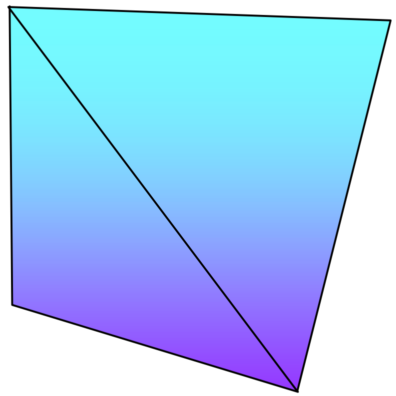
Geometrical Correlation of Itinerant Electrons Probed by Muons and Neutrons



Plan:
- Introduction
- LiV_2O_4-a model case
- Other pyrochlores
- Summary

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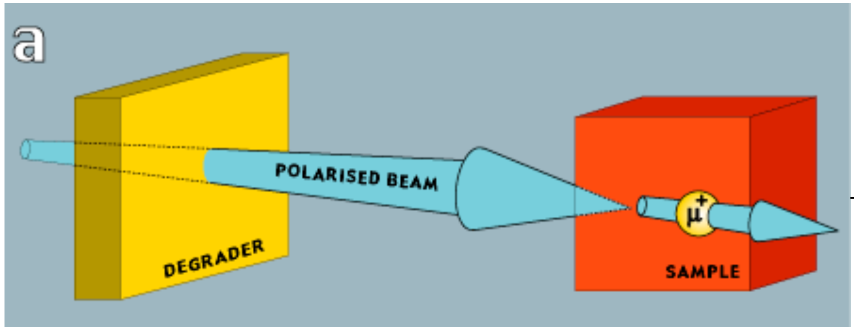
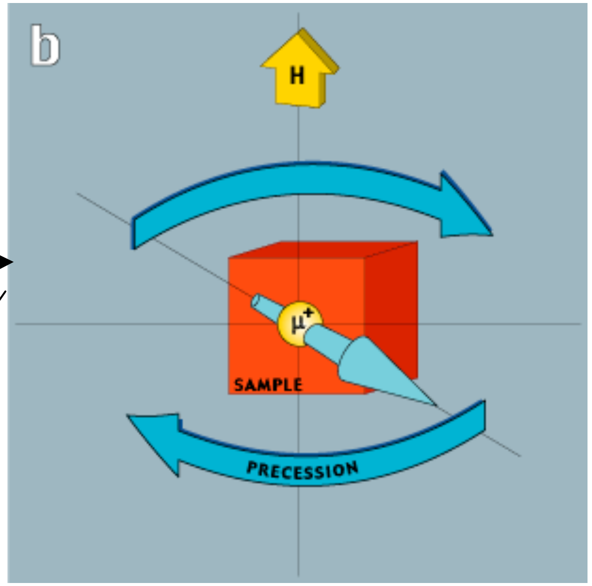
Method:

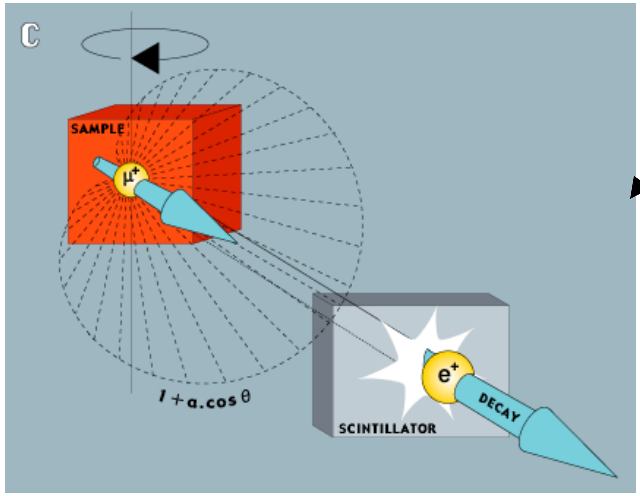
Muon Spin Rotation (μSR)





a) Muons are produced with 100% spin polarizaion and transported by a beamline for implantention to sample.

b) The implanted muons stop between atoms, where they start Larmor precession according to the local magnetic fields.

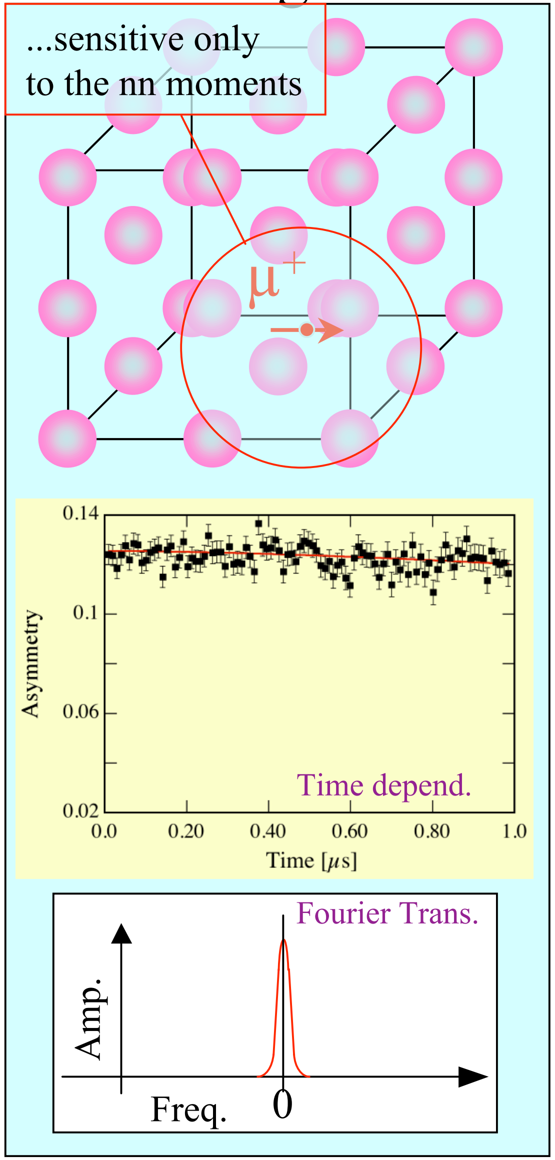


c) Muons emit positrons to the direction when their spins were pointing upon decay, which are detected by scintillation counters.
→The signal of scintillation counters oscillates periodically due to the Larmor precession of muons.

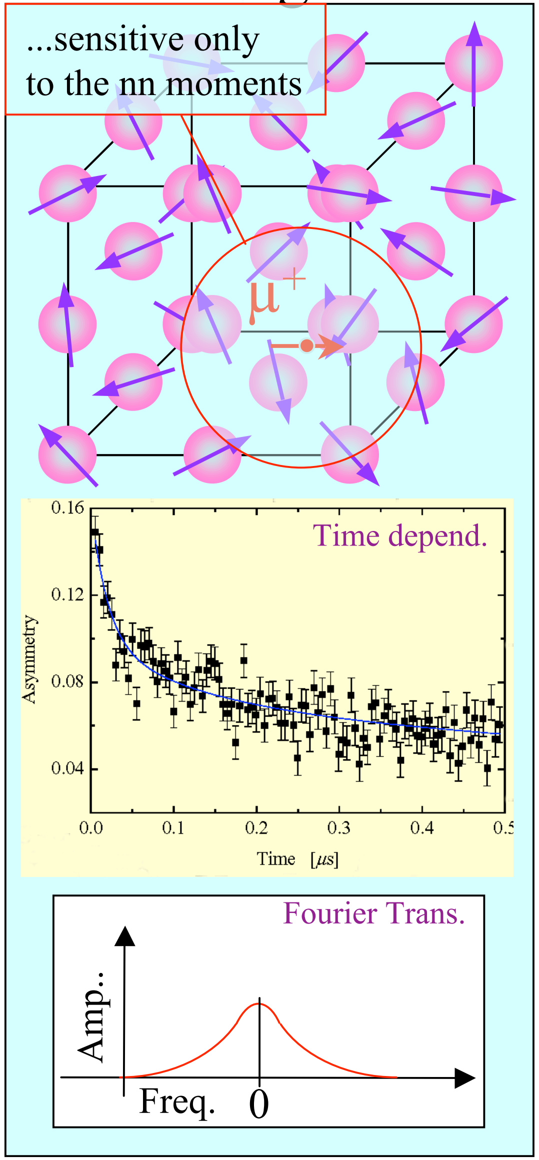
Method: Muon Spin Rotation (μSR)

...How muons probe magnetic state of matter?

