Future shocks: opportunities in magnetism with Super-MuSR

Tom Lancaster
Durham University

(Mega) Events, dear boy, (mega) events

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Opportunities from Super-MuSR

- Data rate and quality

- Enhanced frequency response

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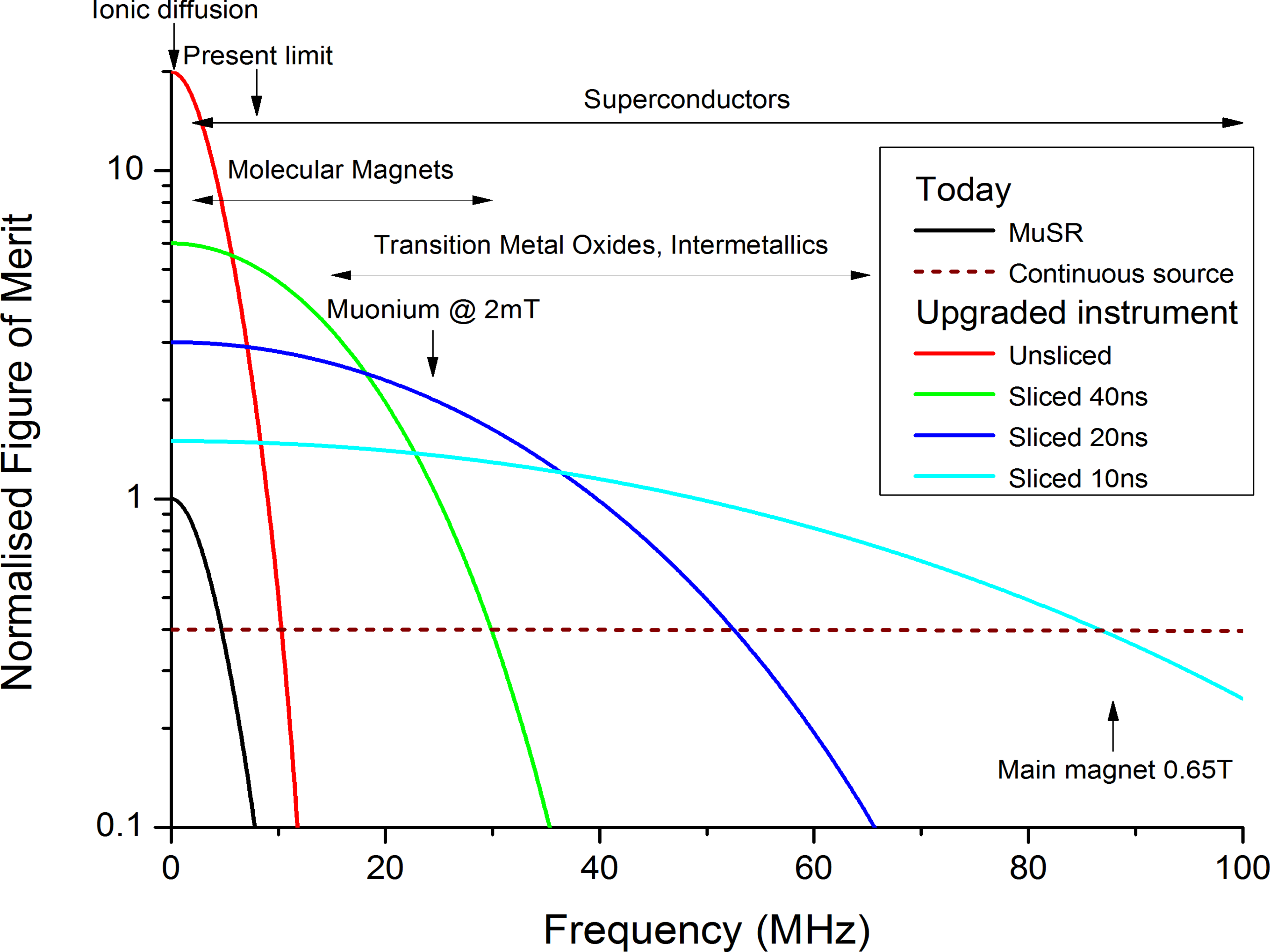
"Super!"

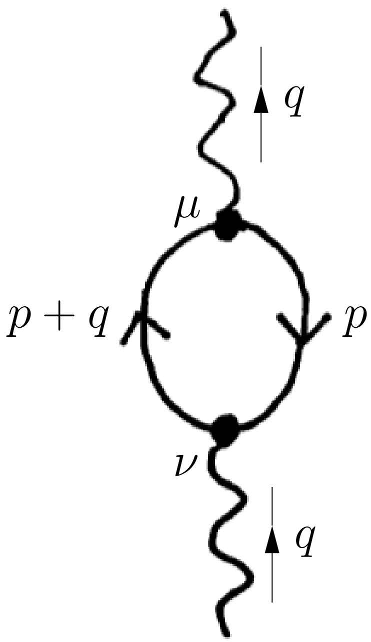


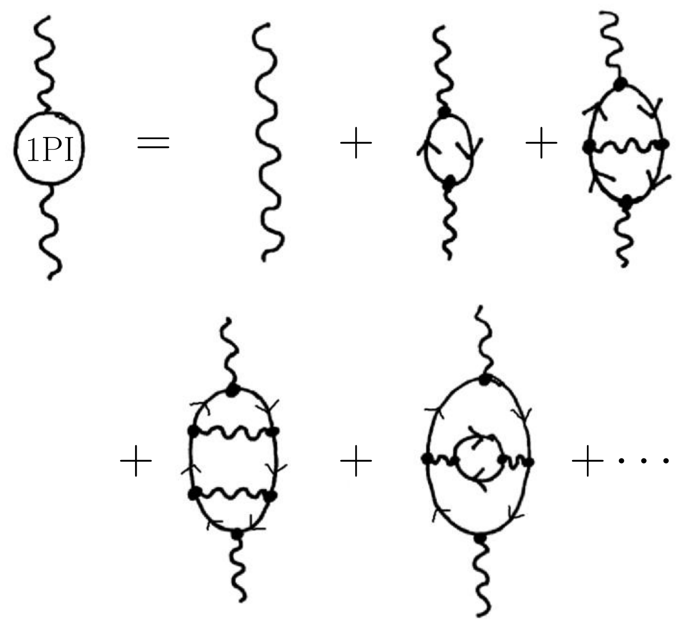
Ionic diffusion
Present limit
Superconductors
Molecular Magnets
Transition Metal Oxides, Intermetallics
Muonium @ 2mT
Main magnet 0.65T
Today
MuSR
Continuous source
Upgraded instrument
Unsliced
Sliced 40ns
Sliced 20ns
Sliced 10ns
Normalised Figure of Merit
Frequency (MHz)
10
1
0.1
0
20
40
60
80
100

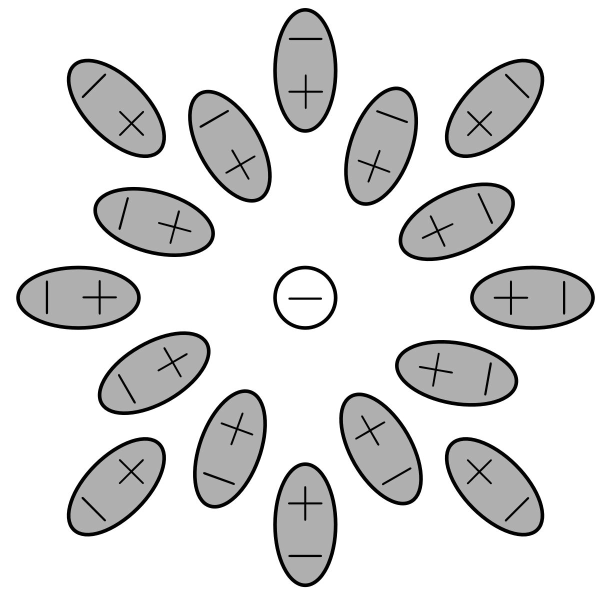
Low moment systems

(reduced dimensionality, molecular systems, heavy fermion magnets…)

An explanation of screening







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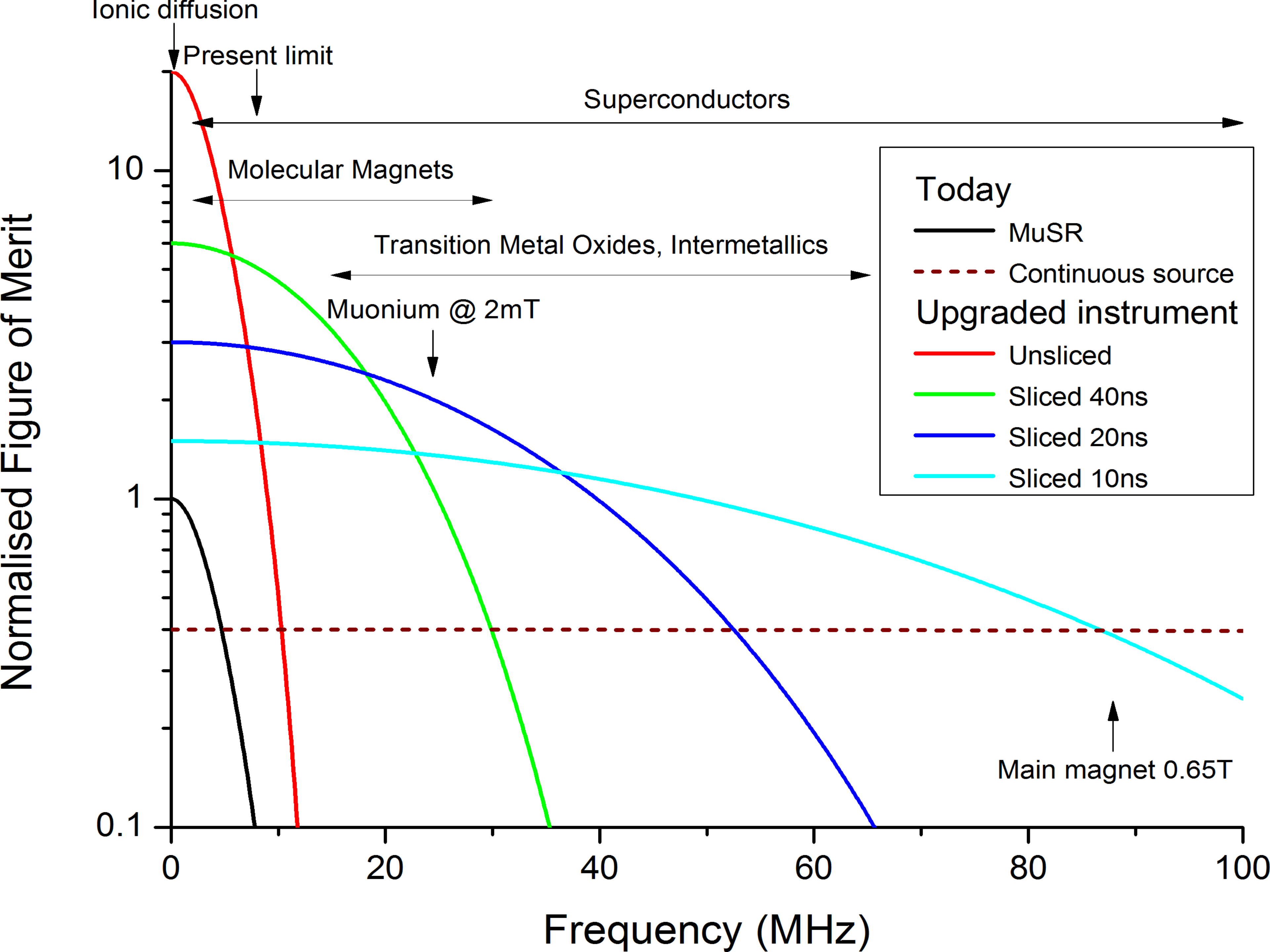
(reduced dimensionality, molecular systems, heavy fermion magnets…)

Count rate increased by a factor of 20

More data

Better quality data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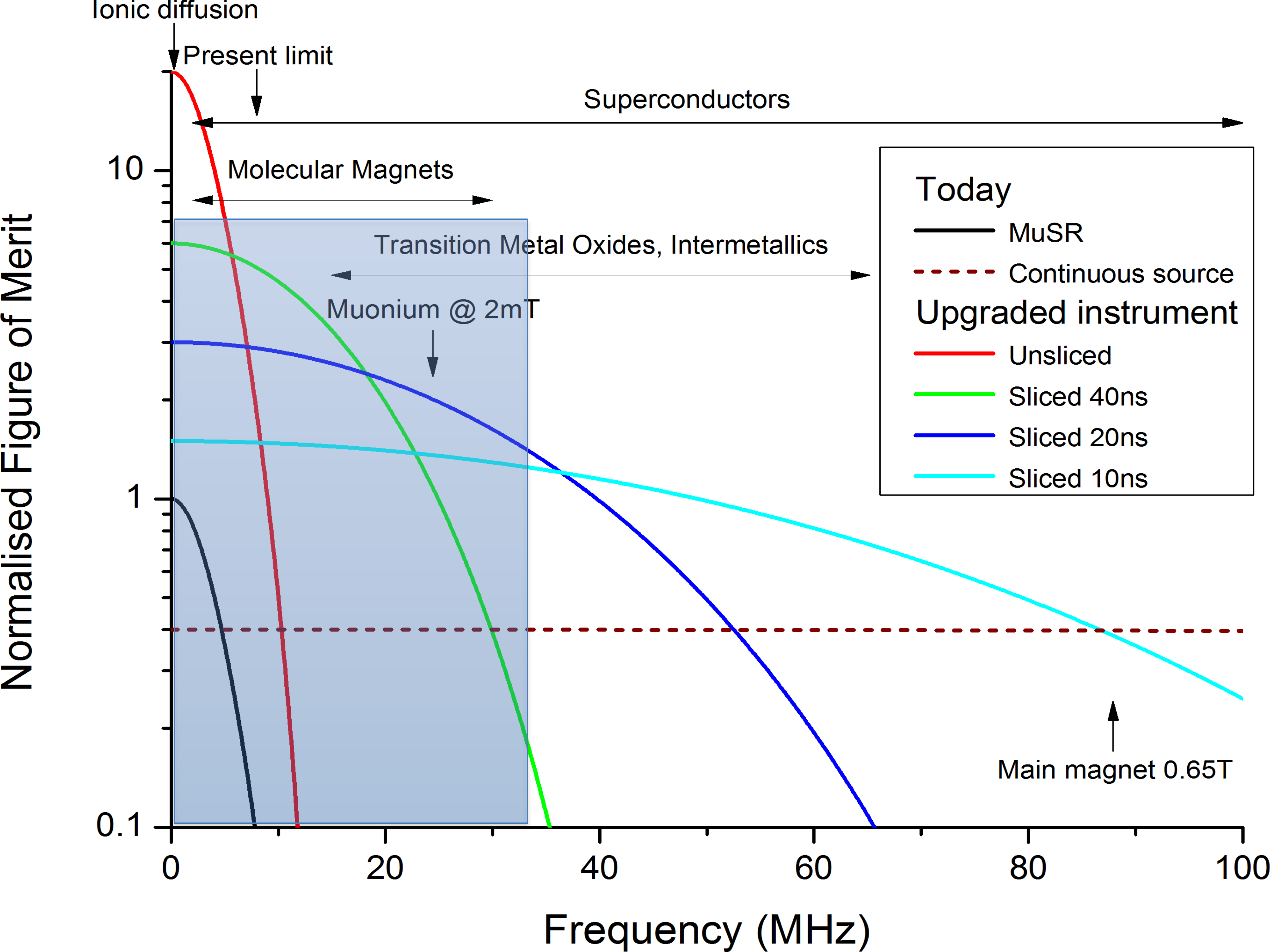
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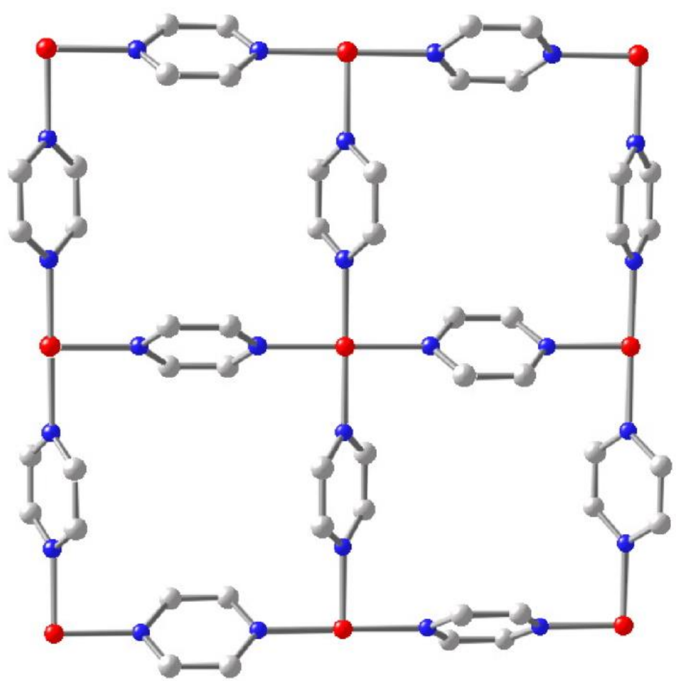
Case study: molecular magnets

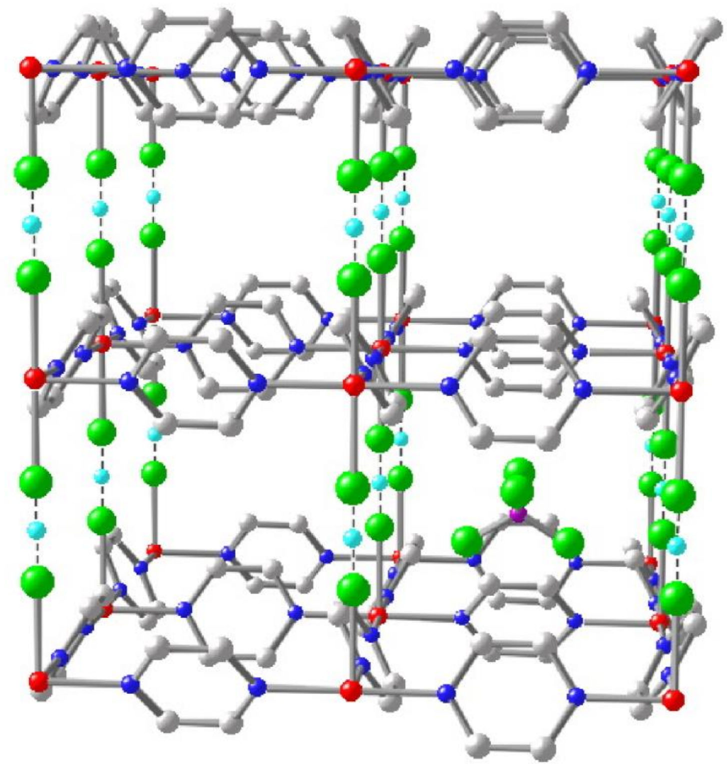
$[Cu(pyz)_2HF_2]X_2$ (X=BF_4, ClO_4, PF_6, AsF_6, SbF_6)

Highly tunable, self-assembled nanostructures with 2D character

First coordination polymer containing the HF_2^- ion
(strongest known hydrogen bond!)

