Motterials
10. – 14. 9. 2007, KITP, Santa Barbara

Frustrated Lattices in Spinel Compounds

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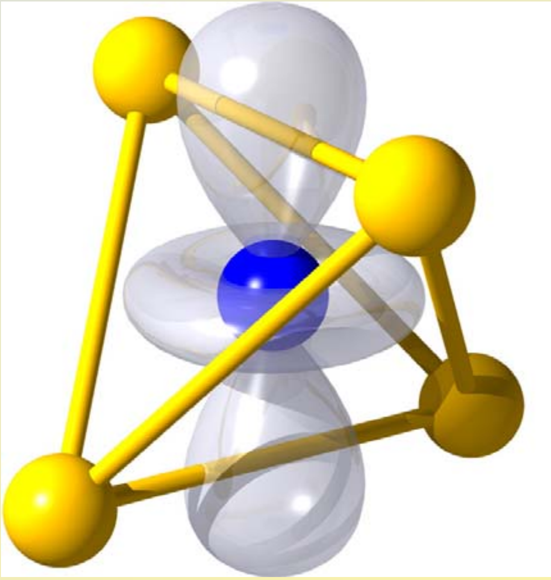

Frustrated Lattices in Spinel Compounds

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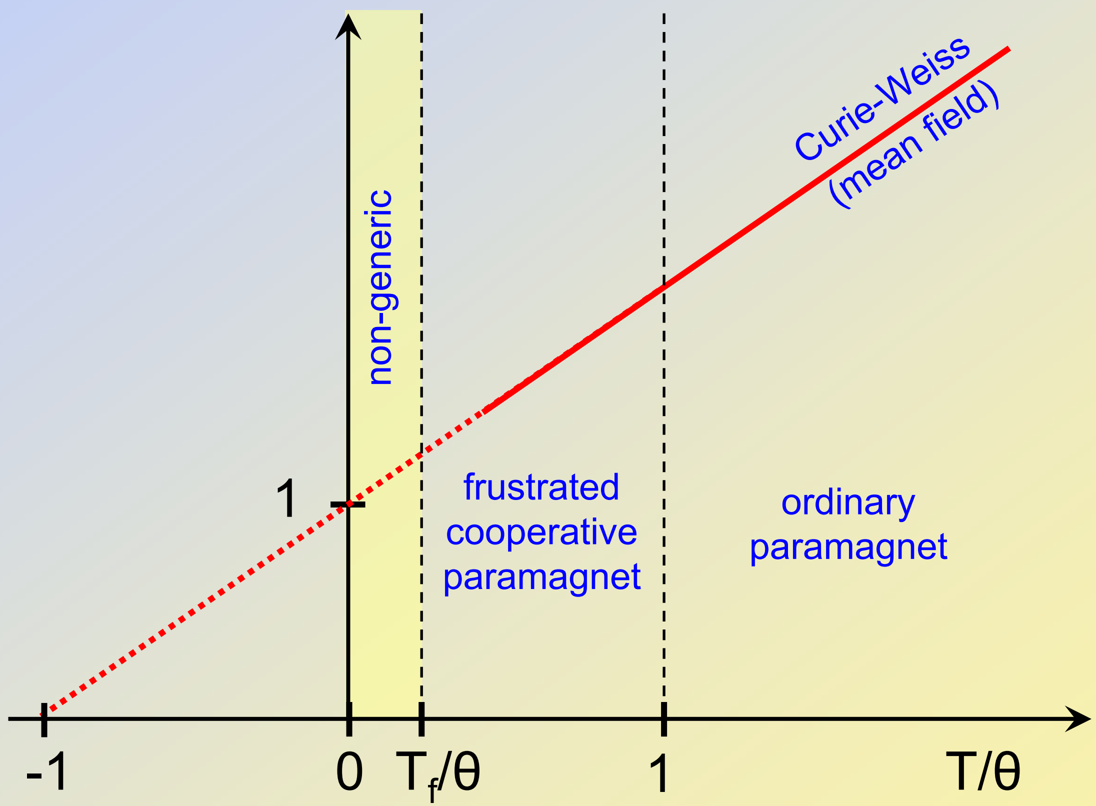
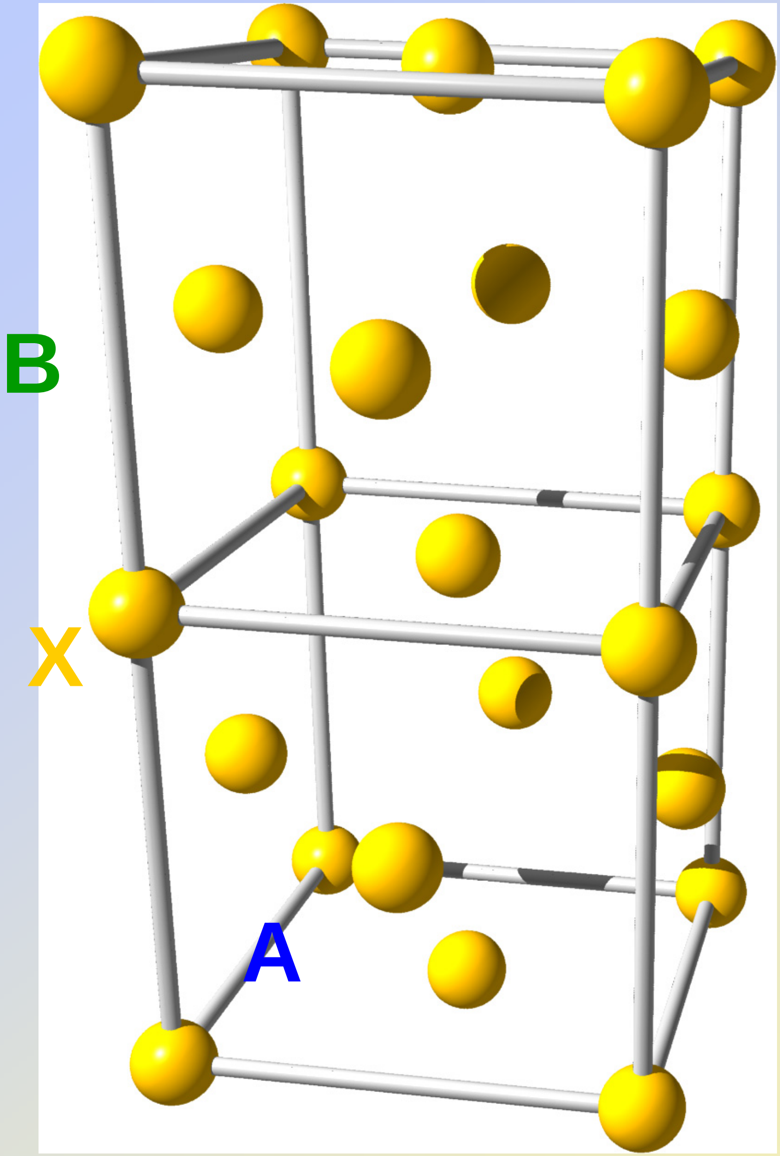
Coworkers:
N. Büttgen, V. Fritsch, J. Hemberger,
Ch. Kant, A. Krimmel, H.-A. Krug von Nidda,
P. Lunkenheimer, T. Rudolf, N. Tristan, V. Tsurkan

Geometric frustration of spin degrees of freedom

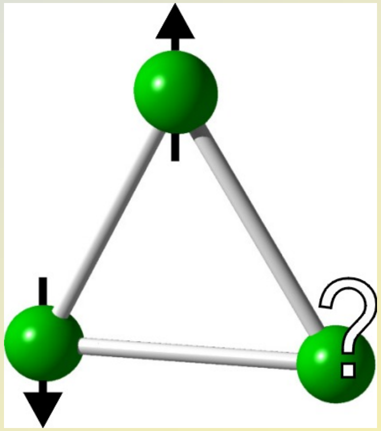


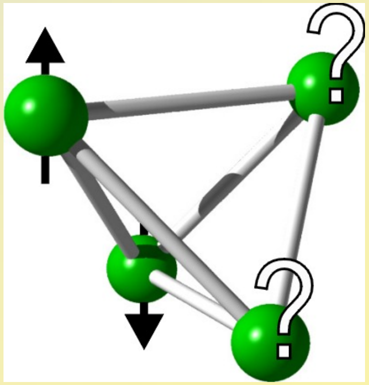
AB_2X_4: The structure of spinels



AB_2X_4 – normal spinel
(e.g. $CdCr_2S_4$, $HgCr_2S_4$, $FeCr_2S_4$)

B-site: Pyrochlore - lattice
Geometrically frustrated!





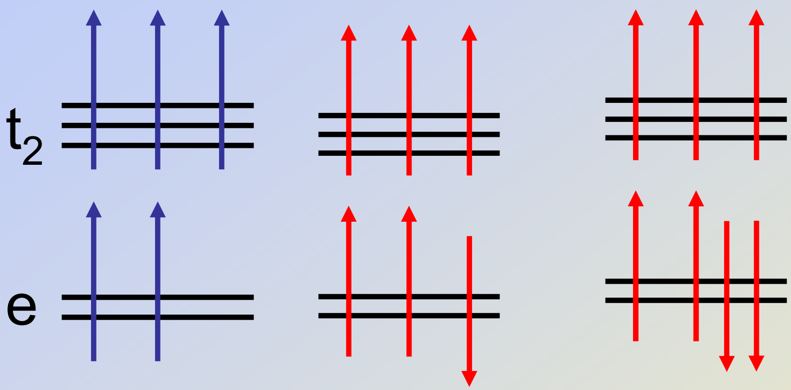
A-site: Diamond lattice
Frustration via competing interactions!

V. Fritsch *et al.*, PRL **92**, 116401, 2004
D. Bergman *et al.,* Nature Physics **3**, 487, 2007

AB_2X_4: Electronic configuration

MnB_2X_4 FeB_2X_4 CoB_2X_4

$Mn^{2+}(3d^5)$ S=5/2 $Fe^{2+}(3d^6)$ S=2 $Co^{2+}(3d^7)$ S=3/2



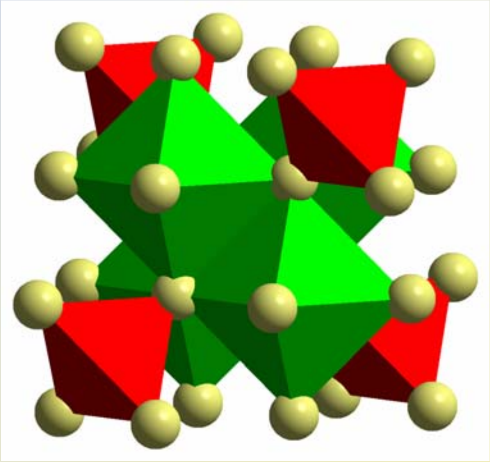
Half filled JT active weak SO coupling

A-sites: tetrahedrally coordinated

Diamond Lattice

B = Sc, Al

X = O, S

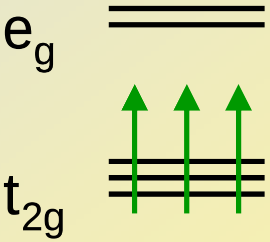


B-sites

octahedrally

coordinated

Pyrochlore Lattice



Cr^{3+} $(3d^3)$, J=3/2

No spin-orbit coupling!