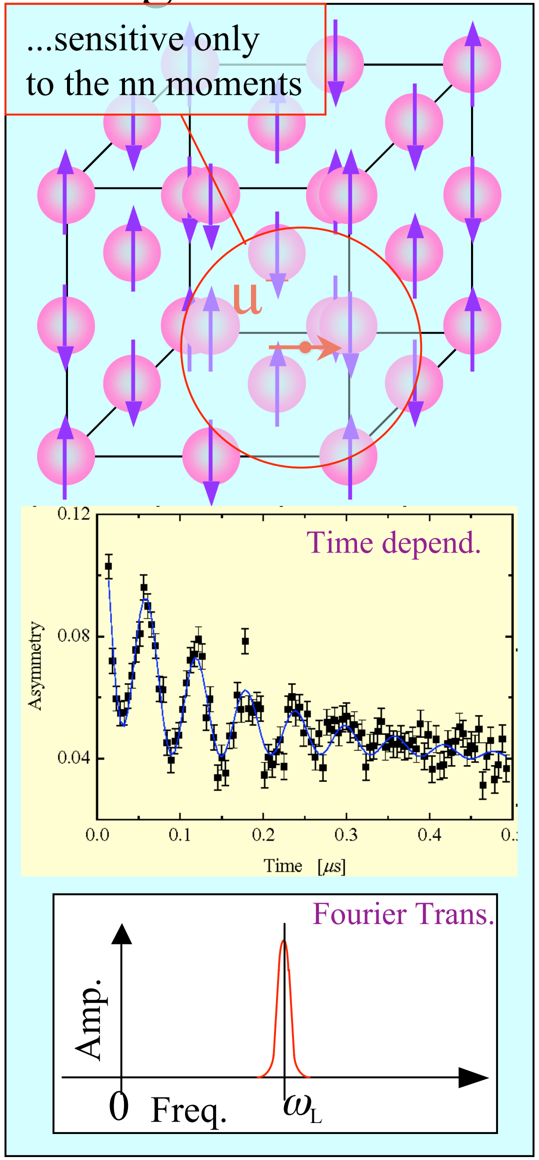
Diamagnetic



Paramagnetic



Magnetic Order

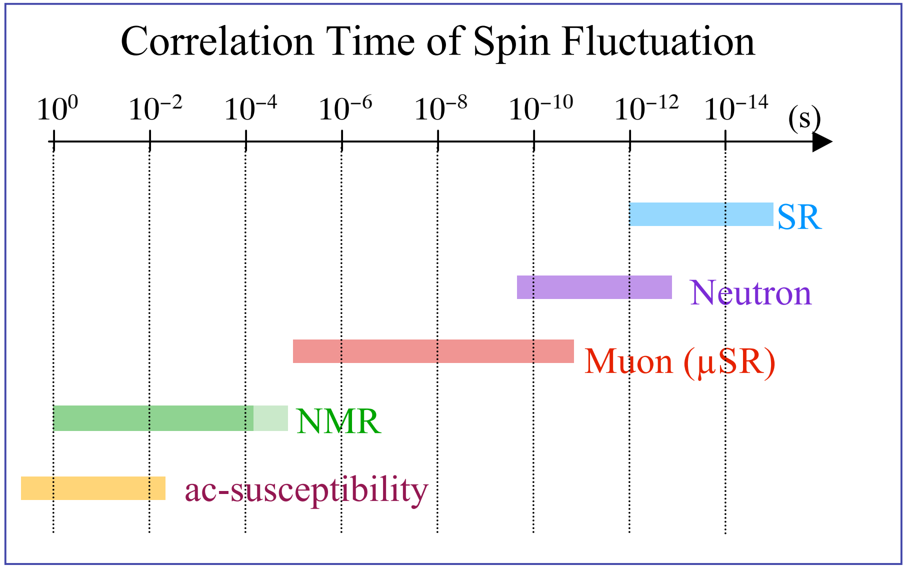


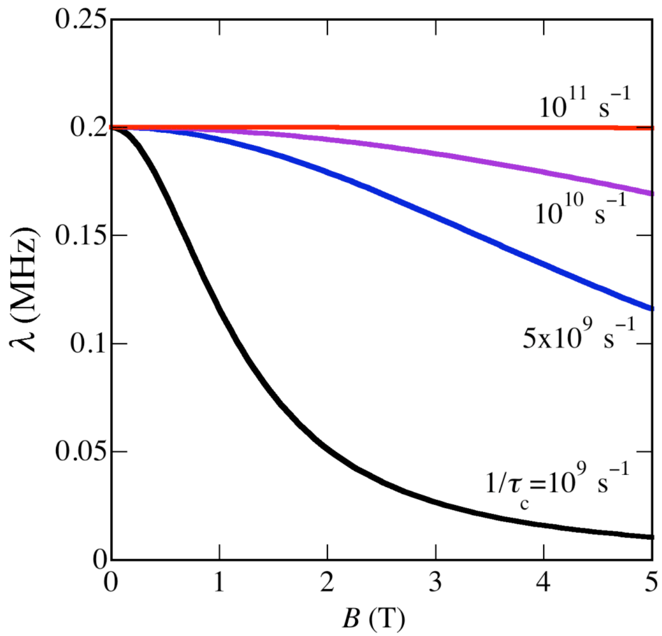
Method: Muon Spin Rotation (μSR)

...Unique time window for the spin dynamics

Spin relaxation rate: $$\lambda \approx \frac{2\delta^2 \nu}{\omega_\mu^2 + \nu^2}$$

$$\nu = \frac{1}{\tau_c}, \quad \omega_\mu = \gamma_\mu B$$



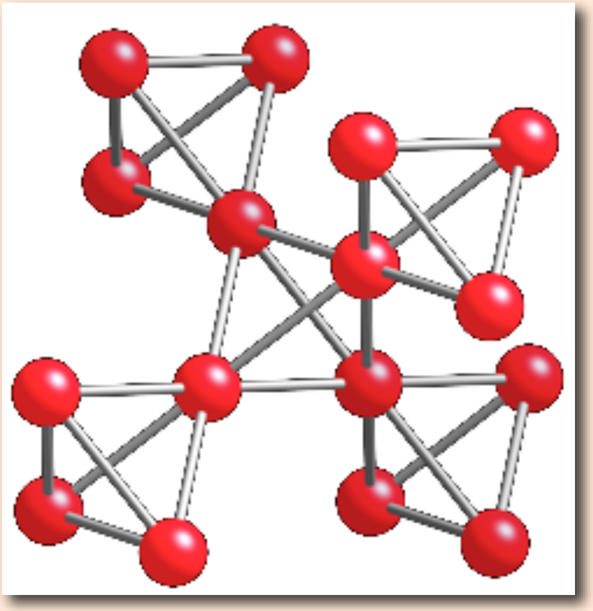


A unique "niche"
between NMR and neutron

Issue: Geometrical Correlation of Itinerant Electrons

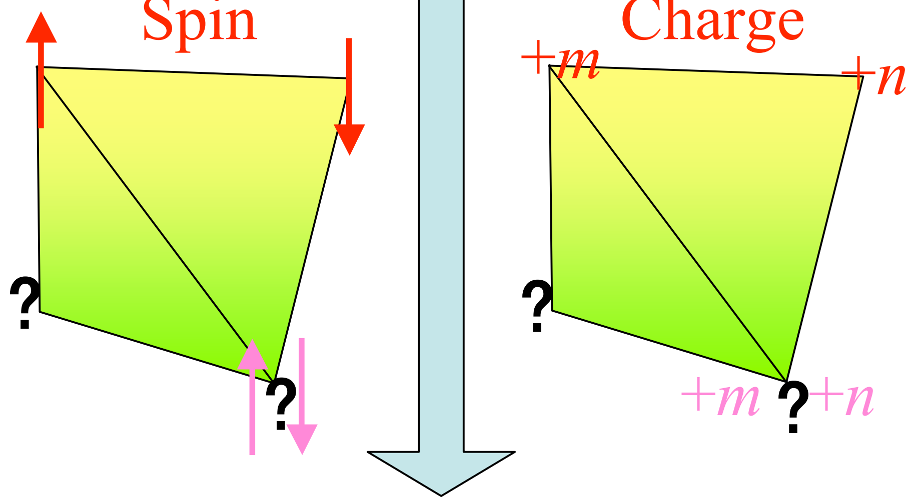
What would happen when frustration acts on metallic conduction?

Stage of itinerancy = highly symmetric crystal



Pyrochlore lattice (Spinel)

Antiferroic correlation
(Local picture)



Frustration
(=Large scale degeneracy)

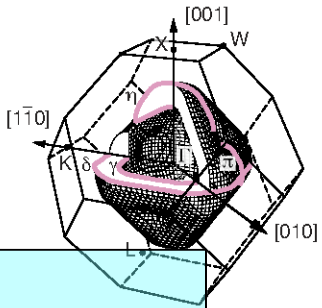
...so far extensively studied on local spin/charge systems.

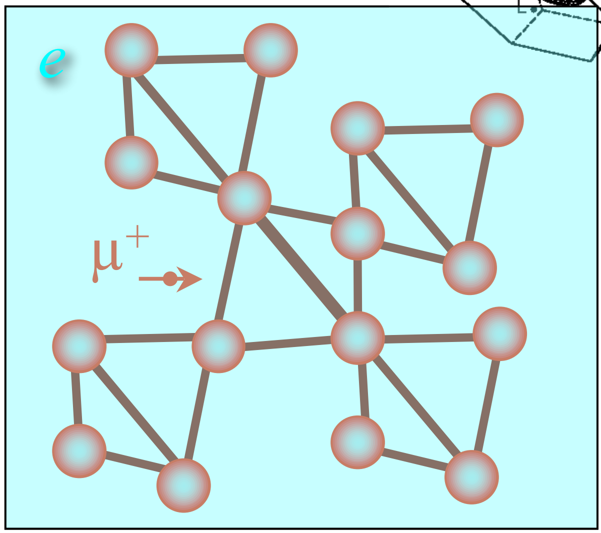
Muon Spin Rotation (μSR) :
...One of the most sensitive probes for frustration

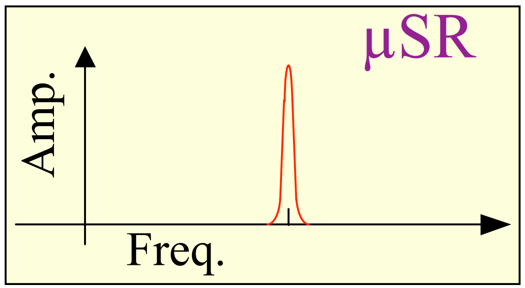
Electronic state of...

