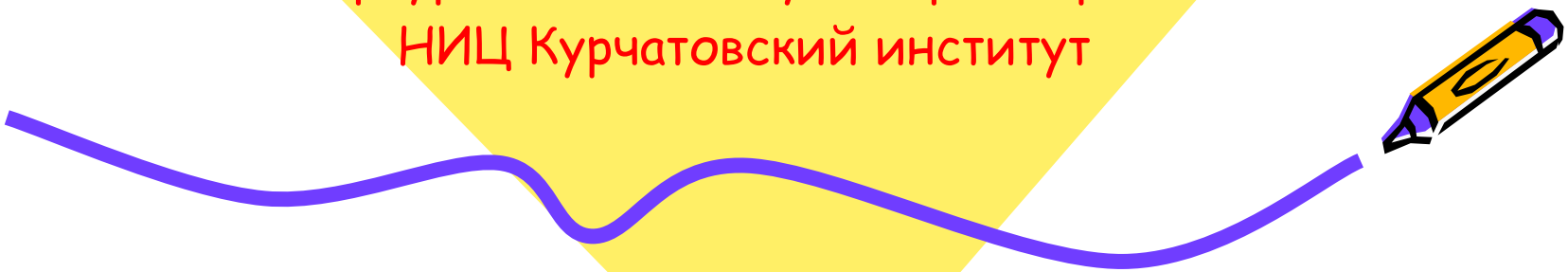
# Киральная катастрофа модели Бака-Йенсена в $Fe_{1-x}Co_xGe$

С.В. Григорьев

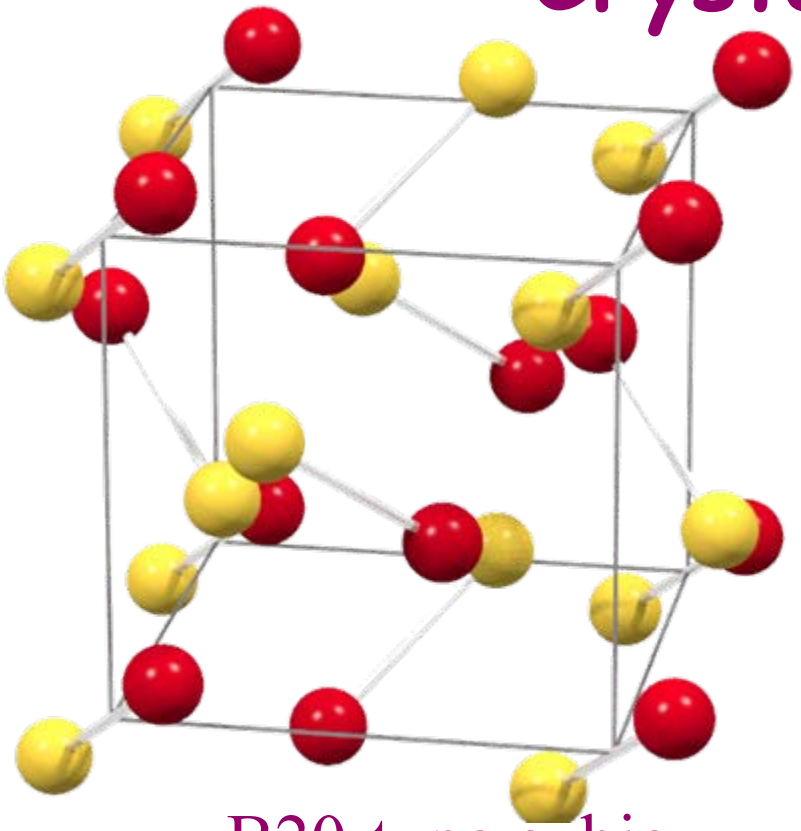
Петербургский институт ядерной физики

НИЦ Курчатовский институт



Зимняя школа ФКС-2014, 10-15 марта 2014

# Crystal structure



Examples

MnSi, FeSi, CoSi

$Mn_{1-y}Fe_ySi$, $Mn_{1-y}Co_ySi$, $Fe_{1-x}Co_xSi$

MnGe, FeGe, CoGe

$Mn_{1-y}Fe_yGe$, $Fe_{1-y}Co_yGe$, $Mn_{1-y}Co_yGe$

Si

Me

*Bòren, 1933*

- B20-type cubic
- Space group $P2_13$, $a \approx 4.6$ Å
- 4 Me and 4 Si atoms are inside a unit cell

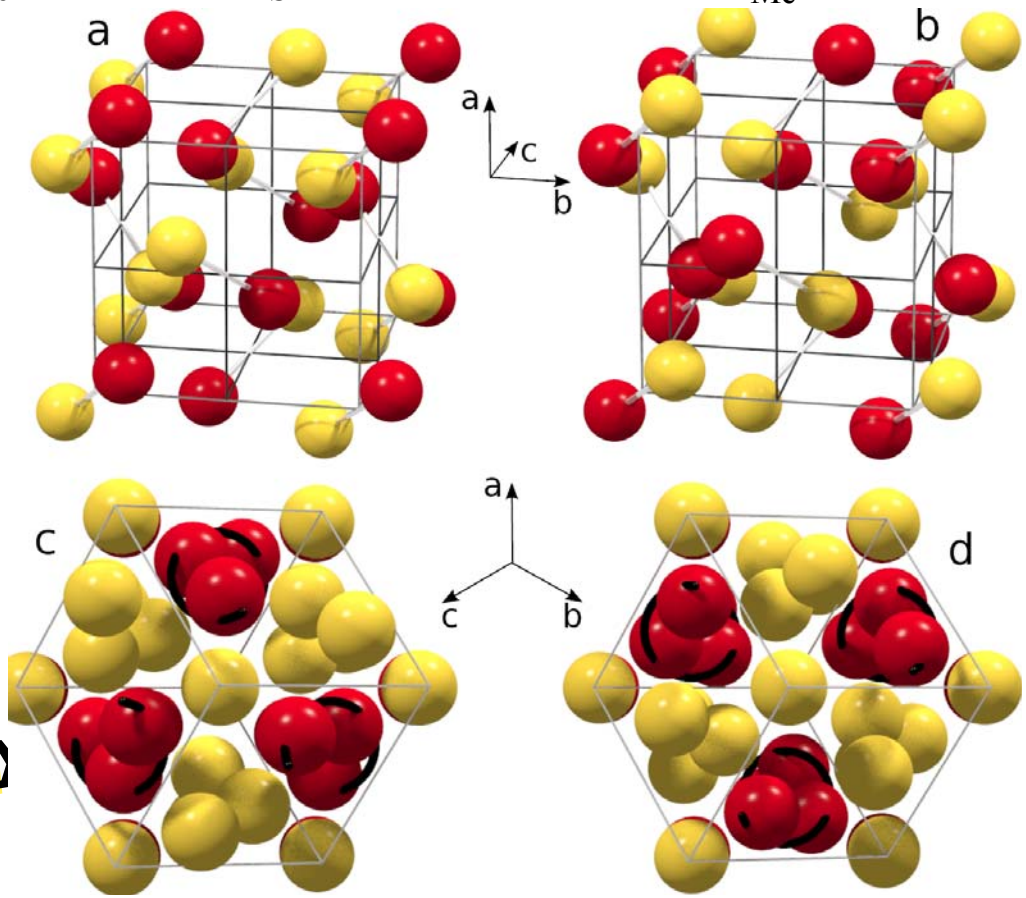
positions (u,u,u), (1/2+u,1/2-u,u), (1/2-u,-u,1/2+u), (-u,1/2+u,1/2+u)

with $u_{Mn} = 0.138$ and $u_{Si} = 0.845$

# What is structural chirality?

(u,u,u), (1/2+u,1/2-u,u), (1/2-u,-u,1/2+u) (-u,1/2+u,1/2+u)
with
$u_{Me} = 0.138$ и $u_{Si} = 0.845$.

(u,u,u), (1/2+u,1/2-u,u), (1/2-u,-u,1/2+u) (-u,1/2+u,1/2+u)
with $u_{Me} = 0.862$ и $u_{Si} = 0.155$.

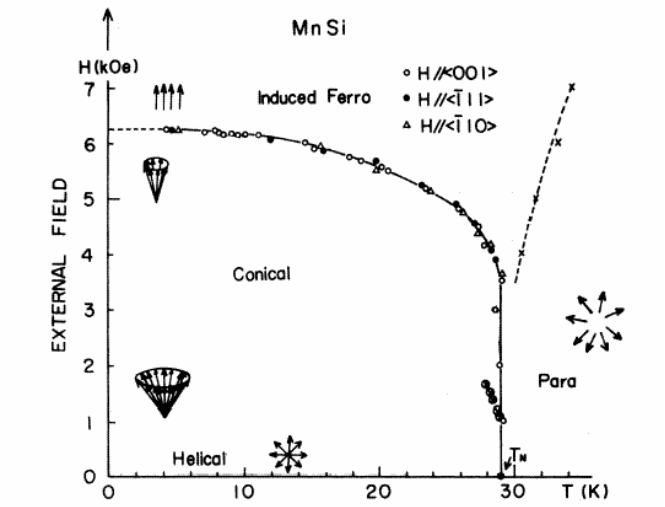



Si, Ge

Fe/Co/Mn

# 1. H-T and T-P phase diagrams

[1] Y. Ishikawa, G. Shirane, J.A. Tarvin, M. Kohgi,
Phys.Rev.B **16** (1977) 4956.