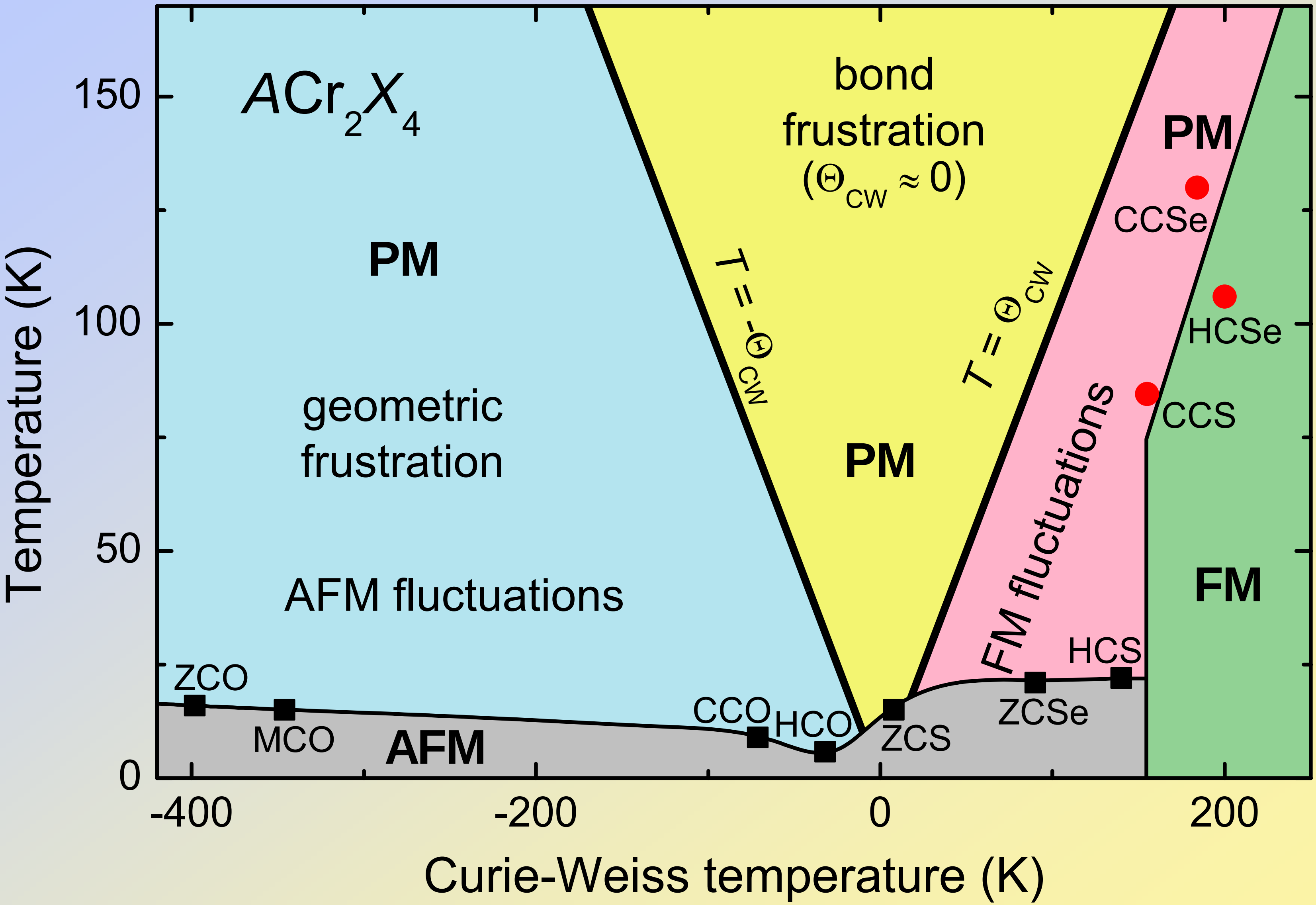
ACr_2X_4

A = Zn, Cd, Hg

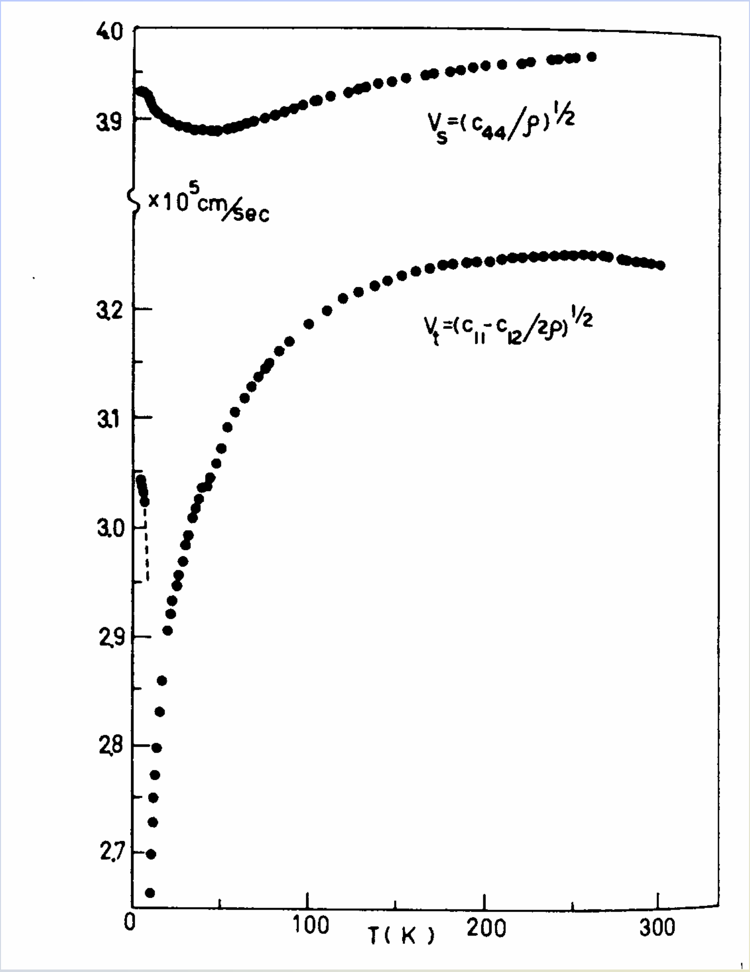
X = O, S, Se

Chromite spinels: Phase diagram

Rudolf *et al.*, New J. Physics **9**, 76, 2007



Cr-Spinels: Spin-driven Jahn-Teller effect



Softening of elastic constants in $ZnCr_2O_4$ at magnetic phase transition

Kino and Lüthi, Solid State Commun. **9**, 805, 1971

Spin-driven Jahn-Teller effect in chromite spinels ($ZnCr_2O_4$ and $CdCr_2O_4$)

Tchernyshyov *et al*., Phys. Rev. Lett. **88**, 067203, 2002

Yamashita and Ueda, Phys. Rev. Lett. **85**, 4960, 2000

Dynamic symmetry breaking in antiferromagnets: Splitting of phonon modes by magnetic exchange interactions, decoupled from lattice distortions (splitting of phonon modes even in cubic lattices)

Theory:

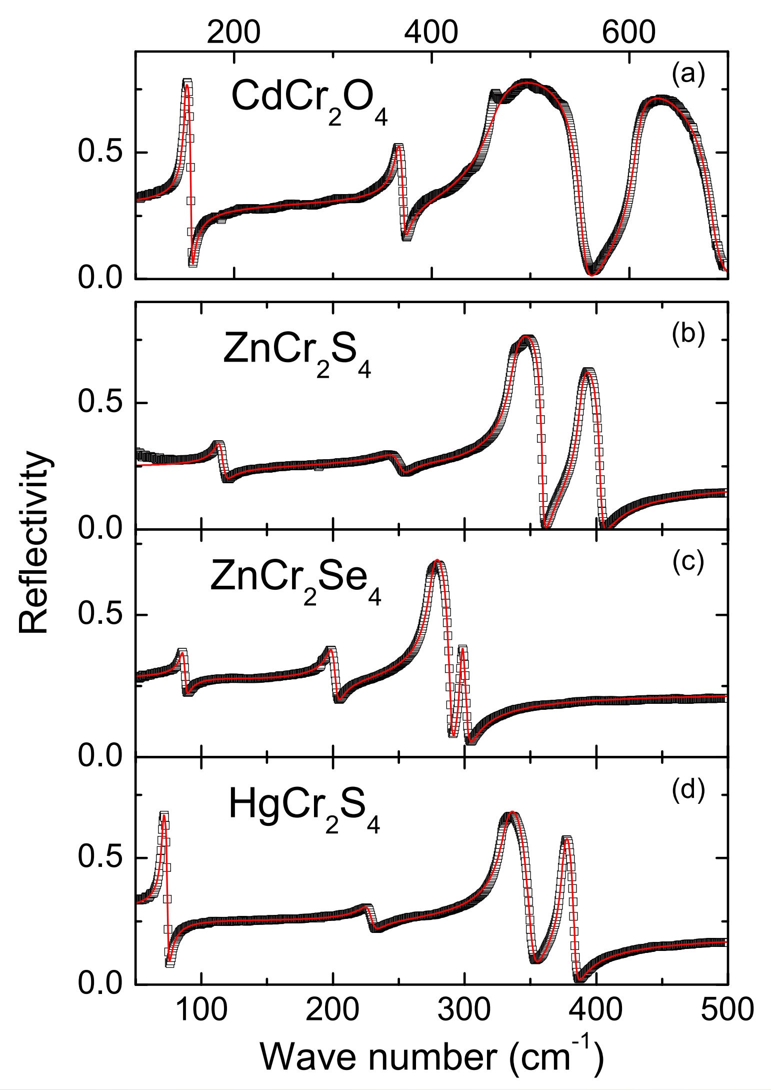
Massida *et al*., Phys. Rev. Lett. **82**, 430, 1999

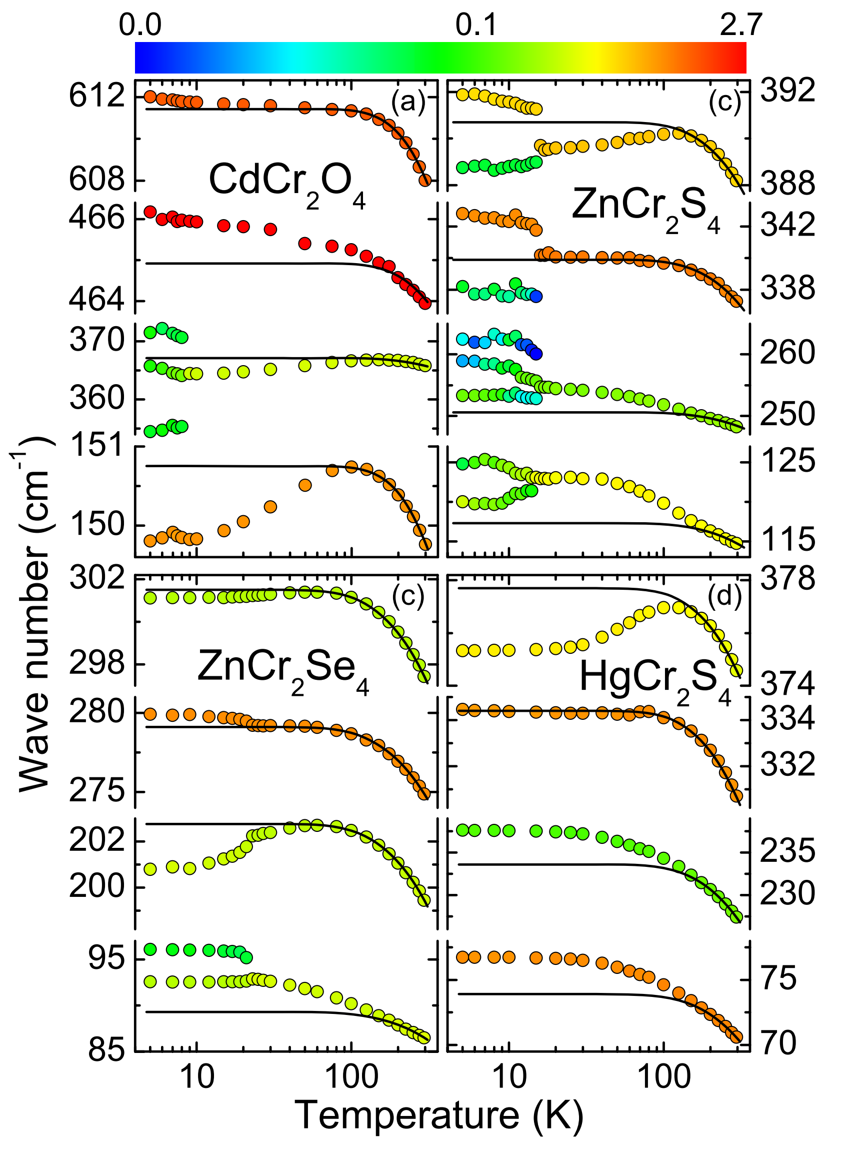
Fennie and Rabe, Phys. Rev. Lett. **96**, 205505, 2006

