Nematic Order in $Sr_3Ru_2O_7$

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PRB **79** 214402 (2009)

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I. Overview

Ruthenates: $Sr_{n+1}Ru_nO_{3n+1}$

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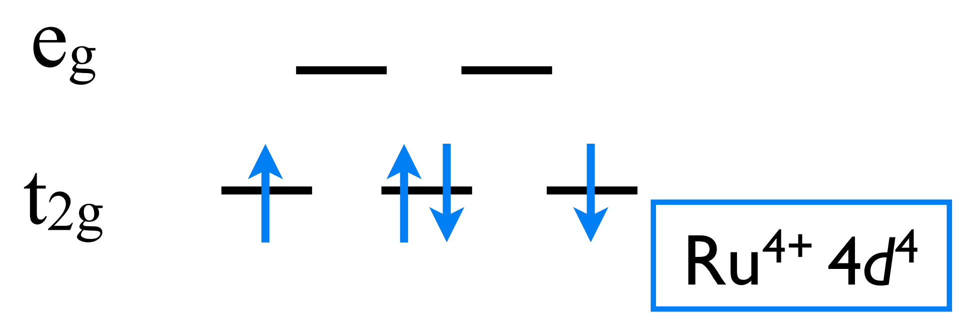

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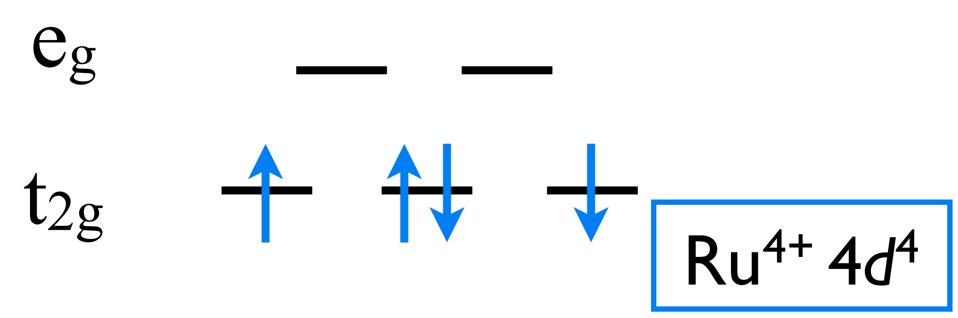
3) In addition to charge and spin degrees of freedom, orbital degeneracy plays an important role.

4) Spin-orbit coupling plays an important role (*e.g.* affects Fermi-surface topology).



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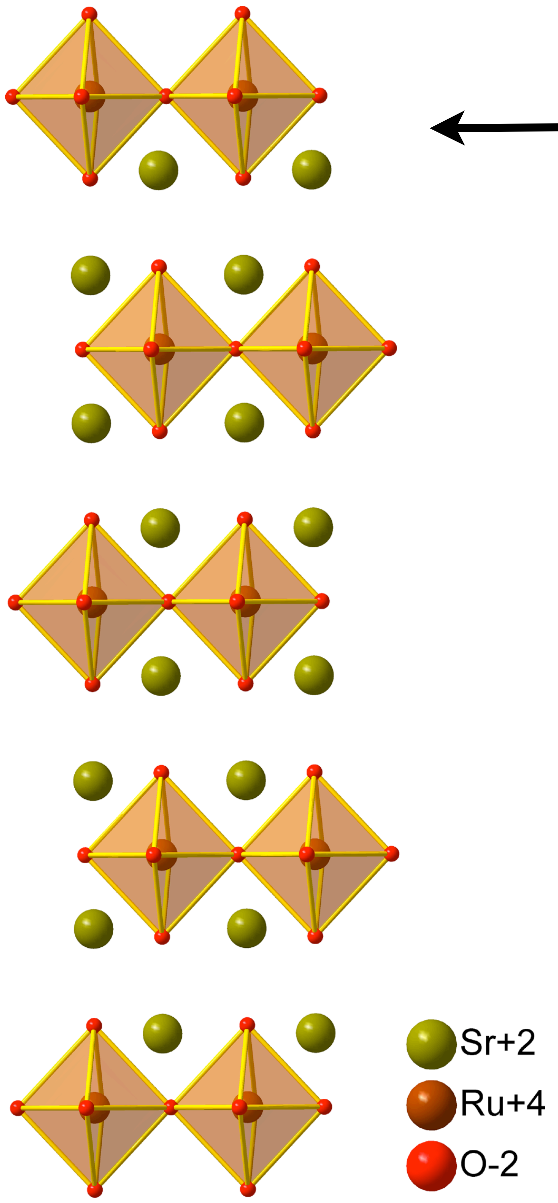