$$W(q) = E_{EX} + E_{DM} + E_{AE} =$$
$$= (A/2)\,(q^2 + \kappa_0^2)\,\mathbf{S}_q^{\,2} +$$
$$+ D\,(\mathbf{q}\,[\mathbf{S}_q \times \mathbf{S}_{-q}]) + E_{AE}$$

$$\Downarrow$$

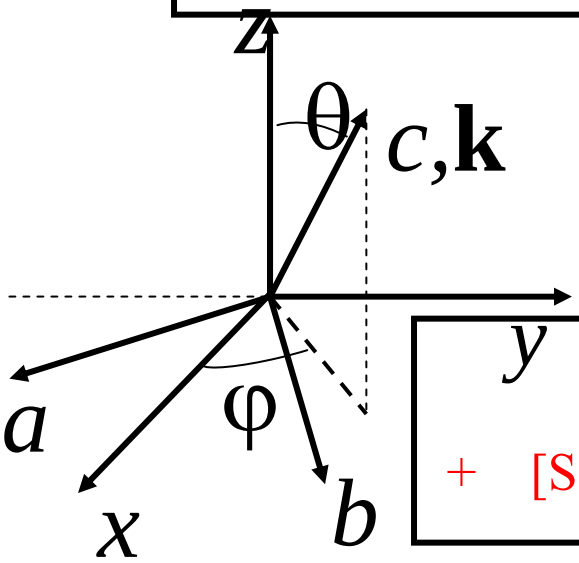
$$k = SD/A$$

# Driving forces in magnetic system of MnSi.

k-dependent part of the classical energy [P.Bak, M.H.Jensen, J.Phys. **C13** (1980) L881]

$$E_{cl} = -(S^2/2)\, J_k \cos^2\alpha \; - \; S^2 D_{\mathbf{k}}\, (\mathbf{k}\,[\mathbf{a}\times\mathbf{b}])\cos^2\alpha \; +$$

$$+ (S^2F/4)[k_x^2\,(a_x^2 + b_x^2) + k_y^2\,(a_y^2 + b_y^2) + k_z^2\,(a_z^2 + b_z^2)\,]\cos^2\alpha + S\,h_{||}\sin\alpha$$




At $(ka << 1)$: $J_k \approx J_0 - Ak^2/S$ and $D_{\mathbf{k}} \approx D_0$.

Hierarchy of interactions: $A >> D\,a >> F$

$$E_{cl} = -(S^2/2)\, J_0 \cos^2\alpha + S\,h_{||}\sin\alpha +$$

$$+ \quad [S\,A\,k^2/2 \; + (S^2\,F\,k^2/4)\Sigma c_i^2\,(a_i^2 + b_i^2) - S^2 D_0\,(\mathbf{k}\,[\mathbf{a}\times\mathbf{b}])]\cos^2\alpha$$

For components of **k**: $SA\,k_i \; + (S^2\,F\,k_i/2)\Sigma c_i^2\,(a_i^2 + b_i^2) \; = \; S^2 D_0 \; [\mathbf{a}\times\mathbf{b}]_i$

For **k**: $S\,A\,k^2 \; + (S^2\,F\,k^2/2)\Sigma c_i^2\,(a_i^2 + b_i^2) \; = \; S^2 D_0 \; (\mathbf{k}\,[\mathbf{a}\times\mathbf{b}]\,)$

# Driving forces in magnetic system of MnSi.

Bak-Jensen model:

$\mathbf{k} = S^2 D_0 \ [\mathbf{a} \times \mathbf{b}] \ / \ \{S\,A \ + (S^2 F/2)\Sigma c_i^2 \ (a_i^2 + b_i^2)\}$

**(i)** $\mathbf{k} \perp [\mathbf{a} \times \mathbf{b}]$

(ii) $k = SD_0 / \{A + (S F/3)\} \approx SD_0/A$

(iii) if $D_0 < 0$ then left-handed spiral & if $D_0 > 0$ then right-handed spiral

(iv) Direction of **k** is not fixed by the Dzialoshinskii interaction. It is the anisotropic exchange $(S^2 F/2) \Sigma c_i^2 \ (a_i^2 + b_i^2)$, which does !!!

# Driving forces in magnetic system of MnSi.

Substitute $\mathbf{k} = S^2 D_0 \ [\mathbf{a} \times \mathbf{b}] / \{S\,A \ + (S^2 F/2)\Sigma c_i^2 (a_i^2 + b_i^2)\}$ into

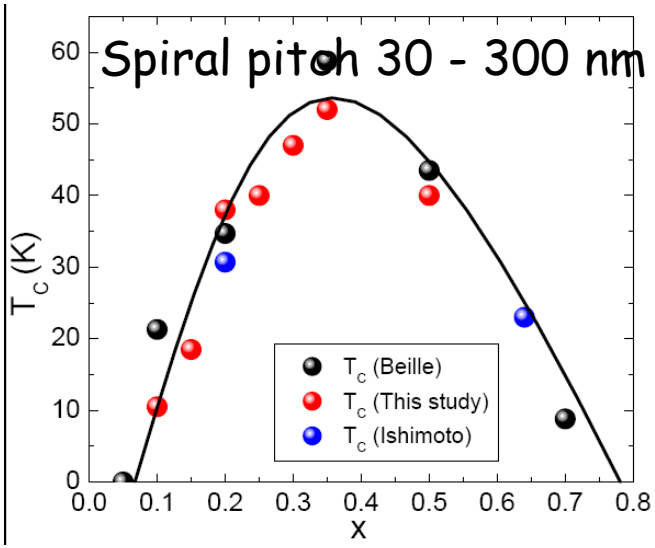
$$E_{cl} = [S\,A\,k^2/2 + (S^2 F\,k^2/4)\Sigma c_i^2 (a_i^2 + b_i^2) - S^2 D_0 (\mathbf{k}\,[\mathbf{a} \times \mathbf{b}])] \cos^2\alpha$$

$\Sigma c_i^2 (a_i^2 + b_i^2)$ is maximal and equal to 2/3 at $(\mathbf{k} \parallel \mathbf{c} \parallel [111])$ and
is minimal and equal to 0 at $(\mathbf{k} \parallel \mathbf{c} \parallel [100])$

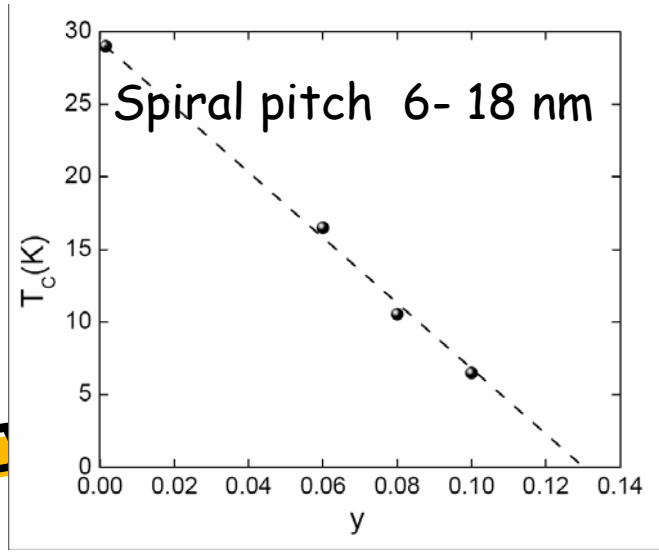
If $F < 0$, then $E_{cl}$ is minimized at $(\mathbf{k} \parallel \mathbf{c} \parallel [111])$;
If $F > 0$, then $E_{cl}$ is minimized at $(\mathbf{k} \parallel \mathbf{c} \parallel [100])$.

# Magnetic order in $Fe_{1-x}Co_xSi$ and $Mn_{1-y}Fe_ySi$

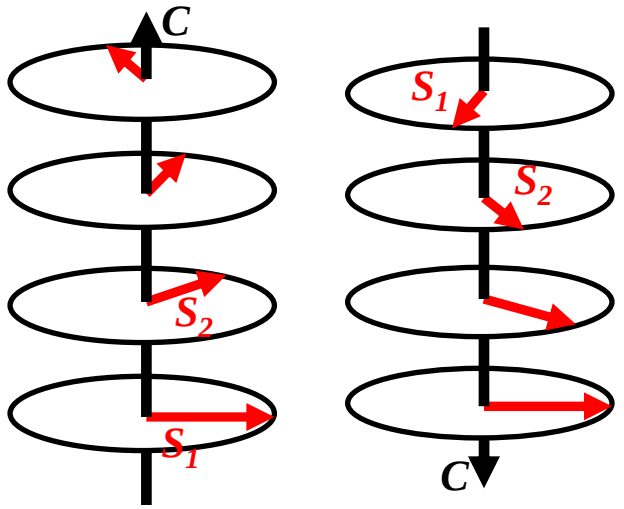
$Fe_{1-x}Co_xSi$




$Mn_{1-y}Fe_ySi$




**Right-handed helix** **Left-handed helix**




$$W(q) = E_{EX} + E_{DM} + E_{AE} =$$
$$= (A/2)\,(q^2 + \kappa_0^2)\,\mathbf{S}_q^2 +$$
$$+ D\,(\mathbf{q}\,[\mathbf{S}_q \times \mathbf{S}_{-q}]) + E_{AE}$$

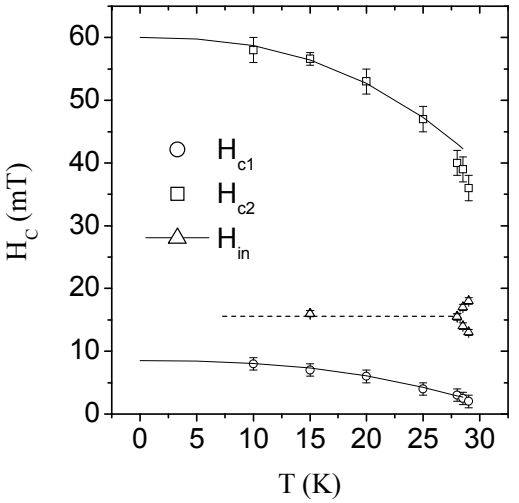
$$k = SD/A$$

# Фазовая диаграмма MnSi в магнитном поле

S.V. Grigoriev, S.V. Maleyev, A.I. Okorokov, Yu. O. Chetverikov, P. Böni, R. Georgii, D. Lamago, H. Eckerlebe and K. Pranzas, Phys.Rev. B, v.**74**, (2006) 214414