FIR experiments in $ZnCr_2O_4$:

Sushko *et al*., Phys. Rev. Lett. **94**, 137202, 2005

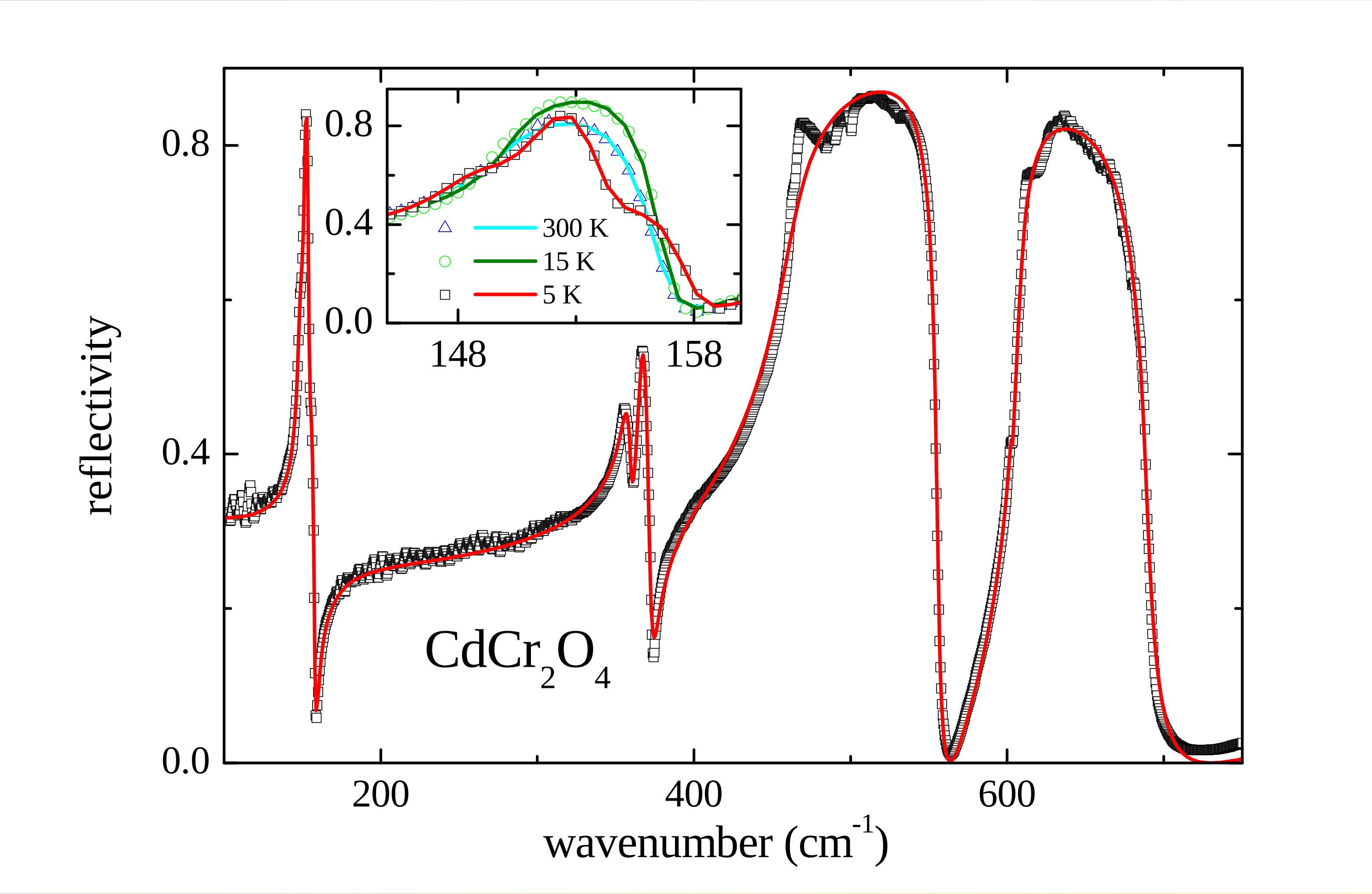
Chromite spinels: Spin-phonon coupling





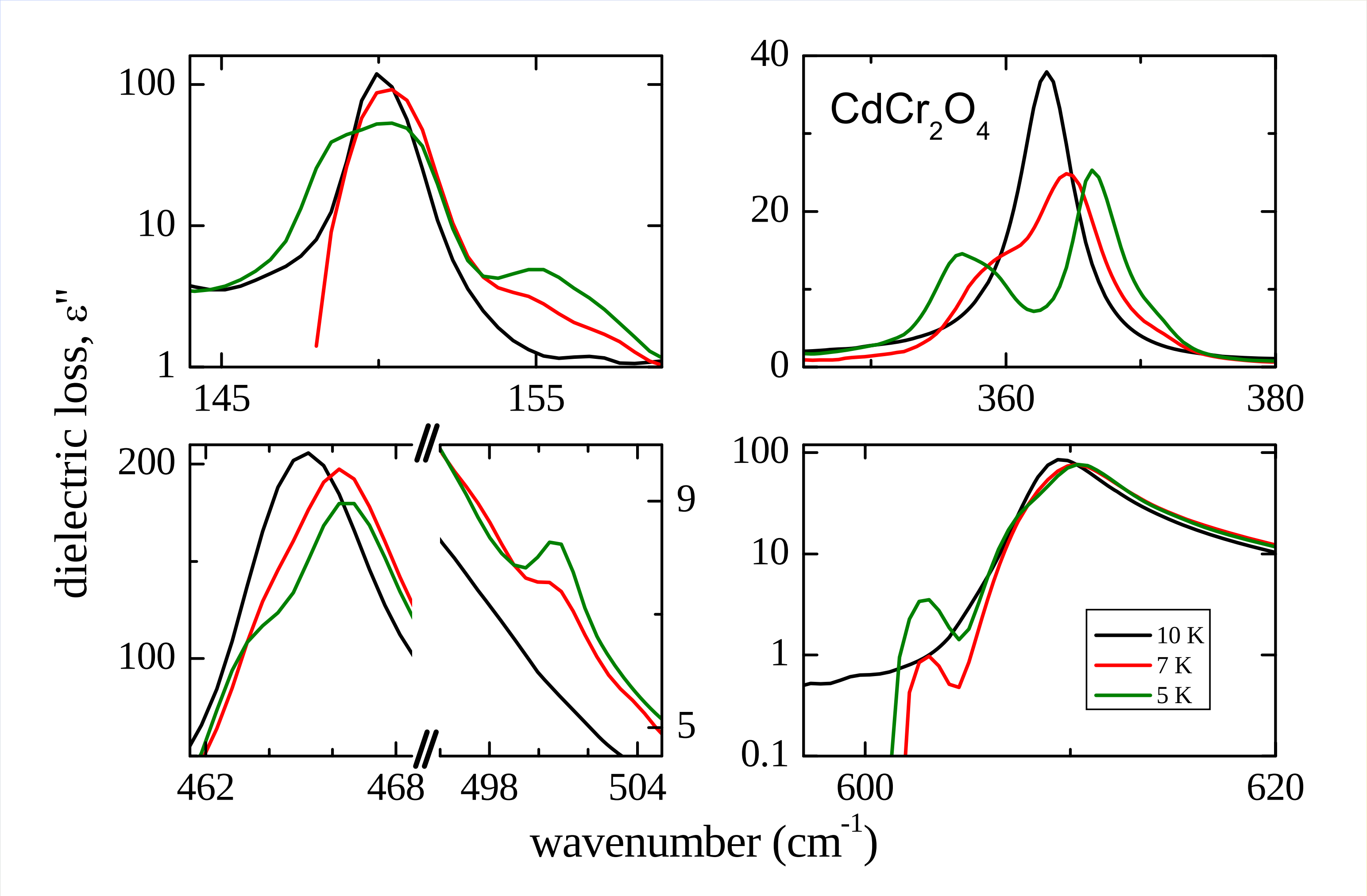
Rudolf *et al.*, New J. Physics **9**, 76, 2007