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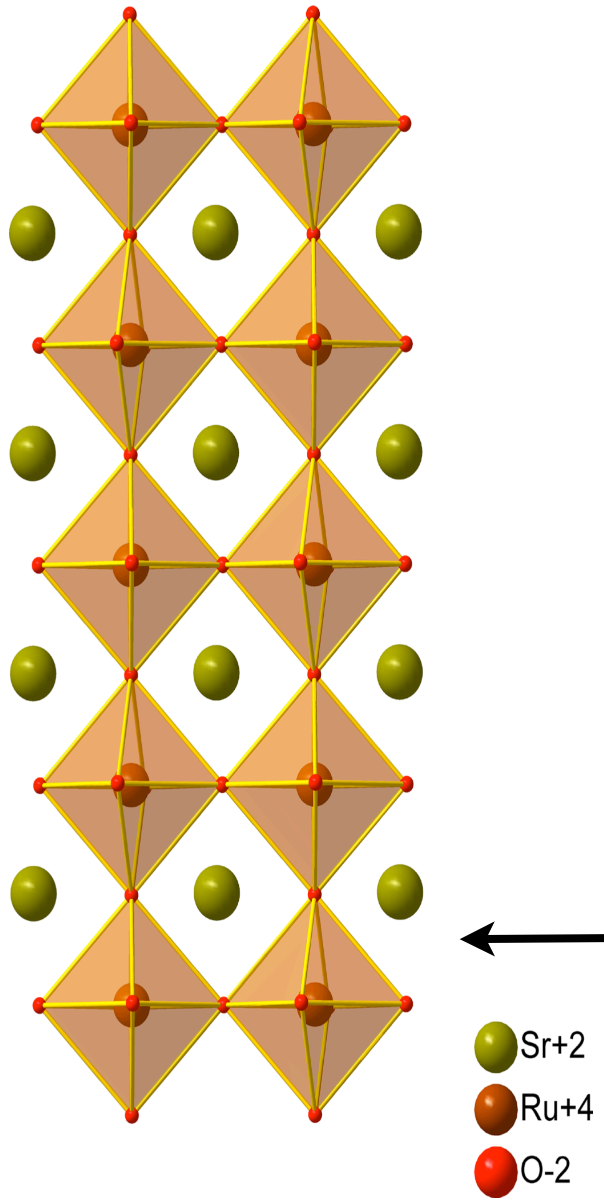

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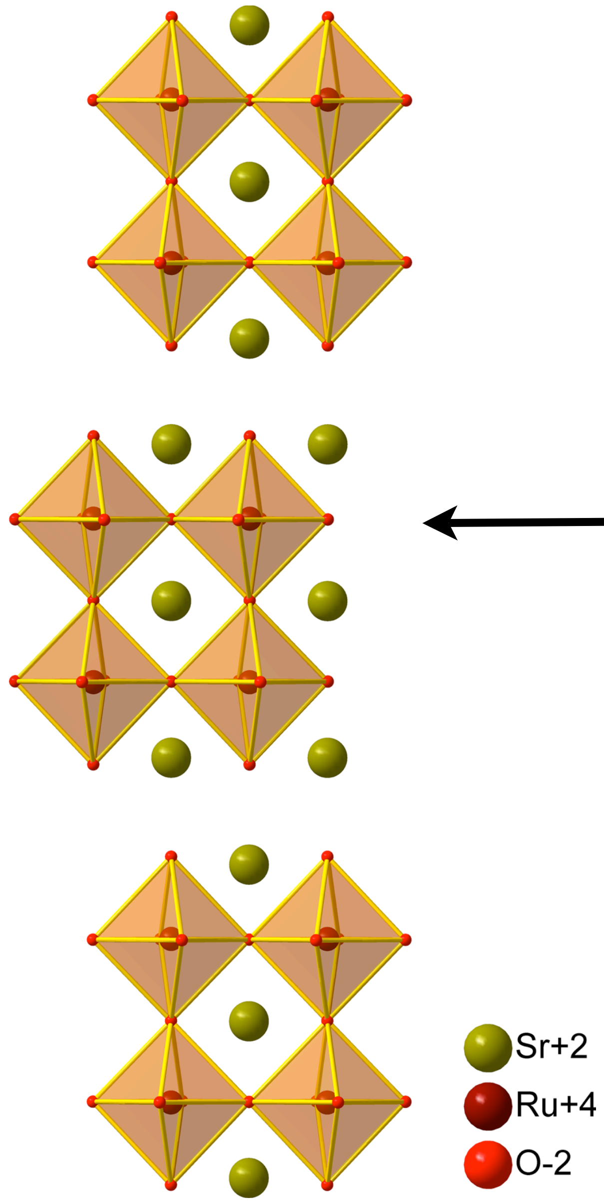

$n = 1$: Sr_2RuO_4 unconventional superconductivity T_c=1.5K.

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increasing itinerancy with n (FM for n >3).