1) $A\,k^2 = g\,\mu_B\,H_{C2}$ критическое поля перехода в ферромагнитную фазу

2) $k = S\,D/\,A$ волновой вектор спирали



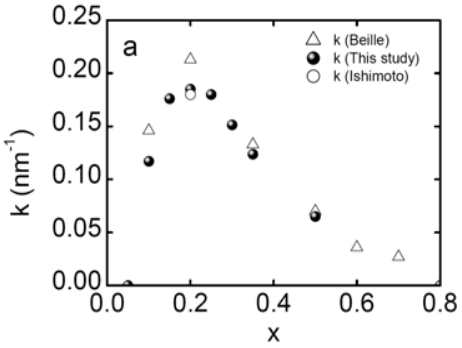

1) $A = g\,\mu_B\,H_{C2}/\,k = 50$ meV $A^2$

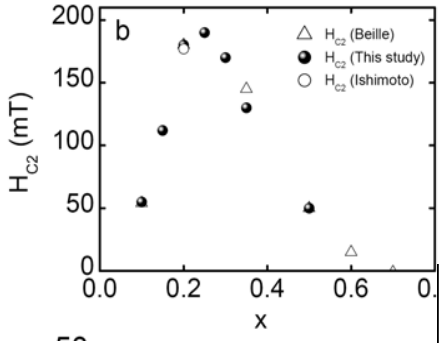
2) $S\,Da = A\,ka = 8$ meV $A^2$

3) $\Delta^2 = H_{in}^2/2 \approx (11\ \mu\text{eV})^2$

# Параметры магнитной системы

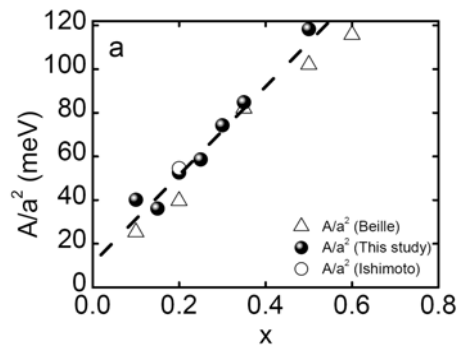
## $Fe_{1-x}Co_xSi$

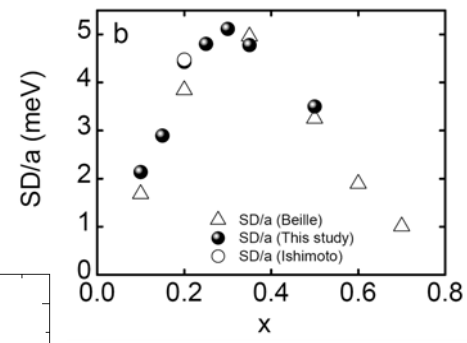


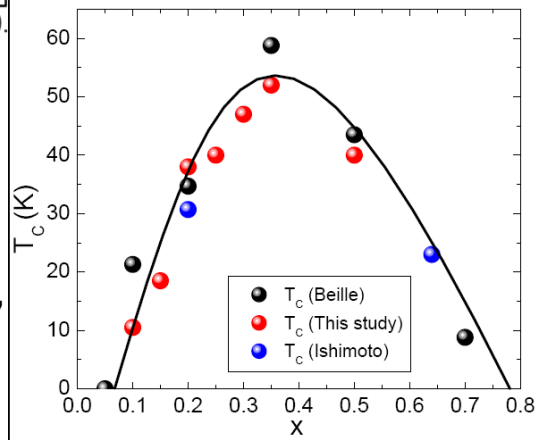




$$A = g\,\mu_B\,H_{C2} / k^2$$

$$S\,D = A\,k$$



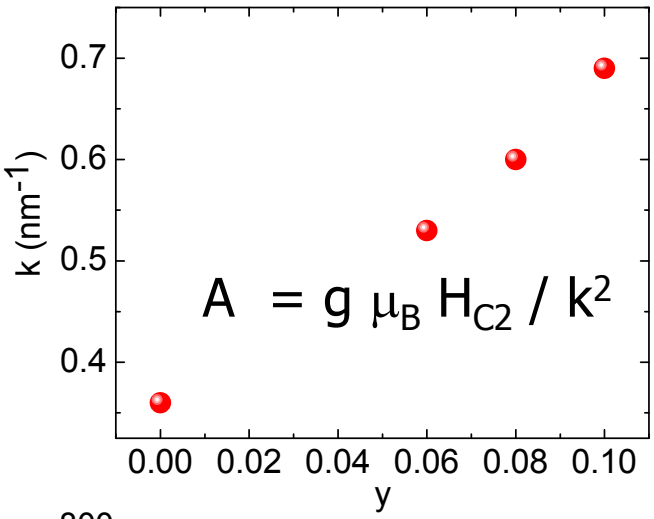



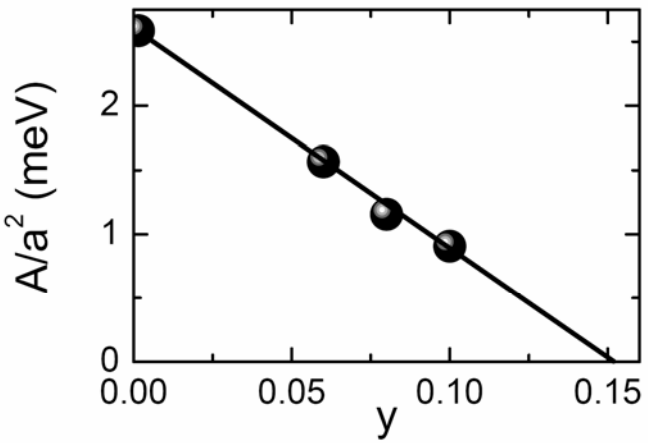



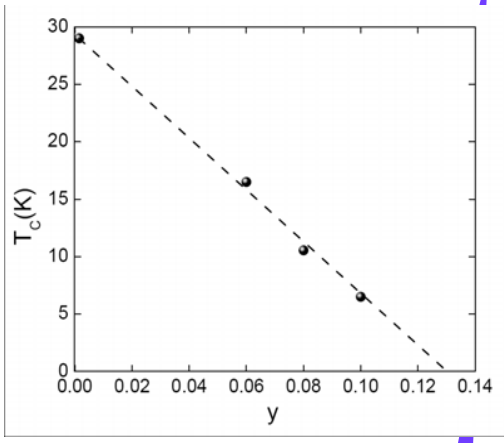

S.V. Grigoriev, S.V. Maleyev, V.A. Dyadkin, D.Menzel, J. Schoenes, H. Eckerlebe, Phys.Rev. B, v.**76**, (2007) 092407

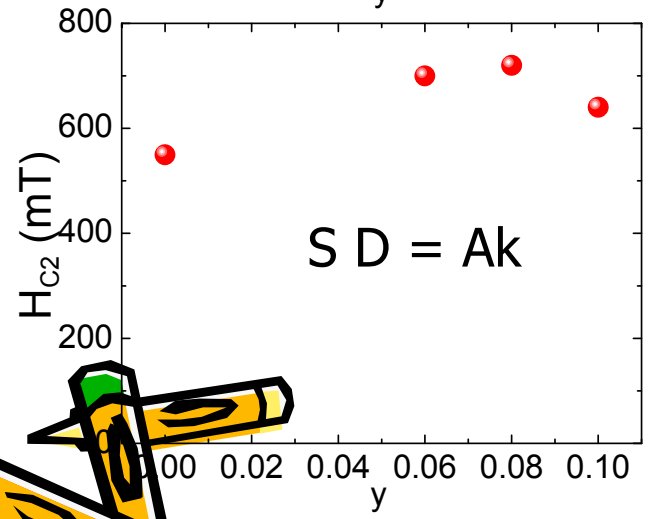
S.V. Grigoriev, V.A. Dyadkin, D.Menzel, J. Schoenes, Yu.O. Chetverikov, H. Eckerlebe, S.V. Maleyev, Phys.Rev. B, v.**76**, (2007) 224424