Chromite spinels: Reflectivity $CdCr_2O_4$



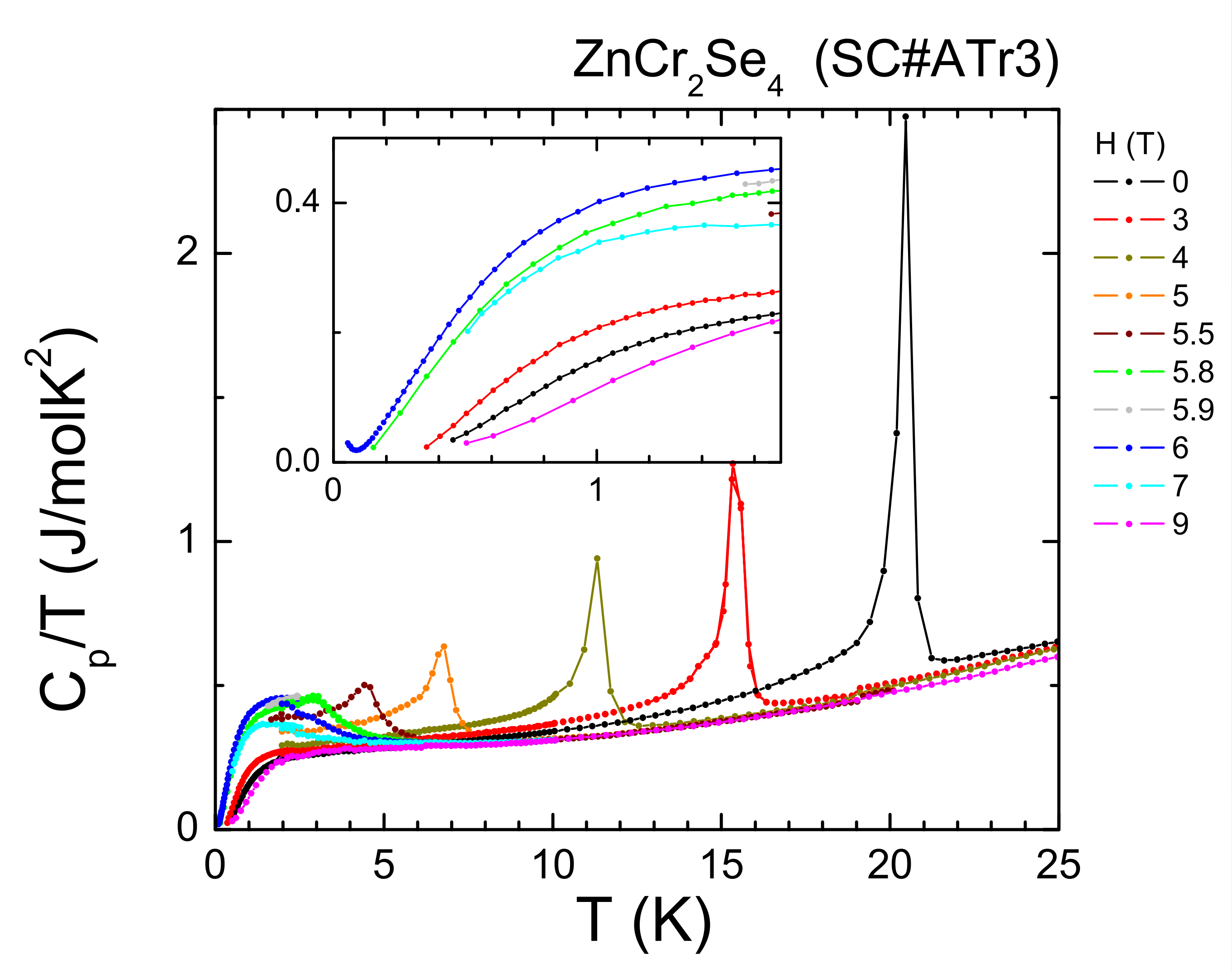
Rudolf *et al.*, unpublished

Chromite spinels: Phonon splitting in $CdCr_2O_4$



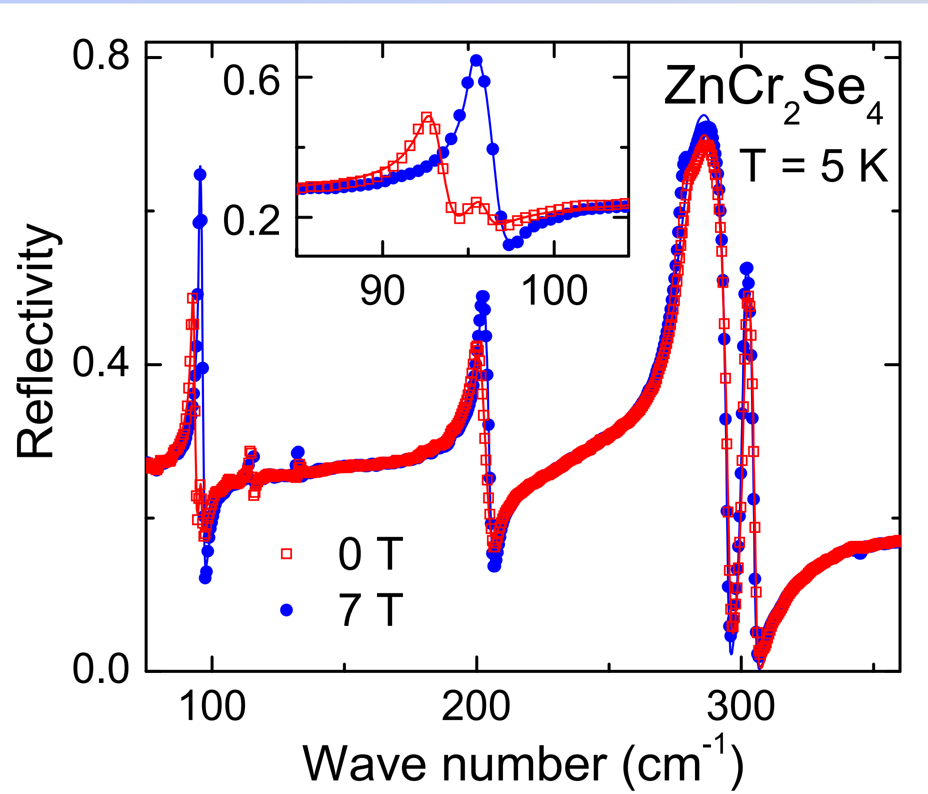
Rudolf *et al.*, unpublished

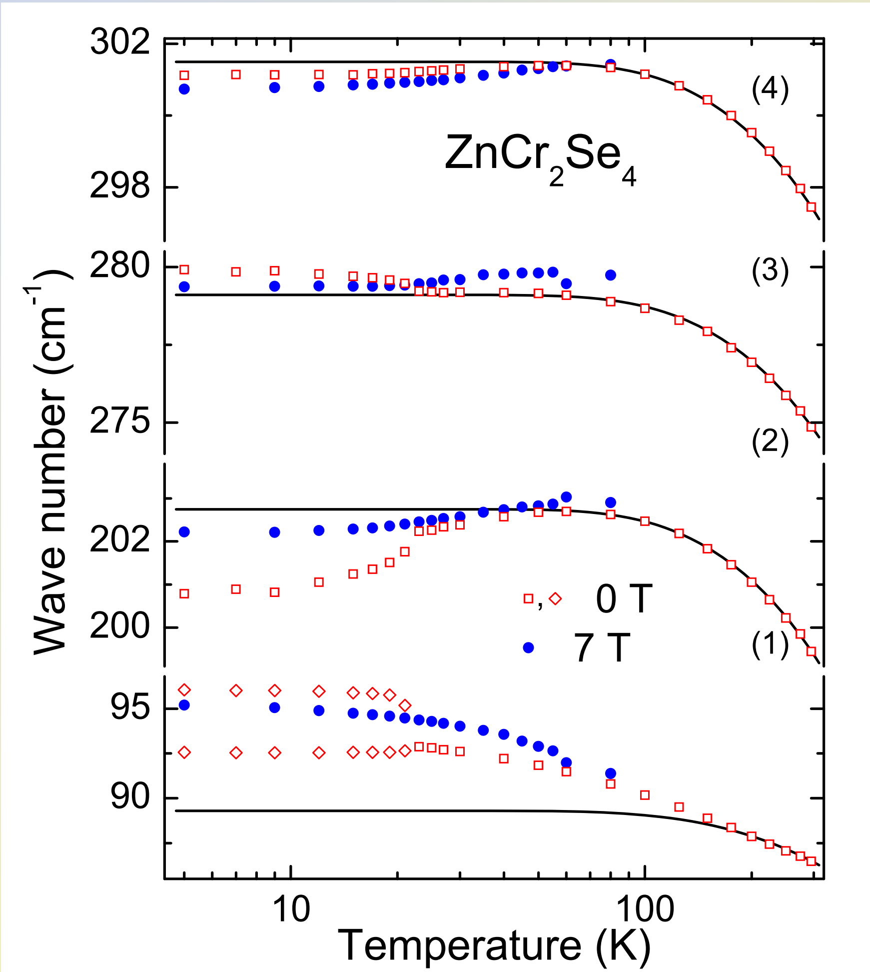
$ZnCr_2Se_4$: Suppression of antiferromagnetic order



J. Hemberger et al. Phys. Rev. Lett. **98**, 147203, 2007

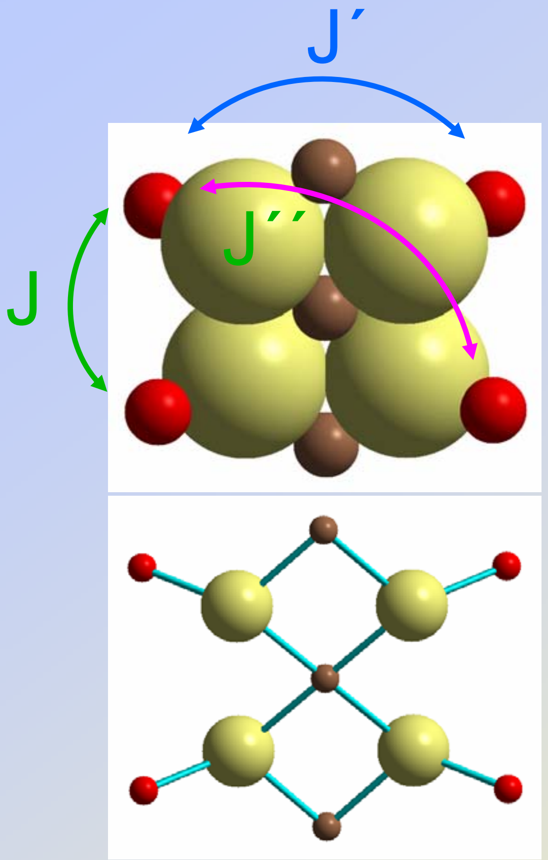
$ZnCr_2Se_4$: Magnetic-field dependence of spin-phonon coupling





Rudolf *et al*., New J. Physics **9**, 76, 2007

A-site magnetism: Competing interactions

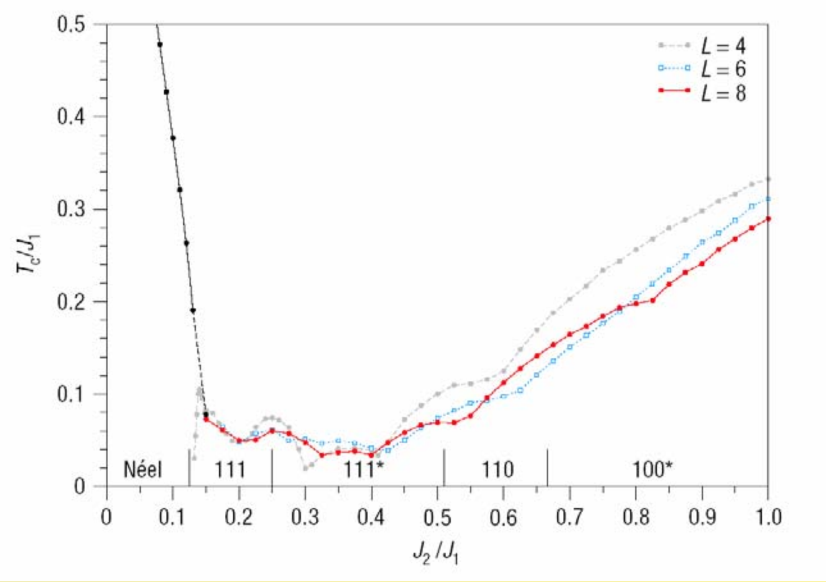


J and J" couple two fcc-sublattices (J_1)

J' exchange within one fcc-sublattice (J_2)