Normal metal

...only reflecting
crystal symmetry
(Single electron)

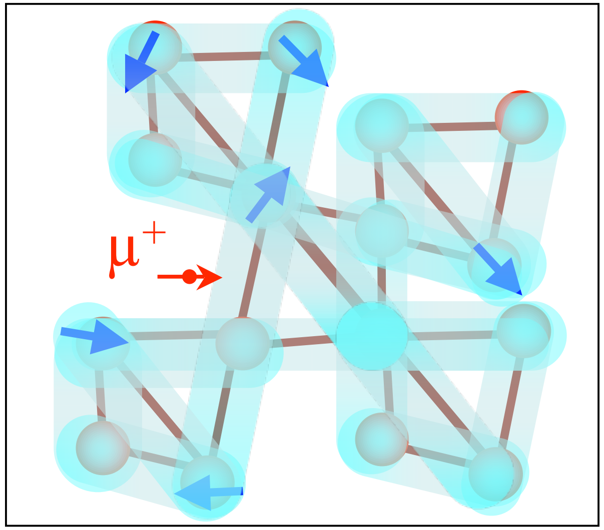


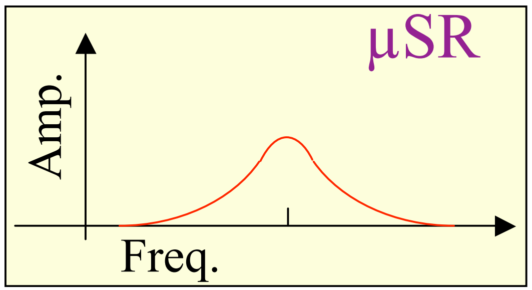




Poor metal
Geometrical Correlation

...inhomogeneous spin/charge flow



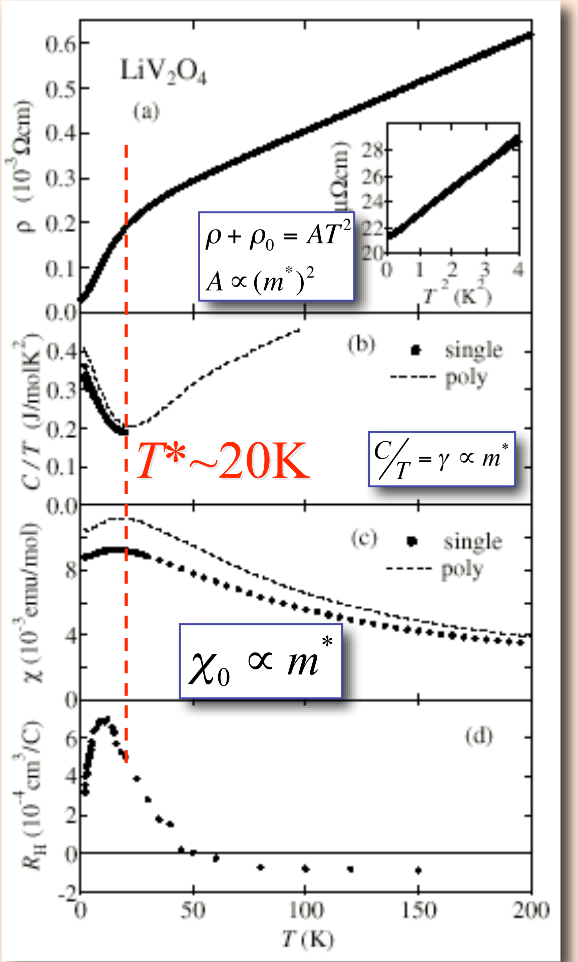


Example:

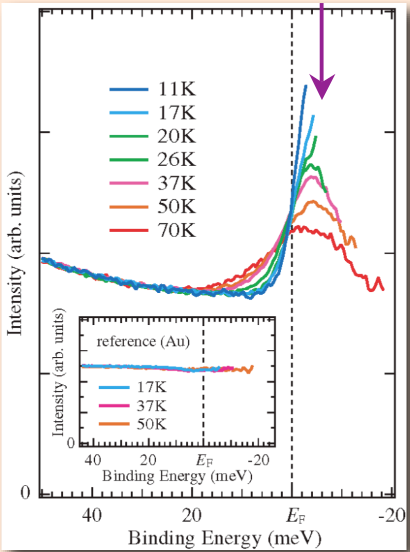
"Heavy Fermion" State in Metallic Spinels

YMn_2('89), LiV_2O_4('97)

LiV_2O_4



[*sc*-LiV_2O_4, Urano *et al.* '00]

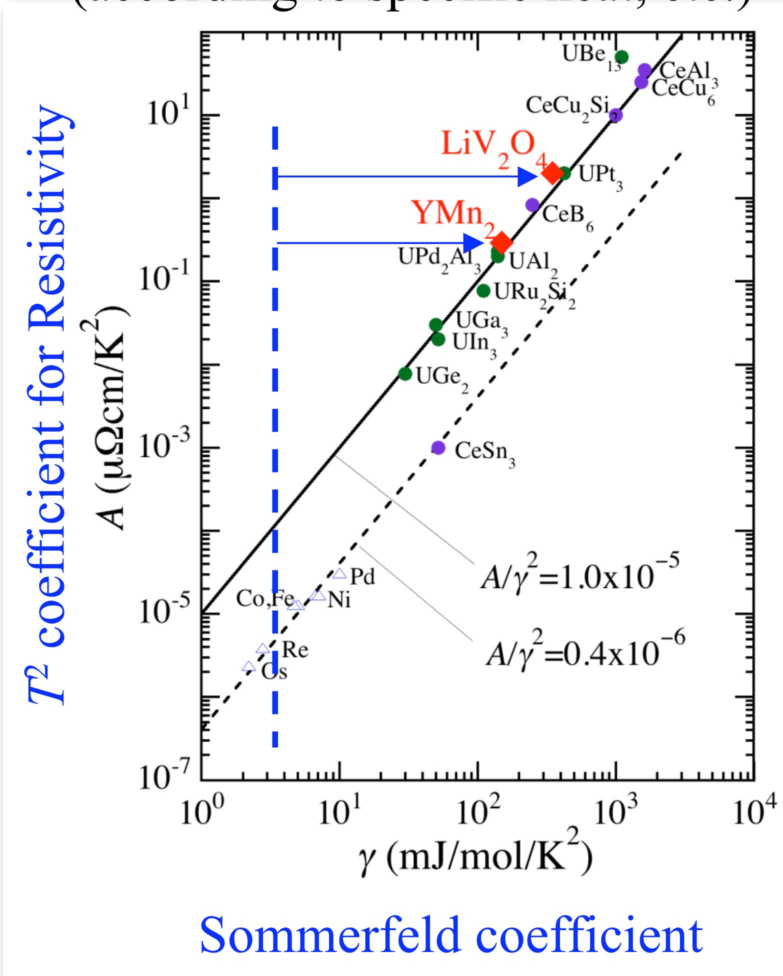


Quasiparticle peak in photo-emission spectra

[Shimoyamada *et al.* '06]

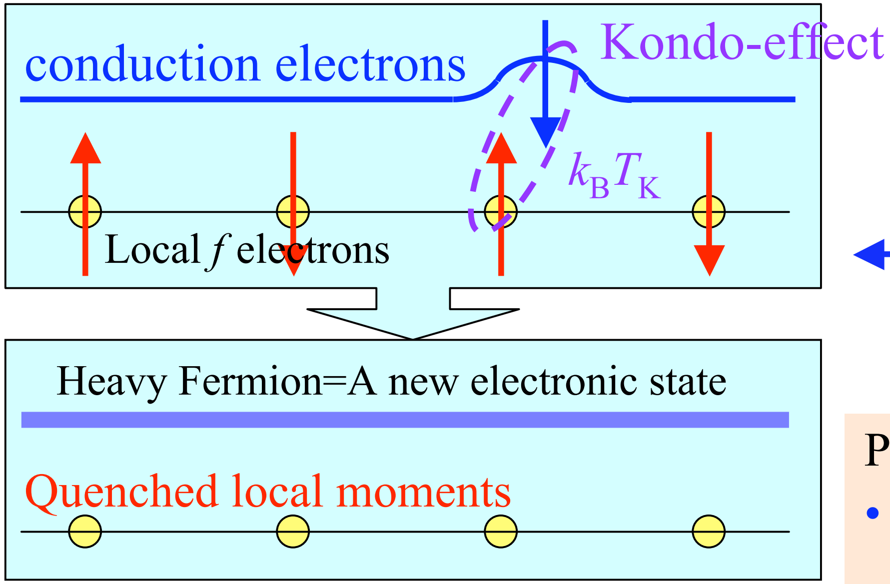
Mass enhancement ~10^2!

(according to specific heat, etc.)

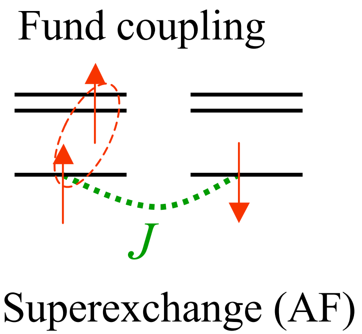


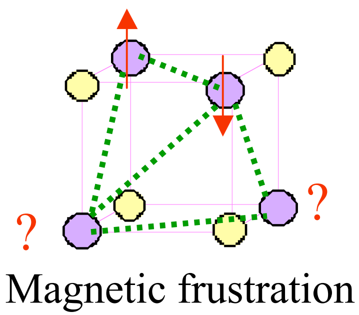
LiV_2O_4: What is the origin of the HF-like behavior?

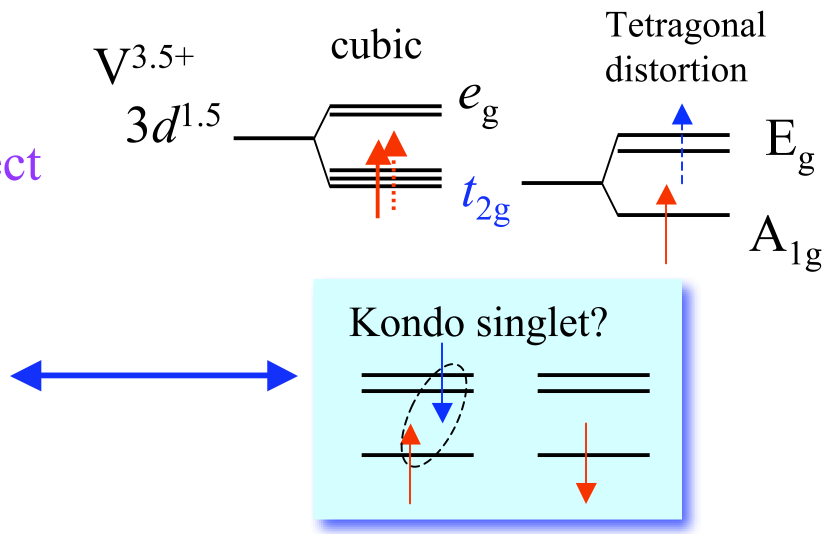
- Conventional Heavy Fermion systems



...competing interactions







Proposed Theoretical Models

- Kondo scenario for 3*d* metals:

  Anisimov *et al.*, PRL **83** (1999) 364.