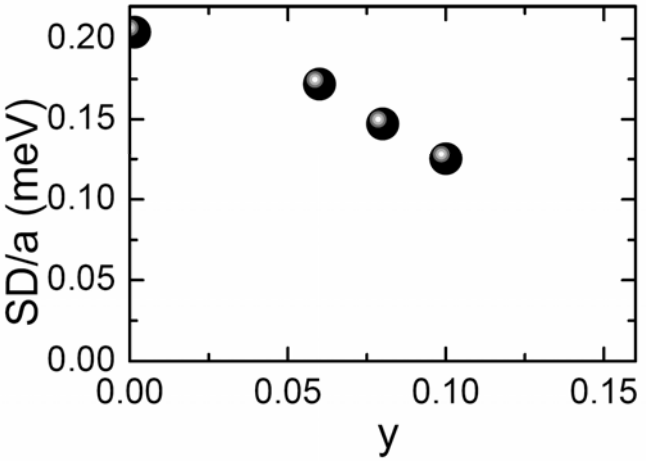
# Manganese silicide $Mn_{1-y}Fe_ySi$

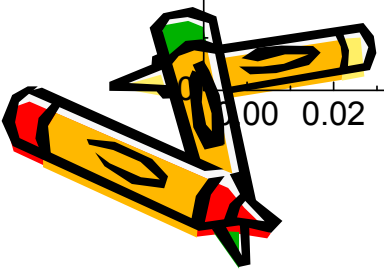


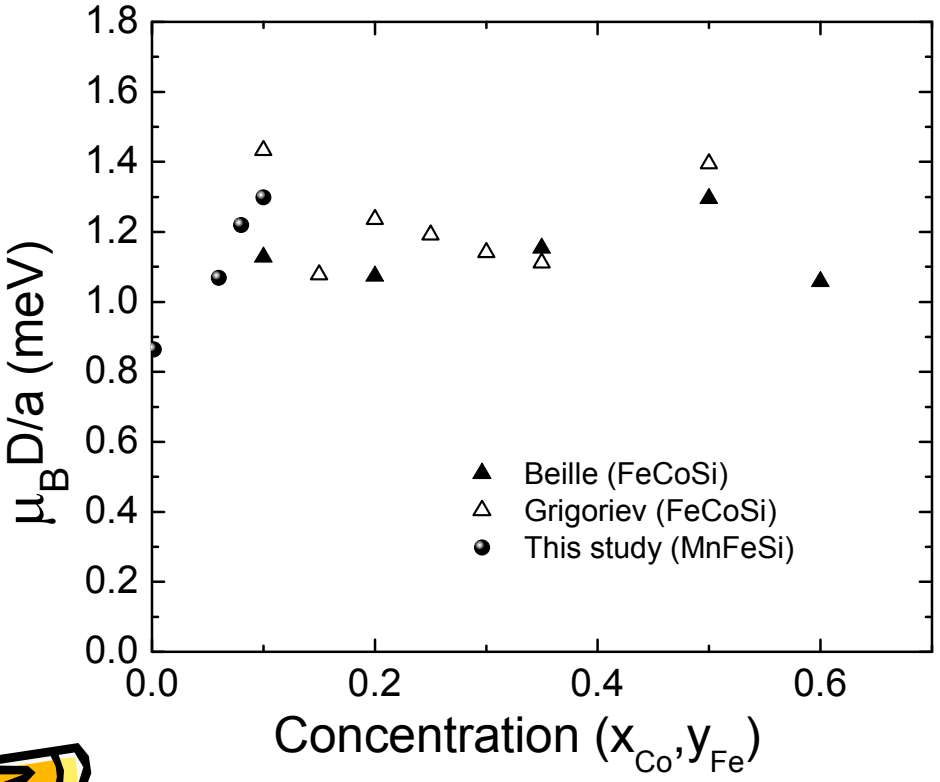



S. V. Grigoriev, V. A. Dyadkin, E. V. Moskvin, D. Lamago, Th. Wolf, H. Eckerlebe, and S. V. Maleyev, Phys.Rev. B **79** (2009) 144417

# Константа Дзялошинского- сколько это для кристаллов этого типа $P2_13$ ?



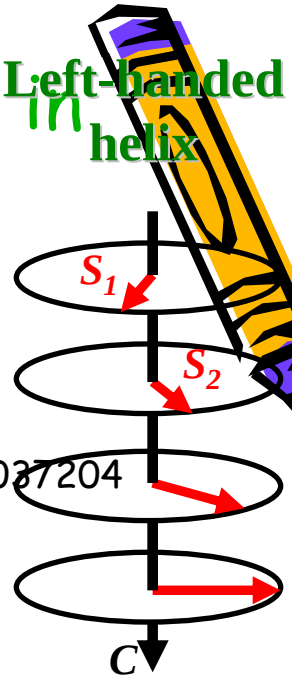
# Crystal chirality and magnetic chirality in $Fe_{1-x}Co_xSi$ and $Mn_{1-y}Fe_ySi$

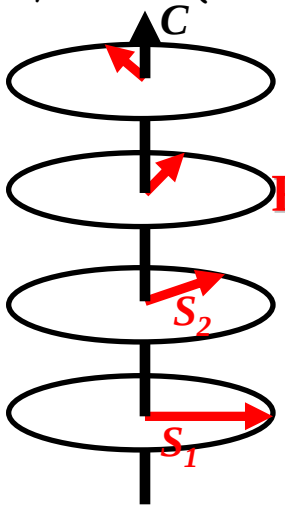
| | $\Gamma_c$ | $\gamma_m$ |
|---|---|---|
| $Fe_{1-x}Co_xSi$ | (+1) | (-1) |
| $Mn_{1-y}Fe_ySi$ | (+1) | (+1) |

*S. V. Grigoriev, et al, Phys. Rev. Lett. 102 (2009) 037204

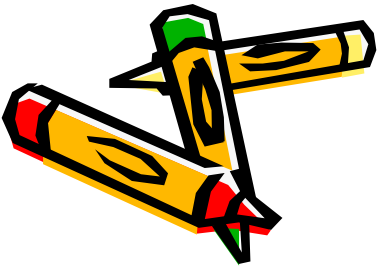
**S. V. Grigoriev, et al, Phys. Rev. B **81** (2010) 012408

***V.A. Dyadkin, et al, Phys. Rev. B **84**, 014435 (2011)

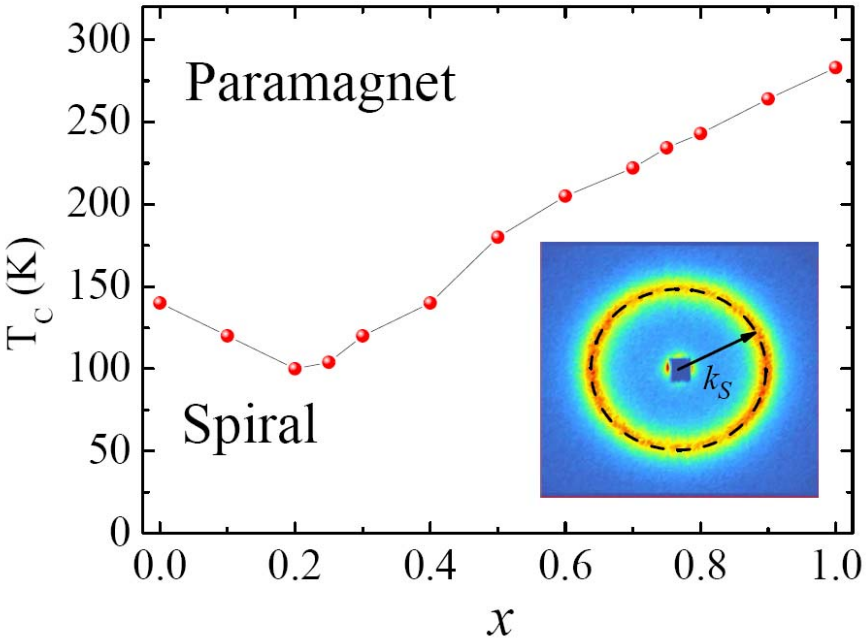


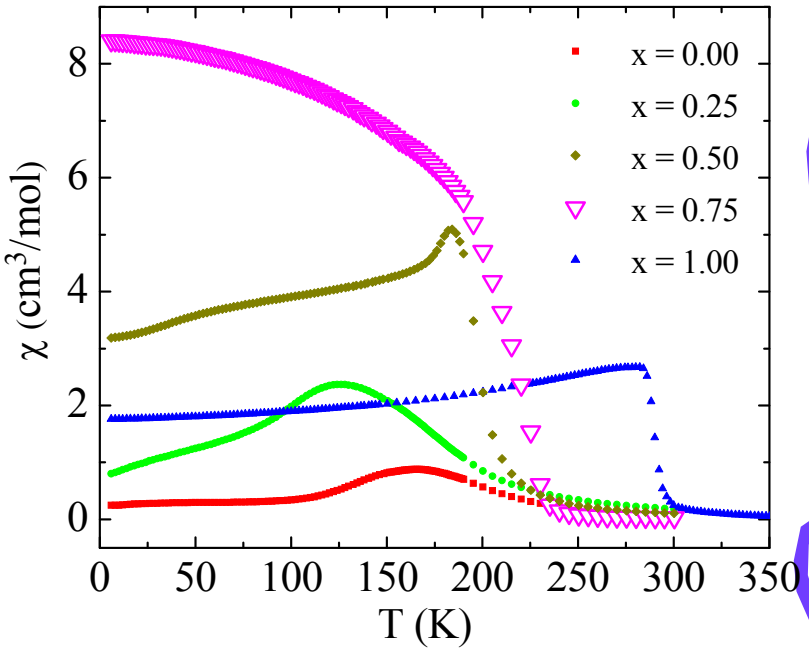




Right-handed helix



# Critical temperature $T_C$ in $Mn_{1-x}Fe_xGe$

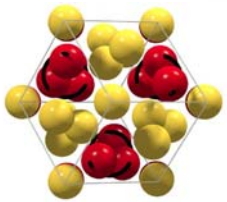



**Samples:** $Mn_{1-y}Fe_yGe$ (0,0.1… -.. 1.0)
(A.V. Tsvyashchenko, Institute for High Pressure Physics, Troitsk, Russia)