Competing Interactions in Diamond Lattice

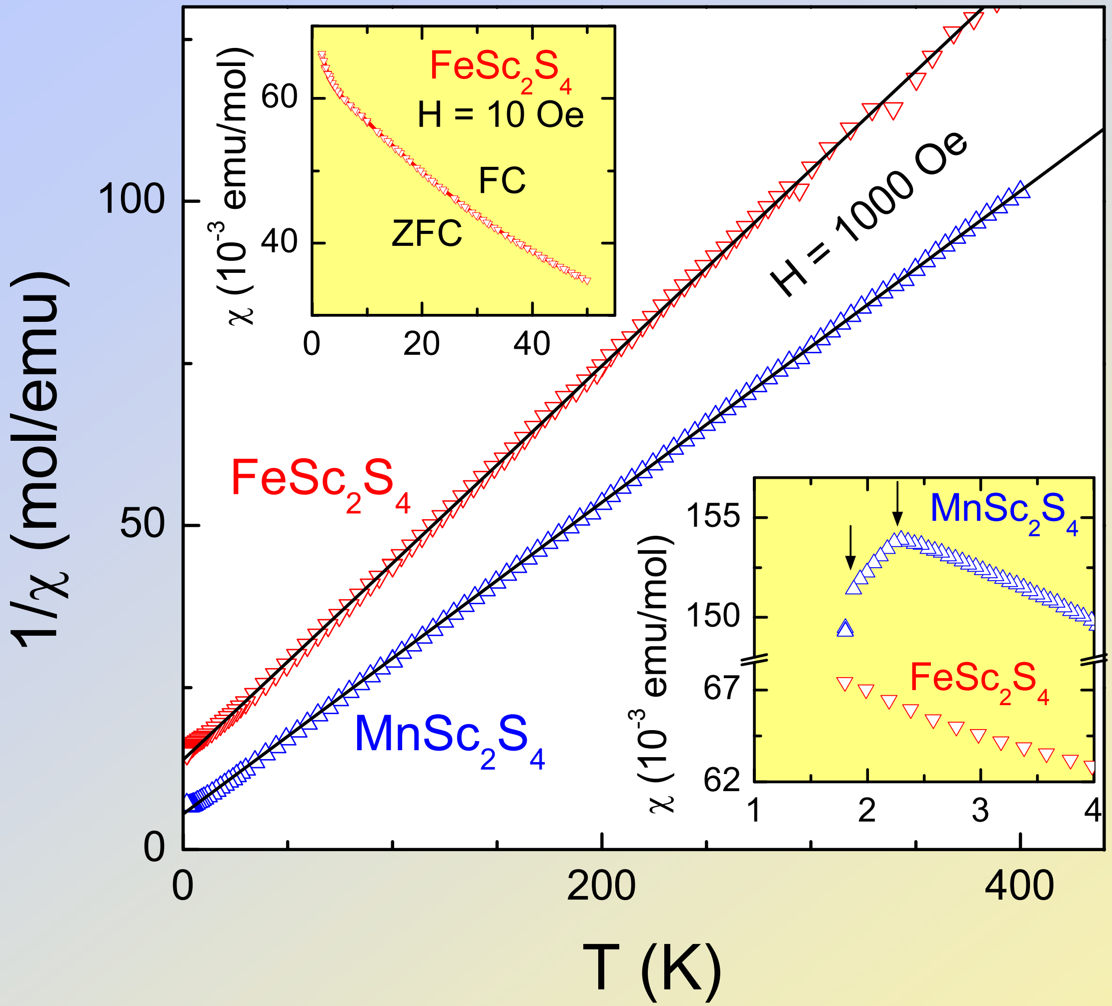
A-sites in spinels form diamond lattice
which is bipartite: Two interpenetrating fcc lattices



Depending on ratio J_2/J_1, strong frustration with complex magnetic ground states can occur:
Spiral Spin Liquid Phase
Bergman *et al.*, Nature Physics **3**, 487, 2007

ASc_2S_4 (A = Fe, Mn): Spin Frustration

Competing interactions on A-site: Diamond lattice



$FeSc_2S_4$: θ_{CW} = 50 K

T > 30 mK:

no long-range magnetic order

no spin-glass

$MnSc_2S_4$: θ_{CW} = 25 K

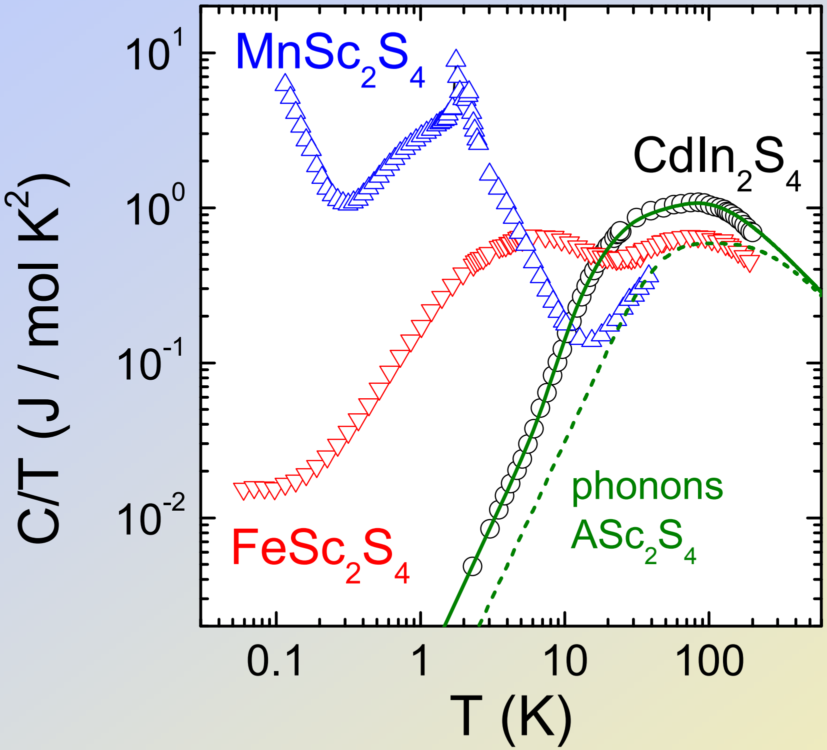
AFM transition @ 2 K

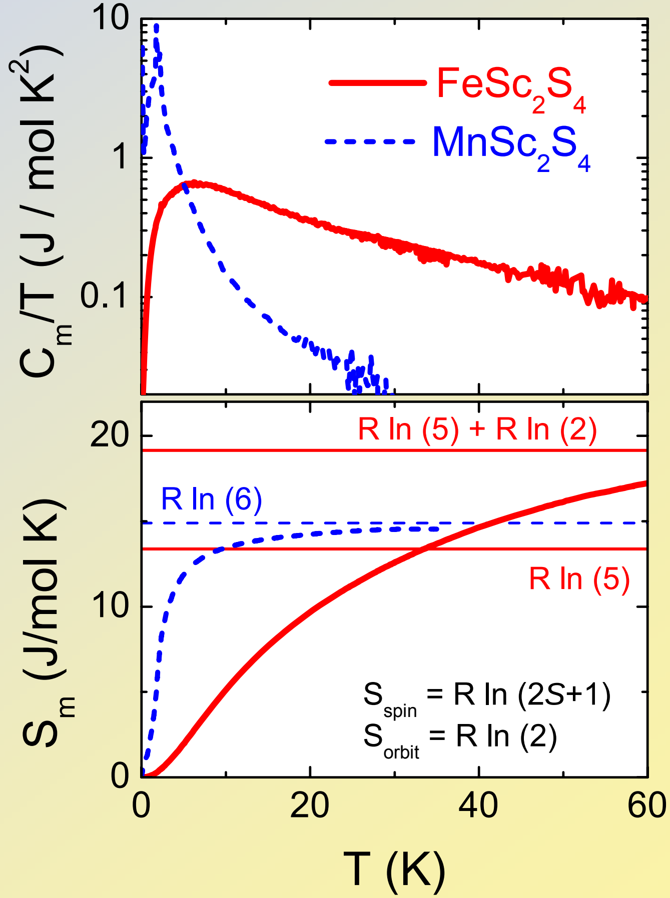
Fritsch *et al.*, PRL **92**, 116401, 2004