- Magnetic frustration:

  Eyert *et al.*, Europhys. Lett. **46** (1999) 762.

- Low-dimensional magnet:

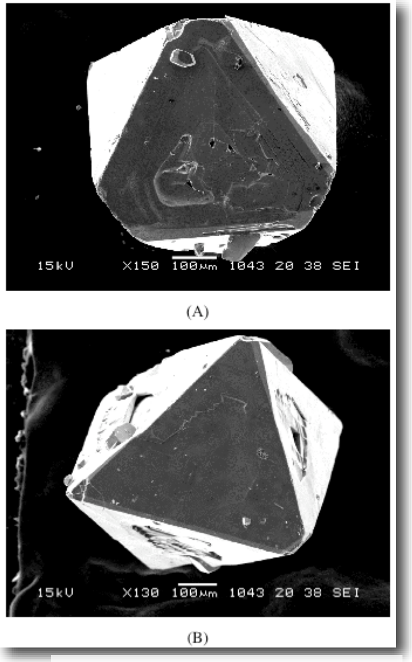
  Fulde *et al.*, Europhys.Lett. **54** (2001) 779.

- Proximty to Mott Insulator:

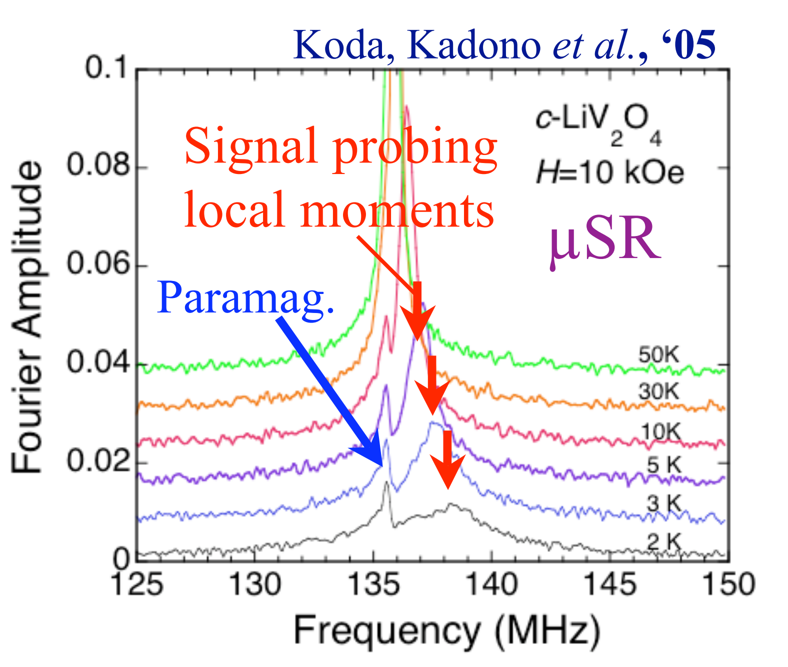
  Arita *et al.*, PRL 98 (2007) 16402.

...

LiV_2O_4: Local moments develop below T^*! ... μSR



single-crystal
(Matsushita *et al.*)
~ 0.1g
μSR measured at
TRIUMF M15.



Analysis: Fits in time domain by

$$A_0 G_{xy}(t) = A_0 e^{-i\phi} \Sigma_i f_i \exp(i\omega_i t)\exp(-\Lambda_i t)$$

A_0 : instrumental asymmetry

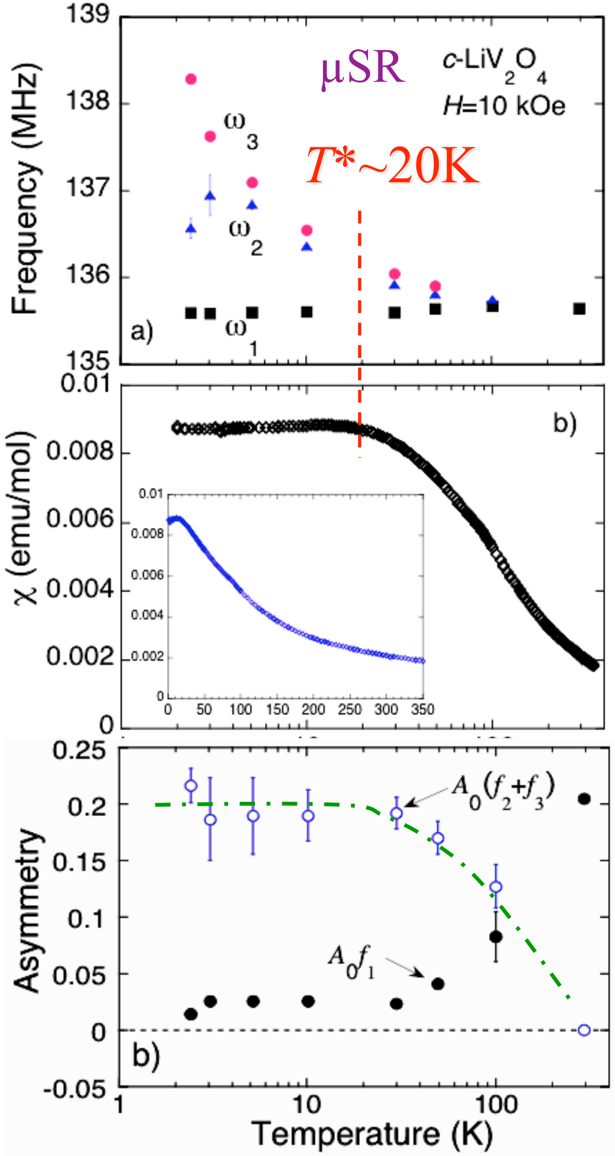
$e^{-i\phi}$: initial phase

f_i : fractional yield of i-th component

ω_i : precession frequency

Λ_i : relaxation rate

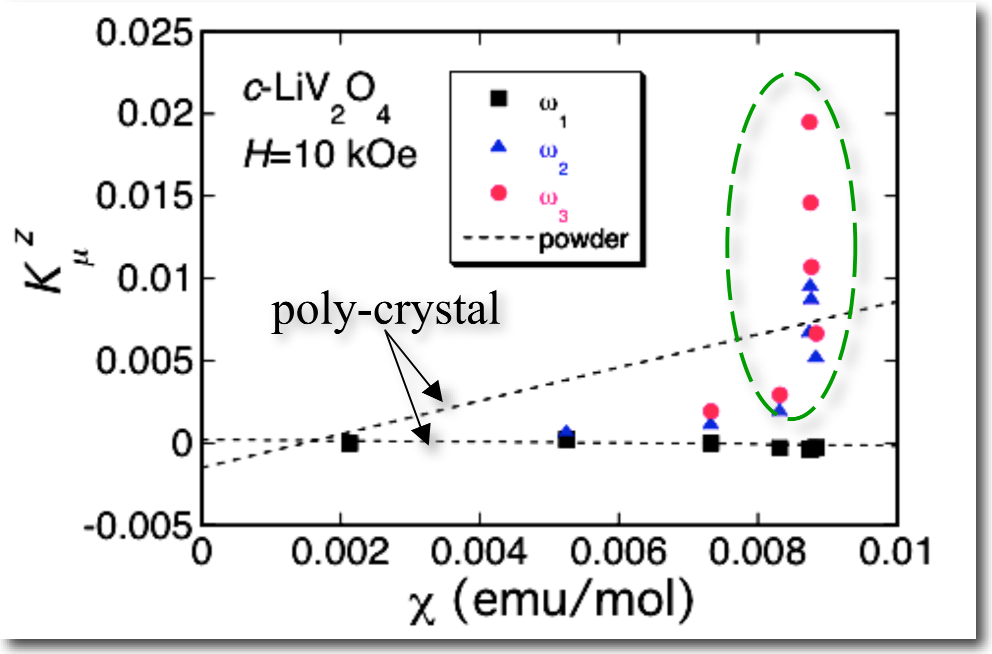
…three components (i=1-3) are enough to reproduce data.



LiV_2O_4: Local inhomogeneity probed by μ^+ Knight shift

K-χ plot:

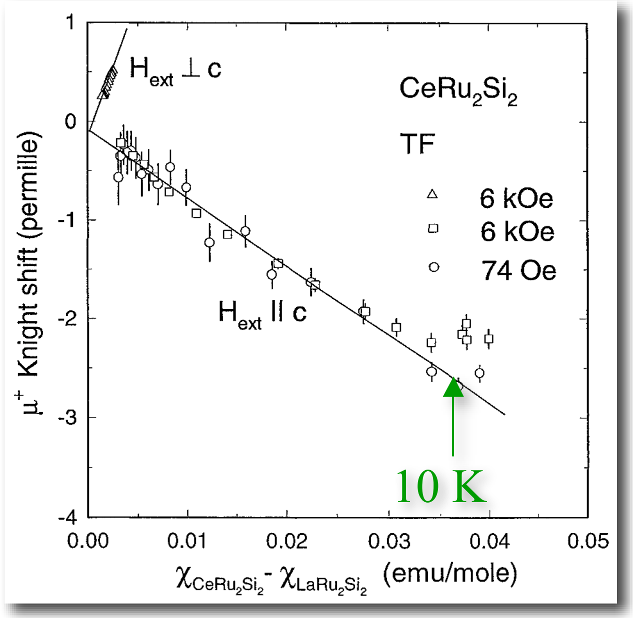
The Knight shift vs bulk susceptibility
…must be linear in normal metals.



↑ The broad lines exhibit highly non-linear behavior below ~*T**.