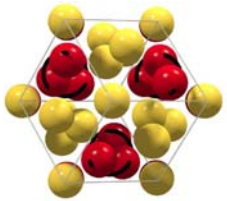
Susceptibility measurements

# Crystal handedness and magnetic chirality in **FeGe**



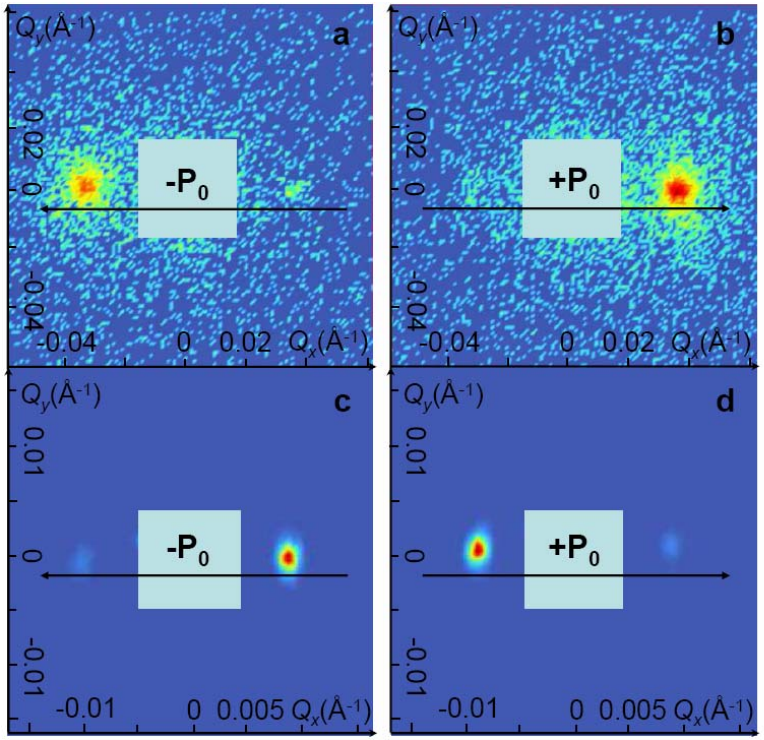
MnSi-etalon

$u_{Mn} = 0.135$
$u_{Si} = 0.845$



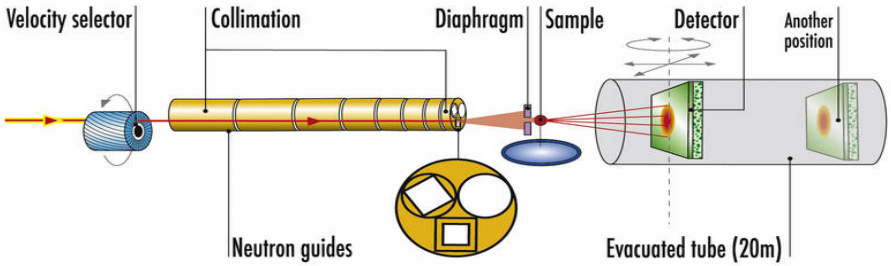
FeGe-sample

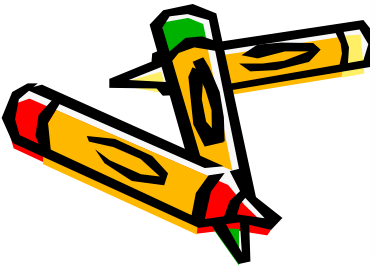
$u_{Fe} = 0.135$
$u_{Ge} = 0.845$

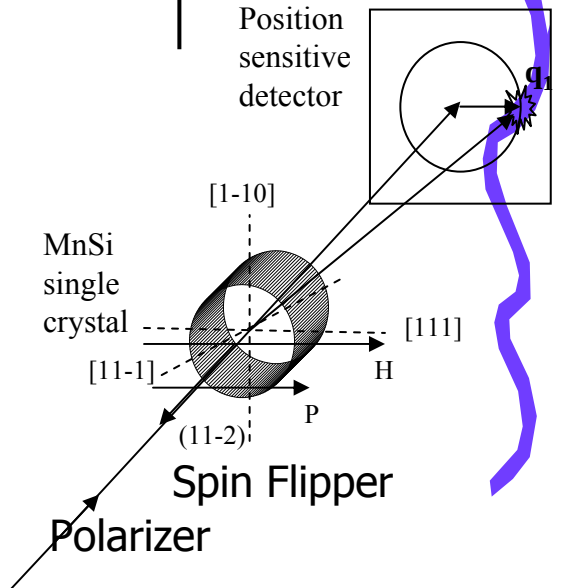



| $\Gamma_c$ | $\gamma_m$ |
|---|---|
| (+1) | (+1) |
| (+1) | (-1) |

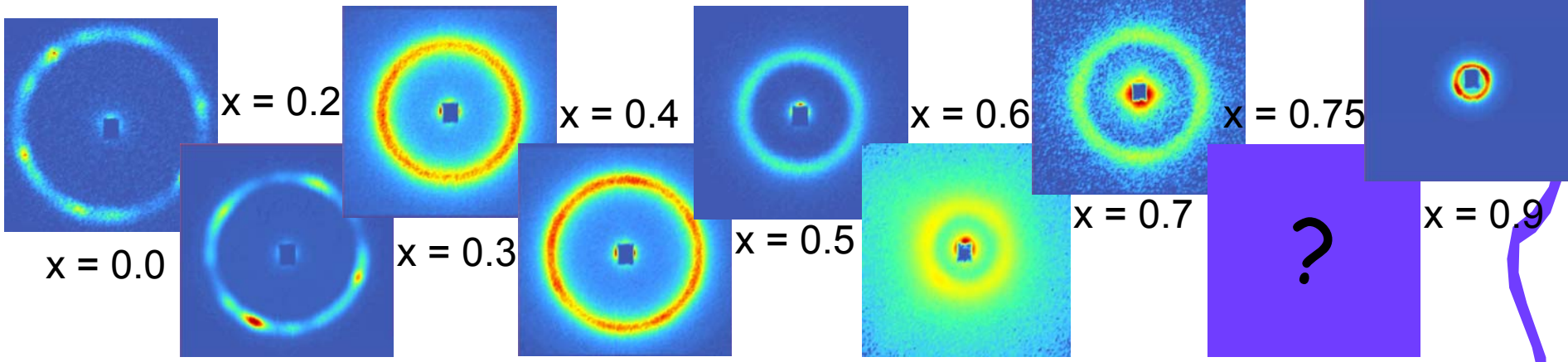
Experimental setup D22 (ILL)



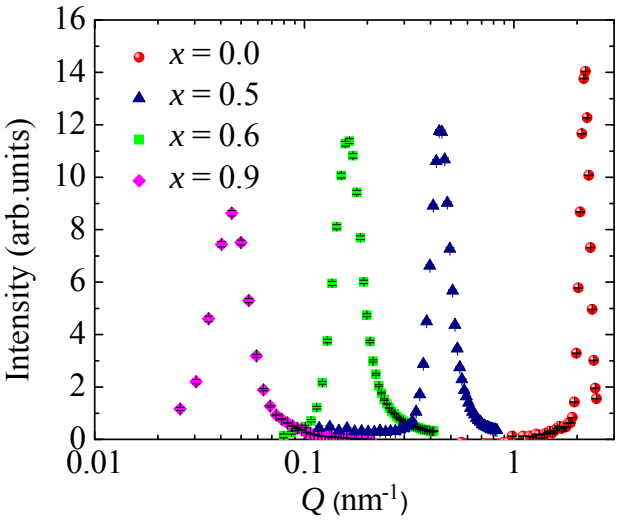





# Small angle neutron scattering on the powder samples $Mn_{1-x}Fe_xGe$



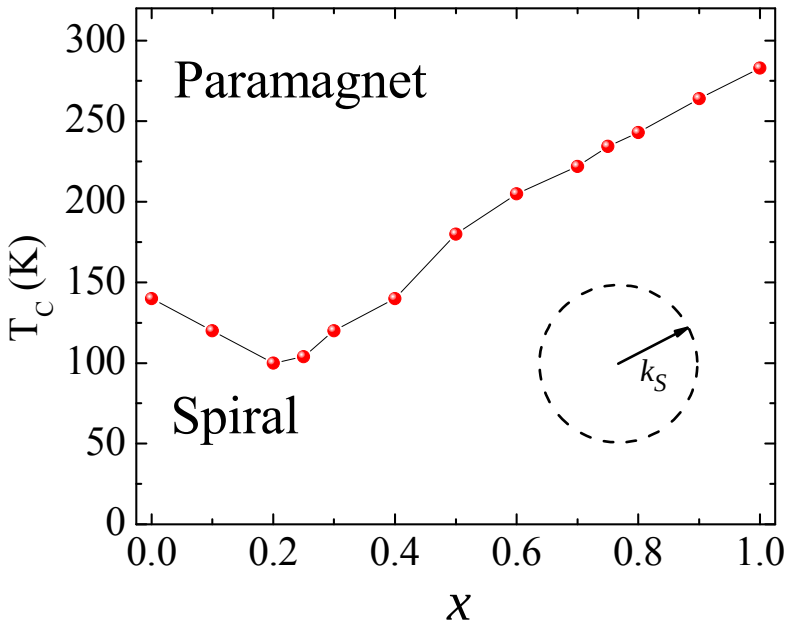

Maps of small angle neutron scattering intensity at low temperatures T ≈ 10 K.

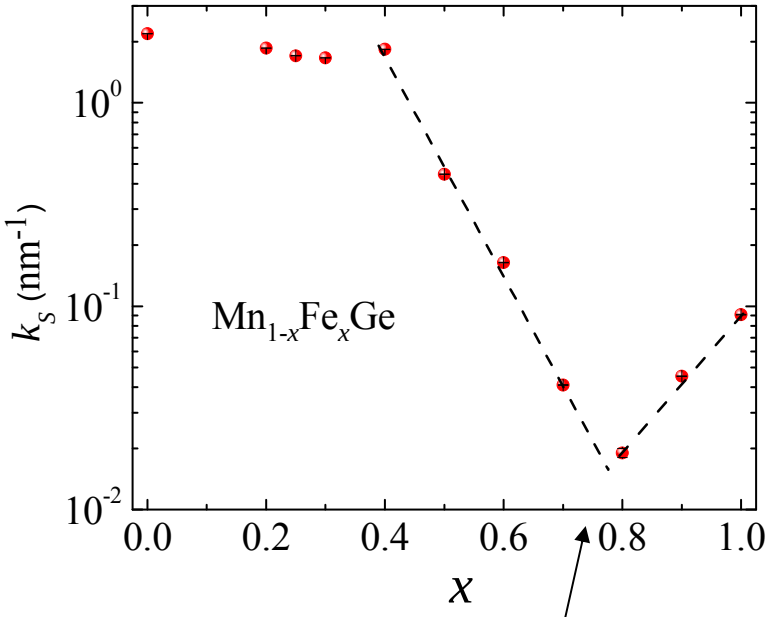


# Critical temperature $T_C$ and spiral wavevector k in $Mn_{1-x}Fe_xGe$

MnGe
$\Gamma_c = +1$
$\gamma_m = +1$

FeGe
$\Gamma_c = +1$
$\gamma_m = -1$




The wavevector k = 0, $T_C$ = 240 K!!!
The system transforms to ferromagnet!