Specific heat in $FeSc_2S_4$: Spin and orbital contributions

$MnSc_2S_4$: Spin liquid for T < 20 K, T_N = 2 K

$FeSc_2S_4$: Ground state - Spin liquid and orbital glass

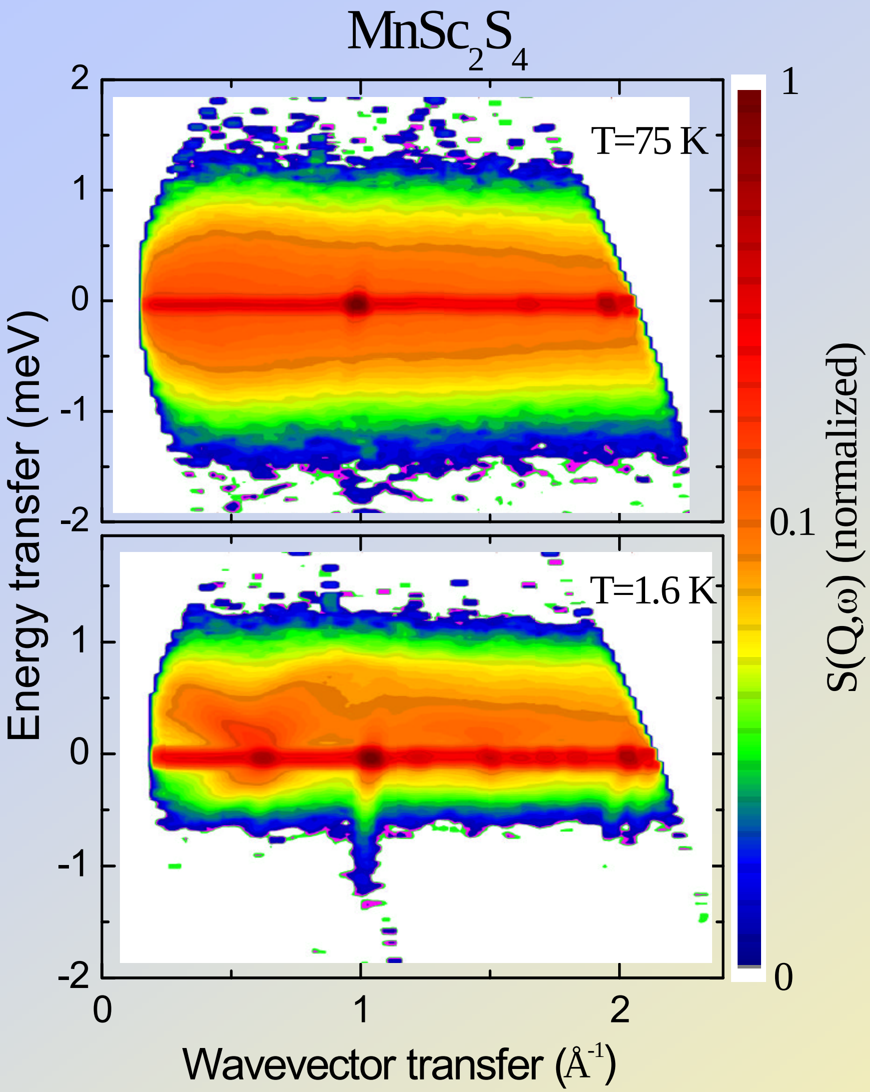


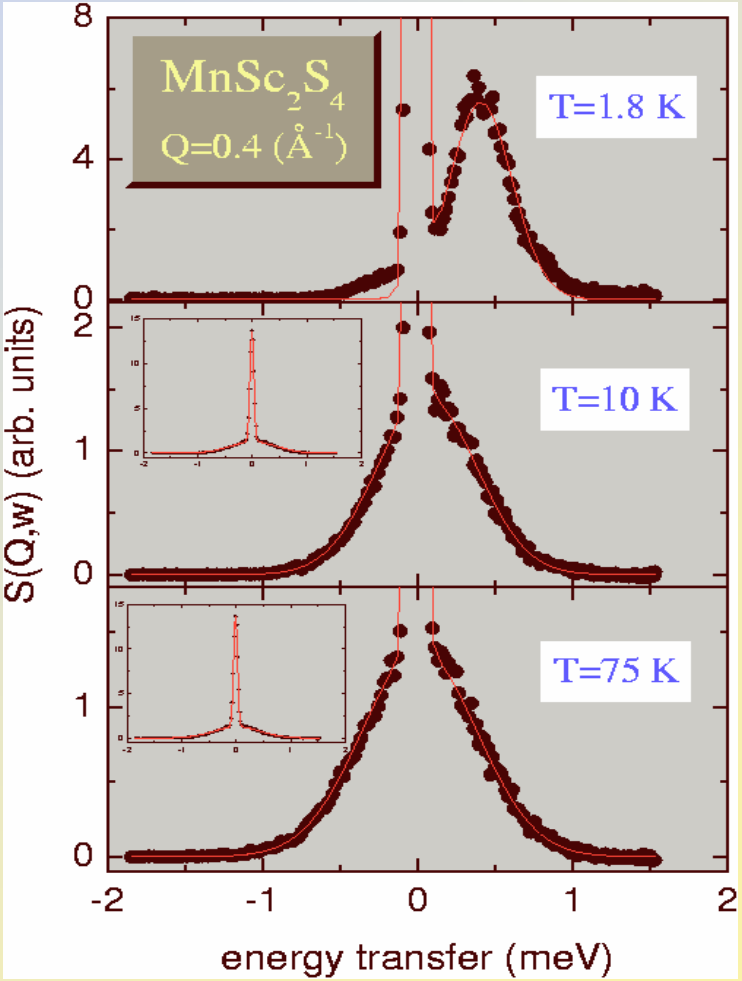


$FeSc_2S_4$: Spin and orbital contributions to specific heat and entropy

Fritsch *et al.*, PRL **92**, 116401, 2004

Neutron scattering: $MnSc_2S_4$





A. Krimmel *et. al.*, PRB **73**, 014413, 2006

Neutron scattering: $MnSc_2S_4$

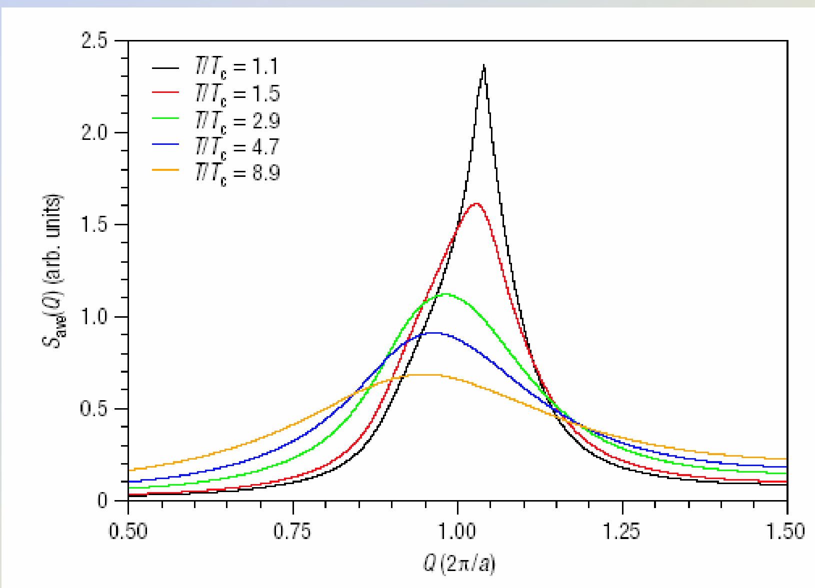
Diamond lattice is a bipartite lattice:

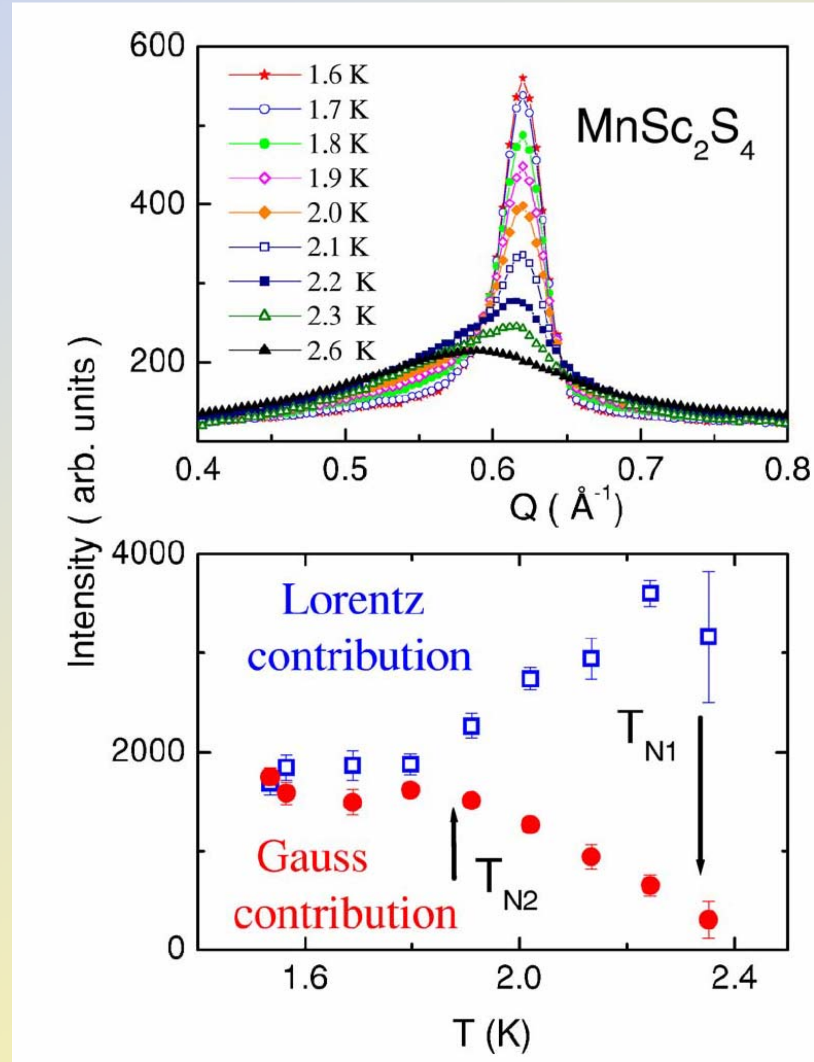
Only nearest neighbour coupling: No frustration!
But strong frustration taking second nearest neighbours into account.

Frustration results in a spin-spiral liquid:

"ground state degeneracy develops amongst spin spirals whose propagation wave vectors reside on a continuous two-dimensional surface in momentum space"

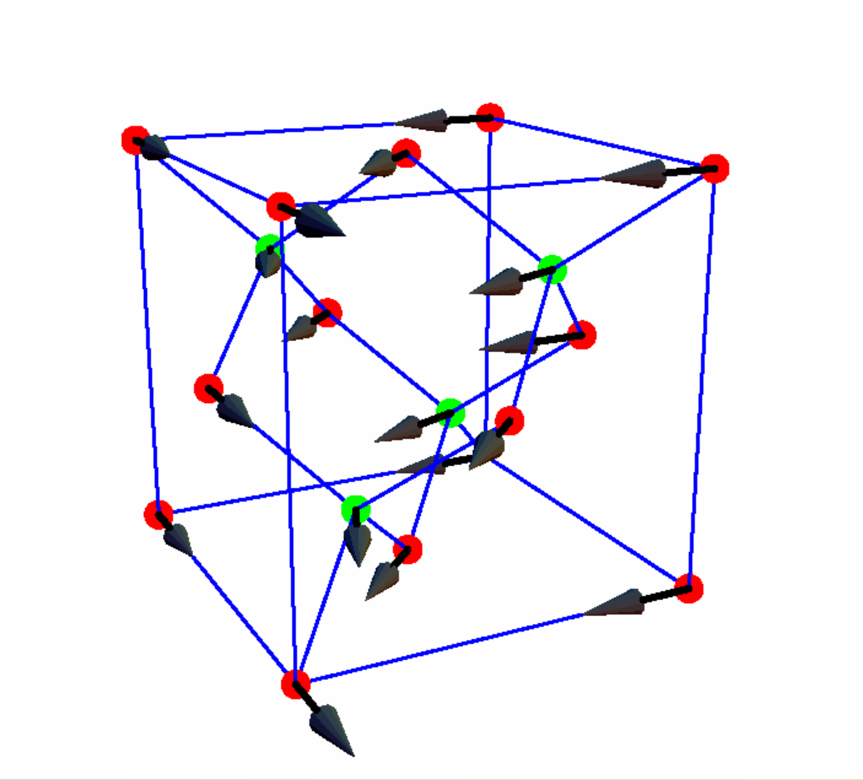
Bergman *et al*., Nature Physics **3**, 487, 2007