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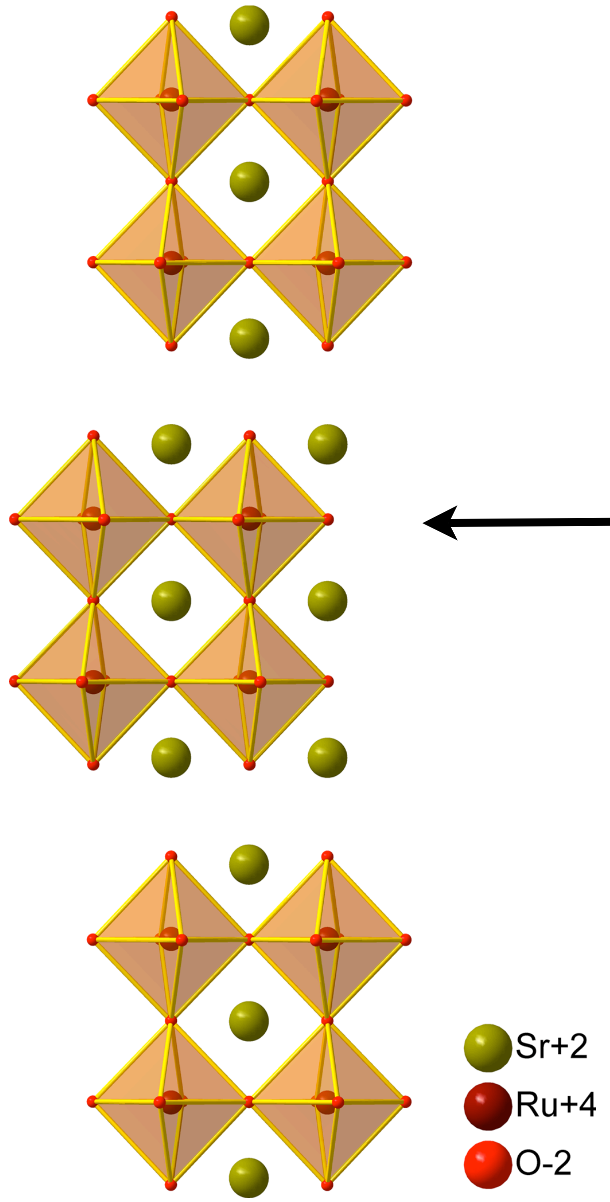

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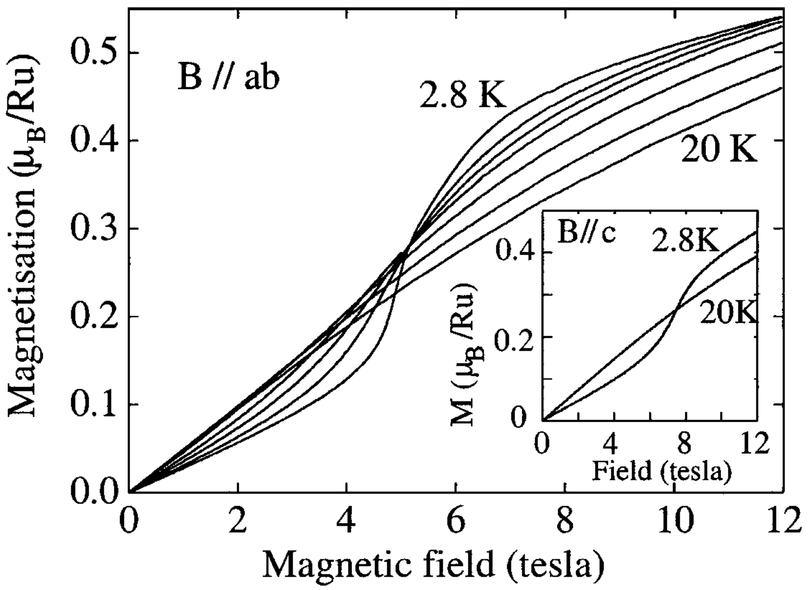
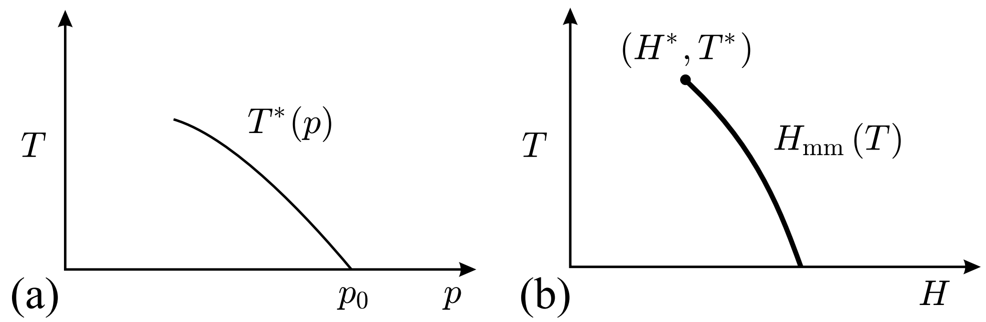
In this talk: we concentrate on n=2: $Sr_3Ru_2O_7$

II. Experimental phase diagram of $Sr_3Ru_2O_7$

Metamagnetism

1st order transition (no symmetry breaking)