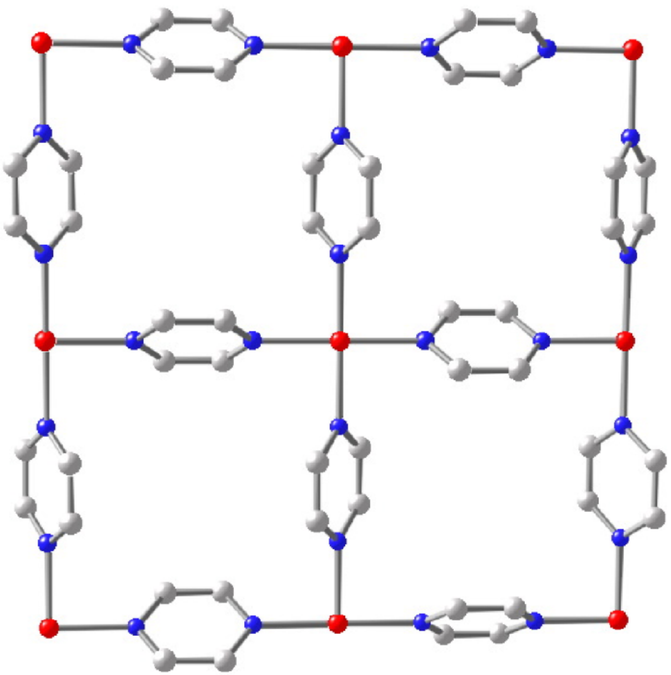


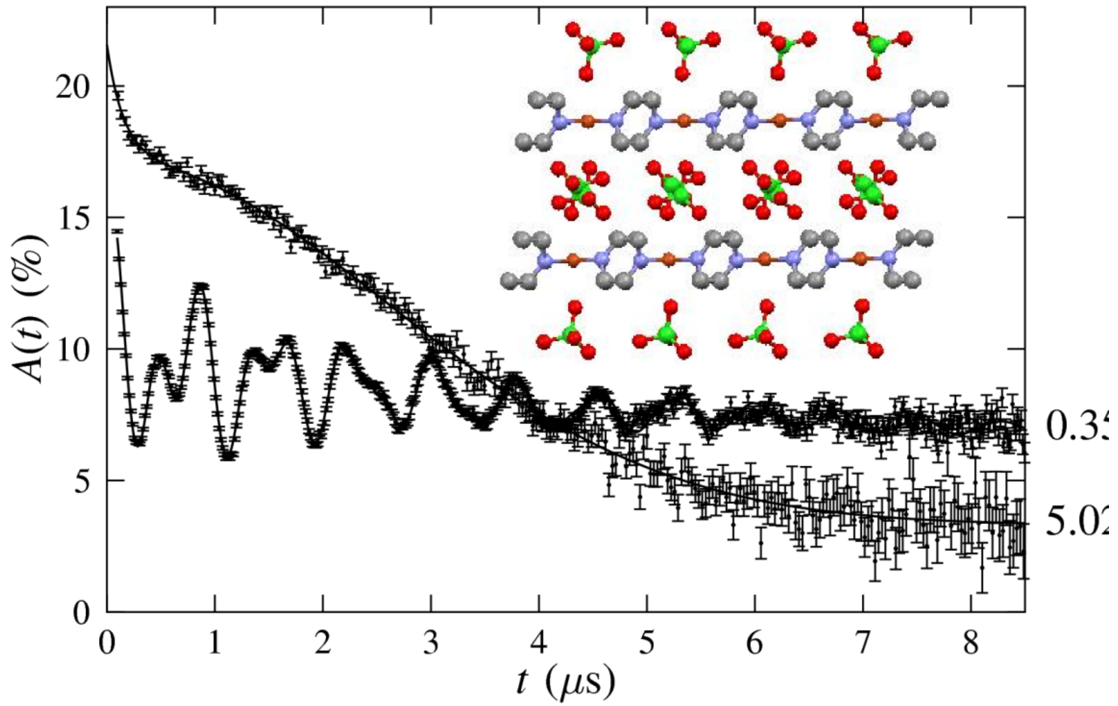
2D square lattice of Cu^{2+} $S=1/2$ spins



Linked by HF_2^- to form 3D structure
(with X anions in the cubes)

$Cu(ClO_4)_2(pyz)_2$ μ^+SR results





Another 2D square lattice Heisenberg system with J=17.8 K

Magnetic order detected with oscillations at three frequencies

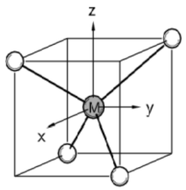
T_N=4.2(1) K

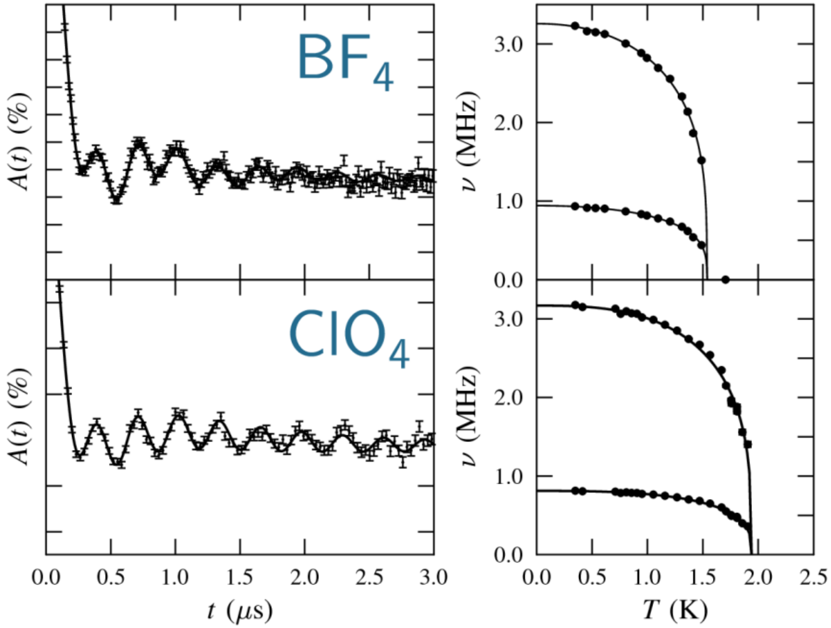
T Lancaster *et al.* Phys. Rev. B **75**, 094421 (2007)

$[Cu(pyz)_2HF_2]X_2$: trends across the series

Tetrahedral vs. octahedral anion in the cubes

Tetrahedral anion





$$T_N \approx 1.5 \text{ K}$$
$$J \approx 7 \text{ K}$$
$$|J'/J| \approx 10^{-3}$$

Goddard *et al.* New J. Phys. **10** 083025 (2008)

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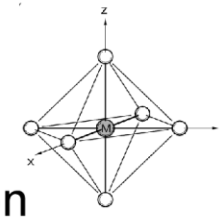
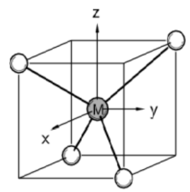
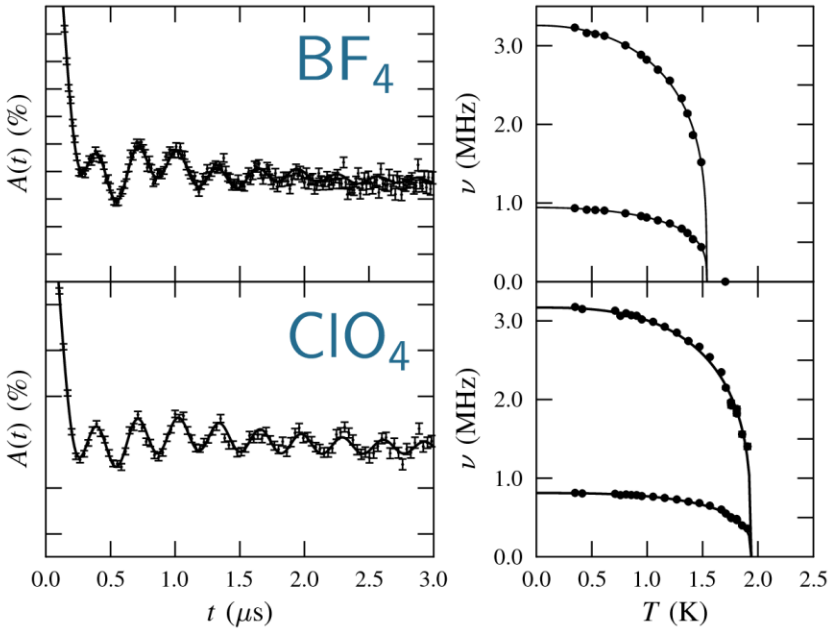
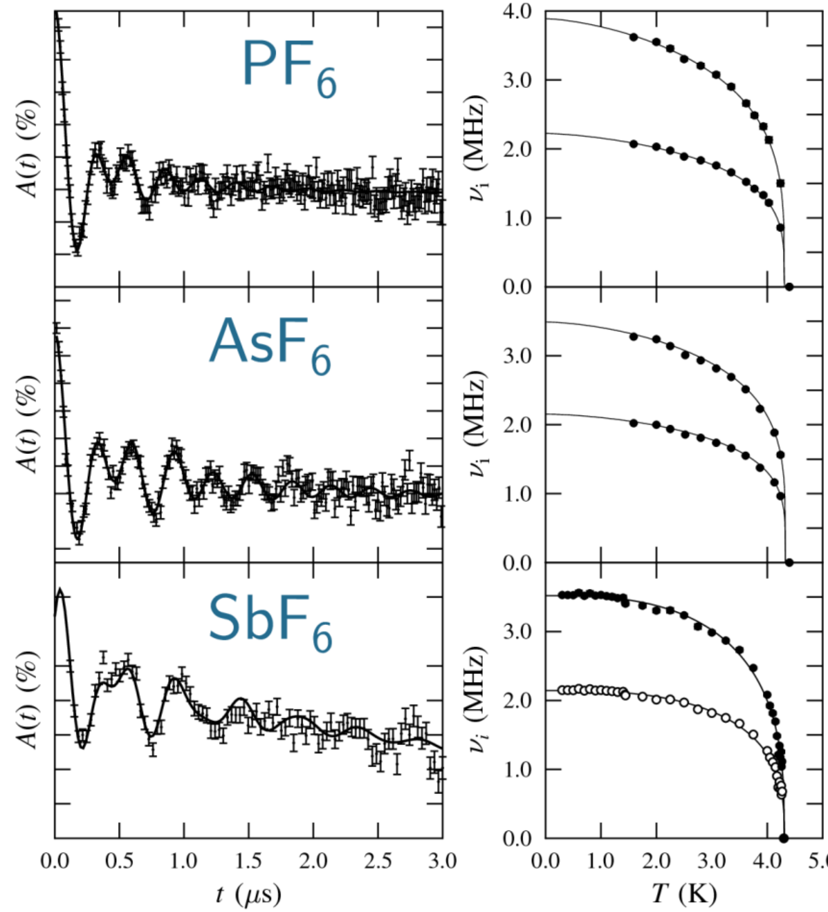


Octahedral anion

Tetrahedral anion







$$
\begin{aligned}
T_{\mathrm{N}} &\approx 1.5\ \mathrm{K} \\
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\end{aligned}
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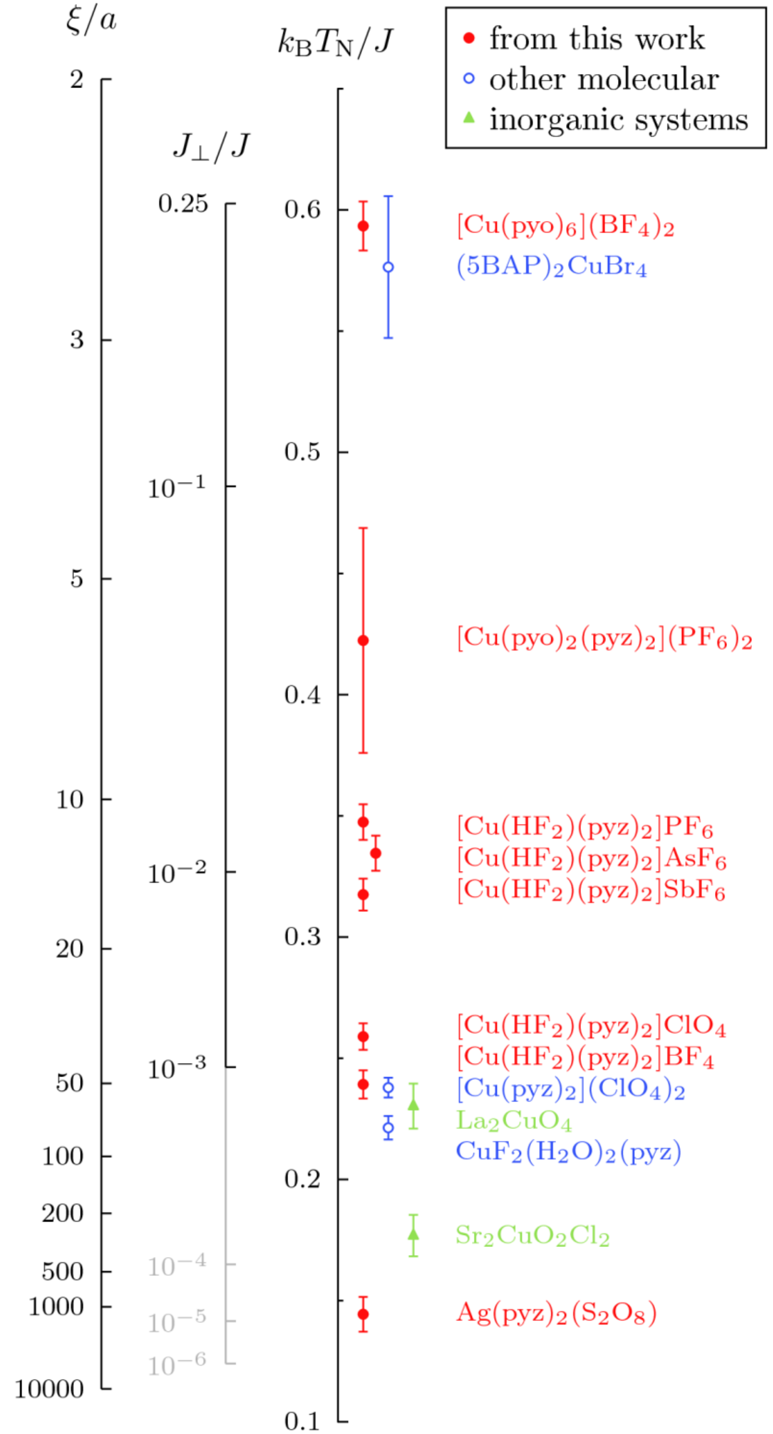
$$
\begin{aligned}
T_{\mathrm{N}} &\approx 4.2\ \mathrm{K} \\
J &\approx 13\ \mathrm{K} \\
|J'/J| &\approx 10^{-2}
\end{aligned}
$$

Goddard *et al.* New J. Phys. **10** 083025 (2008)

2D molecular magnets

Evaluation of the separation of several systems



Steele et al., PRB (2011)

With Super-MuSR

- High statistics results
- More throughput

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- High statistics results
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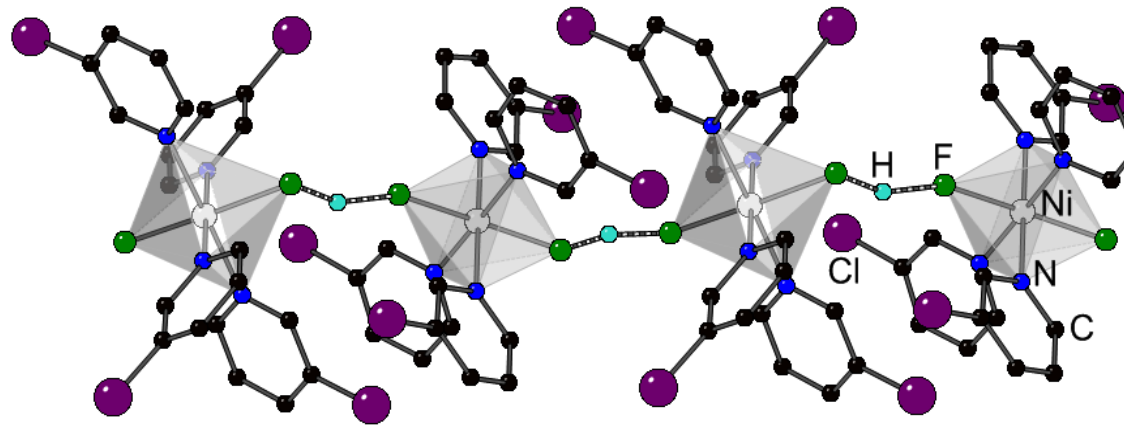
- Extension to other systems…

$[Ni(HF_2)(3\text{-}Clpy)_4]BF_4$: the hunt for Haldane chains

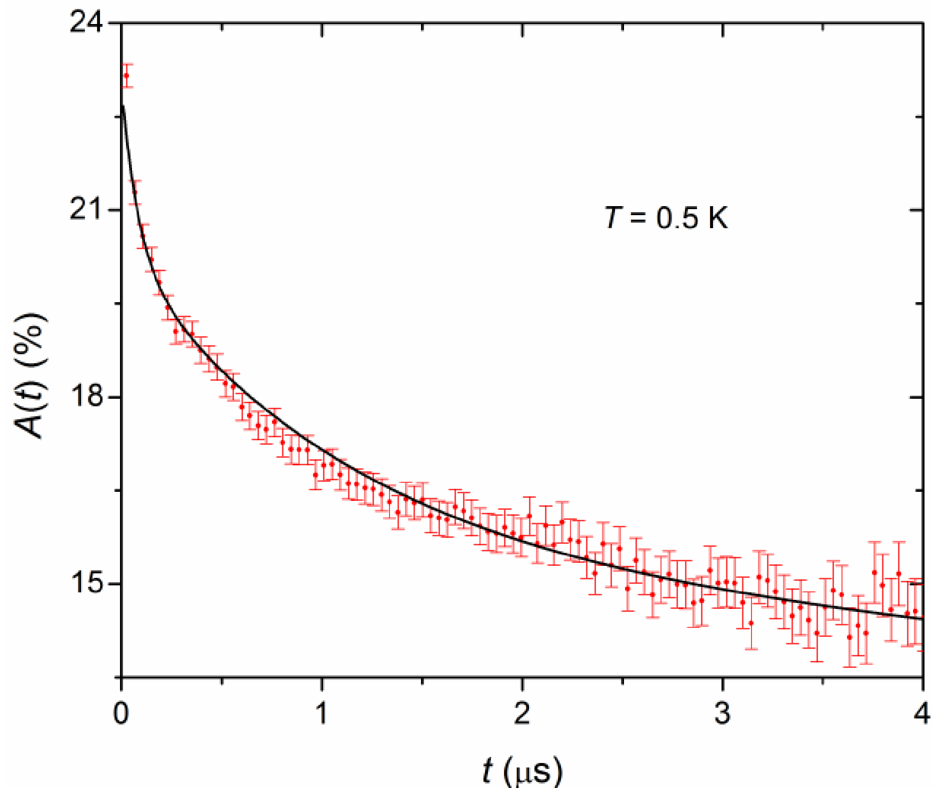


Well separated S=1 chains

J=4.9 K, D≈4 K

Good evidence for gapless, disordered ground state

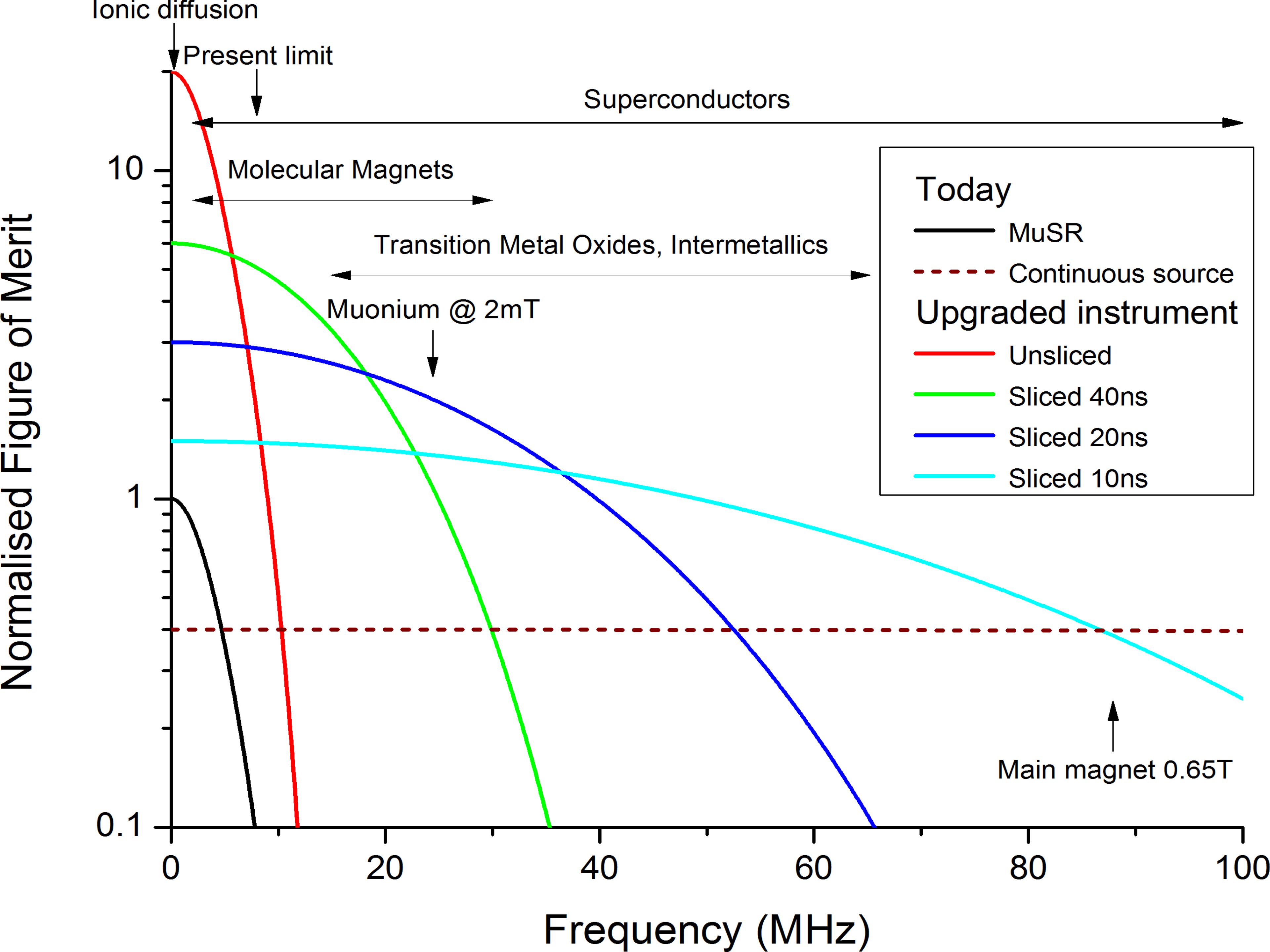
Manson et al., (2012)