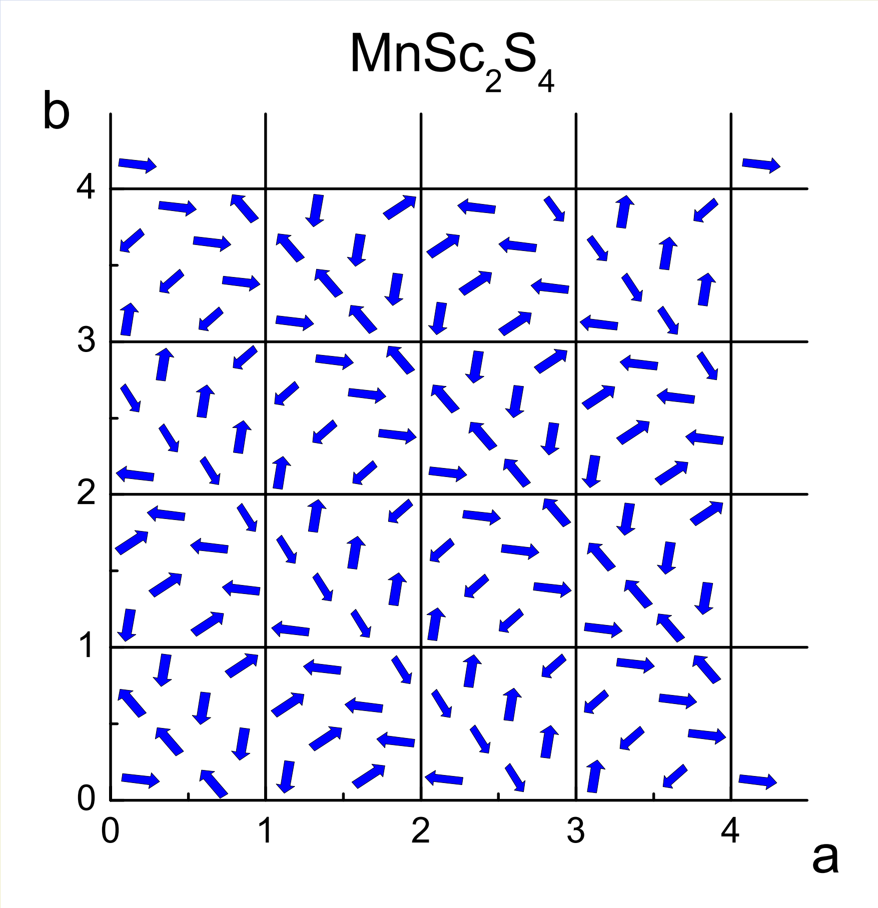




Krimmel *et. al*., Phys. Rev. B **73**, 014413, 2006

$MnSc_2S_4$: Frustrated diamond lattice





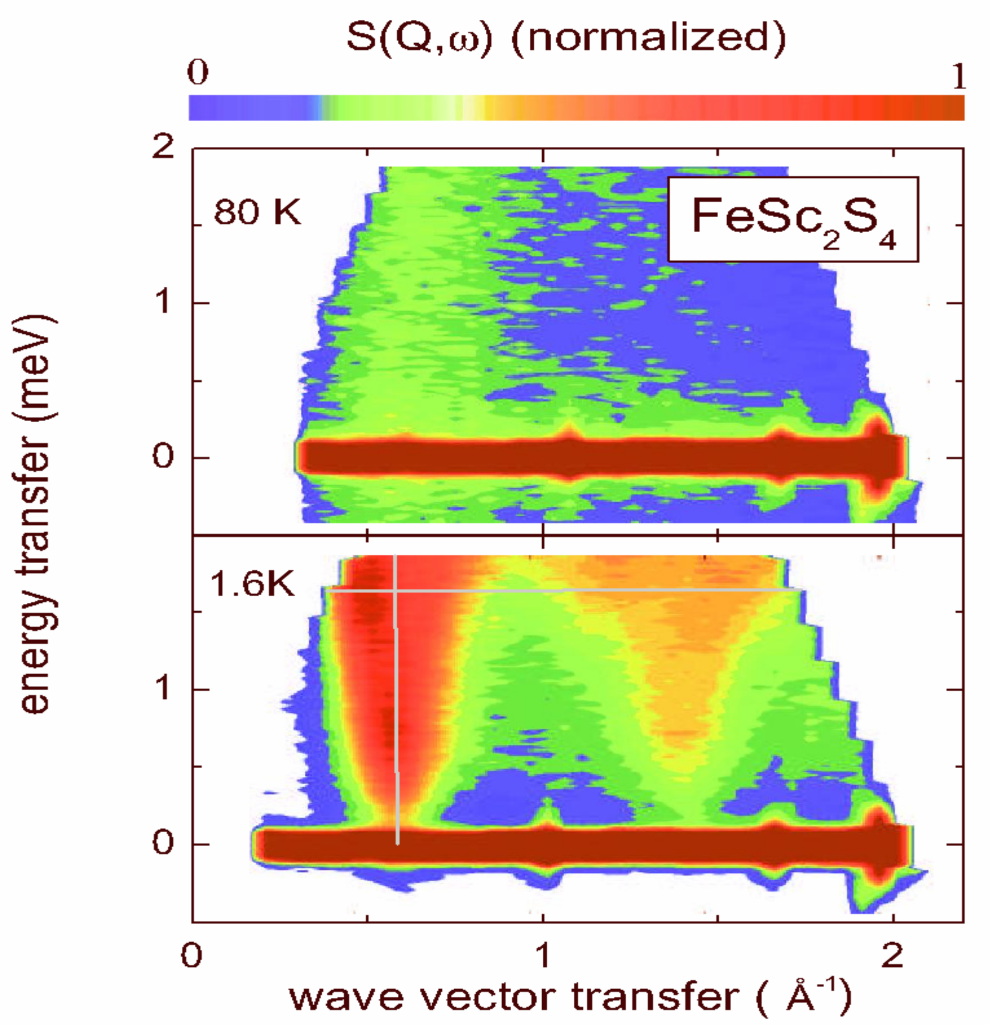
At low temperatures:
Order by disorder mechanism stabilizes
long-range magnetic order

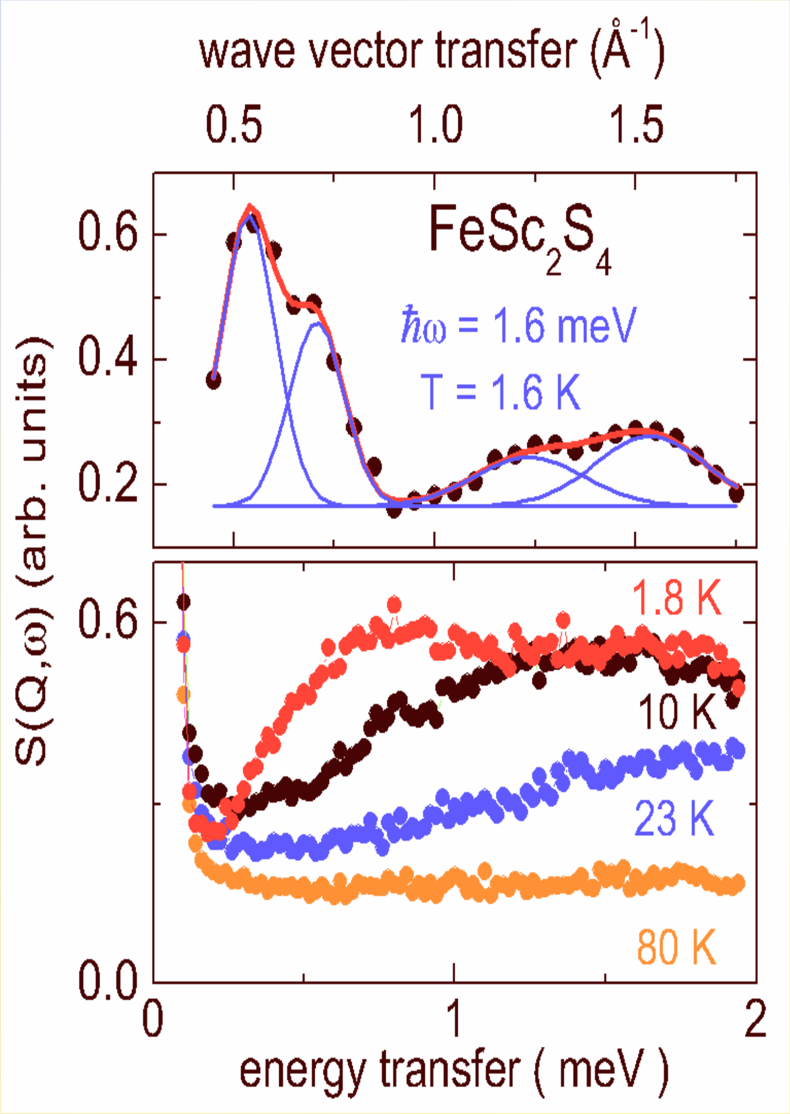
Krimmel *et al.* Phys. Rev. B **73**, 014413, 2006