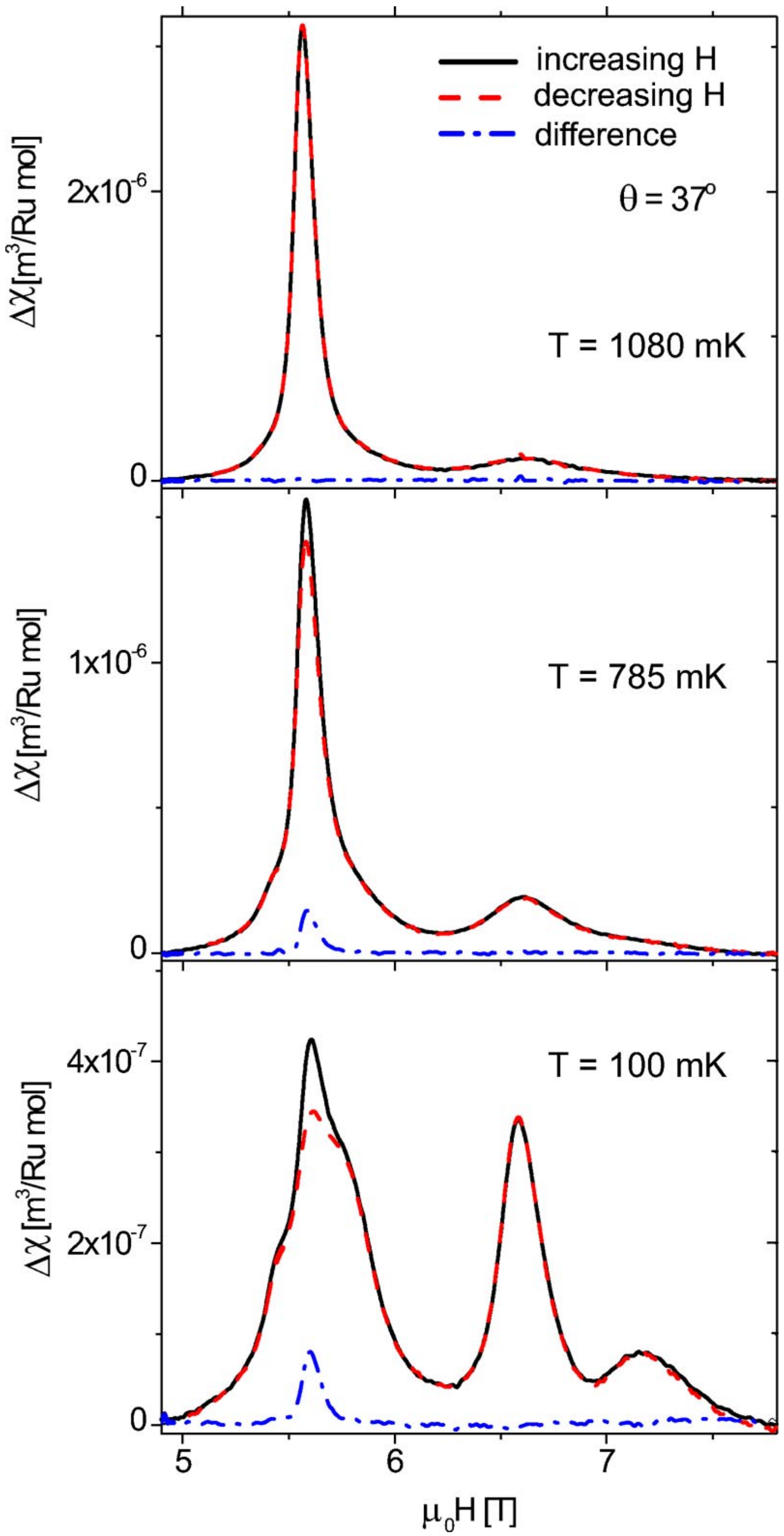




Analogous to Liquid-gas transition: presence of a critical end point

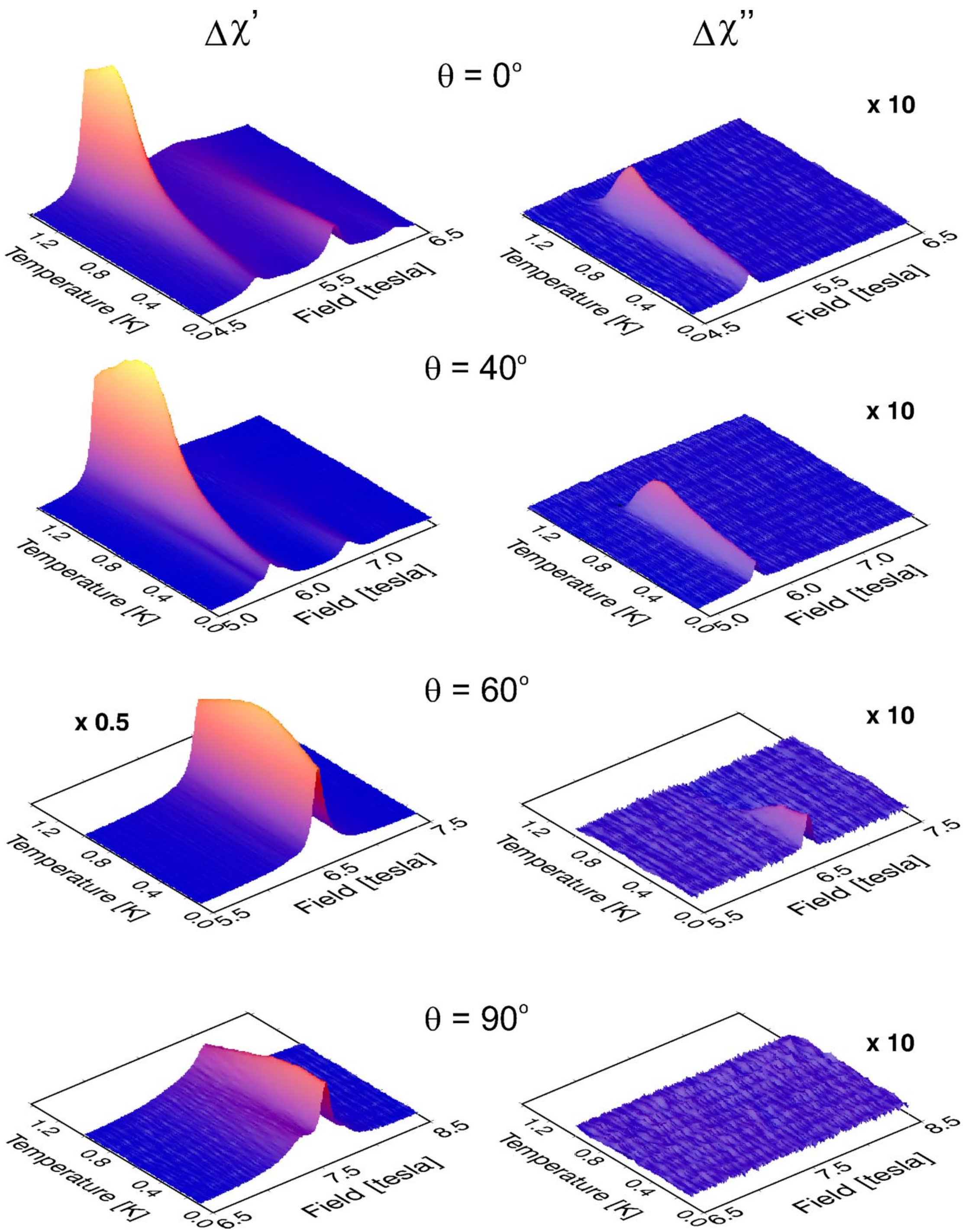