k -> 0, $x_c$ = 0.75

# Crystallographic and magnetic chirality in $Fe_{1-x}Co_xSi$, $Mn_{1-y}Fe_ySi$ and $Mn_{1-y}Fe_yGe$

| | $\Gamma_c$ | $\gamma_m$ |
|---|---|---|
| $Fe_{1-x}Co_xSi$ | (+1) | (-1) |
| | (-1) | (+1) |
| $Mn_{1-y}Fe_ySi$ | (+1) | (+1) |
| | (-1) | (-1) |
| FeGe | (+1) | (-1) |
| | (-1) | (+1) |
| MnGe | (+1) | (+1) |
| | (-1) | (-1) |

# Additional experimental proof

arXiv.org > cond-mat > arXiv:1302.2319
NATURE NANOTECHNOLOGY

**Skyrmions with varying size and helicity in composition-spread helimagnetic alloys $Mn_{1-x}Fe_xGe$**

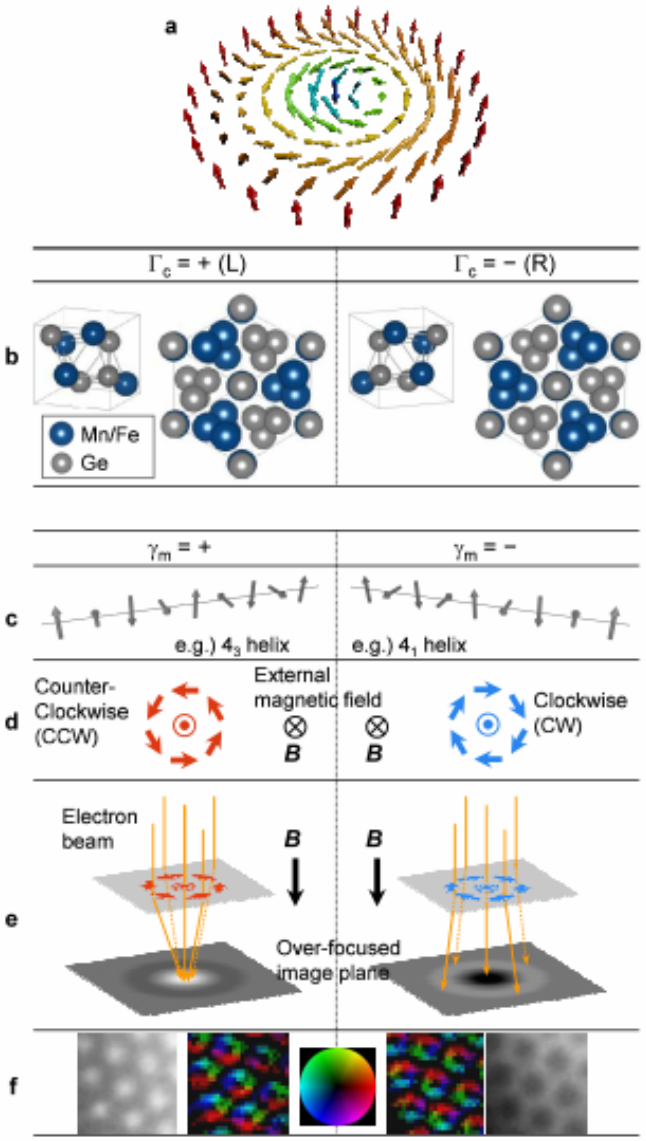
K. Shibata, X. Z. Yu, T. Hara, D. Morikawa, N. Kanazawa, K. Kimoto, S. Ishiwata, Y. Matsui, Y. Tokura

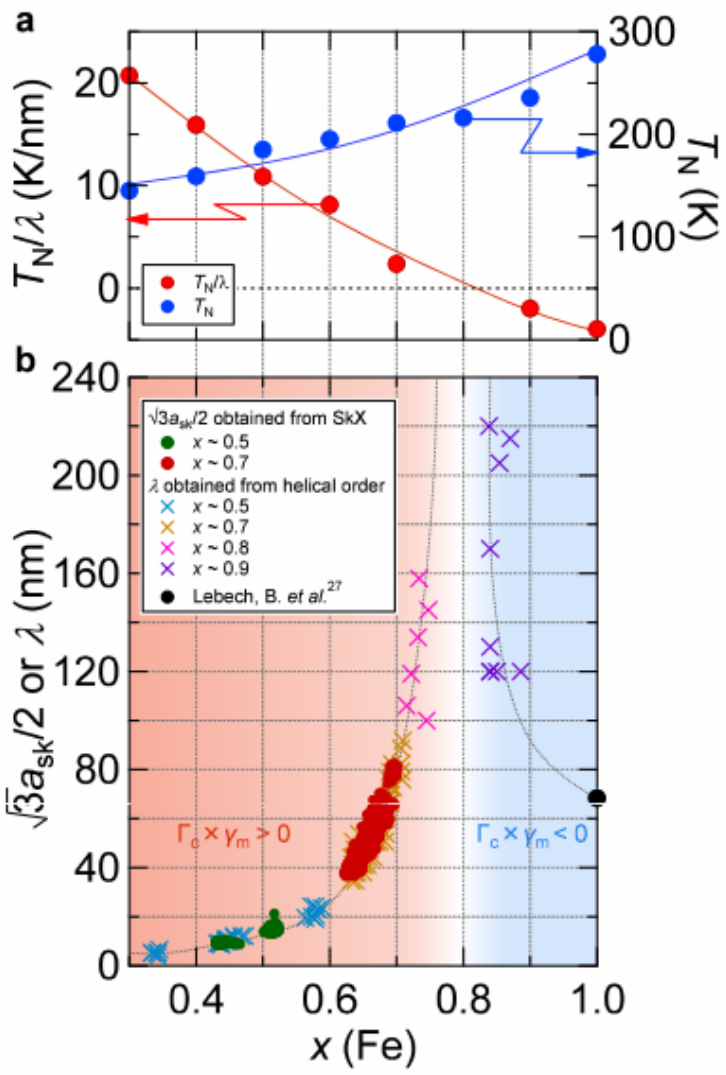
| Composition $x$ | Domain | $\Gamma_c$ | $\gamma_m$ | $\Gamma_c \times \gamma_m$ |
|---|---|---|---|---|
| $\sim 0.5$ | A | + | + | + |
| $\sim 0.5$ | B | − | − | + |
| $\sim 0.7$ | A | − | − | + |
| $\sim 0.9$ | A | + | − | − |
| $\sim 0.9$ | B | − | + | − |
| 1.0 | A | + | − | − |
| 1.0 | B | − | + | − |

