**

**Violation of the standard Korringa relaxation law $W(T)\sim 1/\chi(T)\sim(T-T_{SP})$.**

**Weakening of the W(*T*) temperature dependence just at quantum critical points.**

# ESR in $Mn_{1-x}Fe_xSi$. Theory vs. experiment.

**Theory of the ESR in strongly correlated metals**

**Korringa relaxation should be valid even in strongly correlated metallic case**

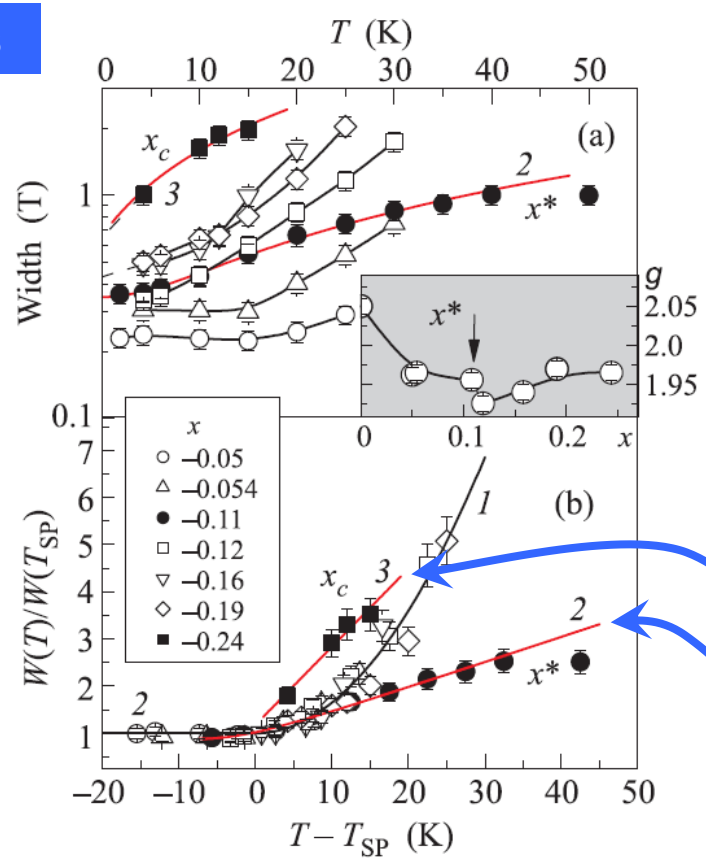
P. Schlottmann, Phys. Rev. B **86**, 075135 (2012)

**Expression for ESR line width in strongly correlated metal in vicinity of the QC point:**

$$W(T) = AT\arctan(T/T_x) + W_0$$

$T_x$ is a crossover temperature between Fermi-liquid $(T \ll T_x)$ and non-Fermi-liquid $(T \gg T_x)$ regimes.

P. Wölfle and E. Abrahams, Phys. Rev. B **80**, 235112 (2009).




**Reasonable fit of the experimental data assuming $T_x \sim T_{SP}$, i.e. $T_x \sim 11$ K for $x^*$ and $T_x \sim 0$ K for $x_c$.**

**Even in strong magnetic field QC points x* and $x_c$ derived in the limit B→0 are still here.**

**ESR is a right tool to visualize QC points including the underlying QC point.**

# *Conclusions.*

Magnetic phase diagram of $Mn_{1-x}Fe_xSi$ is driven by the sequence of two quantum phase transitions.

First (underlying) QCP is located at $x^*$~0.11 and controlled by exchange effects.

Second QCP is located at $x_c$~0.24 and is disorder controlled. This QC point corresponds to the change of the magnetic system topology at the percolation threshold. For $x>x_c$ ground state is a Griffiths phase.

New line on $T$-$x$ diagram, which corresponds to a crossover between the classical and quantum fluctuations, is predicted in quantum bicritical model and observed experimentally.

Substitution of Mn by Fe leads to enhancement of spin fluctuations (a route from Heisenberg to itinerant case).

Anomalous spin relaxation is a tool to visualize QC points in ESR experiments.

Pis'ma v ZhETF, vol. 98, iss. 12, pp. 933 – 937 © 2013 December 25

## Quantum bicriticality in $Mn_{1-x}Fe_xSi$ solid solutions: exchange and percolation effects

*S. V. Demishev*[+1)], *I. I. Lobanova*[+*], *V. V. Glushkov*[+*], *T. V. Ischenko*[+], *N. E. Sluchanko*[+], *V. A. Dyadkin*, *N. M. Potapova*, *S. V. Grigoriev*

Pis'ma v ZhETF, vol. 100, iss. 1, pp. 30 – 33 © 2014 July 10

## Anomalous spin relaxation and quantum criticality in $Mn_{1-x}Fe_xSi$ solid solutions[1)]

*S. V. Demishev*[+* 2)], *A. N. Samarin*[+*], *V. V. Glushkov*[+*], *M. I. Gilmanov*[+*], *I. I. Lobanova*[+*], *N. A. Samarin*[+], *A. V. Semeno*[+], *N. E. Sluchanko*[+], *N. M. Chubova*[×], *V. A. Dyadkin*[×], *S. V. Grigoriev*[×]

## Acknowledgements

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