$[Ni(HF_2)(3\text{-}Clpy)_4]BF_4$: the hunt for Haldane chains

Bring these S=1 systems into the ISIS time window

Larger moment systems



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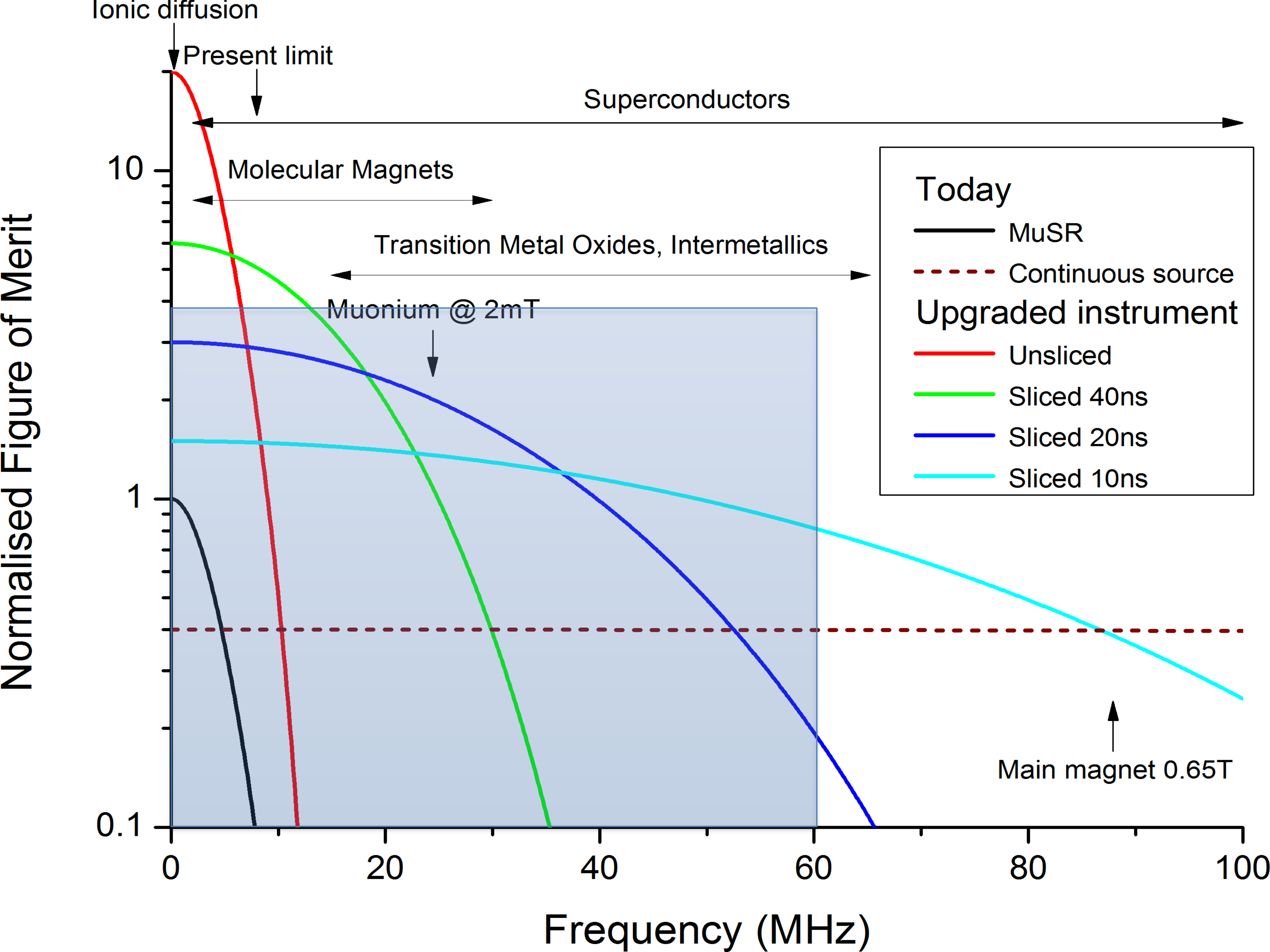

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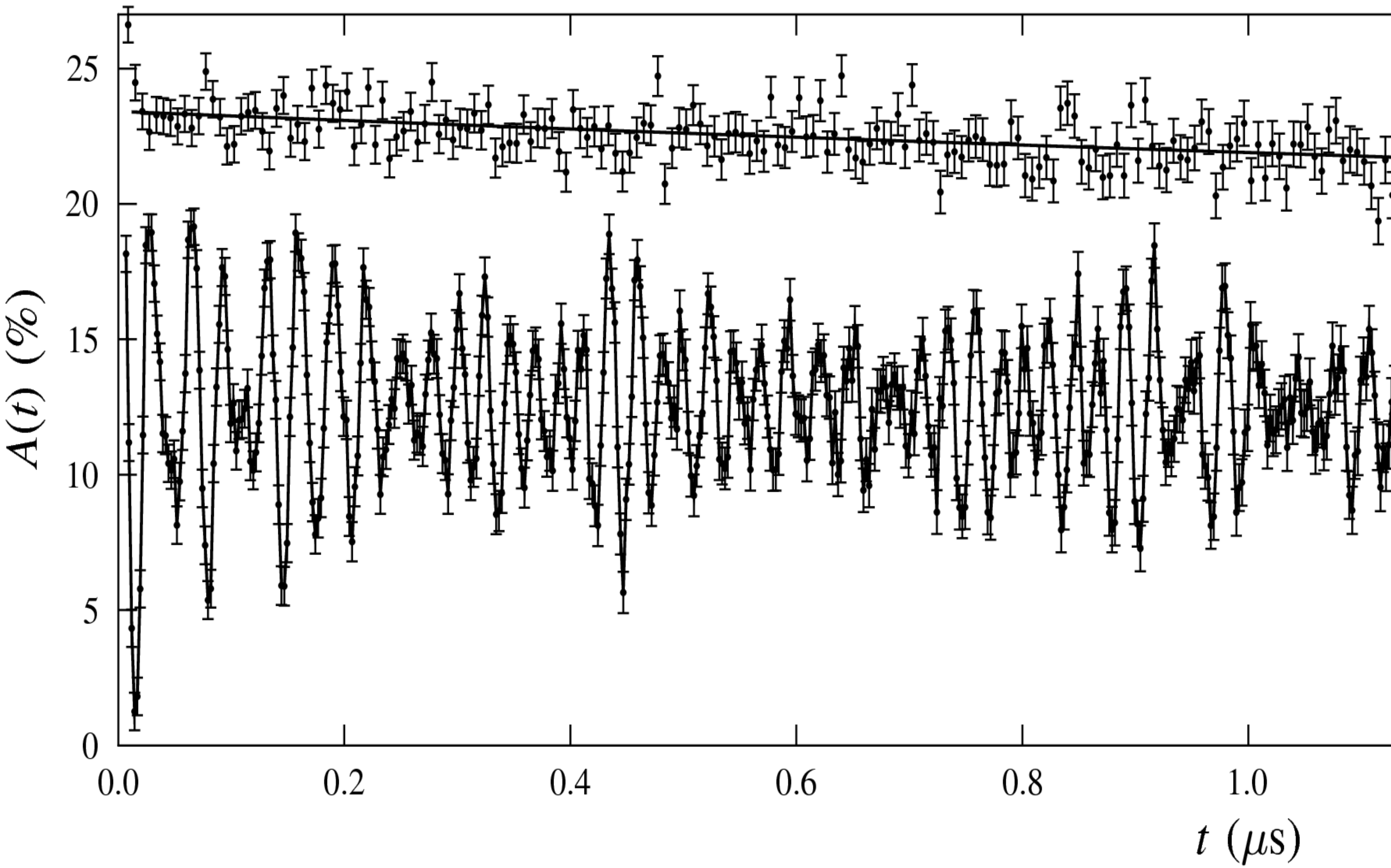
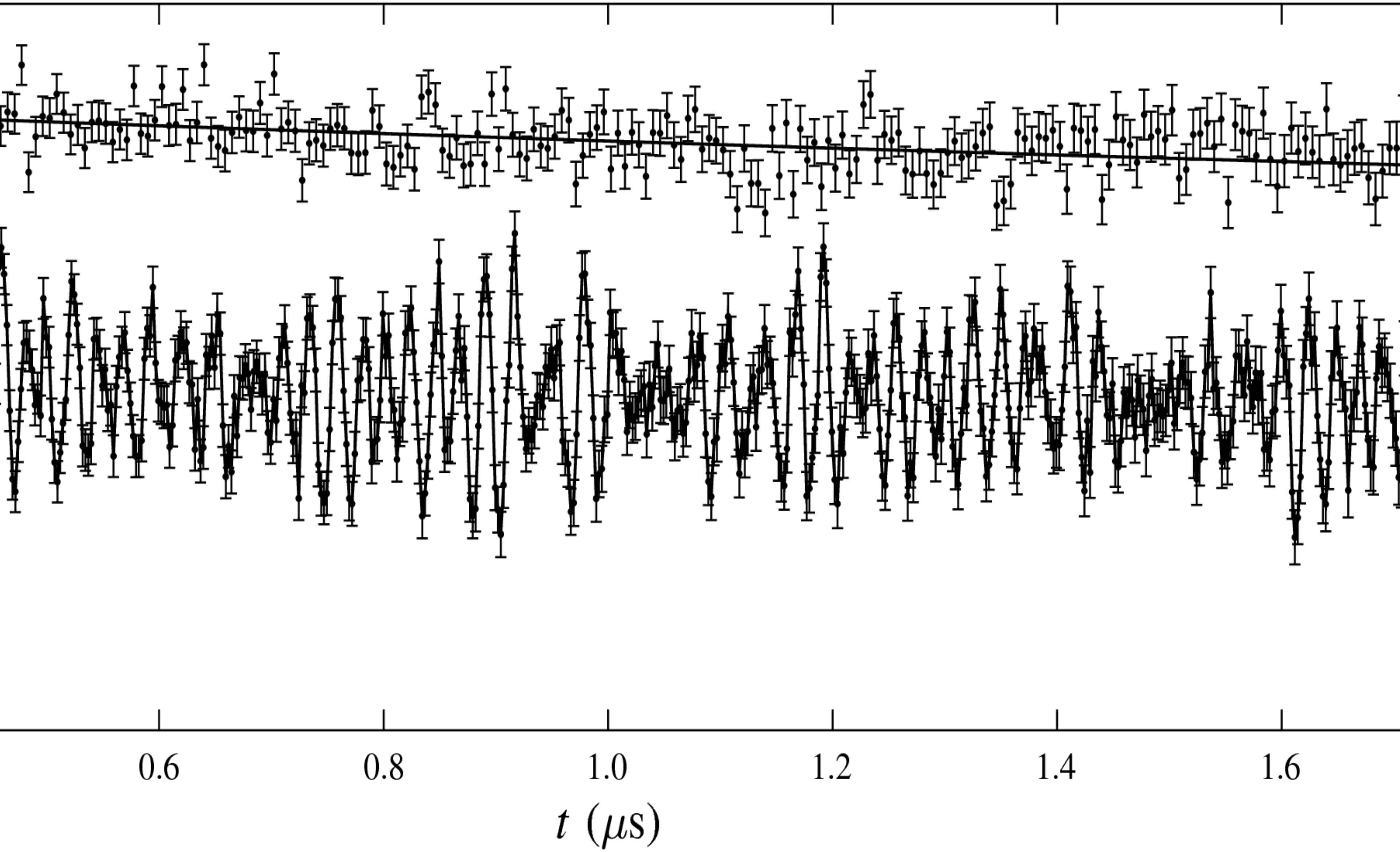
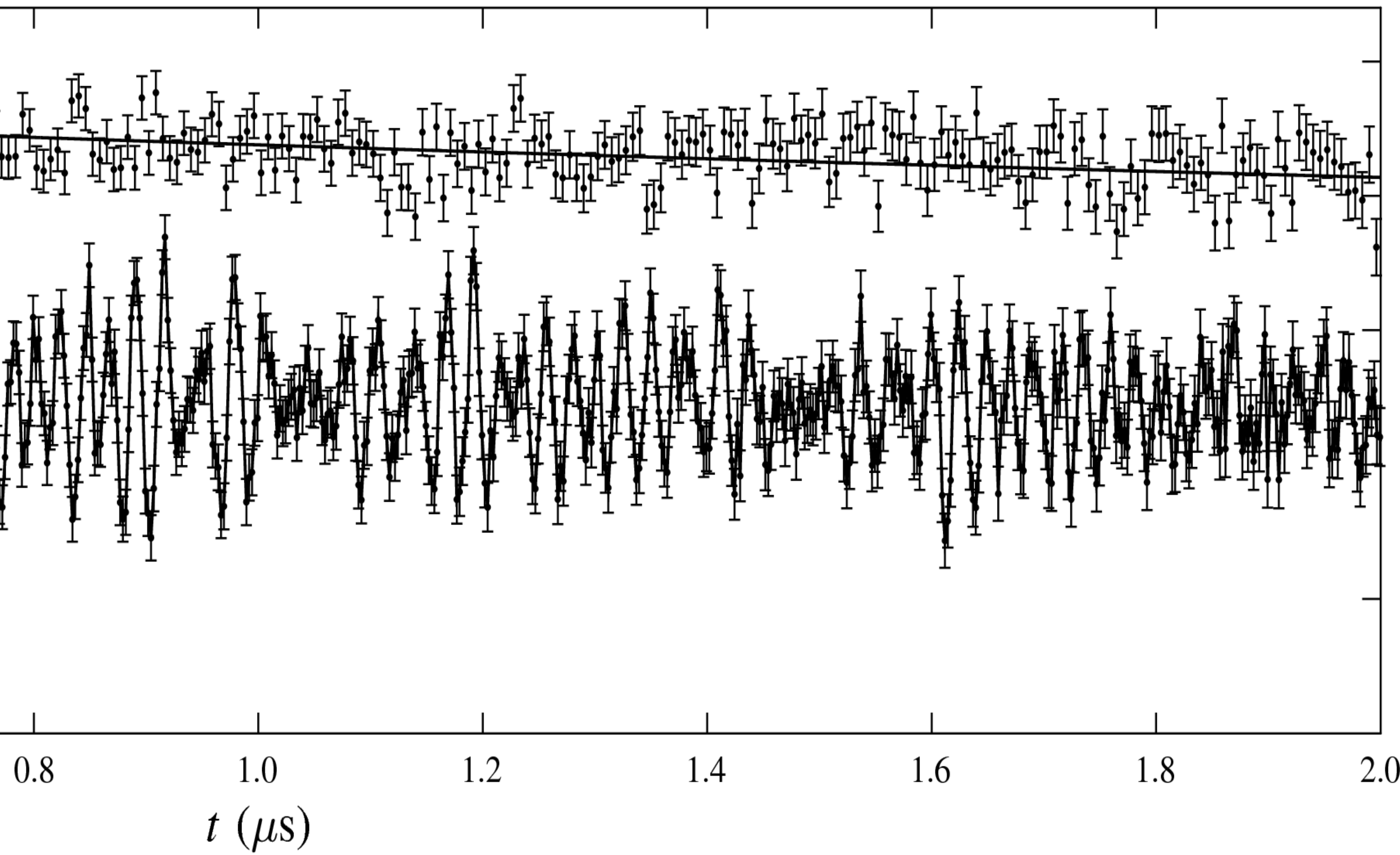
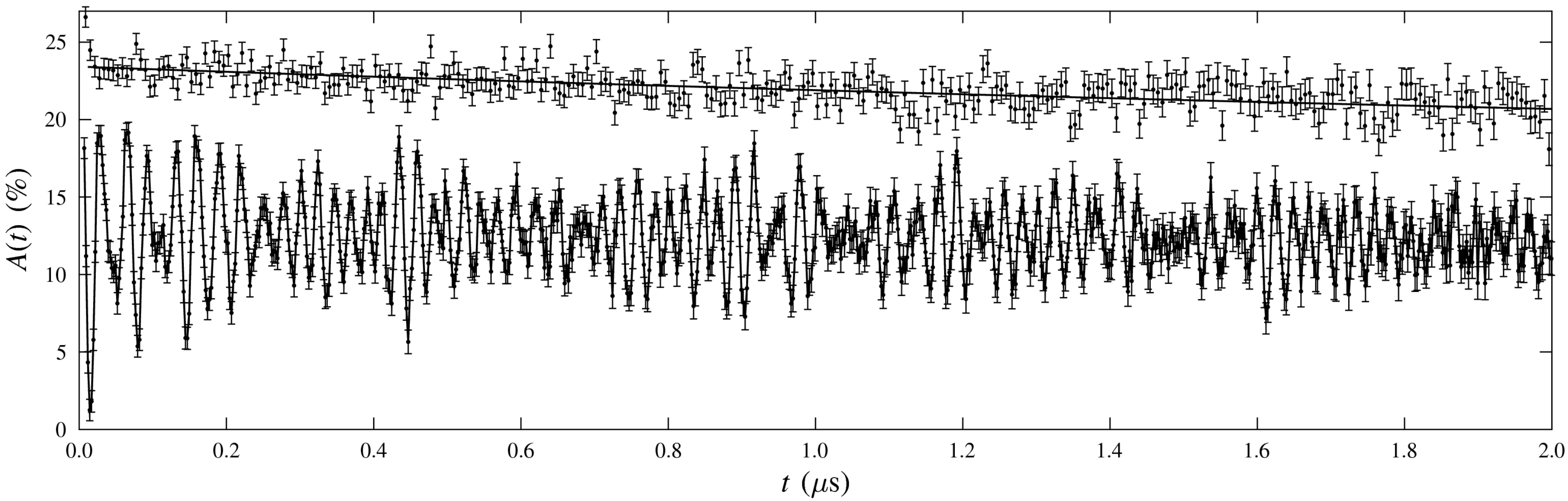
The most beautiful magnetic spectrum ever measured?



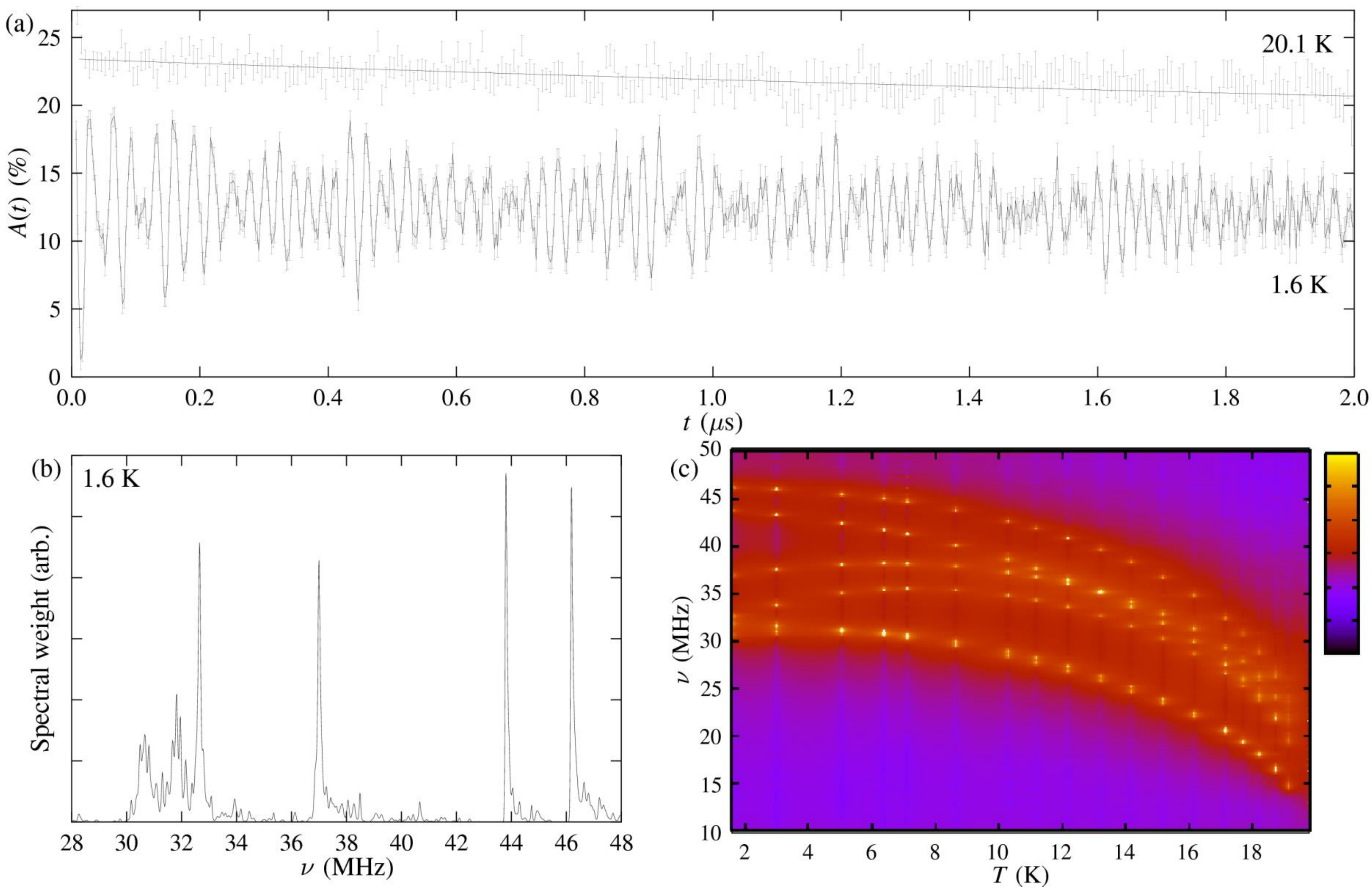


0.6
0.8
1.0
1.2
1.4
1.6
t (μs)


0.8
1.0
1.2
1.4
1.6
1.8
2.0
t (μs)