A broad distribution of hyperfine parameter
$A_\mu \sim 6 \pm 3$ kOe/μ_B

cf. Typical example of HF metal:
$CeRu_2Si_2$ (T_K~10-20 K)



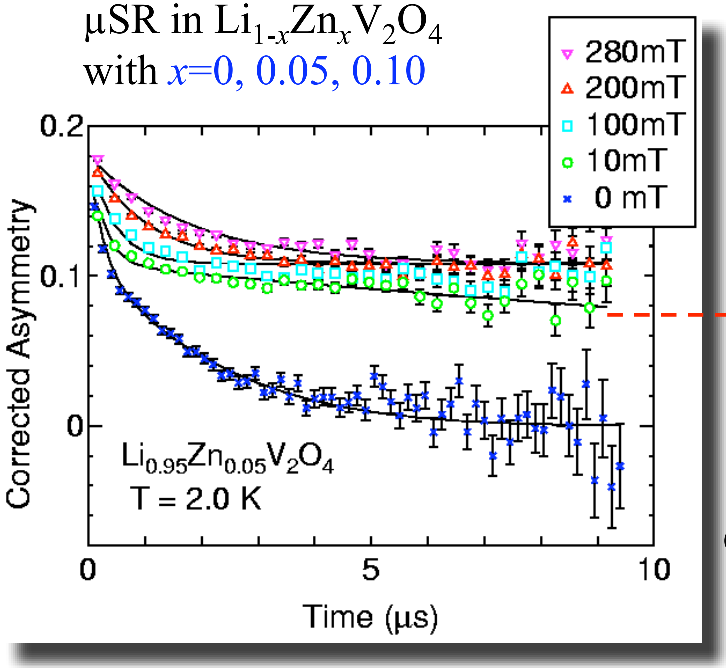
↑ no such anomaly
(homogeneous metal)

LiV_2O_4: Spin fluctuation probed by LF-μSR

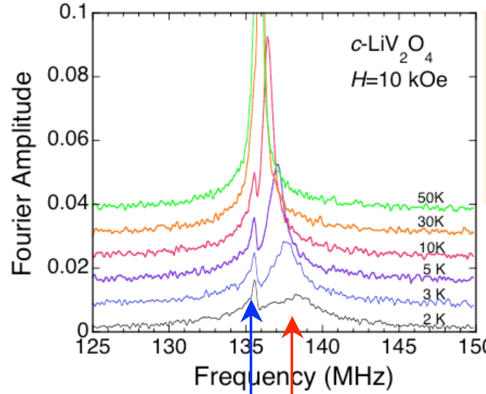
Spin-lattice relaxation: response to a longitudinal field (LF)

↓ There are two components with their fluctuation rate much different with each other as inferred from the response to LF.

μSR in $Li_{1-x}Zn_xV_2O_4$
with x=0, 0.05, 0.10



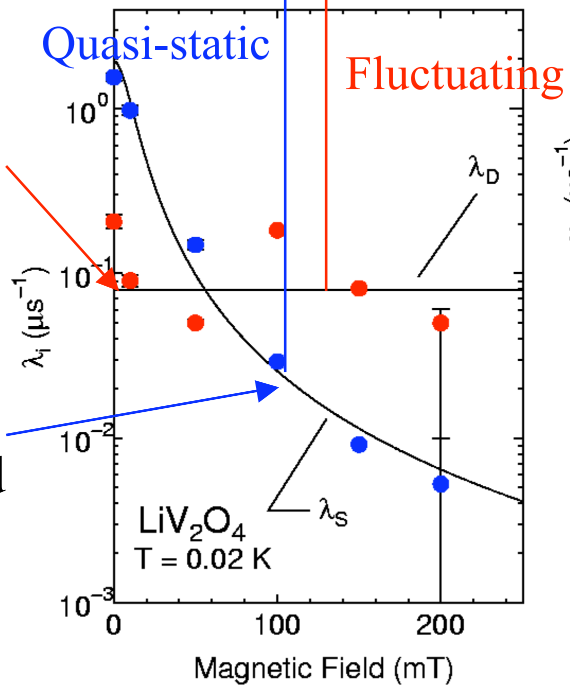
Koda, Kadono *et al.*, **'04**

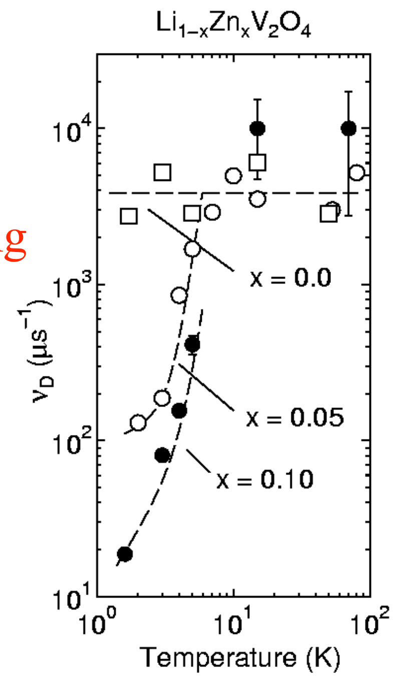


...corresponding to the components observed in TF.

...hardly quenced

...easily quenched





...fluctuation is suppressed for x>0 at low T.

LiV_2O_4: The ground state suggested from μSR

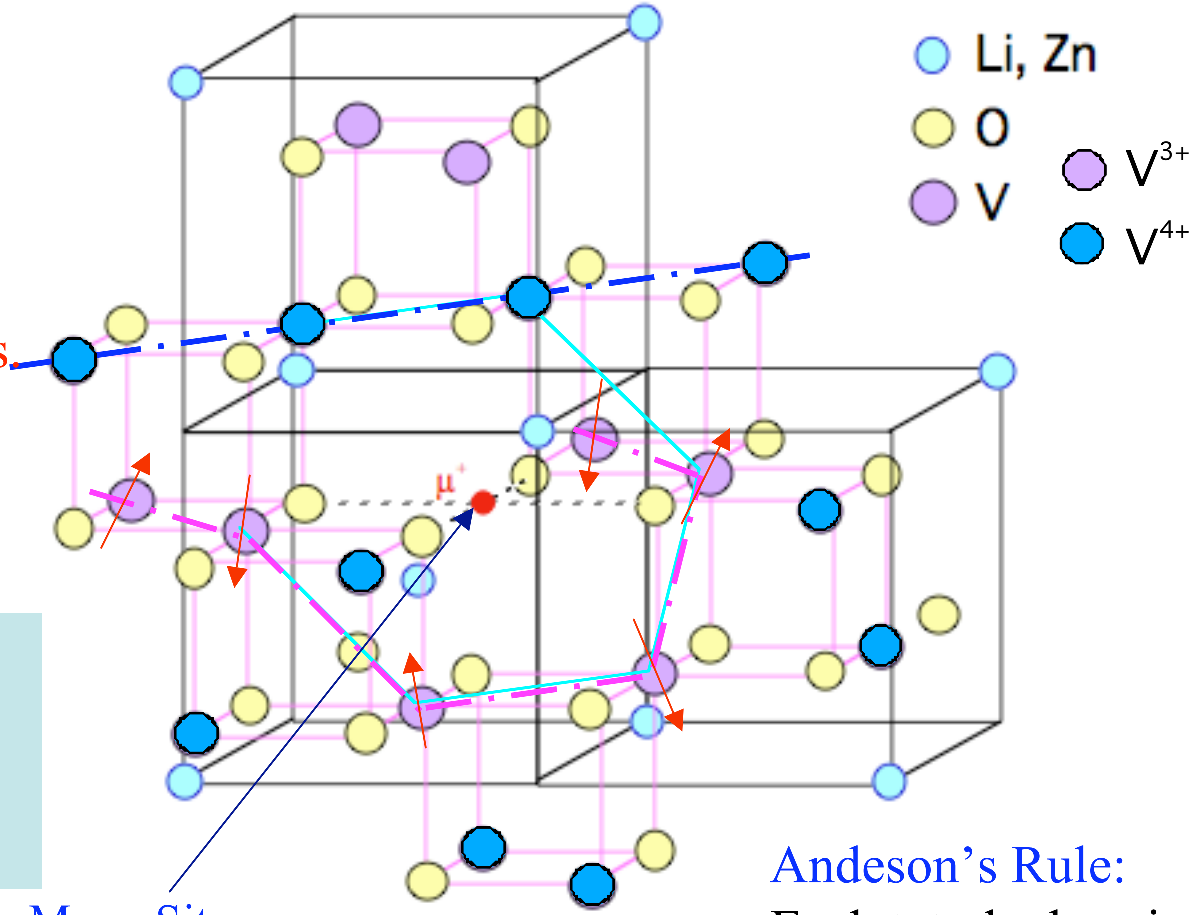
Two kinds of signals in μSR suggests development of
(a) weakly magnetic (~or non-magnetic) state, and
(b) inhomogeneous paramagnetic state fluctuating over a frequency range of $\nu \sim 10^6$-10^9/s.

$\nu < k_B T^* \sim 10^{11}$/s
...not like Kondo fluctuaion

One possibility:
quasi-1D chain correlations for V^{3+} (S=1, Haldane?) and V^{4+} (S=1/2, Heisenberg) ions,

[...a model suggested by Fulde *et al.*, '01]

...A snap shot



Muon Site:
…Center of O-octahedron, with nn V ions forming a hexagon ring.

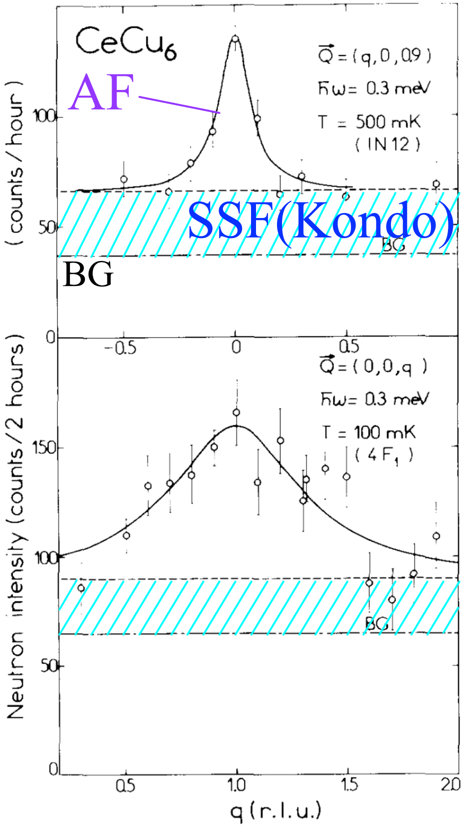
Andeson's Rule:
Each tetrahedron is occupied by two V^{3+} and V^{4+} ions.