Lorentz transmission electron microscopy

# Lorentz transmission electron microscopy

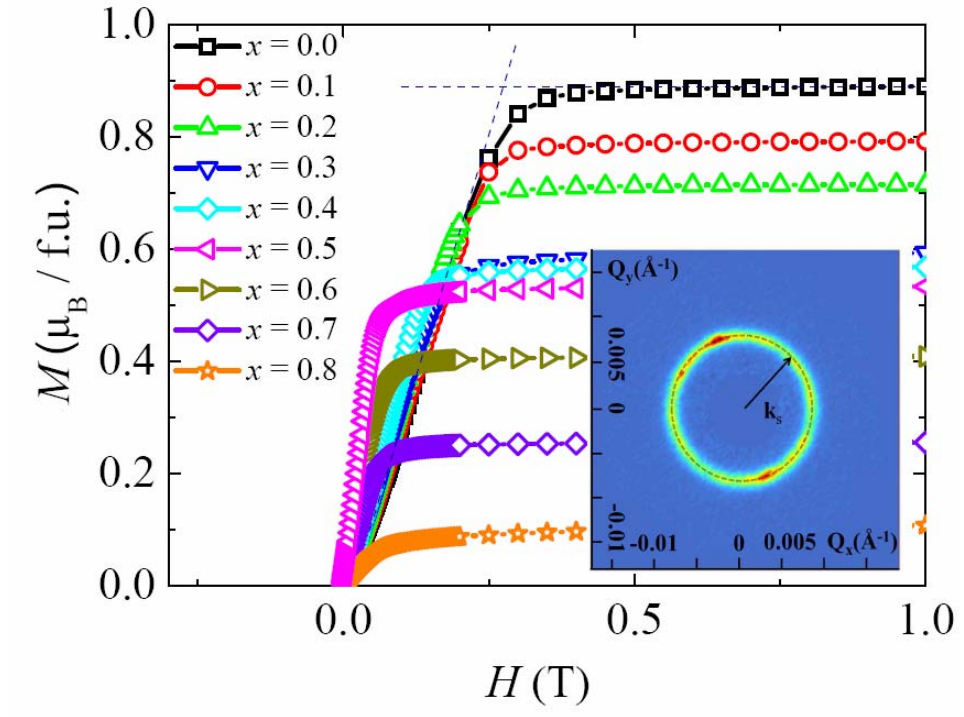
## Results

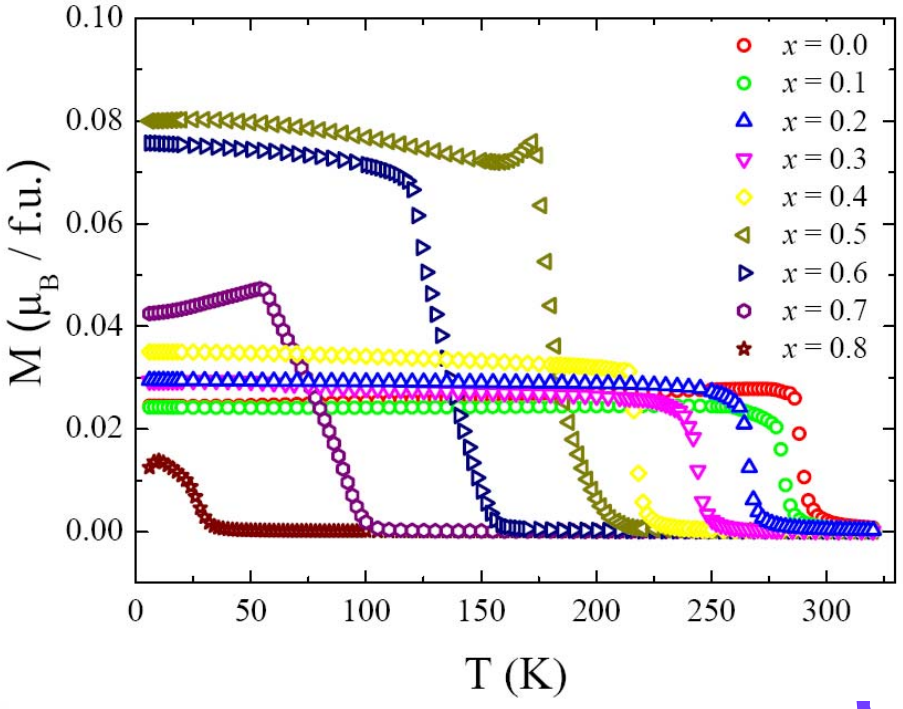



NATURE NANOTECHNOLOGY, K. Shibata, et al

# Magnetic ordering in $Fe_{1-x}Co_xGe$

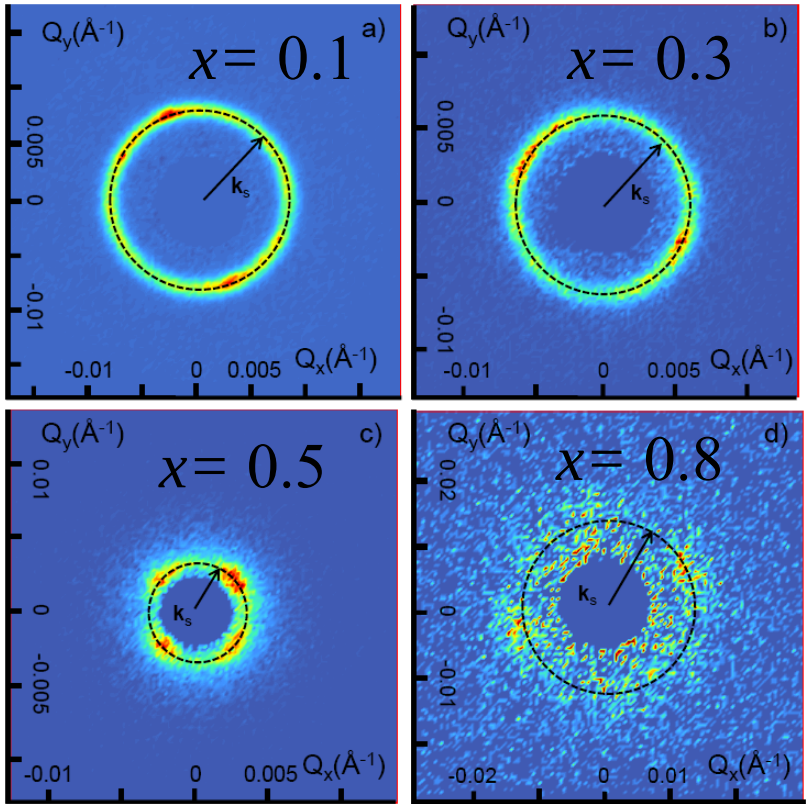


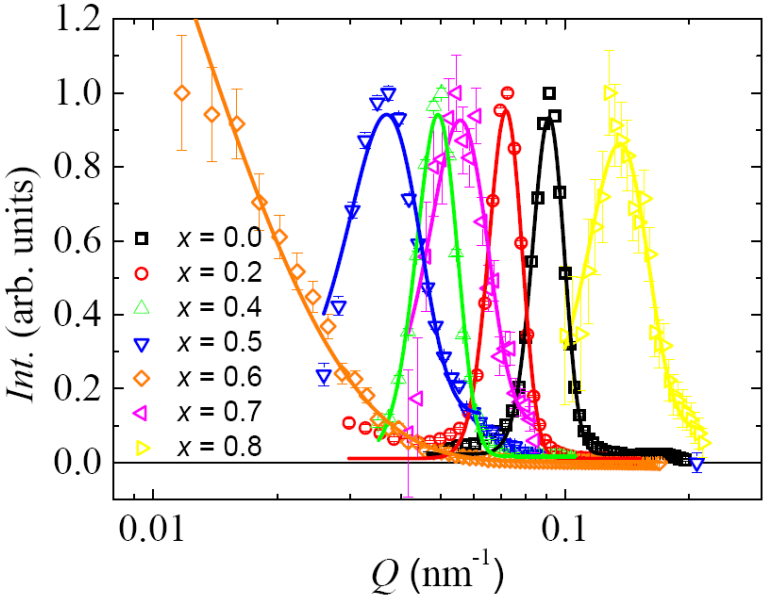



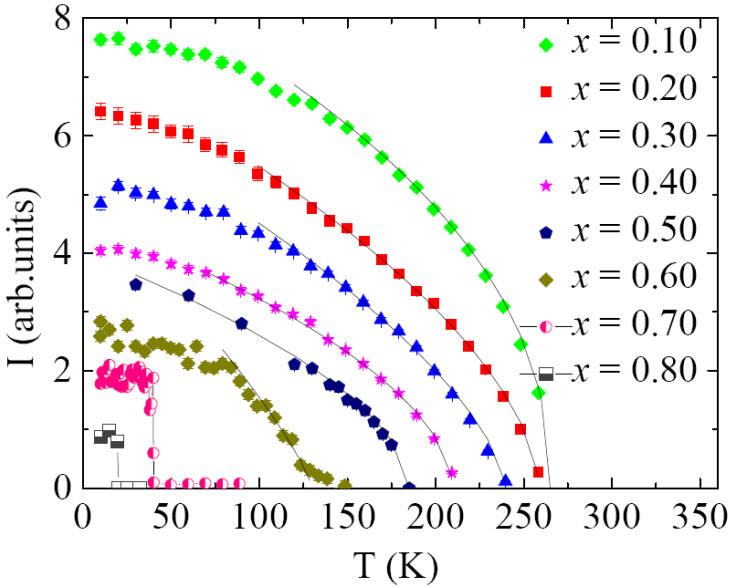

**Samples:** $Fe_{1-y}Co_yGe$ (0,0.1… -.. 1.0)
(A.V. Tsvyashchenko, Institute for High Pressure Physics, Troitsk, Russia)

Susceptibility measurements

# Small angle neutron scattering on the powder samples $Fe_{1-x}Co_xGe$




**Samples:** $Fe_{1-x}Co_xGe$ (0,0.1… -.. 1.0)
(A.V. Tsvyashchenko,
Institute for High Pressure Physics,
Troitsk, Russia)