T<T*: 1st-order transition
T>T*: crossover

Hysteresis

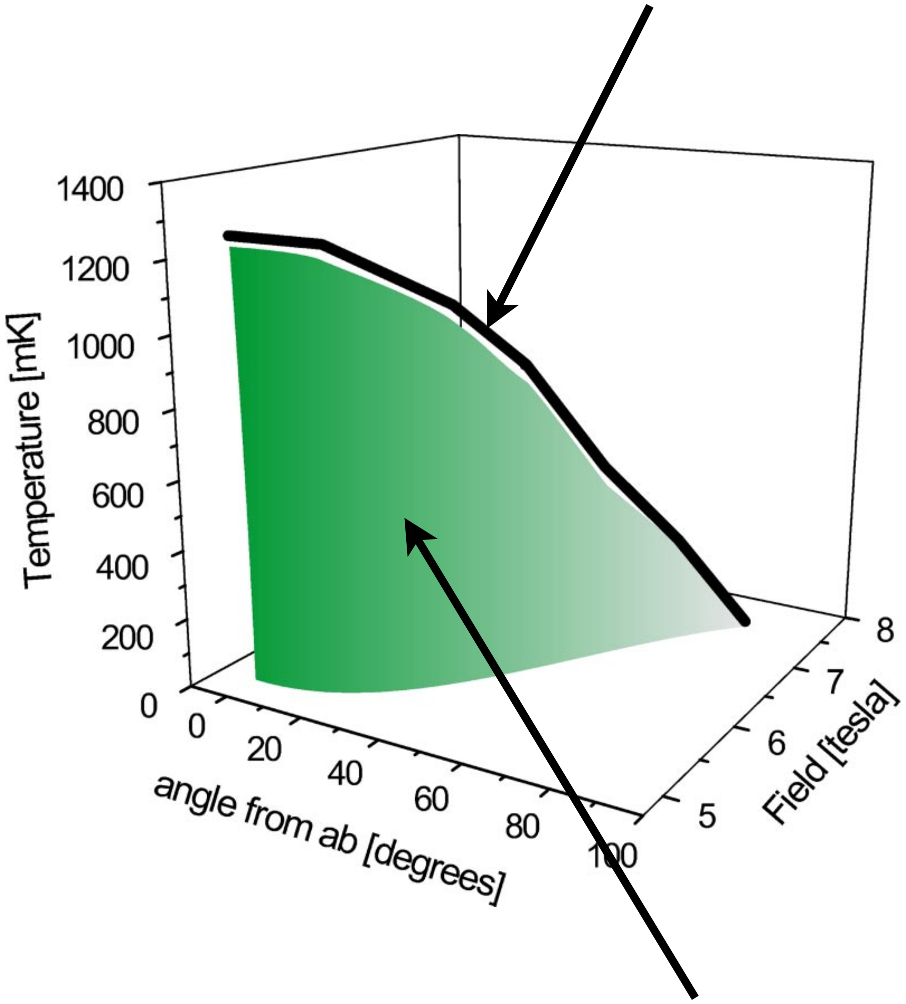


PRL **86**, 2661 (2001)