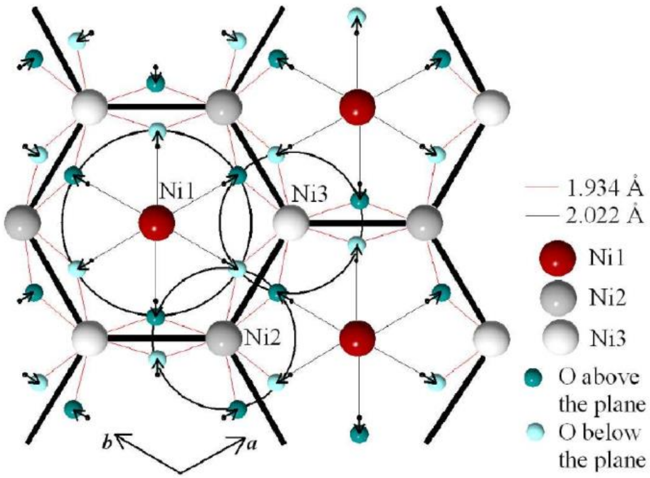


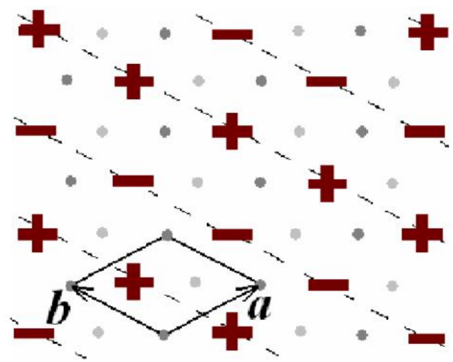
A(t) (%)
t (μs)
0
5
10
15
20
25
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0

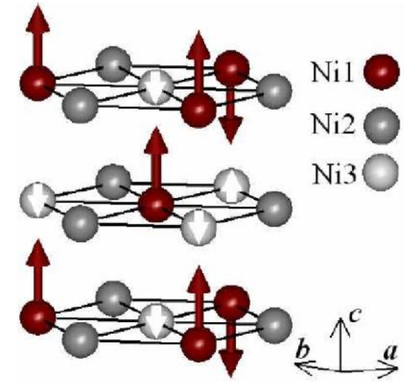


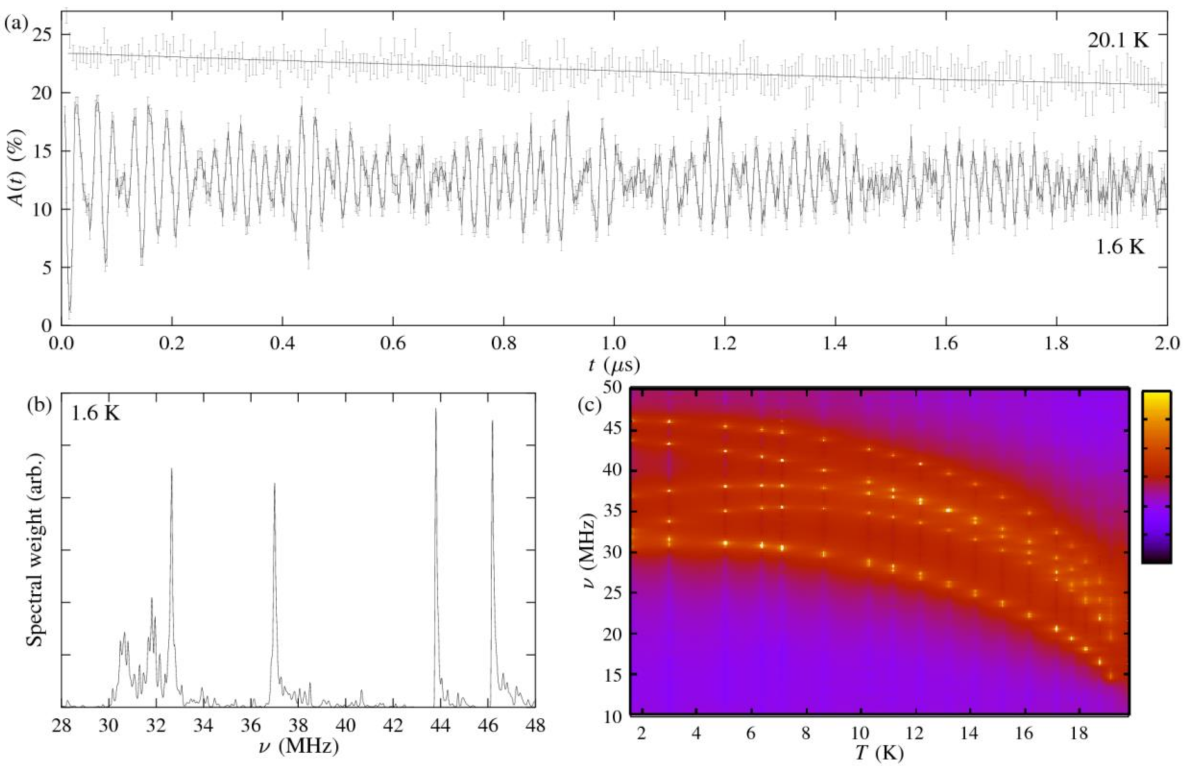
(a)
20.1 K
1.6 K
$A(t)$ (%)
t (μs)
(b)
1.6 K
Spectral weight (arb.)
ν (MHz)
(c)
ν (MHz)
T (K)

$AgNiO_2$: a new charge ordered state of matter?









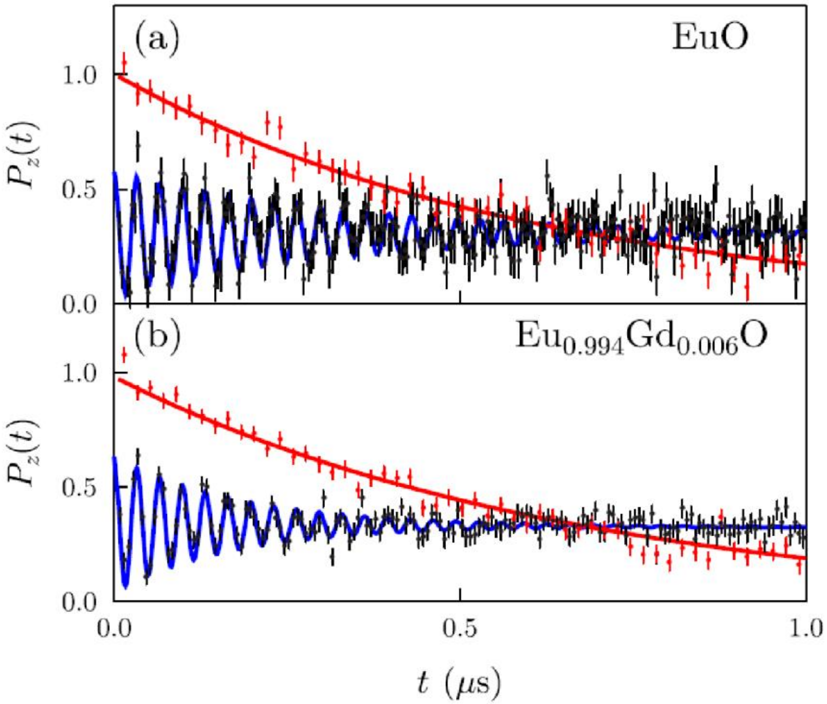
Orbital degeneracy lifted via a charge ordering mechanism

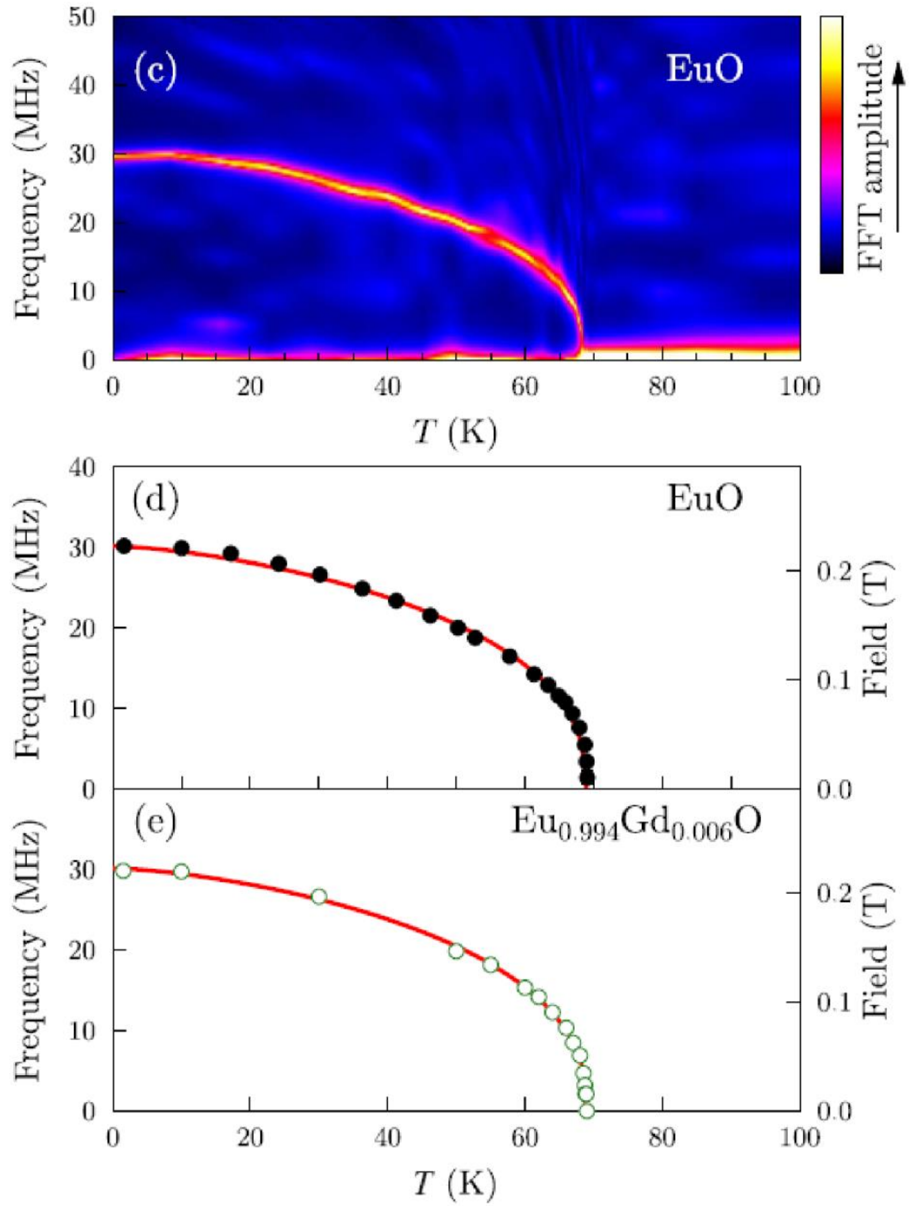
This gives rise to a well defined magnetic structure

Muons see this, but show an anomalous T dependence

Lancaster *et al.*, PRL **100** 017206 (2008)

EuO is THE localized ferromagnet





$$\nu(T) = \nu(0)\left[1 - (T/T_{\mathrm{c}})^{\alpha}\right]^{\beta}$$

T_{c}=69.01(1) K

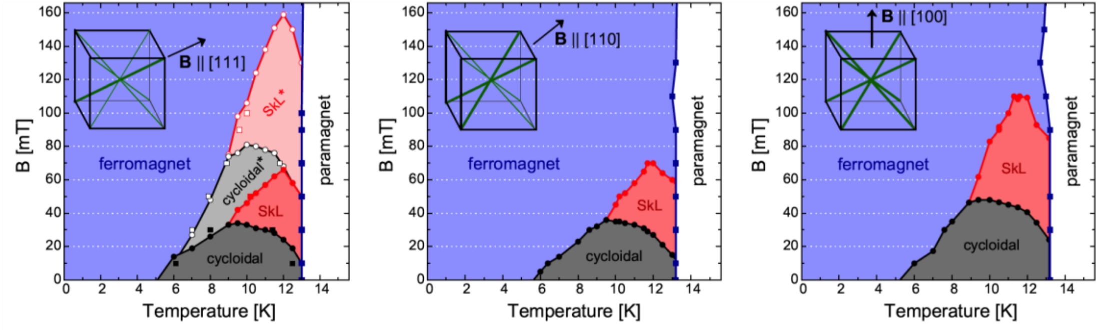
β= 0.32(1)

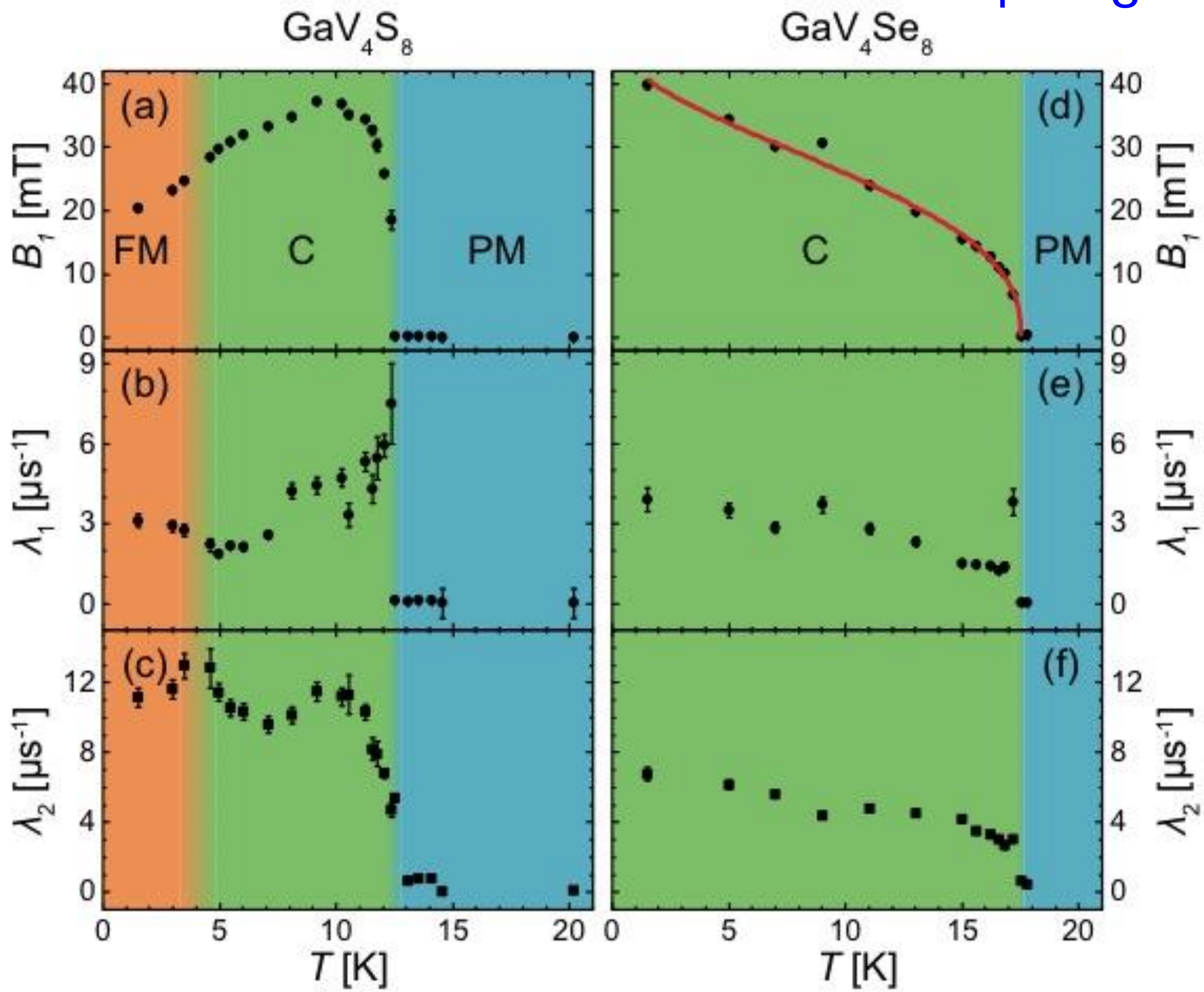
S.J. Blundell *et al.* PRB **81**, 092407 (2010)

Dynamic and static magnetism combined

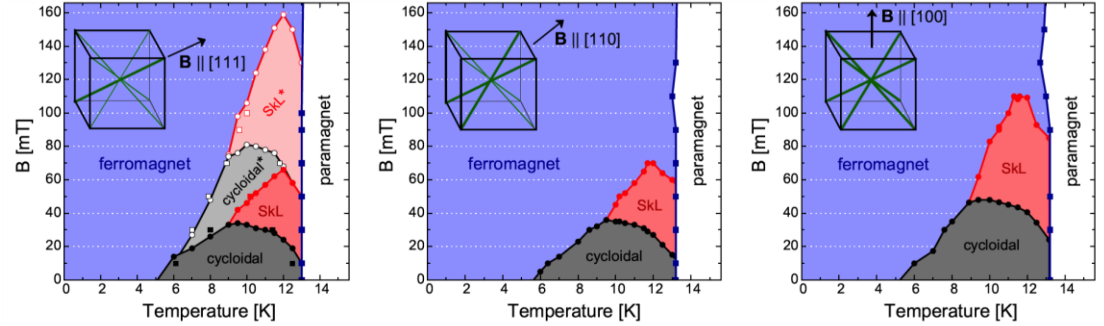
Case study: the skyrmion lattice

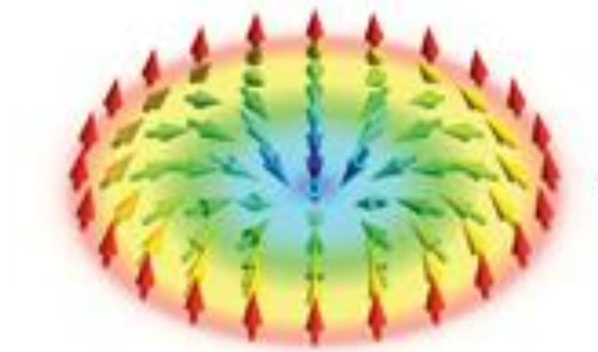
GaV_4S_8 and GaV_4Se_8



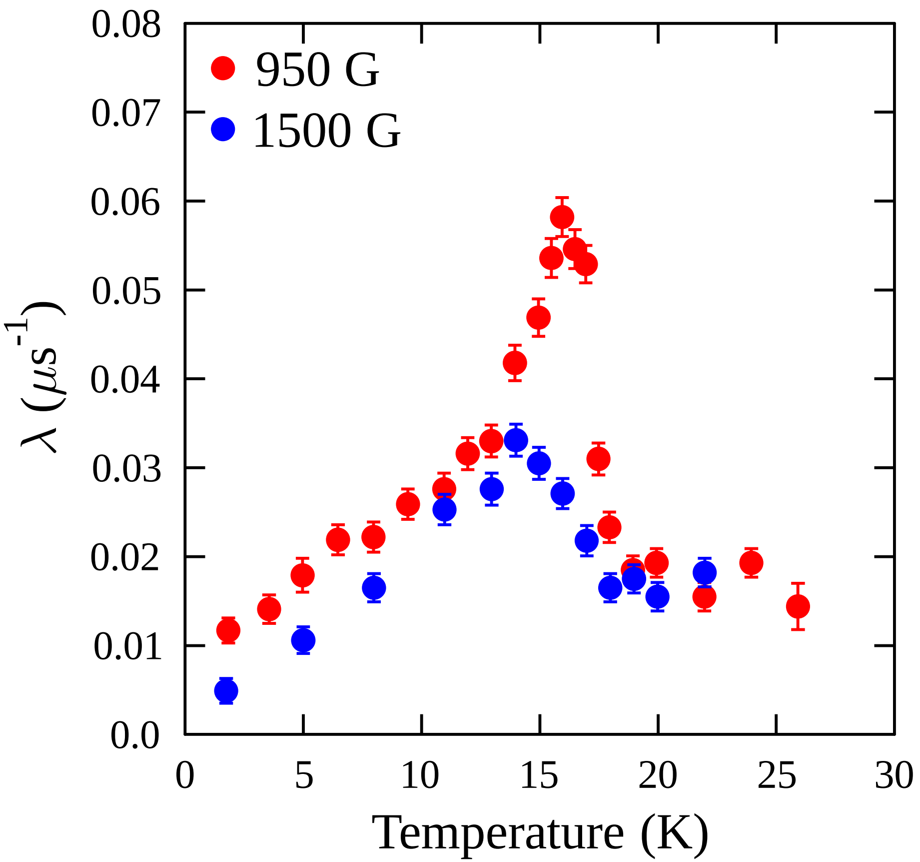


Franke *et al*., arXiv:1806.00412 (2018)