LiV_2O_4: Inelastic Neutron Scattering ($T<T^*$)

Antiferromagnetic correlation vs single-site fluctuation (SSF)

SSF...due to the Kondo coupling to conduction electrons

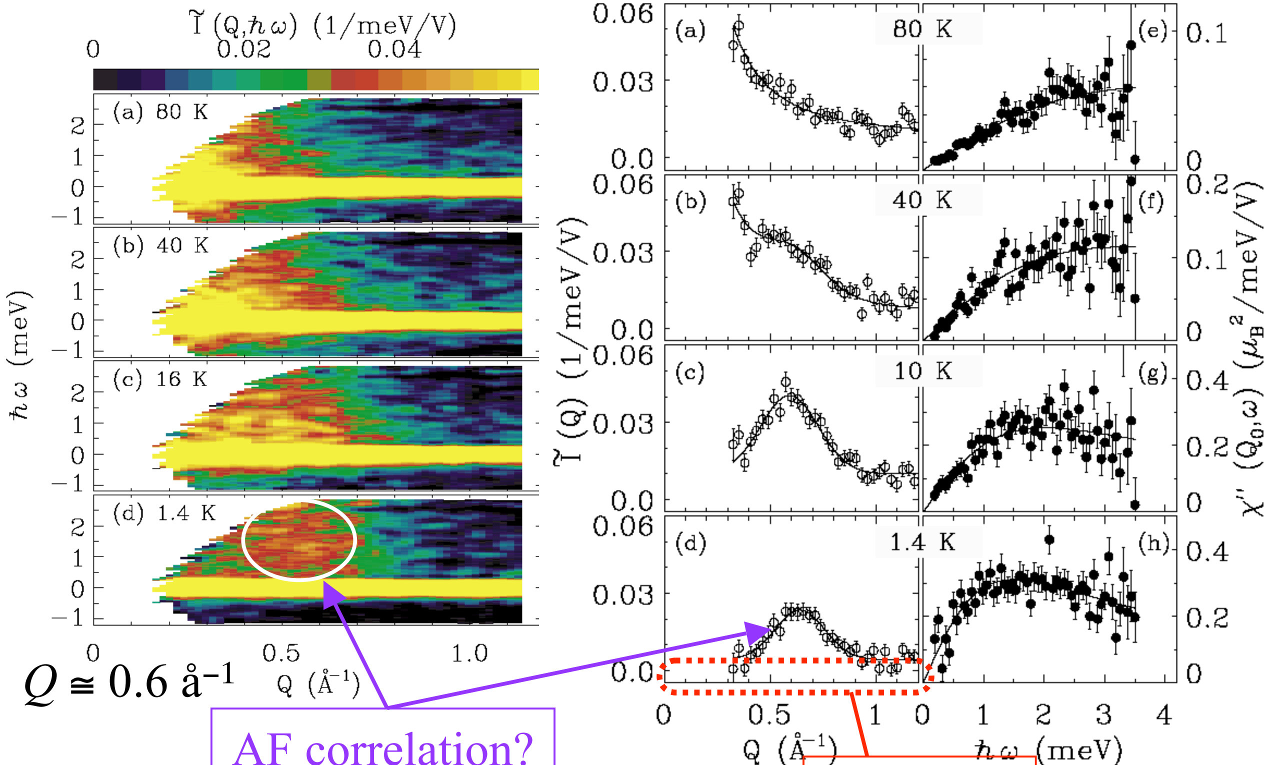
HF-system



k_BT_K~ 10^0 meV (~10^{11}/s)

LiV_2O_4

S.-H. Lee *et al.*, 2001



$Q \cong 0.6$ å$^{-1}$

AF correlation?
(FS nesting?)

No SSF?

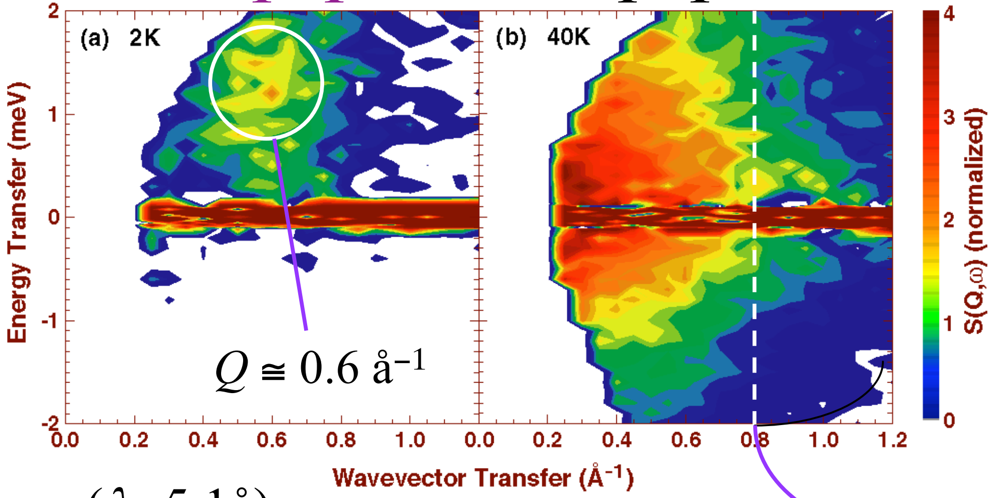
(NB: phonon parts subtracted using $LiTi_2O_4$ data)

LiV_2O_4: Inelastic Neutron Scattering (*T*>*T**)

Paramagnetic response: observation of two components

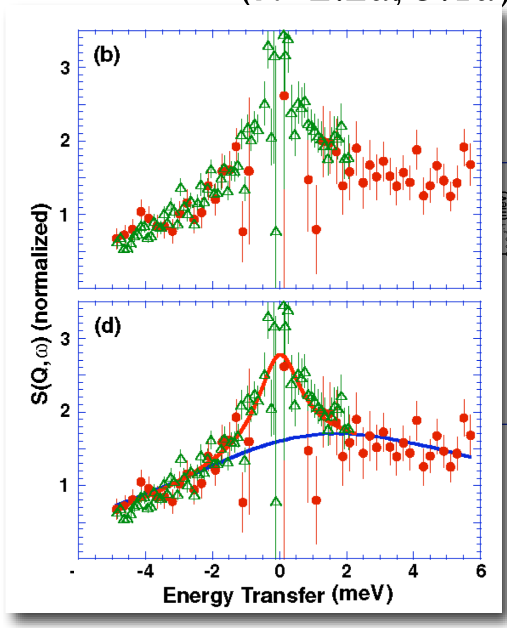
A. P. Murani *et al.*, 2004

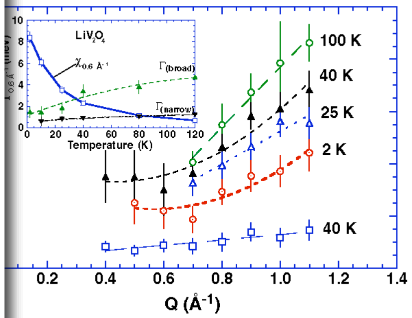
T<*T** *T*>*T**



(λ=5.1å)

T>*T** (λ=2.2å, 5.1å)

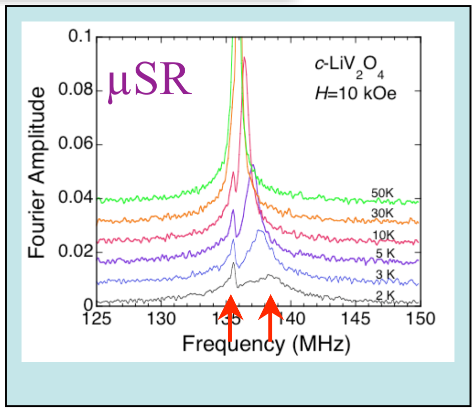




Imaginary part of χ for "spin glass"

$$\chi''(Q,\omega) = \omega \sum_i \frac{\chi_i^Q \Gamma_i^Q}{(\Gamma_i^Q)^2 + \omega^2}$$

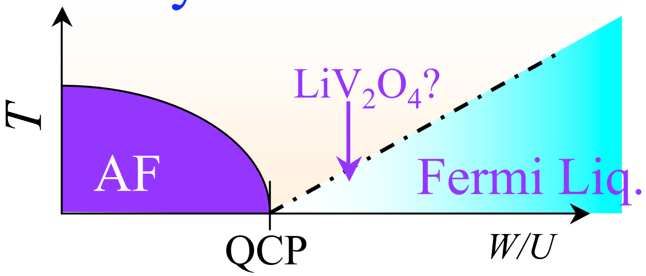
i=2 seems to be needed to reproduce data. → ...in good accord with μSR.



LiV_2O_4: A New Class of Metal?

Implications from other experiments: Effect of Pressure

HF system:

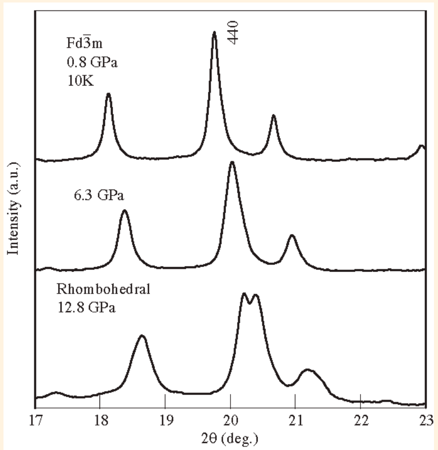


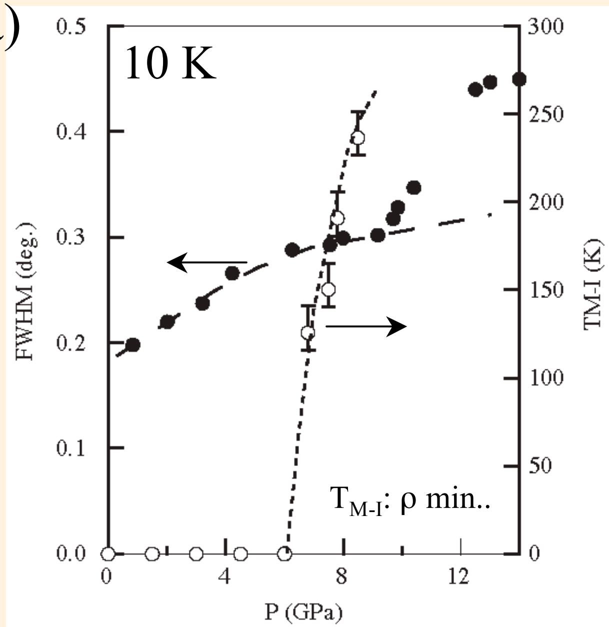
$P \propto W$

...getting further into the Fermi liquid state with *P*.