Dependence on field orientation



line of critical end-points



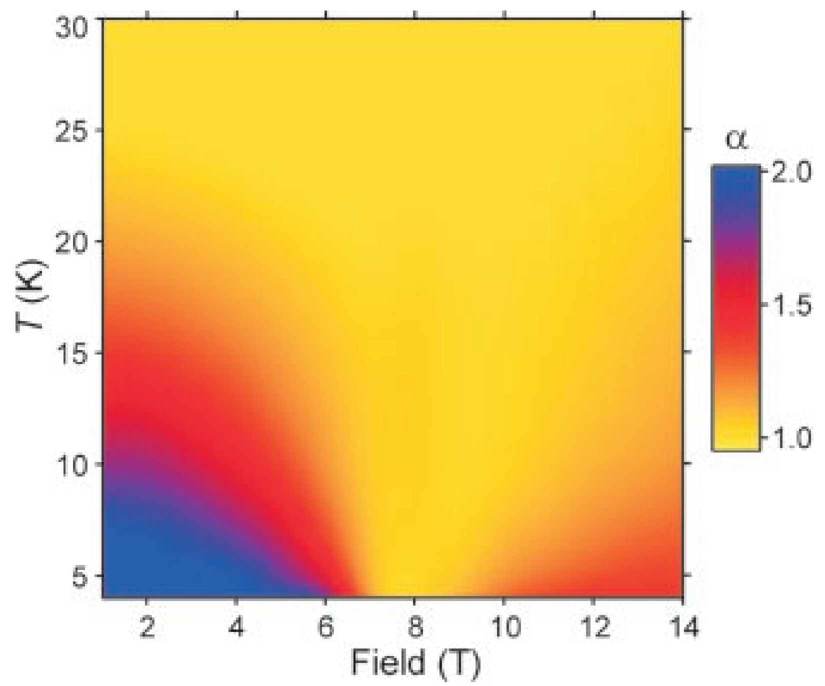
1st order phase boundary

T* -> 0 for H parallel to c-axis

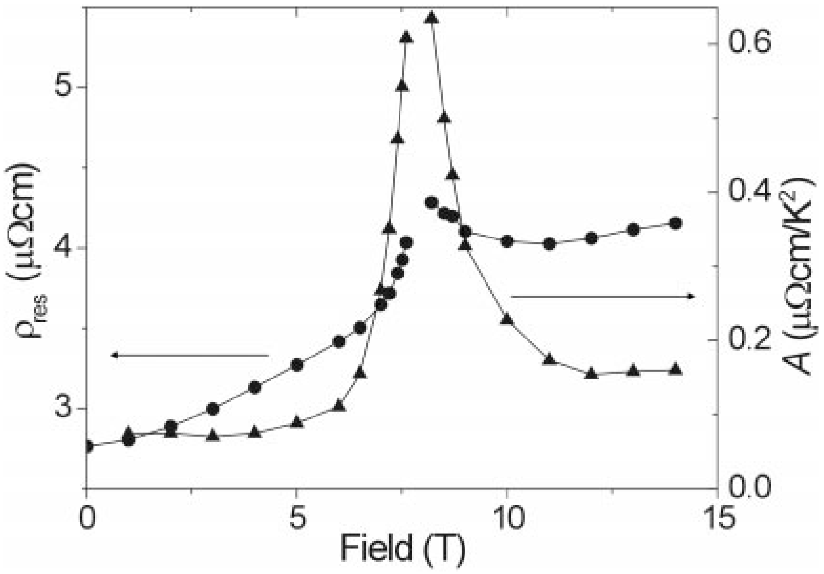
PRB **67**, 214427 (2003)

“Metamagnetic quantum criticality”