GaV_4S_8

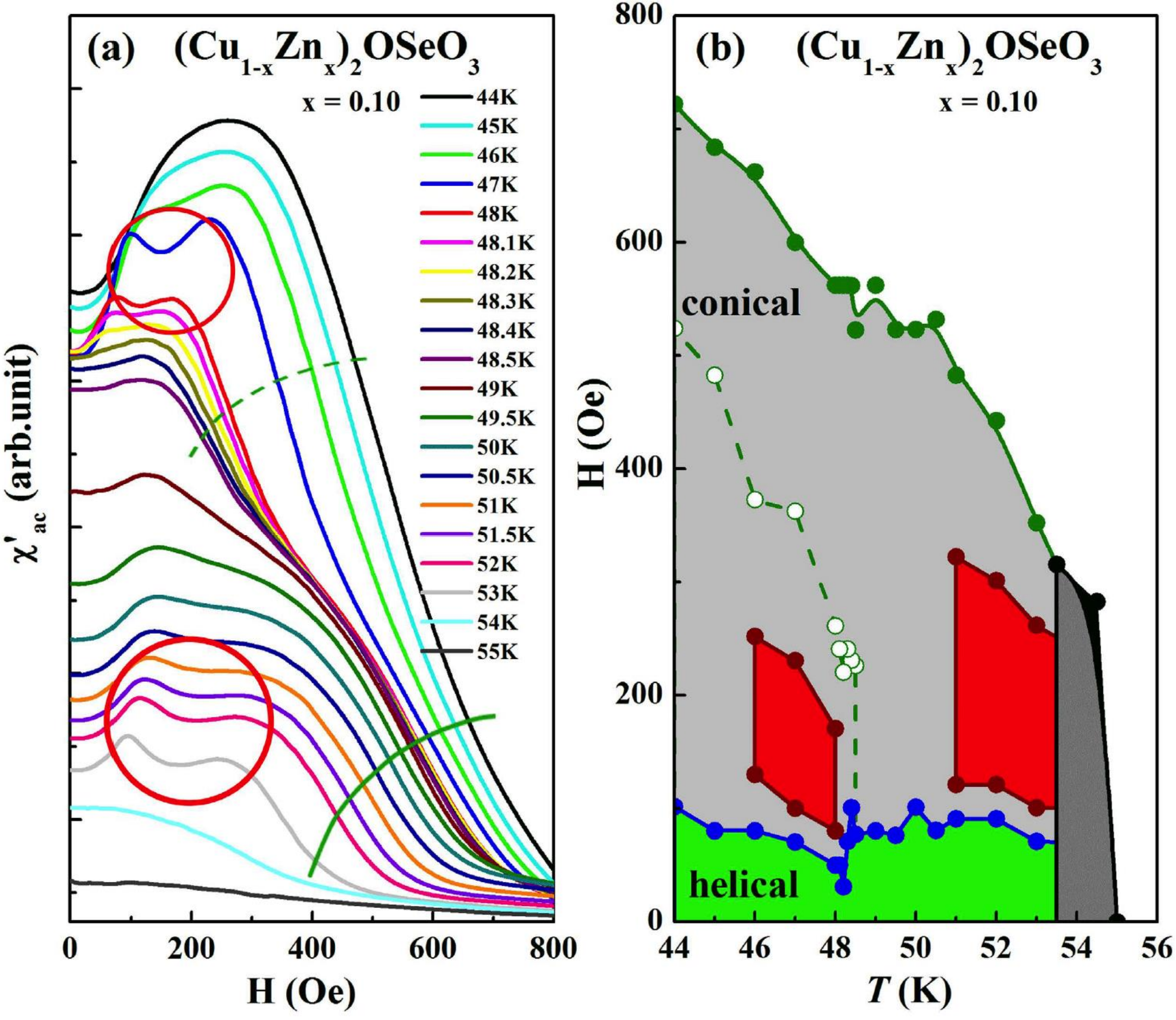


Large enhancement
in dynamic response
in the SkL

Franke *et al.*, arXiv:1806.00412 (2018)

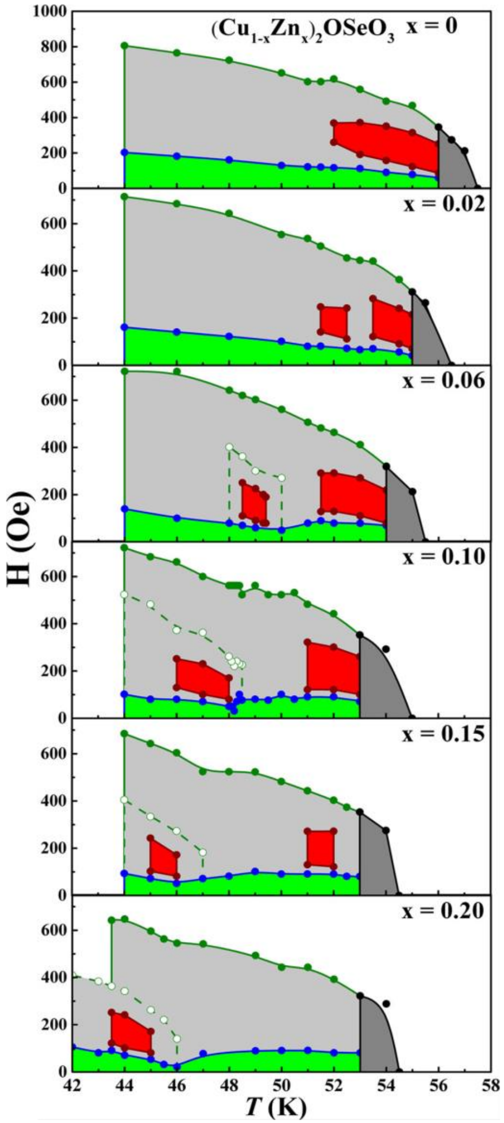
Reentrant skyrmion phases in Zn-doped Cu_2OSeO_3

Stefancic *et al*., arXiv:1807.04641 (2018)



H.C. Wu et al., Scientific Reports 5, 13579 (2015)

Introducing disorder



Stefancic *et al*., arXiv:1807.04641 (2018)

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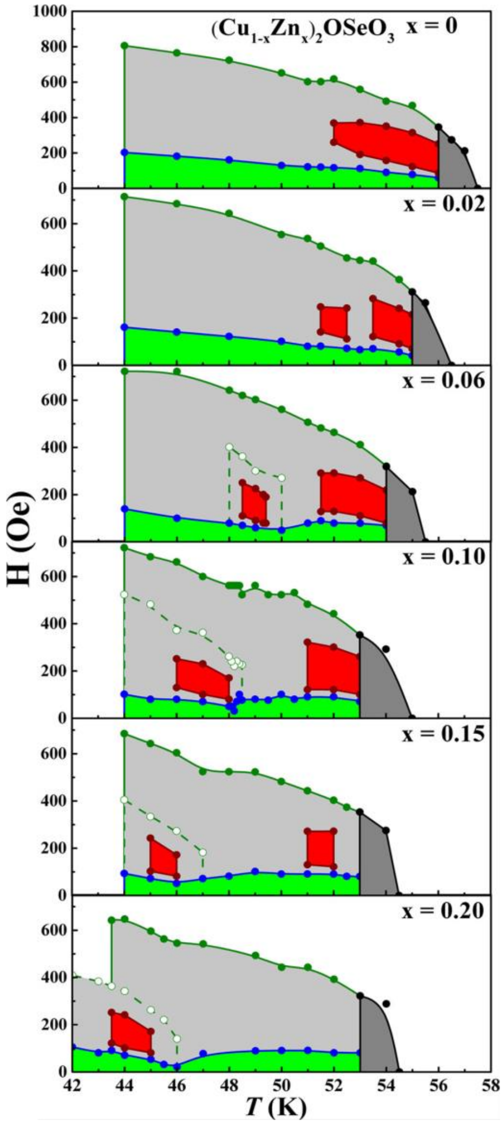

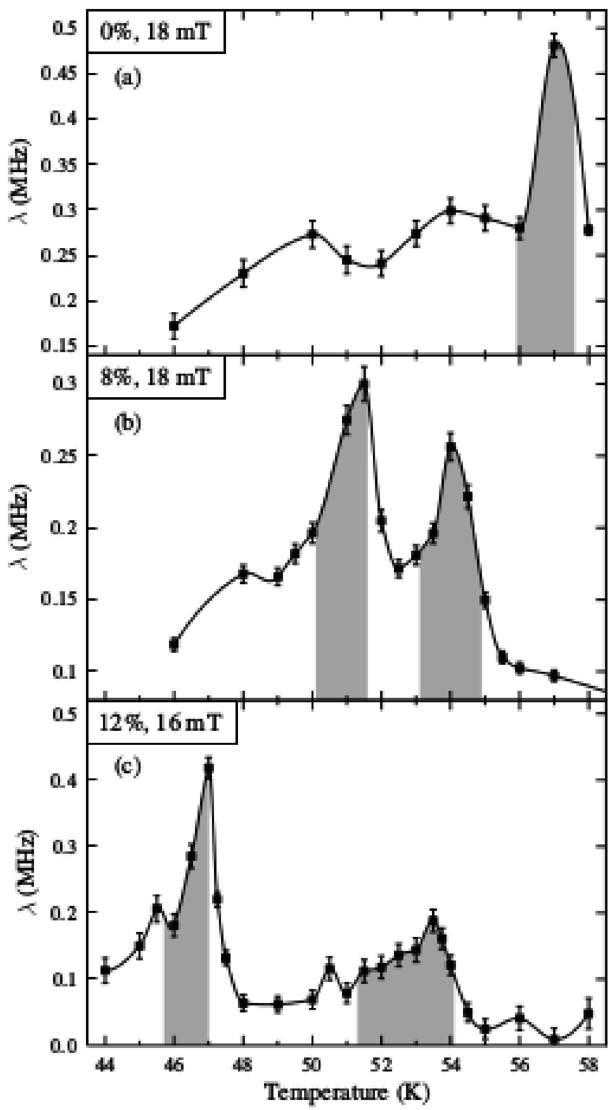

x=0%

x=8%

X=12%

Stefancic *et al*., arXiv:1807.04641 (2018)

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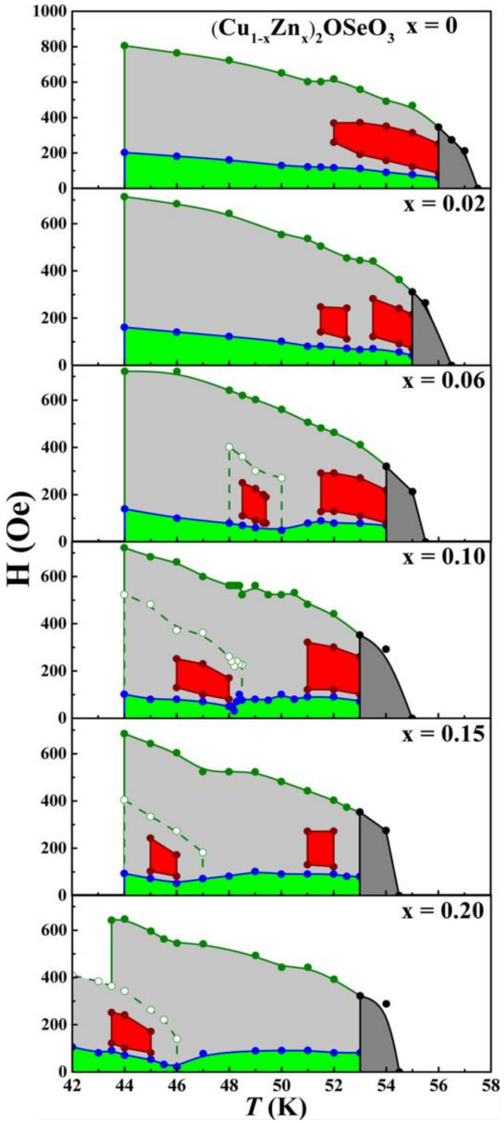
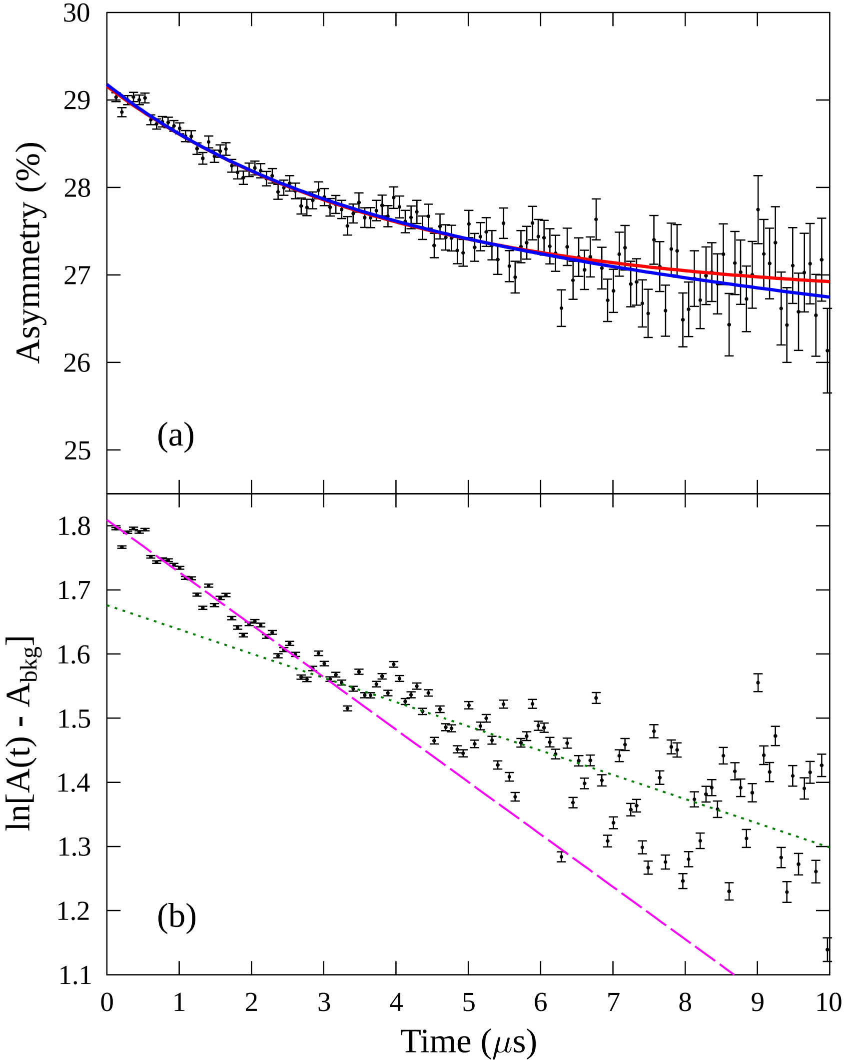




2 exponentials,
implying
2 muon sites

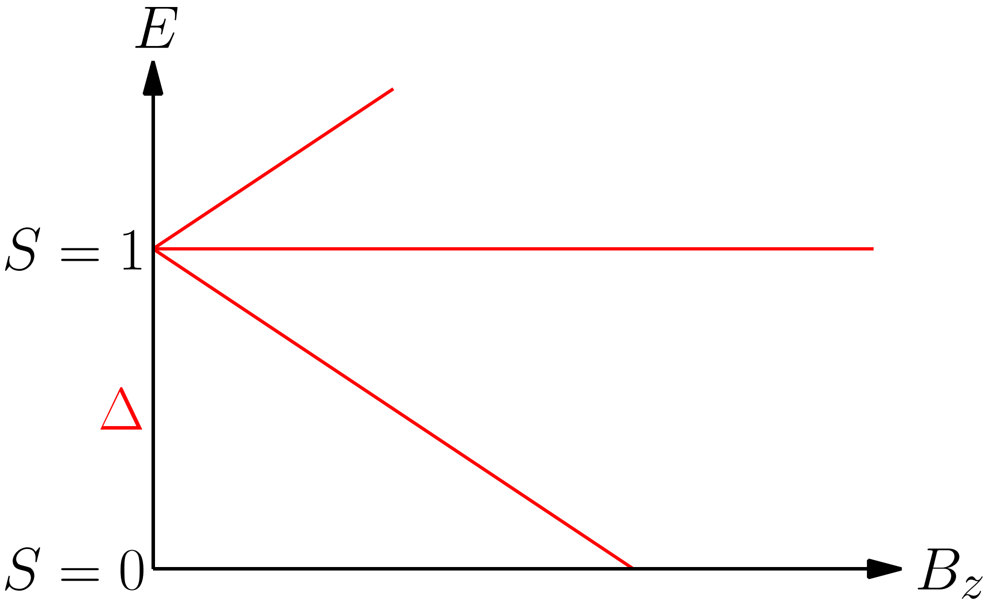
Evidence for
Phase separation

Stefancic *et al.*, arXiv:1807.04641 (2018)

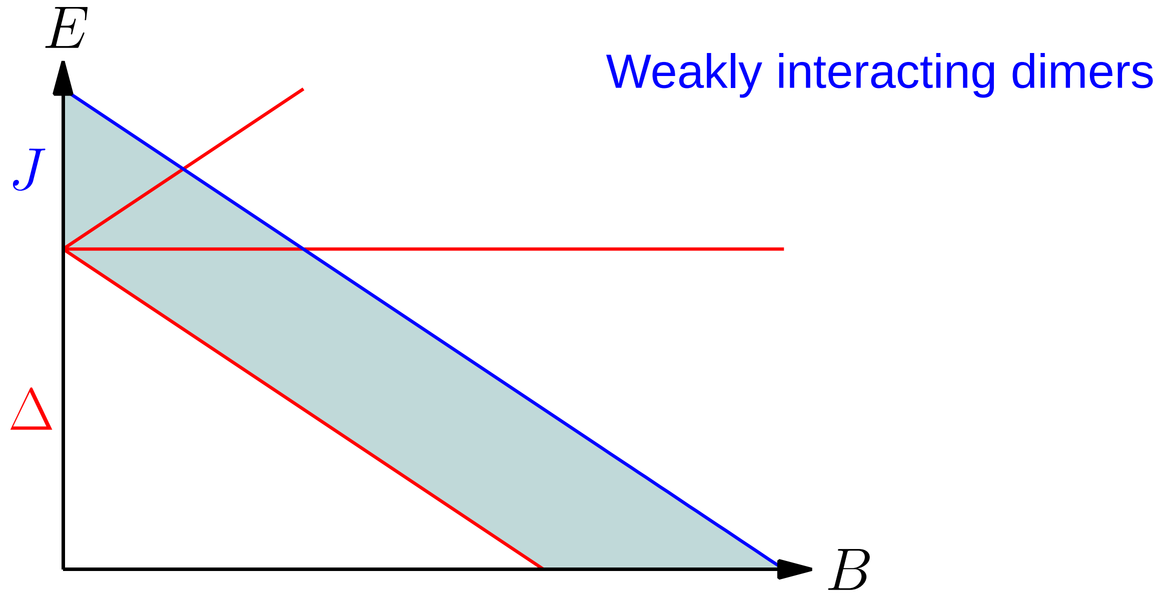
Future directions in quantum magnetism:

Systems built from dimers

Isolated dimers

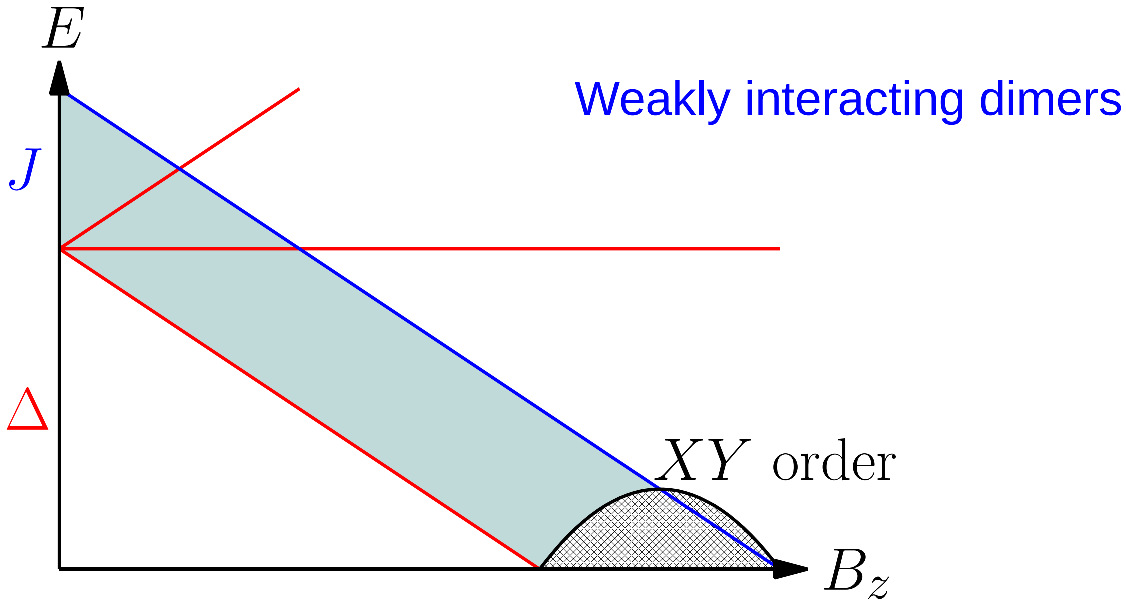


Weakly coupled dimers



In an idealized case we expect a quantum phase transition to *XY* magnetic order

Weakly coupled dimers

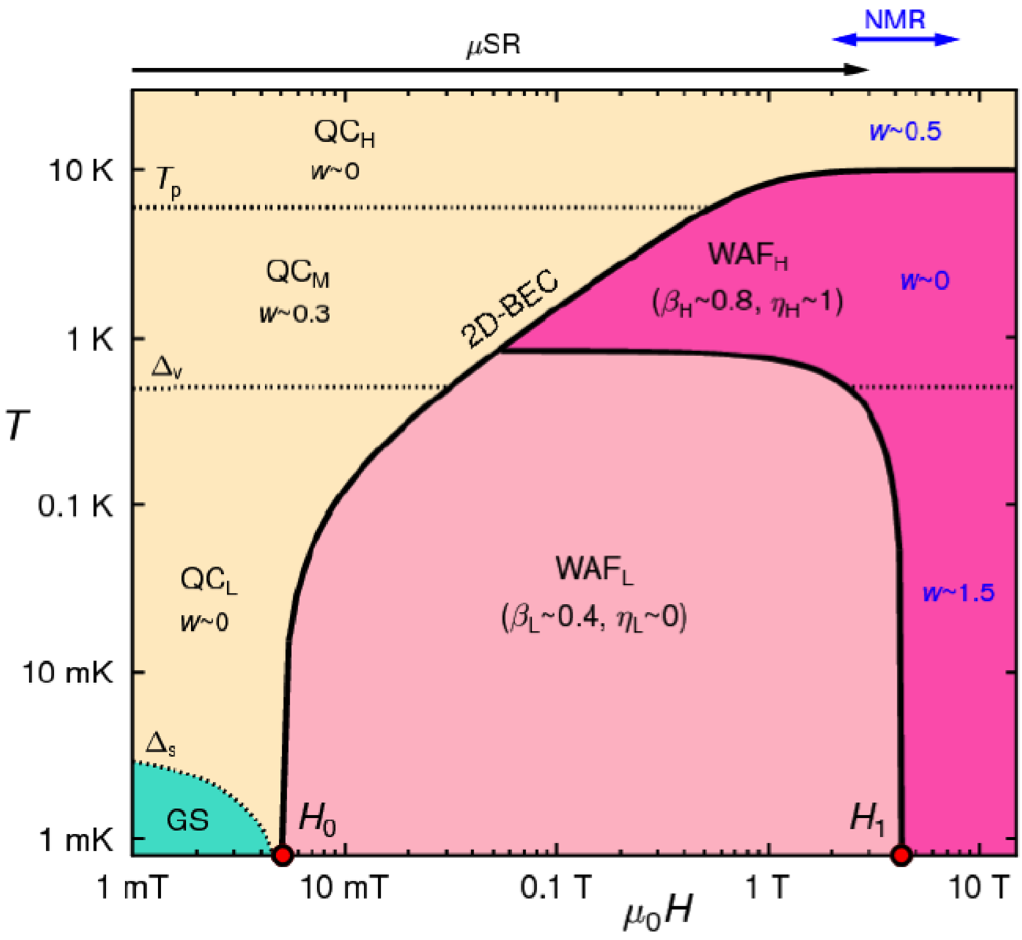


In an idealized case we expect a quantum phase transition to *XY* magnetic order

Spin liquids

Frustration and fluctuations lead to an exotic ground state

Spin liquid state in κ-$ET_2Cu_2(CN)_3$



Ground state order suppressed by QM fluctuations

Field induced quantum phase transition

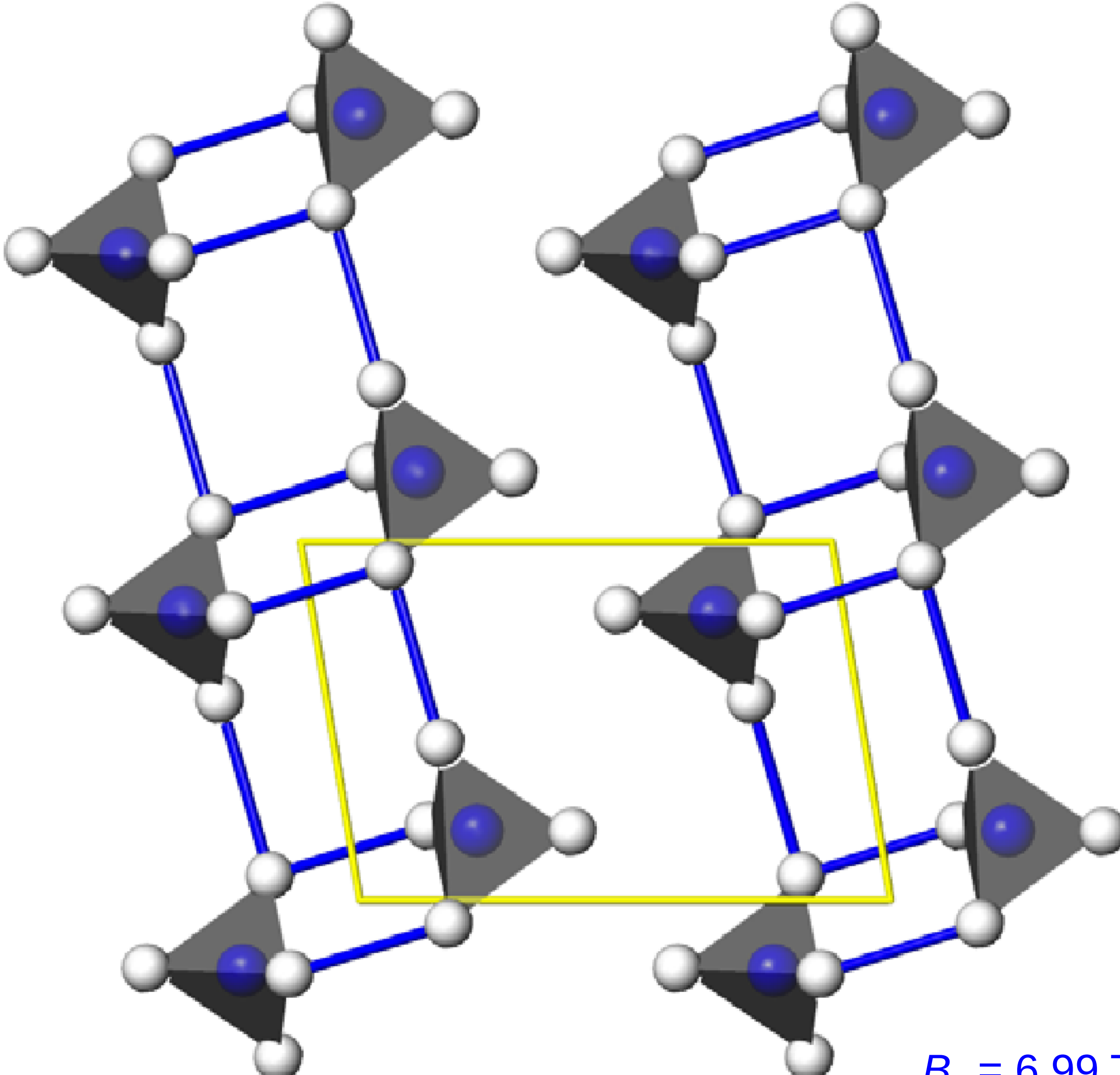
Critical behaviour consistent with bosonic or fermionic excitations

Nature **471** 612616 (2011)

Spin ladders as intermediate systems

$(Hpip)_2CuBr_4$: strong run spin ladder

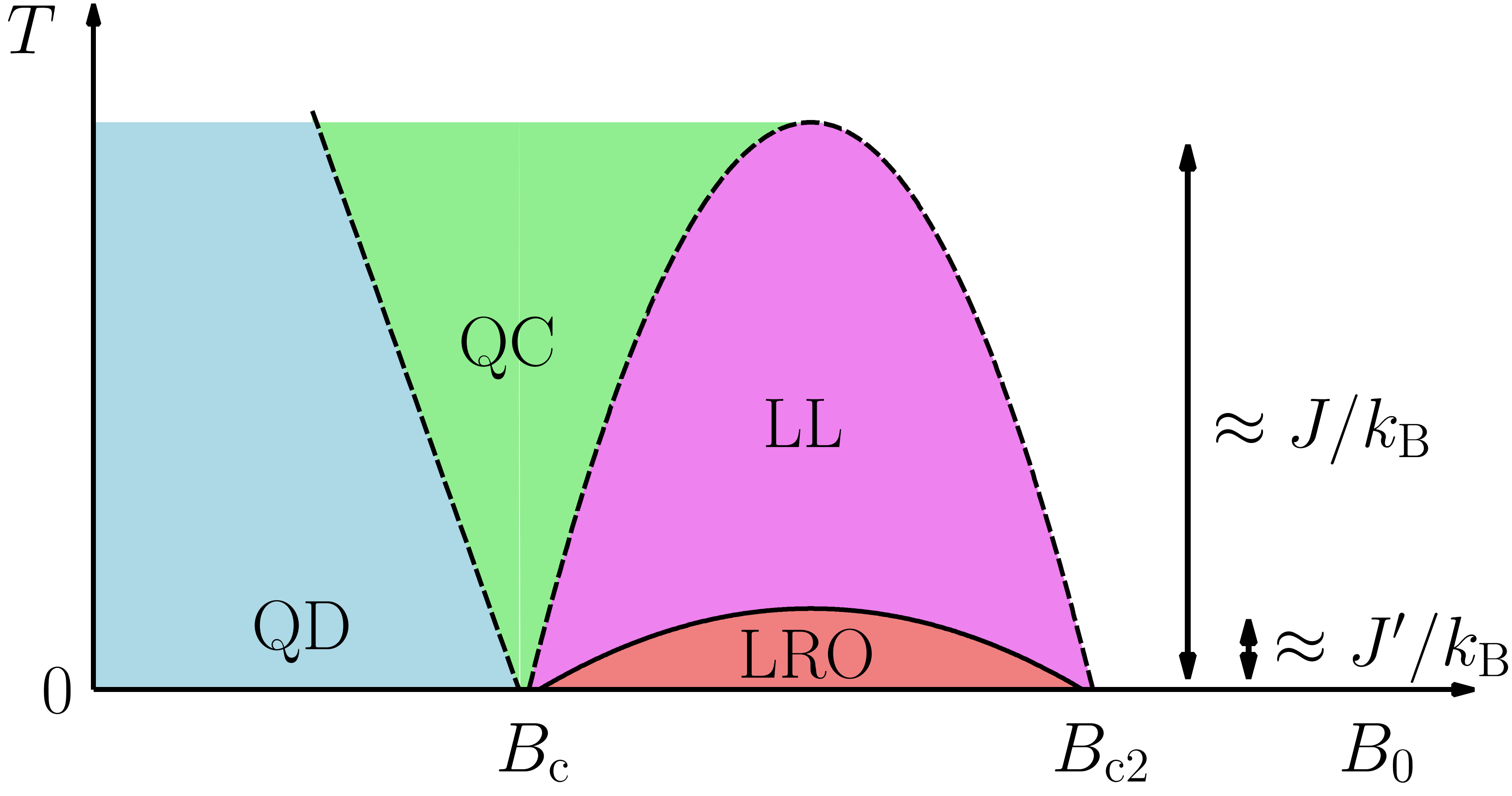
J_{leg}/J_{rung} =0.25



$(C_5H_{12}N)_2CuBr_4$

B_c = 6.99 T

Generic phase diagram



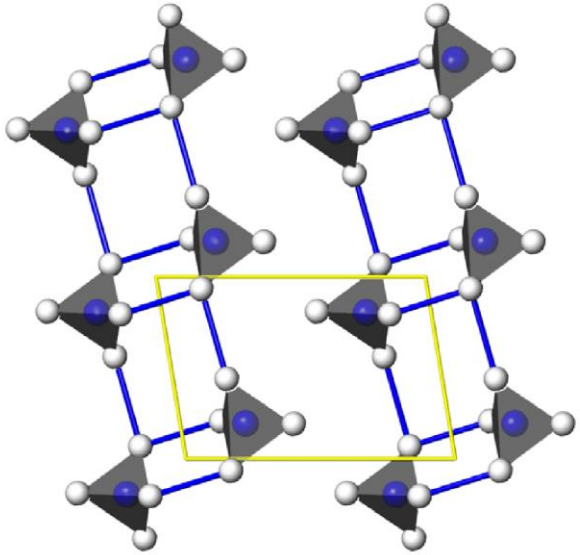
Diffusion and dynamics

arXiv:1806.09402

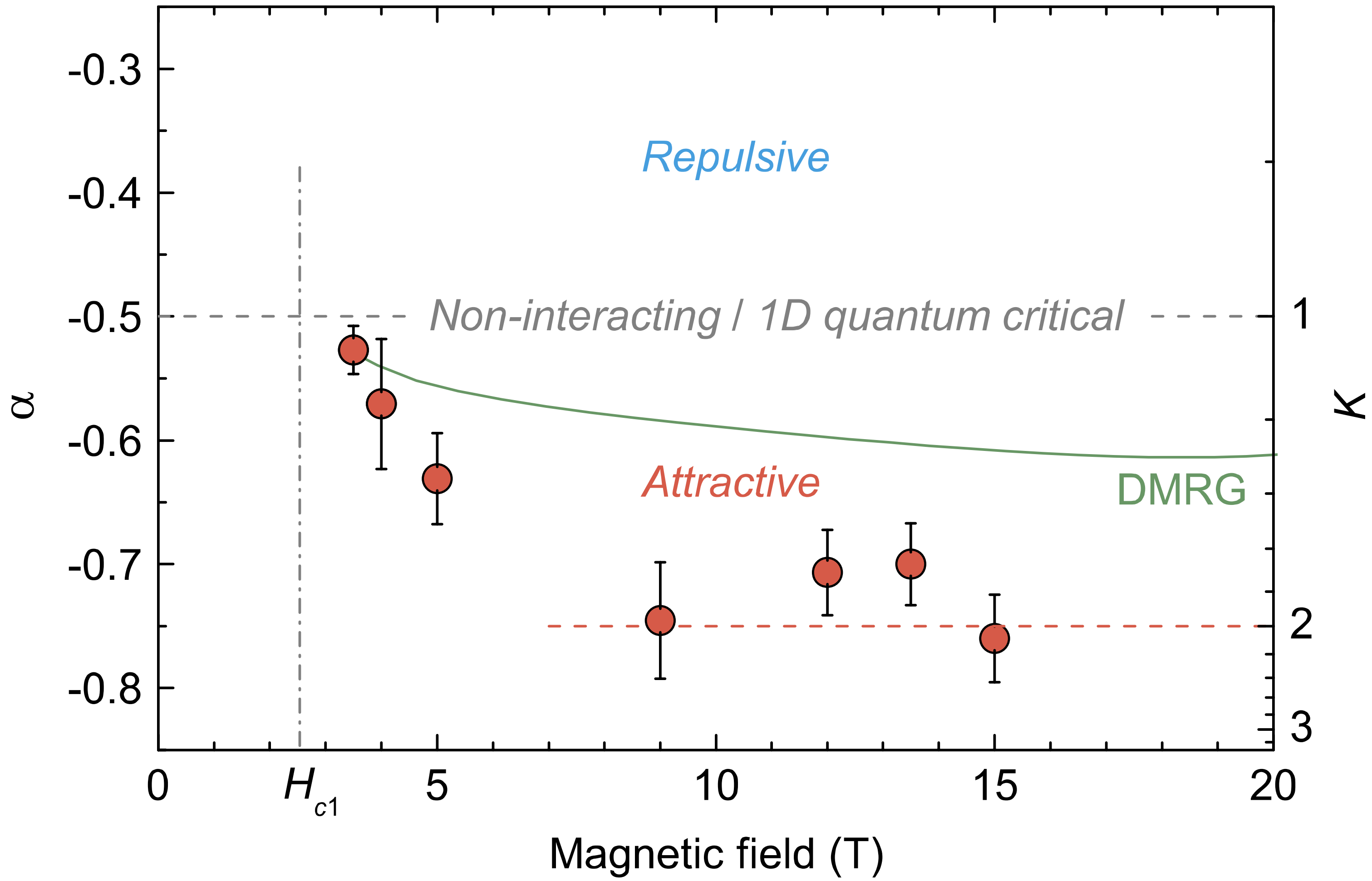
Two predicted regimes of spin ladder behaviour:

Strong rung: repulsive interactions,
$1/T_1 \sim T^{\alpha}$, $\alpha > -0.5$

Strong leg: attractive interactions,
$1/T_1 \sim T^{\alpha}$, $\alpha < -0.5$



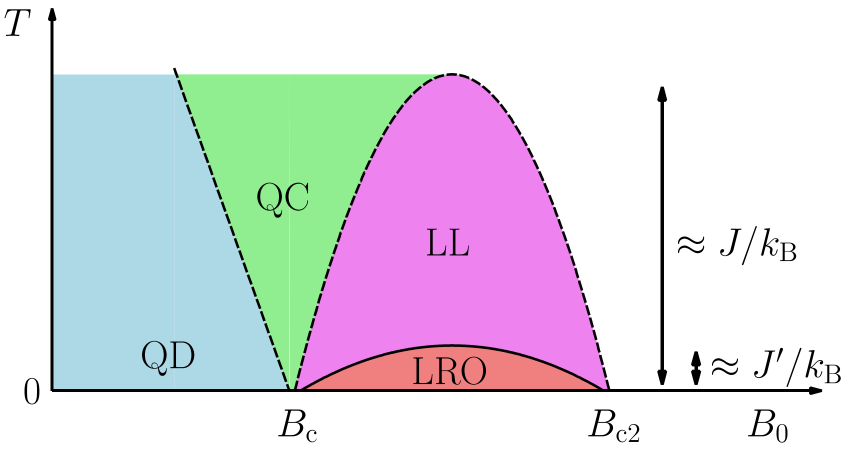
DIMPY: a strong-leg spin ladder

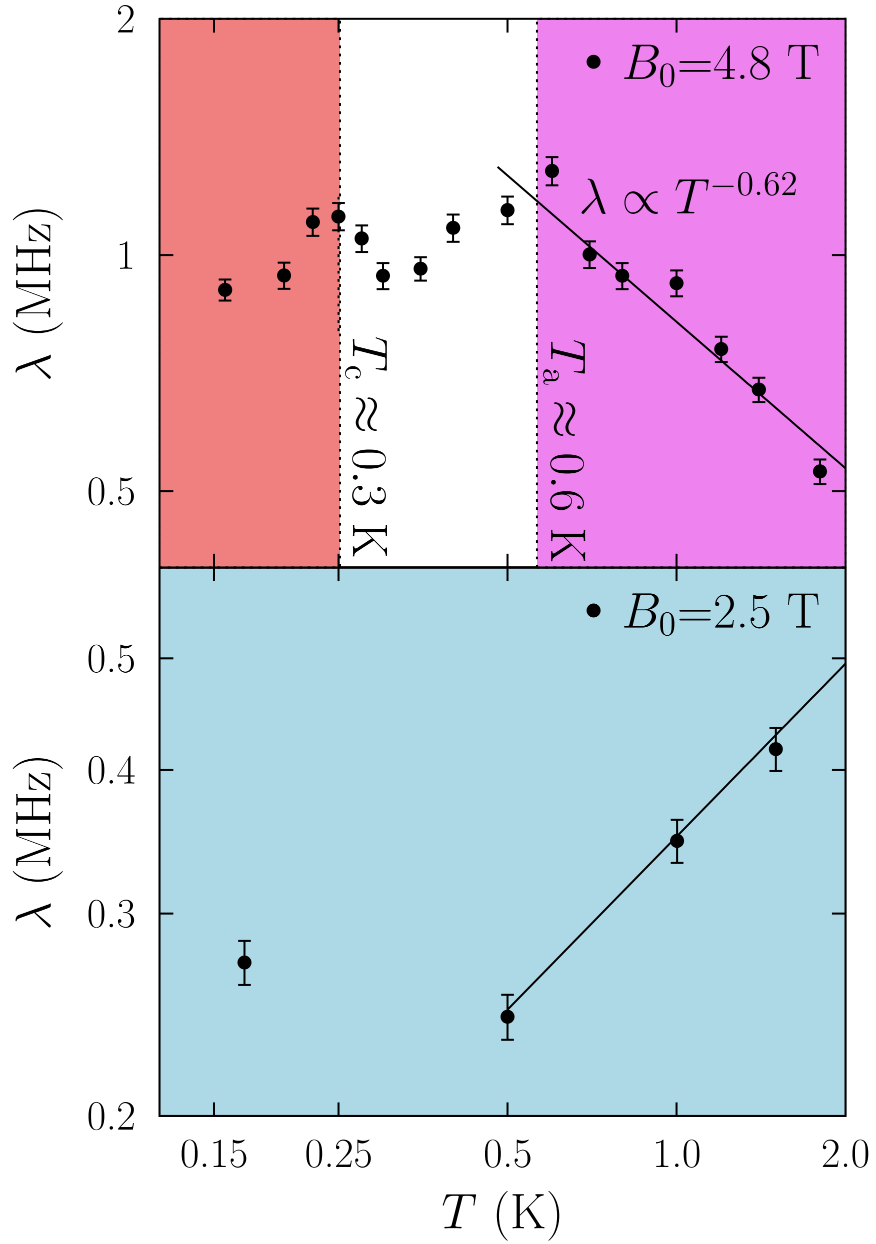


Power law in spin relaxation $1/T_1$ gives an insight into interactions

M. Jeong, *et al.*, Phys. Rev. Lett. **111**, 106404 (2013).

DIMPY: a strong-leg spin ladder





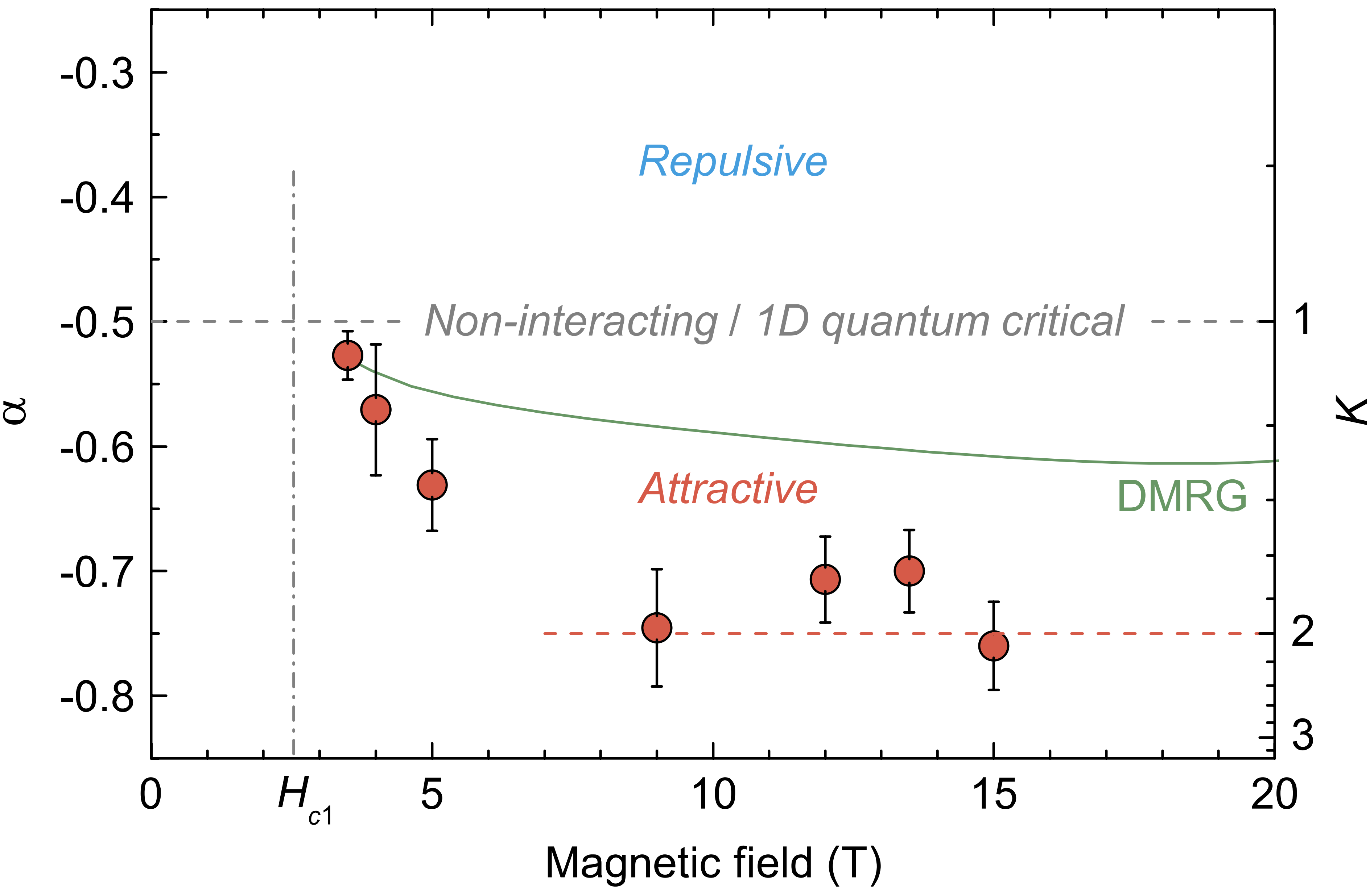
$(C_7H_{10}N)_2CuBr_4$

J_{leg}/J_{rung}=2.3

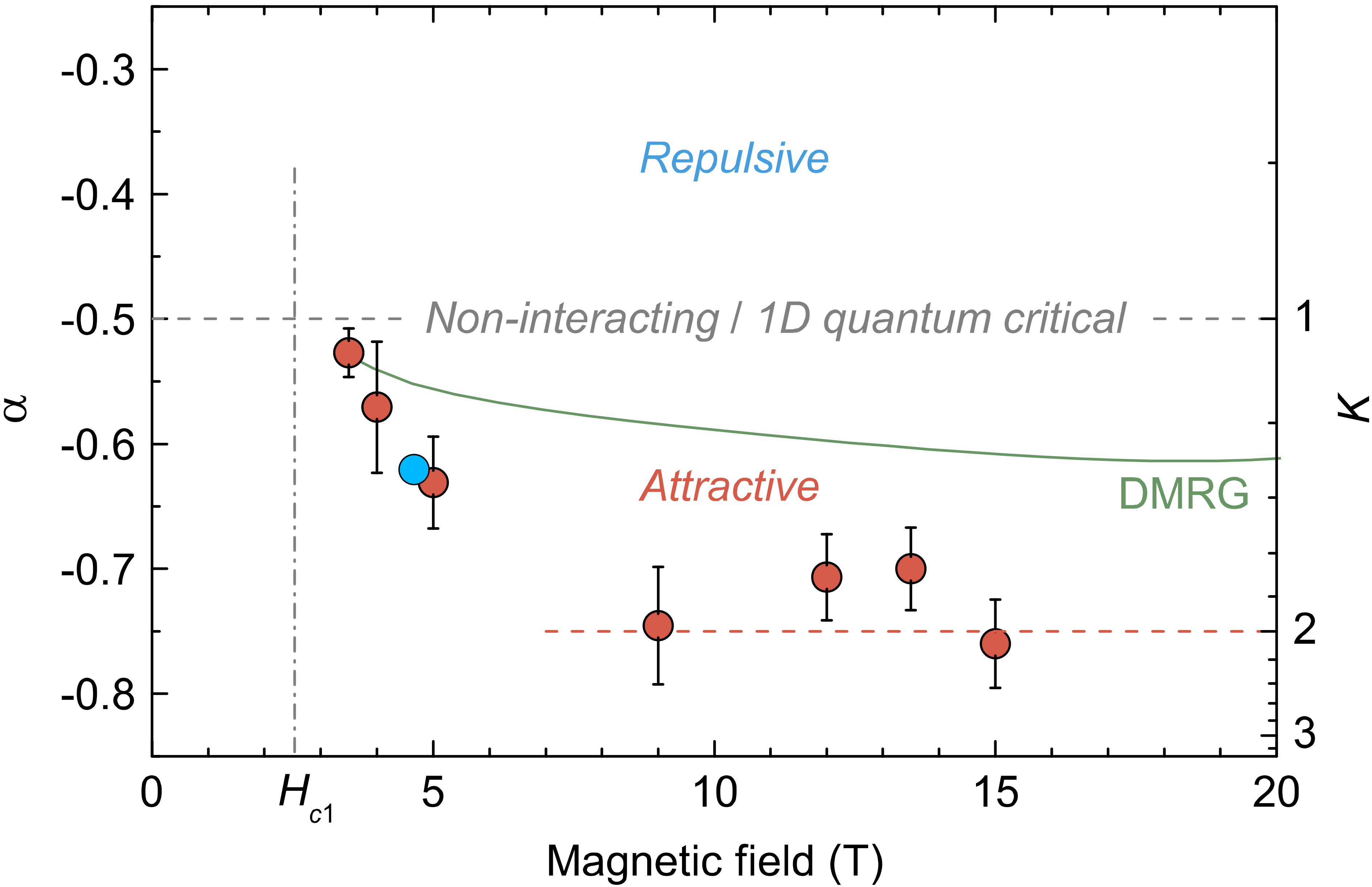
B_c = 3.0 T

J.S. Möller *et al*., Phys. Rev. B **95** 020402(R) (2017)

DIMPY: a strong-leg spin ladder

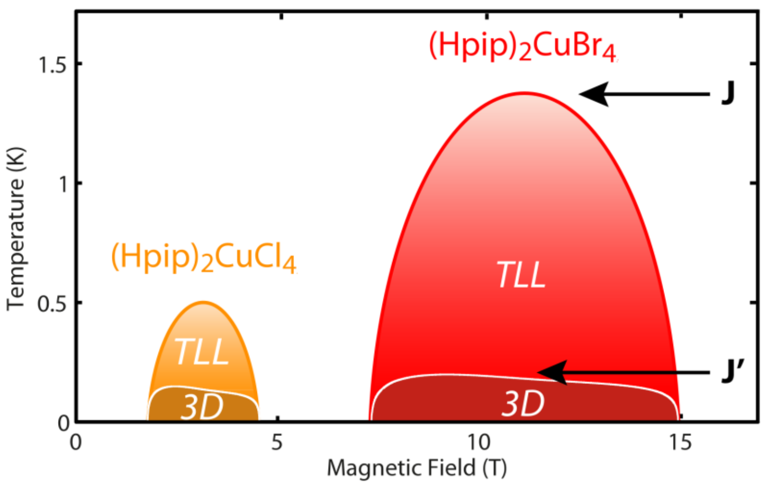


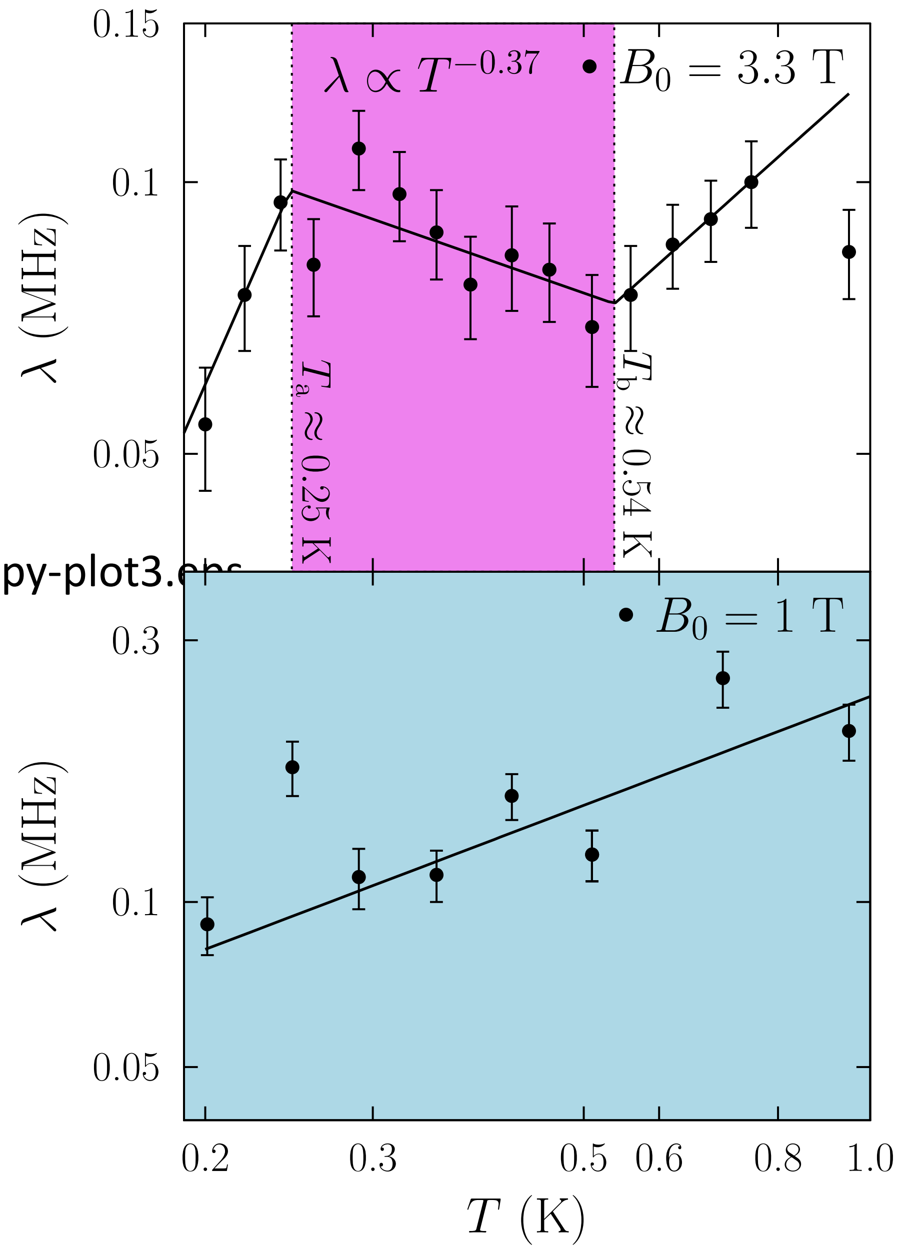
DIMPY: a strong-leg spin ladder

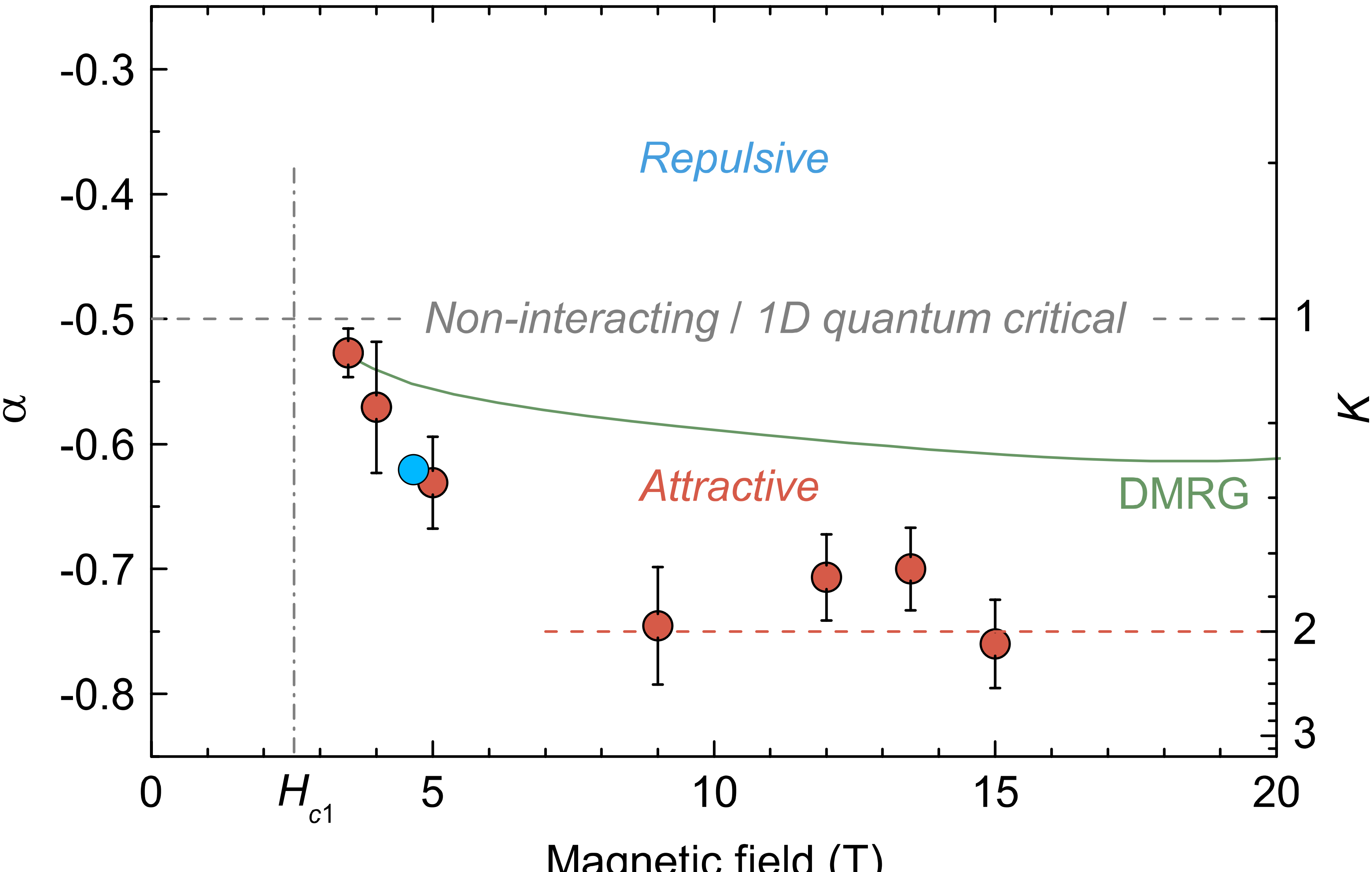


$(Hpip)_2CuCl_4$: a strong rung ladder

This strong-*rung* ladder has α = -0.37

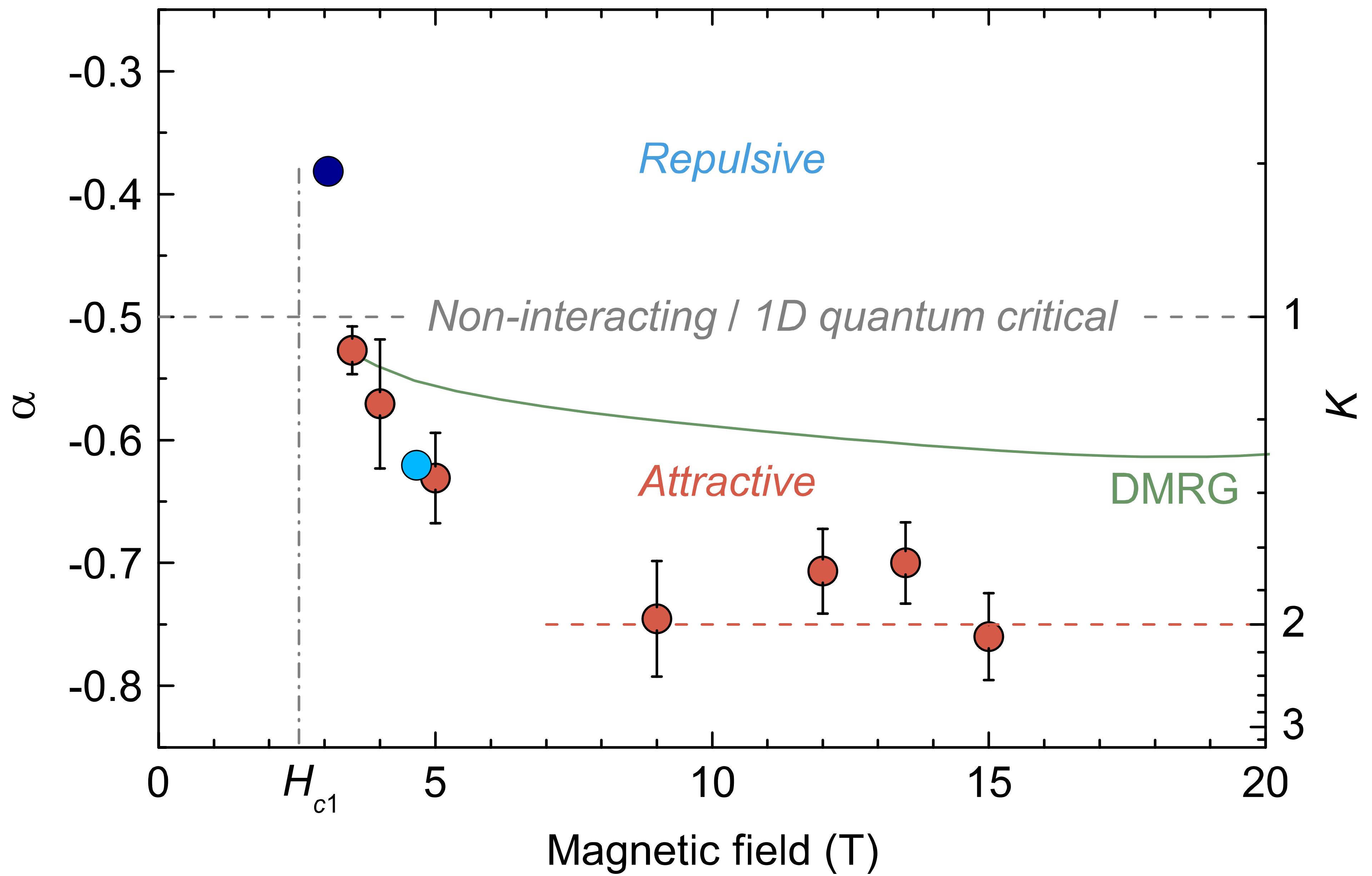






-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
α
Repulsive
Non-interacting / 1D quantum critical
Attractive
DMRG
1
2
3
K
0
H_{c1}
5
10
15
20
Magnetic field (T)

arXiv:1806.09402

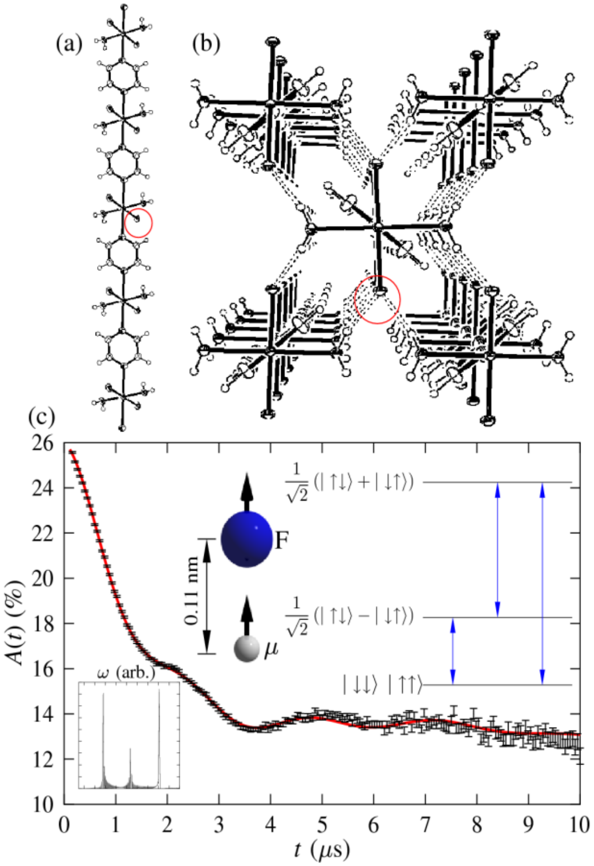


And finally…

Muon sites and DFT

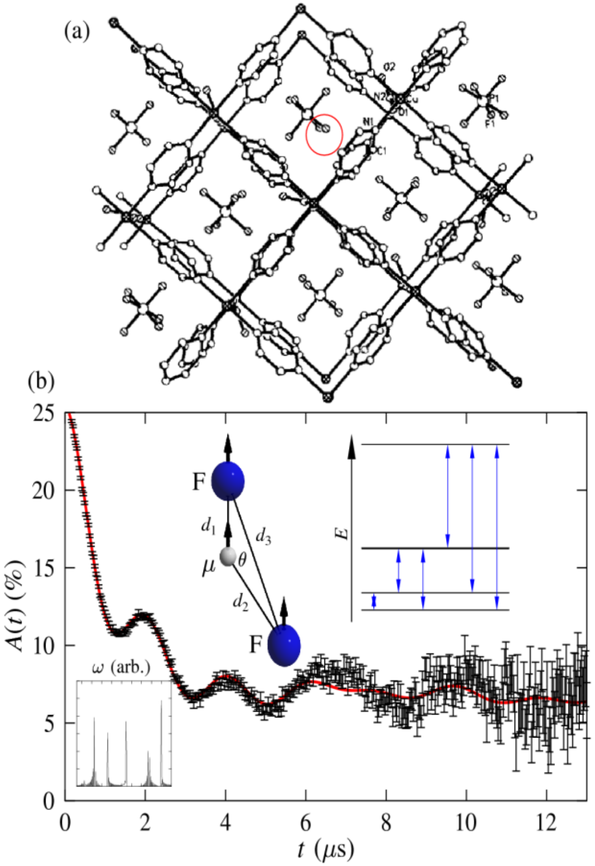
Muon-fluorine entangled states in molecular magnets