LiV_2O_4: *P*-induced MI transition and reduction of symmetry (*P* > 10 GPa)

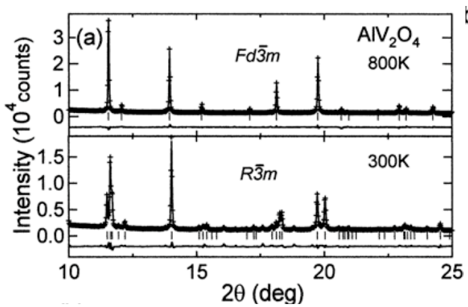
$Fd\bar{3}m \rightarrow R\bar{3}m$



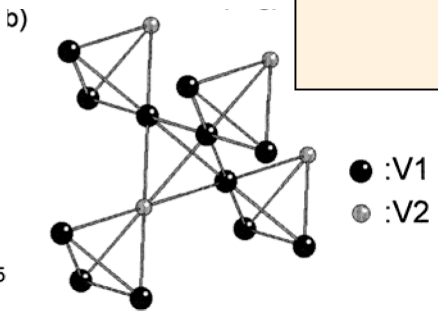


...not like a canonical HF system

cf. Charge order in AlV_2O_4



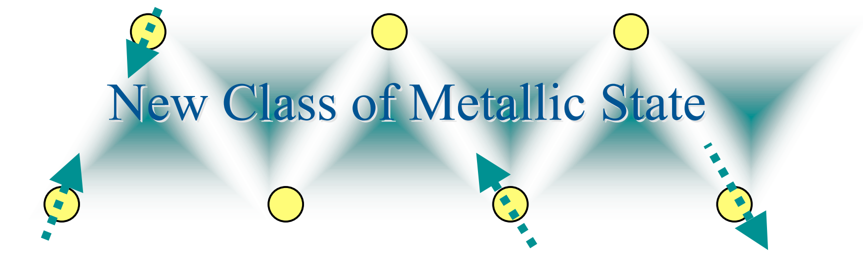
$Fd\bar{3}m \rightarrow R\bar{3}m$



$V^{2.5+} \rightarrow V^{2.5\pm\delta}$

Matsuo *et al*., 01

Geometrical Correlation

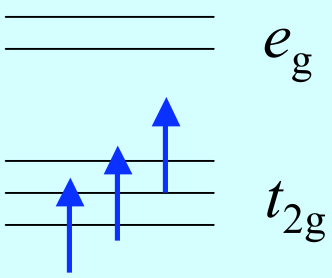


Geometrical correlation: Other pyrochlore examples

Problem for $A_2B_2O_7$: Structural and associated MI transition

Q: How to preserve cubic symmetry?

A: Let the t_{2g} band half-filled (no orbital degeneracy).



t_{2g} half-filled

Structural phase transition is suppressed by the lack of OD.

Ru^{5+} $(4d^3)$ S=3/2

$Hg_2Ru_2O_7$ (MIT)
$Cd_2Ru_2O_7$ (CDW?)
$Ca_2Ru_2O_7$ (Metal?)

Os^{5+} $(5d^3)$ S=3/2

$Cd_2Os_2O_7$ (MIT)
$Hg_2Os_2O_7$ (Metal)

Ion Radius

$Ru^{5+} < Os^{5+}$

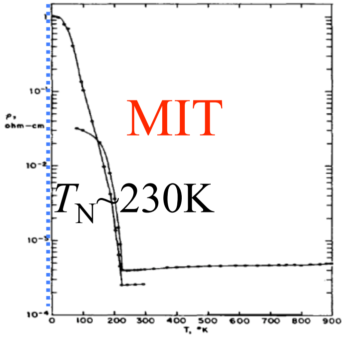
$Cd^{2+} < Ca^{2+} < Hg^{2+}$

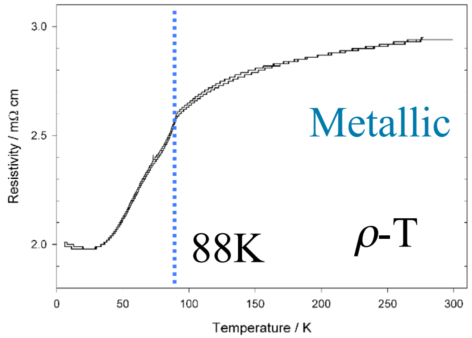
...It seems not trivial to obtain high quality specimens (some of them requires high pressure for synthesis).

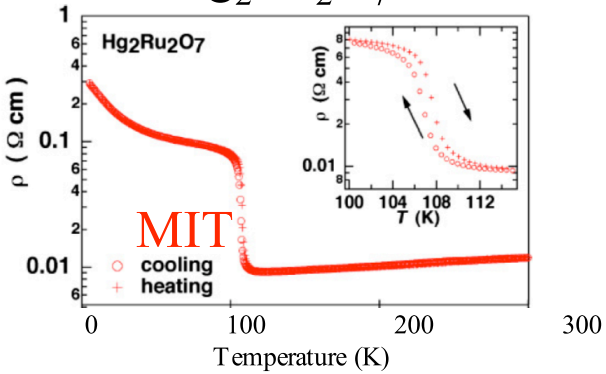
Geometrical correlation: Other pyrochlore examples