$$\rho(T) = \rho_{res} + AT^{\alpha}$$



non-FL behavior, quantum critical fluctuations



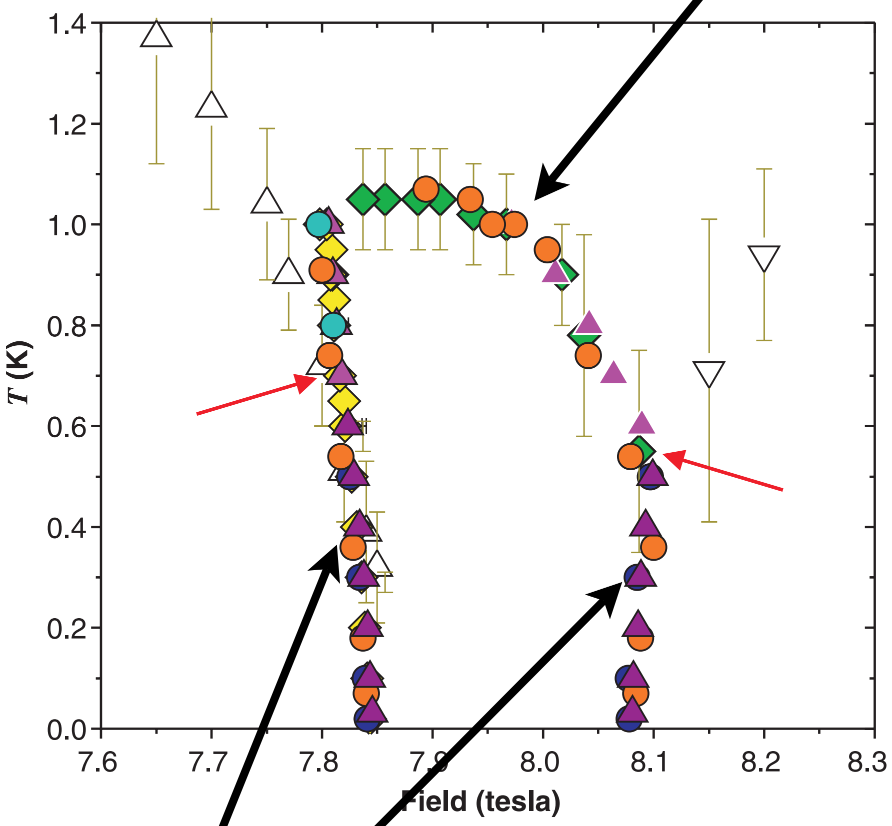
divergence of qp mass near qcp (also seen in quantum oscillations).

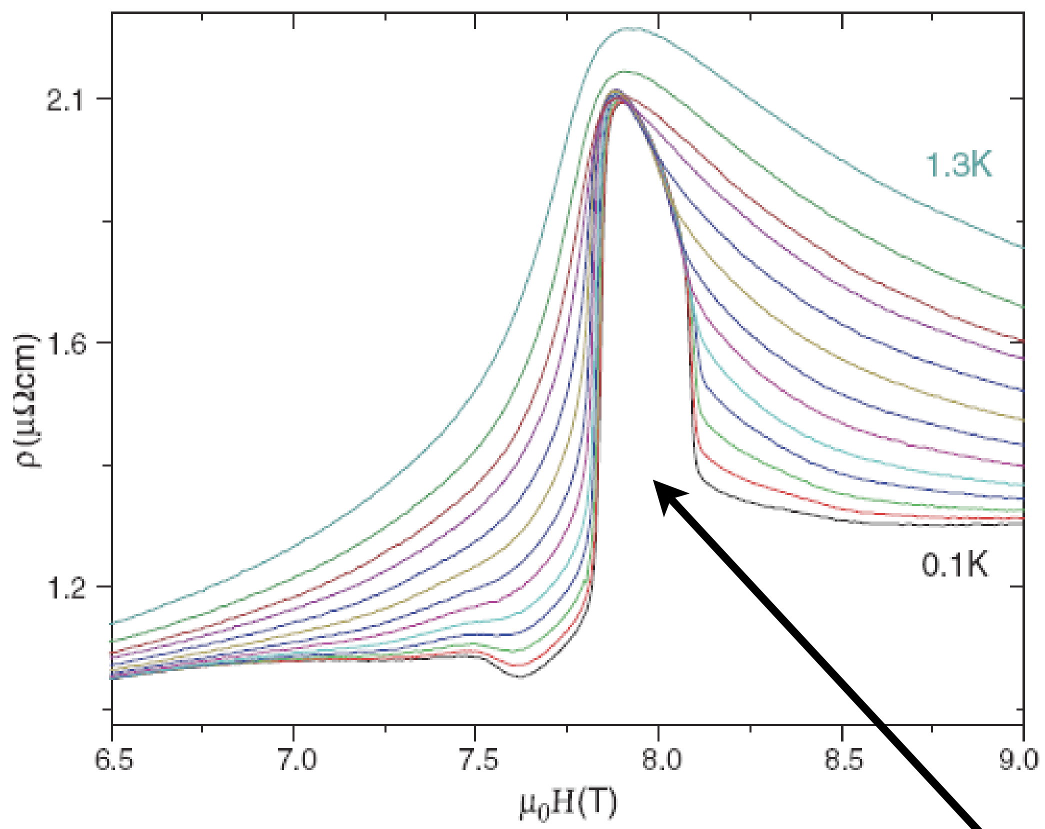
Science **306**, 1154 (2004)

This is a new type of quantum critical phenomena: associated with a critical end point, and no symmetry breaking. However...

Ultra-pure crystals: new low T phase

2nd order





Science **306**, 1154 (2004)