Bergman *et al*., Nature Physics **3**, 487, 2007

Neutron scattering in $FeSc_2S_4$: Spin liquid state

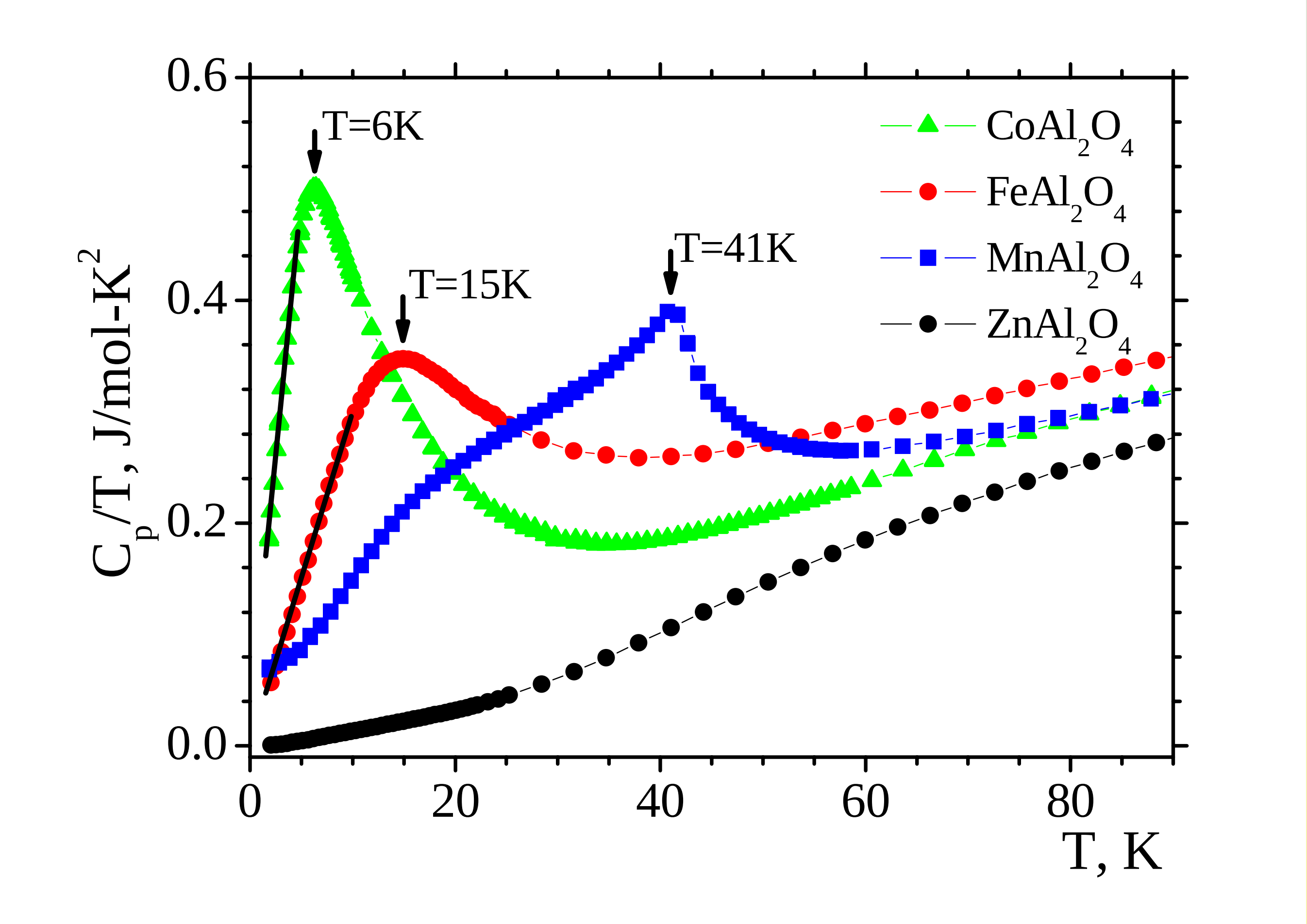
Opening of a spin gap in $FeSc_2S_4$





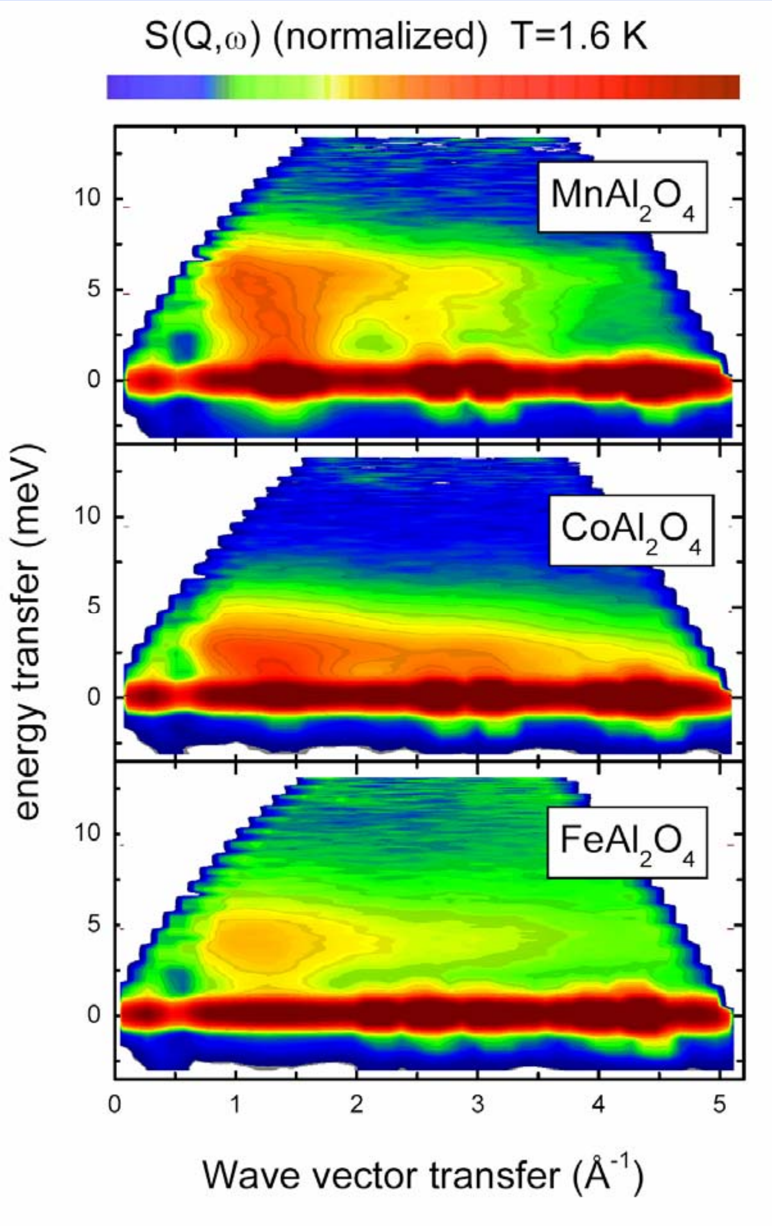
A. Krimmel *et al*., Phys. Rev. Lett. **94**, 237402, 2005

Specific heat of Alumino Spinels: AAl_2O_4 (A = Mn, Fe, Co)

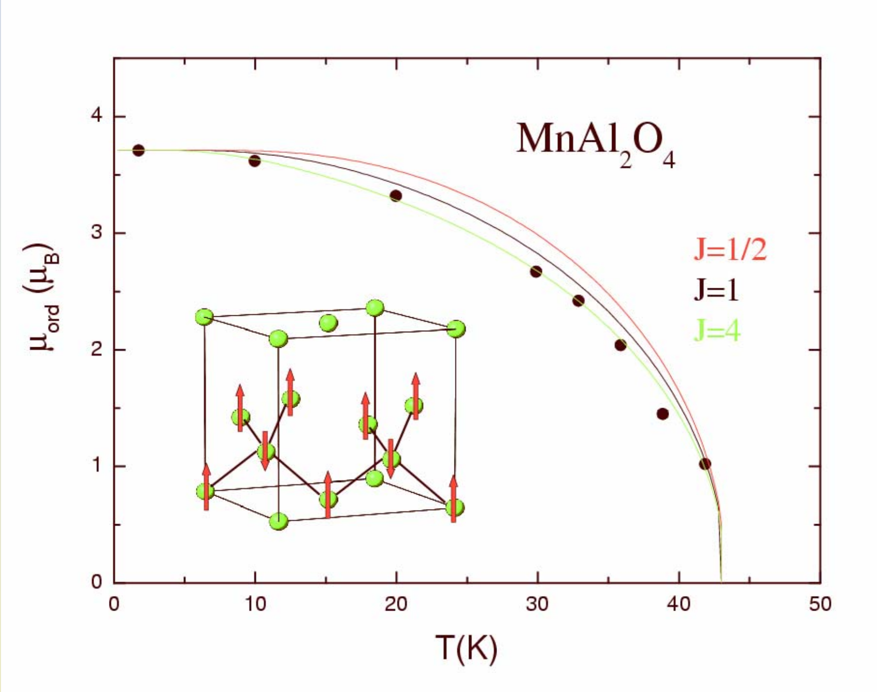


N. Tristan *et al*., Phys. Rev. B **72**, 174404, 2005

Neutron scattering: AAl_2O_4 (A = Mn, Fe, Co)



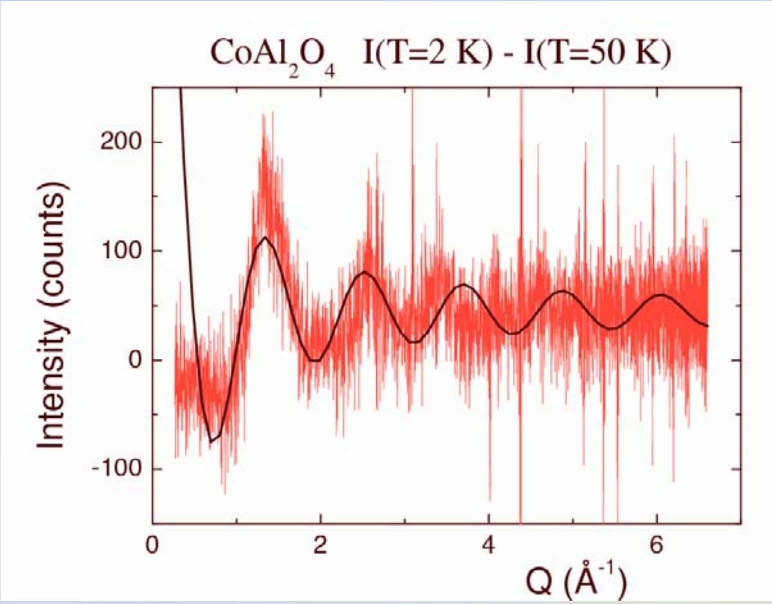
$MnAl_2O_4$: Long range spin order,
spin-wave dispersion

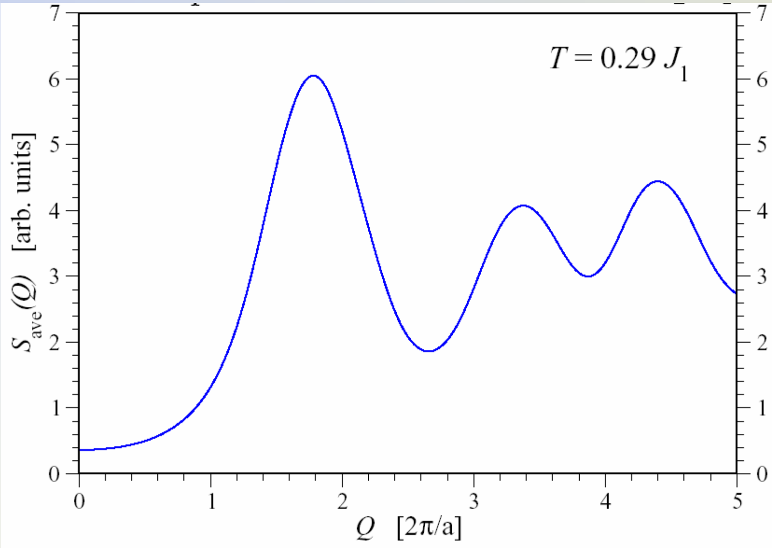


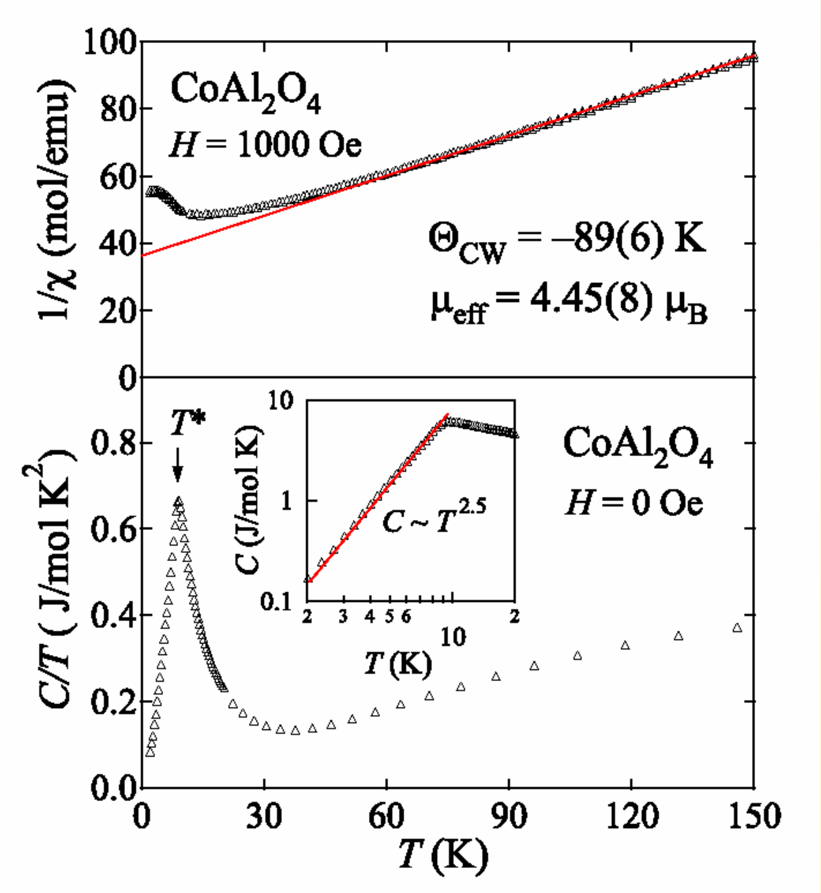
AAl_2O_4 (A = Co, Fe):
No long range spin order

A-site spinels: $CoAl_2O_4$

Structure factor $CoAl_2O_4$: Exp.: Krimmel et al. 2007; **Theory**: Bergman et al. 2006;







Heat capacity: C ~ T $^{2.5}$

T. Suzuki *et al.*,
J. Phys. Condens. Matter **19**,145265, 2007

Conclusion and Summary

AB_2X_4 spinels:

A treasure chest for solid state physics and material science

B-site pyrochlore lattice:
Geometrical Frustration

The chromite spinels:
Spin-driven Jahn-Teller effect

A-site diamond lattice:
Frustration by competing interaction

$FeSc_2S_4$, $FeAl_2O_4$
Frustration of spin and orbital degrees of freedom:
Cooperative paramagnet; opening of a spin gap at low temperatures

$MnSc_2S_4$; $MnAl_2O_4$, $CoAl_2O_4$
Competing interactions of spin moments on a diamond lattice: spiral spin liquid

EKM

The wonderful world of Spinels

„Black Prince‘s Ruby“

„Neuschwanstein 3“


news and views

Catch a falling star

Jack Drummond

concluded that most meteors were of interstellar origin. In New Mexico, in the late 1940s and early 1950s, Fred Whipple and colleagues made photographic studies using a rotating shutter in front of fast cameras to measure the meteors' velocities. In what is some of the most precise work even by today's standards, these experiments showed that most meteors in fact originated from comets, but that a substantial fraction were in asteroid-like orbits — that is, the furthest points of their orbit from the Sun (their 'aphelia') fell in the asteroid belt, between Mars and Jupiter.

Shortly thereafter, astronomers began to

the meteor stream than had been thought.

where it came from, a big piece of the puzzle might be uncovered. As a result, several networks of cameras, spanning areas of a million square kilometres, were set up in Europe, Canada and the United States. The

as being of magnitude −19, much brighter than the full Moon.

That historic night, his fireball network had photographed and tracked the meteor's path through the atmosphere, and its orbit in

Drummond, Nature 423, 17 (2003)