	$Cd_2Os_2O_7$	$Hg_2Os_2O_7$	$Hg_2Ru_2O_7$

ρ-T

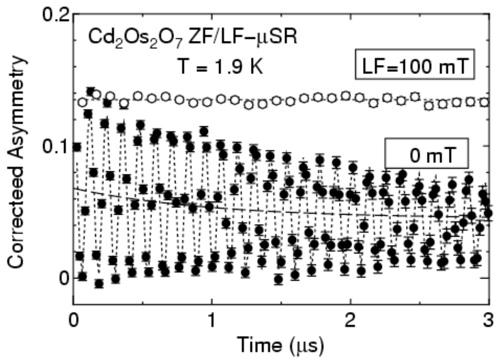


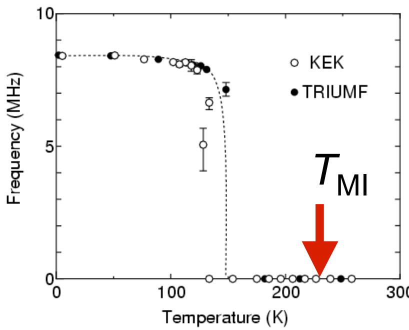




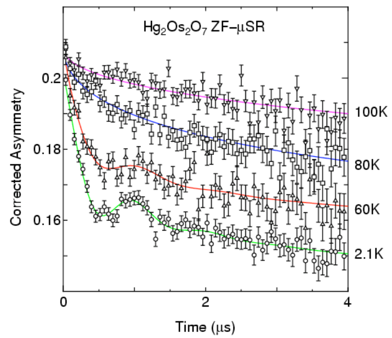
μSR

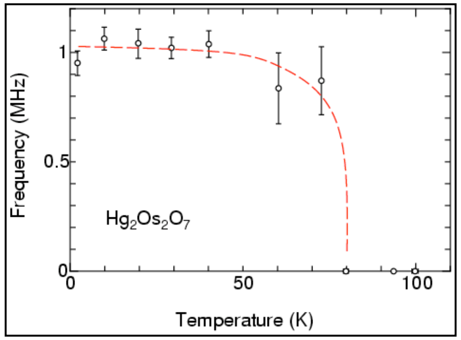
A.Koda *et al.*,'07



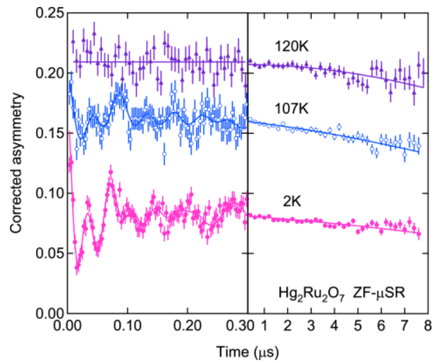


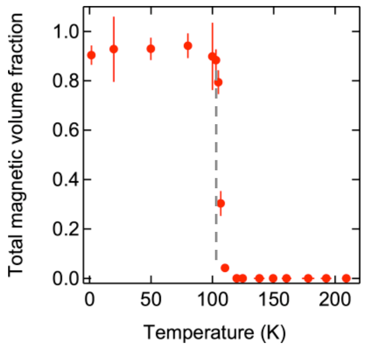
A.Koda *et al.*, '06





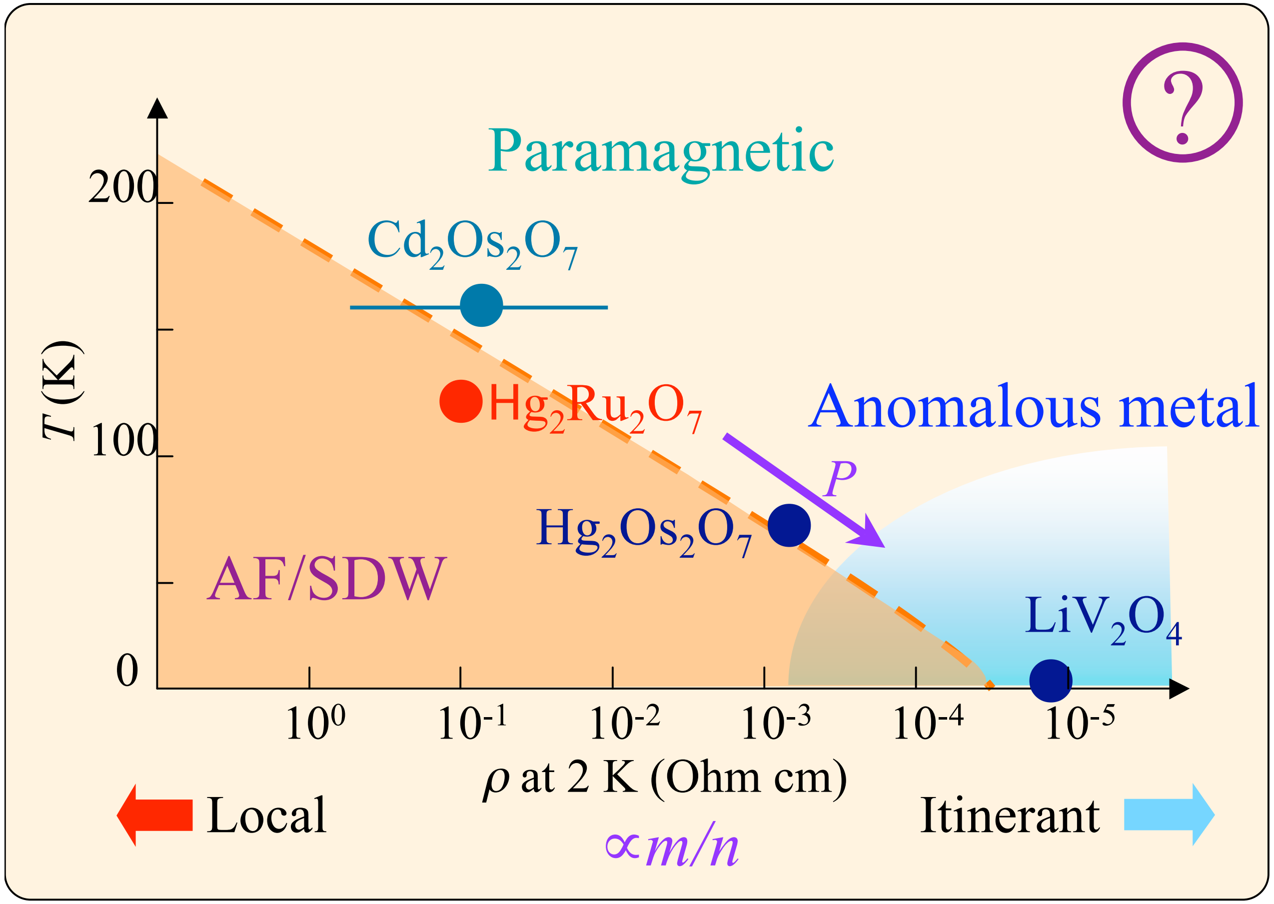
K.H. Satoh *et al.*, '08





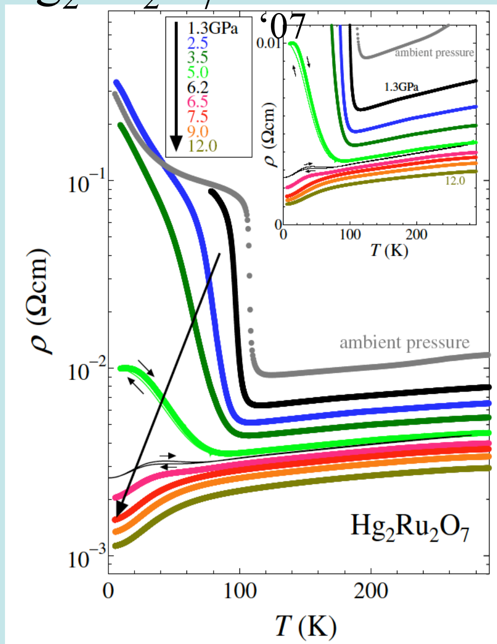
Geometrical correlation: Other pyrochlore examples

"Metal"ness vs Frustration



Heavy Fermion state

$Hg_2Ru_2O_7$ Takeshita *et al.*, '07

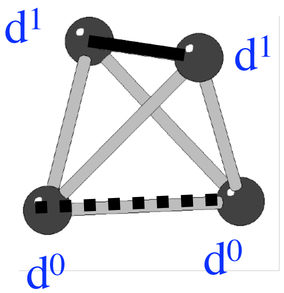


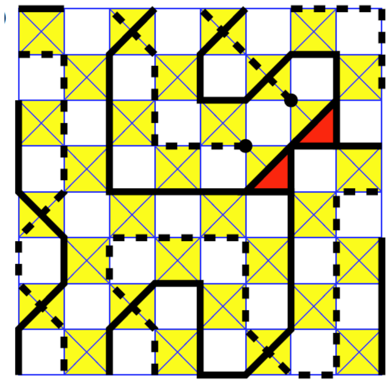
...suppression of MI transition (by pressure) leads to HF-like behavior similar to LiV_2O_4.

Geometrical correlation: Other pyrochlore examples

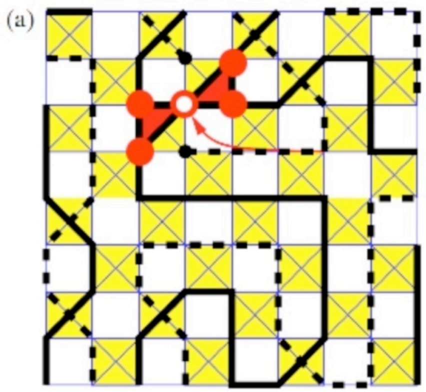
Other exotic ground states:

Fractional Charge State

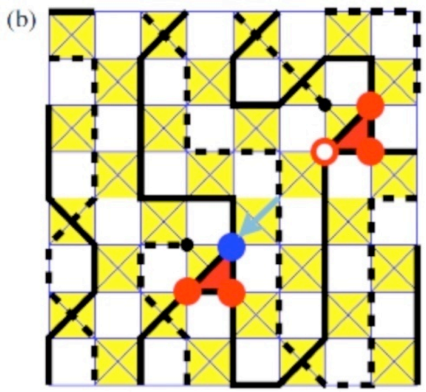




Distribute charges according to the Anderson's rule....then put one electron into the lattice:



Migration of a doped electron:

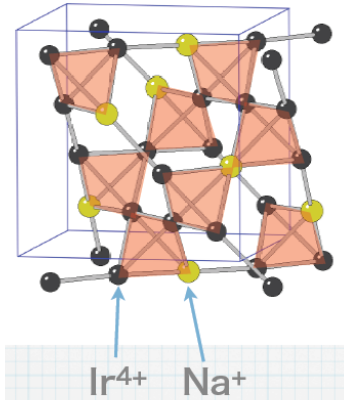


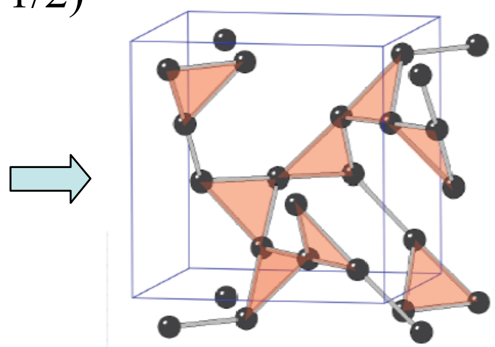
Migration of host electron: 5 electrons split into effectively 2.5 e charges.

(Fulde *et al.*, '02)

Chiral metal

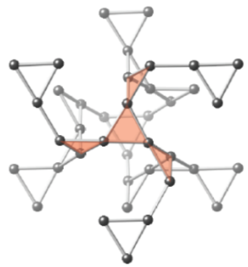
$Na_4Ir_3O_8$ ($5d^5$,S=1/2)



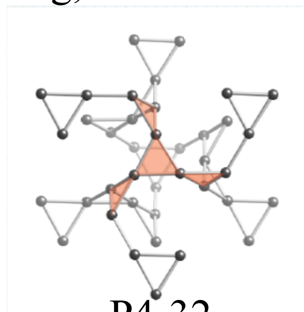


"Hyper-Kagome"

...If one can get it carrier-doped, and even get superconducting, then...



$P4_132$



$P4_332$

Exotic superconductivity due to the lack of inversion symmetry?

(Nohara)

Summary

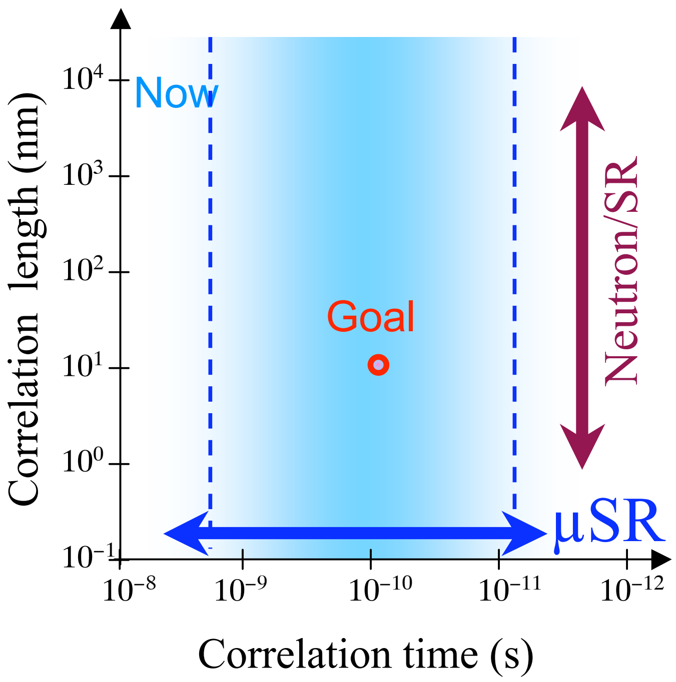
•Geometrically antiferroic correlation (GAC) between electrons conducting on highly symmetric orbits might give rise to new class of metallic state, where the HF behavior in cubic spinels/pyrochlores might be one such manifestation.

•Both μSR, neutron scattering, and SR should work together to elucidate the microscopic details of the new metallic ground state observed in cubic spinels/pyrochlores.

•Now it seems that time is mature to launch an in-depth studies of GAC in combination with a systematic and large-scale search for new candidates for "frustrated metals".

Our Goal:

...to pin down the characteristic scales of time/length with unprecedented precision.



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