Above T_N entanglement allows us to locate the muon site



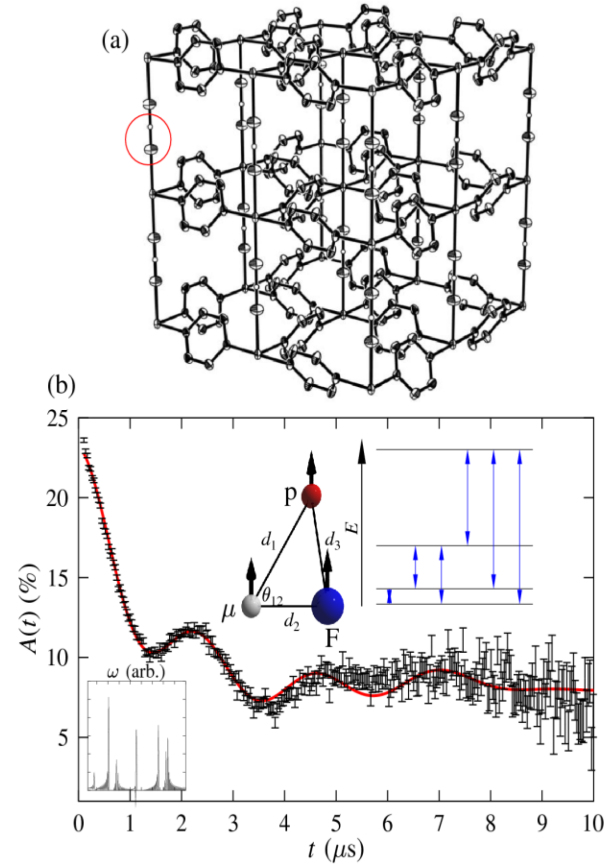
$CuF_2(H_2O)_2(pyz)$

Single fluorine



$[Cu(pyz)_2(NO_3)](PF_6)$

Octahedral PF_6^-



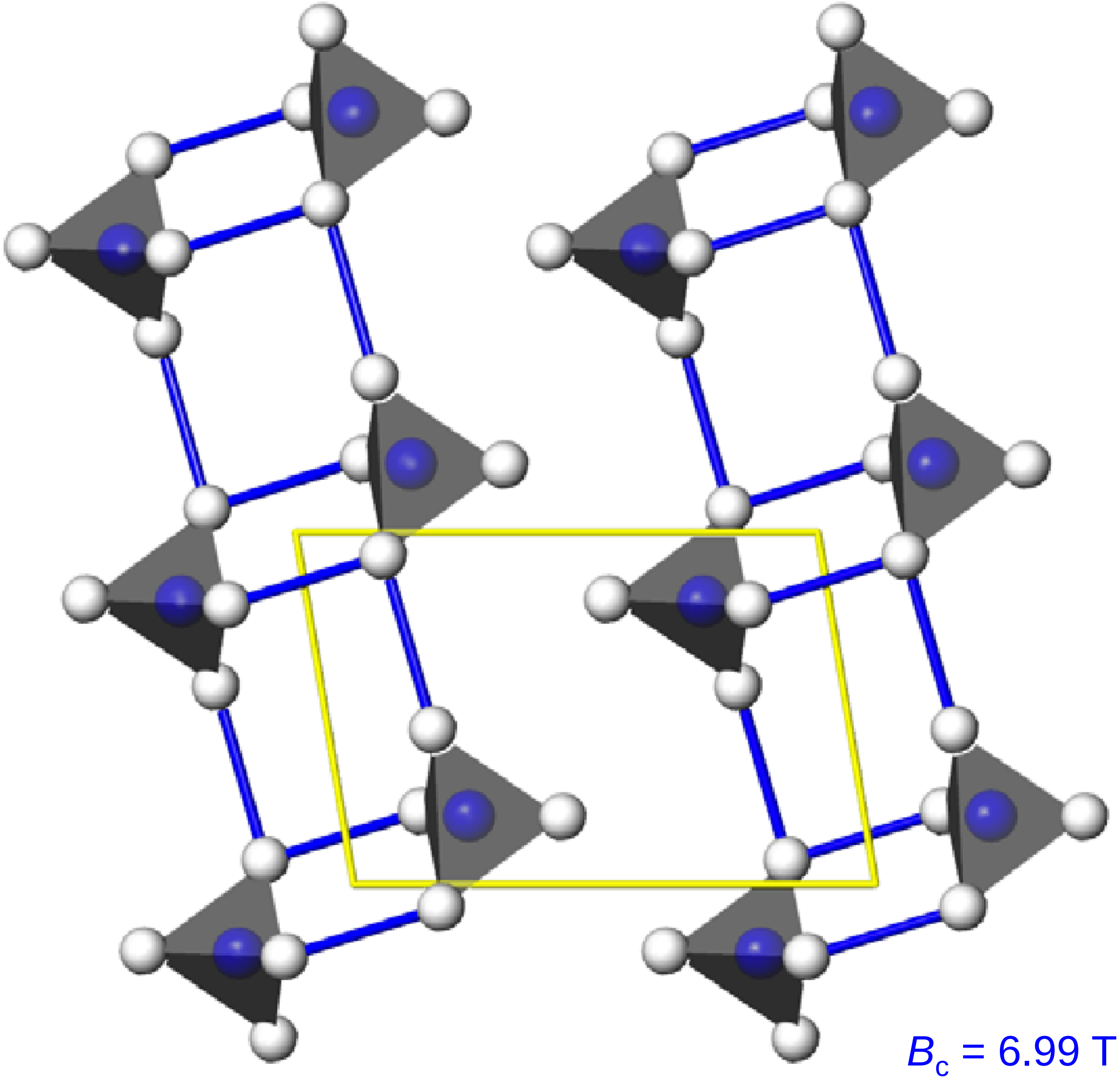
$[Cu(HF_2)(pyz)_2]ClO_4$

HF_2^- ion

T Lancaster *et al.* PRL **99** 267601 (2007)

$(Hpip)_2CuBr_4$: strong run spin ladder

J_{leg}/J_{rung} =0.25



$(C_5H_{12}N)_2CuBr_4$

B_c = 6.99 T

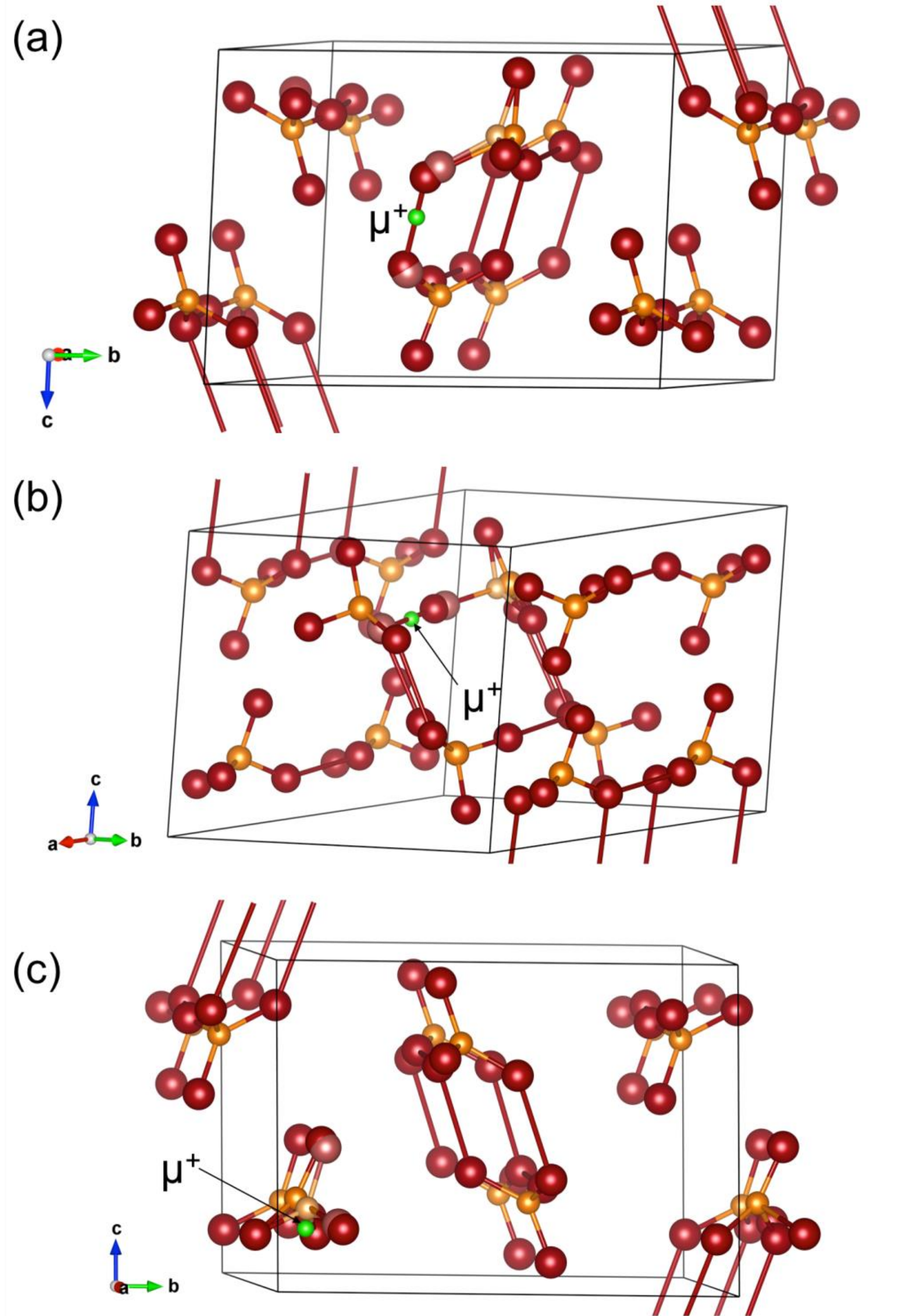
Muon sites from DFT

1) Along the ladder rungs

2) Along the ladder legs

3) Inside the $CuBr_4$ tetrahedra

In each case the muon forms a
Br – μ^+ – Br state

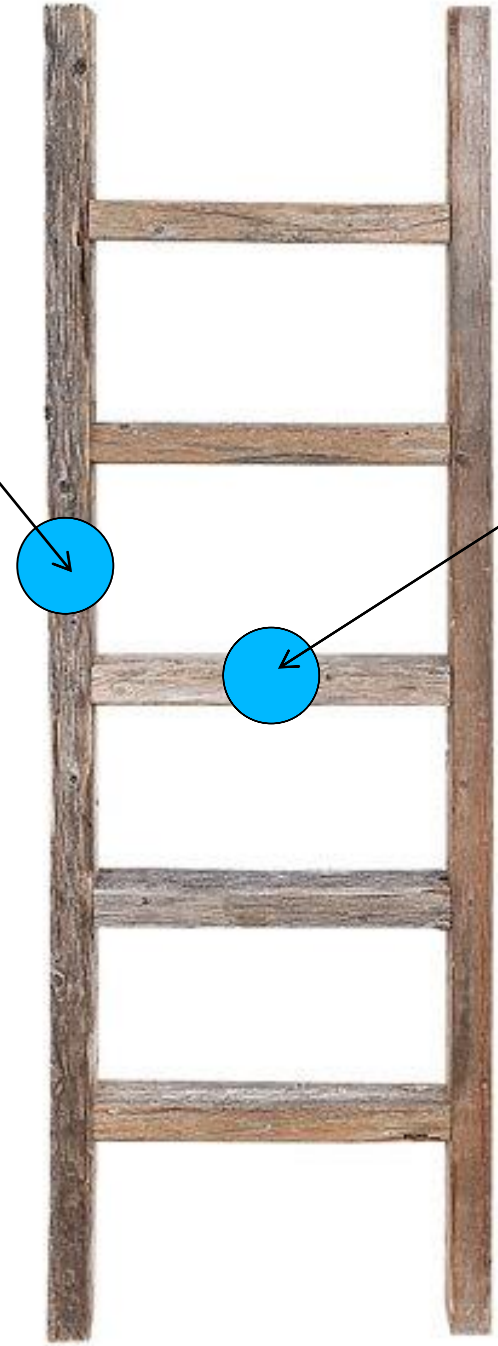


arXiv:1806.09402

Muon sites DFT analysis

Muon site 2

Muon site 1



Making local singlets?

Hyperfine enhancement?

Breaking dimers?

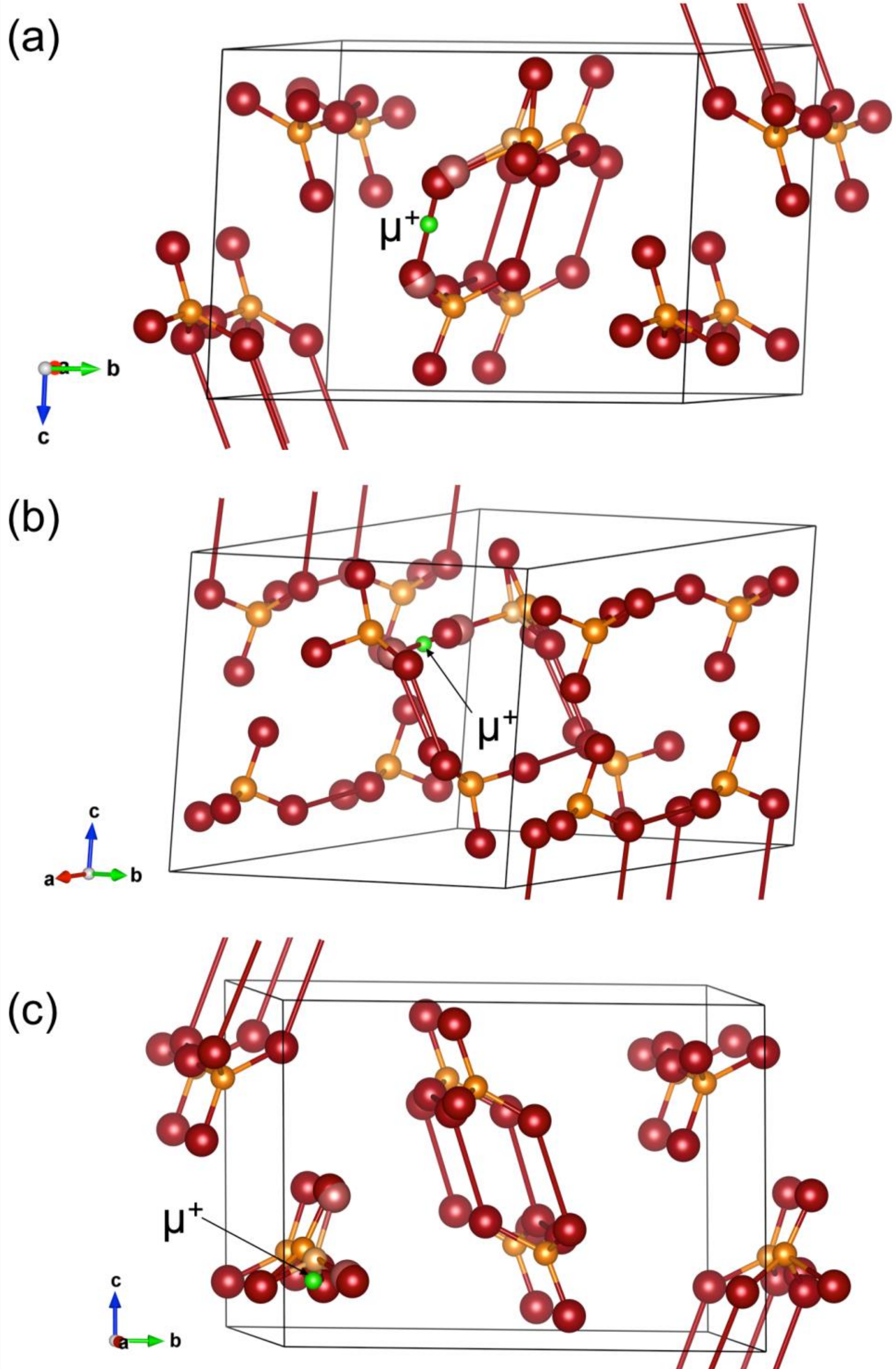
Muon sites from DFT

1) Along the ladder rungs

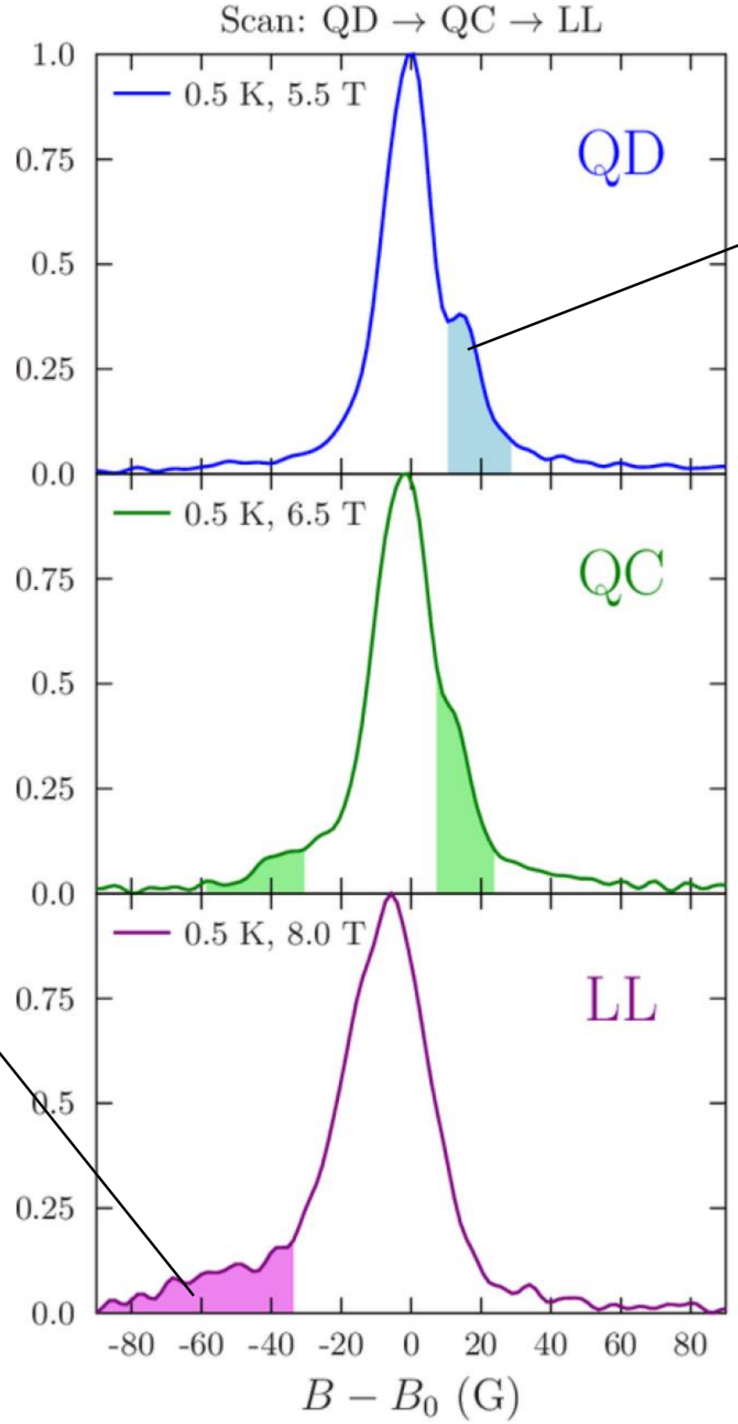
2) Along the ladder legs

3) Inside the $CuBr_4$ tetrahedra

In each case the muon forms a
Br – μ^+ – Br state



TF results from PSI



Rung site disrupting a dimer

Leg site disrupting a chain

arXiv:1806.09402

Conclusions

Super-MuSR will greatly expand the ISIS capability in magnetism

Data quality and quantity will be enhanced in small-moment systems

Increased frequency resolution will open up the variety of magnets

Data rate will transform studies of dynamics

Muon site determination frequently rests on high statistics data sets

Acknowledgements

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