# Critical temperature $T_C$ and spiral wavevector k in $Fe_{1-x}Co_xGe$

FeGe

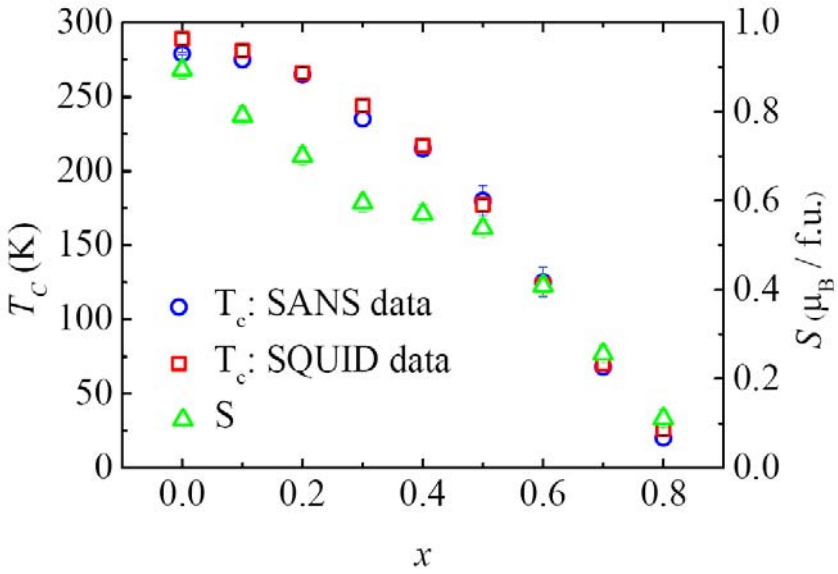
$\Gamma_c = +1$

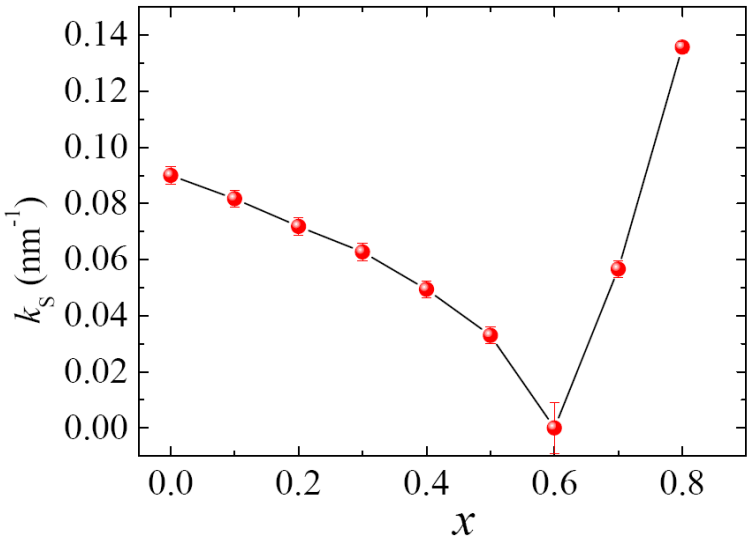
$\gamma_m = -1$

CoGe

$\Gamma_c = +1$

$\gamma_m = +1$



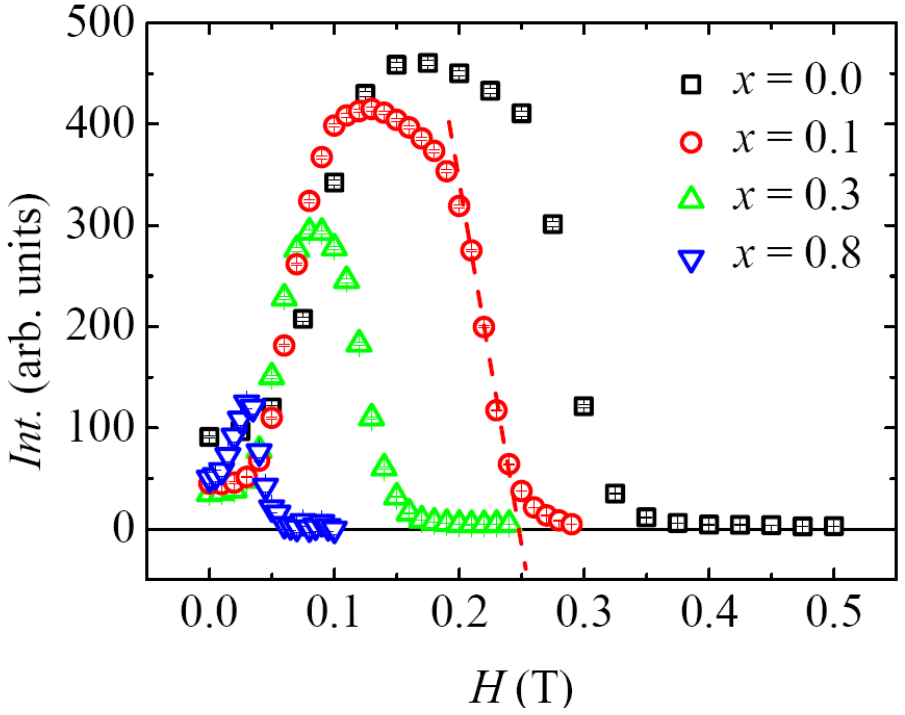



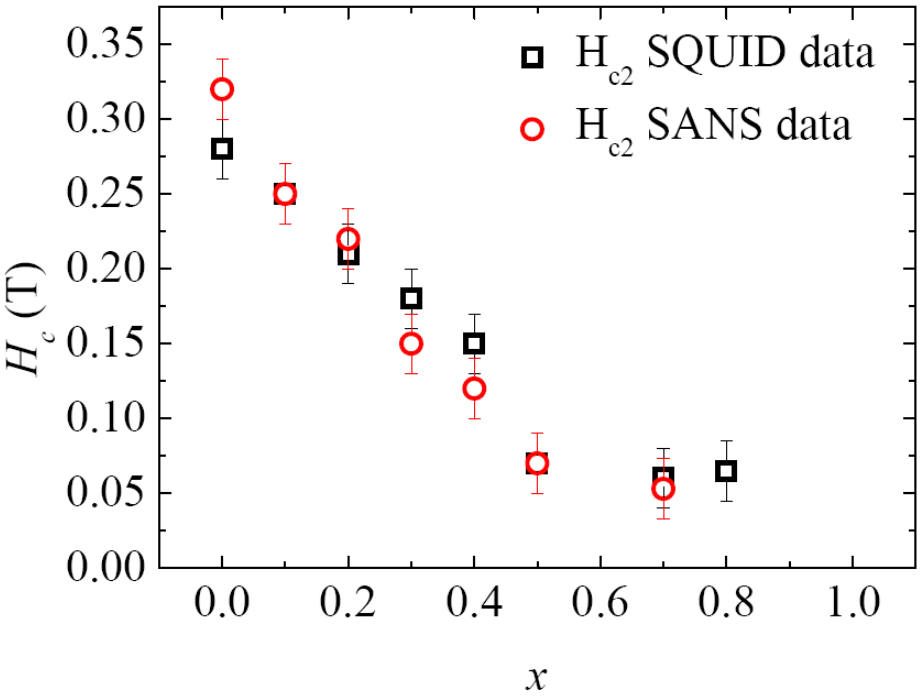

k -> 0, $x_c$ = 0.6

The wavevector k = 0, $T_C$ = 140 K!!!

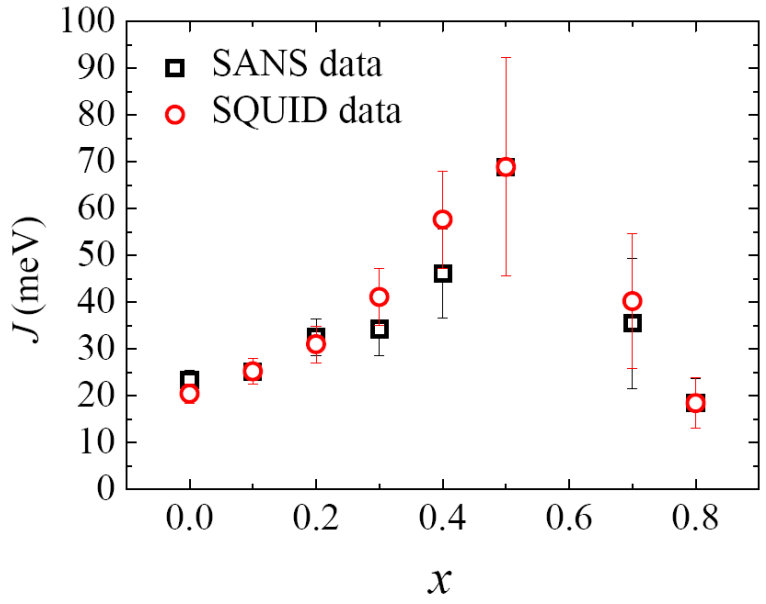
The system transforms to ferromagnet as well !

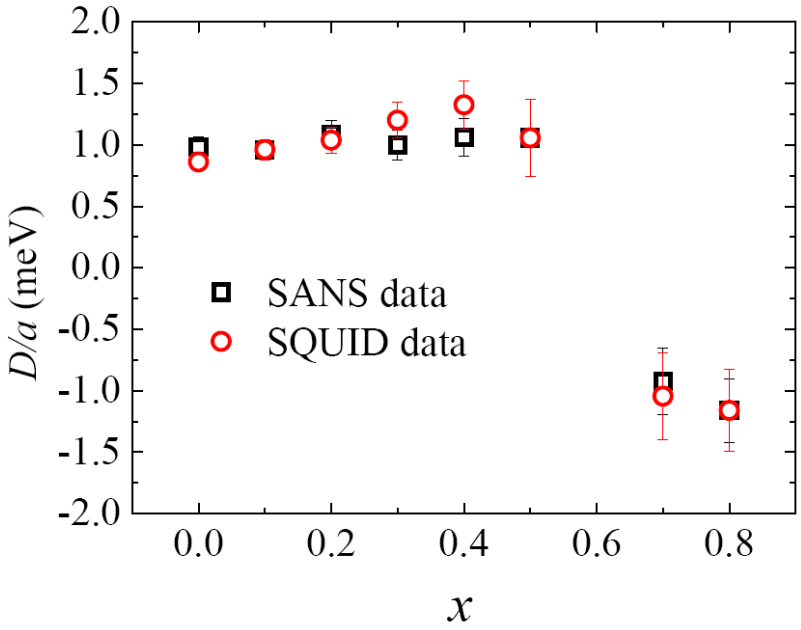
# Critical field $H_{c2}$ in $Fe_{1-x}Co_xGe$



# Driving interactions of the magnetic system



# Crystallographic and magnetic chirality in $Fe_{1-x}Co_xSi$, $Mn_{1-y}Fe_ySi$, $Mn_{1-y}Fe_yGe$, $Fe_{1-x}Co_xGe$

| | $\Gamma_c$ | $\gamma_m$ |
|---|---|---|
| $Fe_{1-x}Co_xSi$ | (+1) | (-1) |
| $Mn_{1-y}Fe_ySi$ | (+1) | (+1) |
| FeGe | (+1) | (-1) |
| MnGe | (+1) | (+1) |
| CoGe | (+1) | (+1) |

# Выводы

- Рост J при $x \rightarrow x_c$ противоречит плавному уменьшению $T_C$ в этих кристаллах. Что происходит с J?
- Константа Дзялошинского остается константой во всем диапазоне концентраций x, но меняет знак при $x = x_c$. При этом она равна этой же величине в MnSi и $Fe_{1-x}Co_xSi$.

Коллектив авторов этой работы выражает благодарность всем тем людям, которые поддерживают их в экспери-ментах, обсуждают результаты, комментируют и критикуют.

Григорьев Сергей Валентинович, д.ф.-м.н., ведущий научный сотрудник, ПИЯФ НИЦ КИ, Гатчина

Москвин Евгений Владимирович, к.ф.-м.н., старший научный сотрудник, ПИЯФ НИЦ КИ, Гатчина

Дядькин Вадим Александрович, к.ф.-м.н., научный сотрудник, ПИЯ НИЦ КИ, Гатчина

Чубова Надежда Михайловна, младший научный сотрудник, ПИЯФ НИЦ КИ, Гатчина

Свен Арне Зигфрид, аспирант, Helmholtz-Zentrum Geesthacht, Германия.

Алтынбаев Евгений Владимирович, студент, СПбГУ

Чернышов Дмитрий Юрьевич, к.ф.-м.н., научный сотрудник, SNBL ESRF, Гренобль, Франция

Цвященко Анатолий Васильевич, к.ф.-м.н., старший научный сотрудник, ИФВД РАН, Троицк

Дирк Мензель, доктор, Technische Universitaet Braunschweig, Германия.