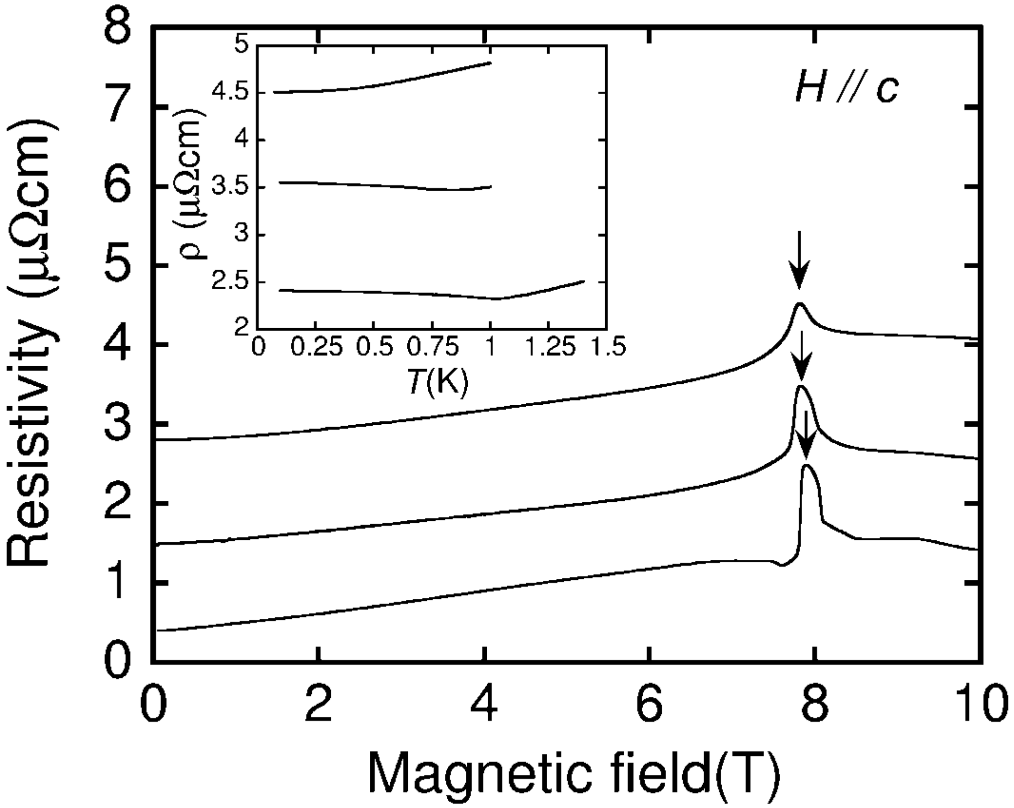
enhanced scattering

1st order boundaries

In the purest crystals, the “metamagnetic qcp” is enveloped by a thermodynamic phase at low T.

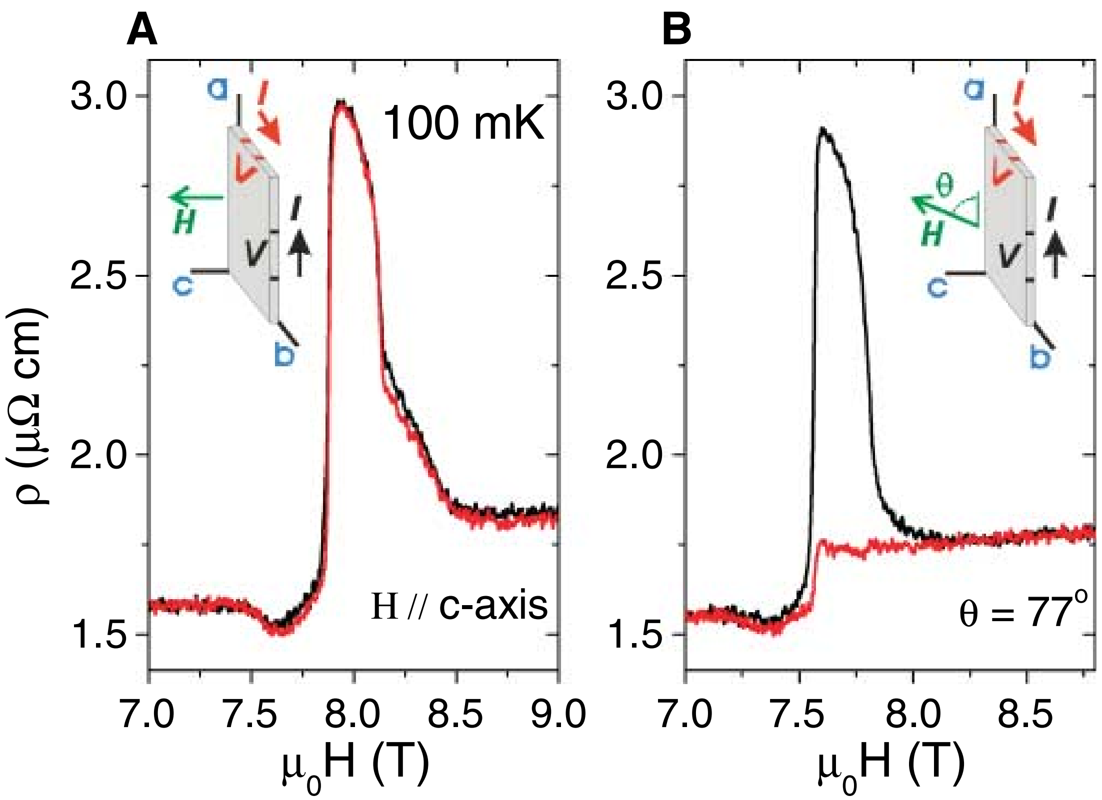
Properties of the low T phase near Hc

PRL **92**, 166602 (2004)



Very sensitive to disorder

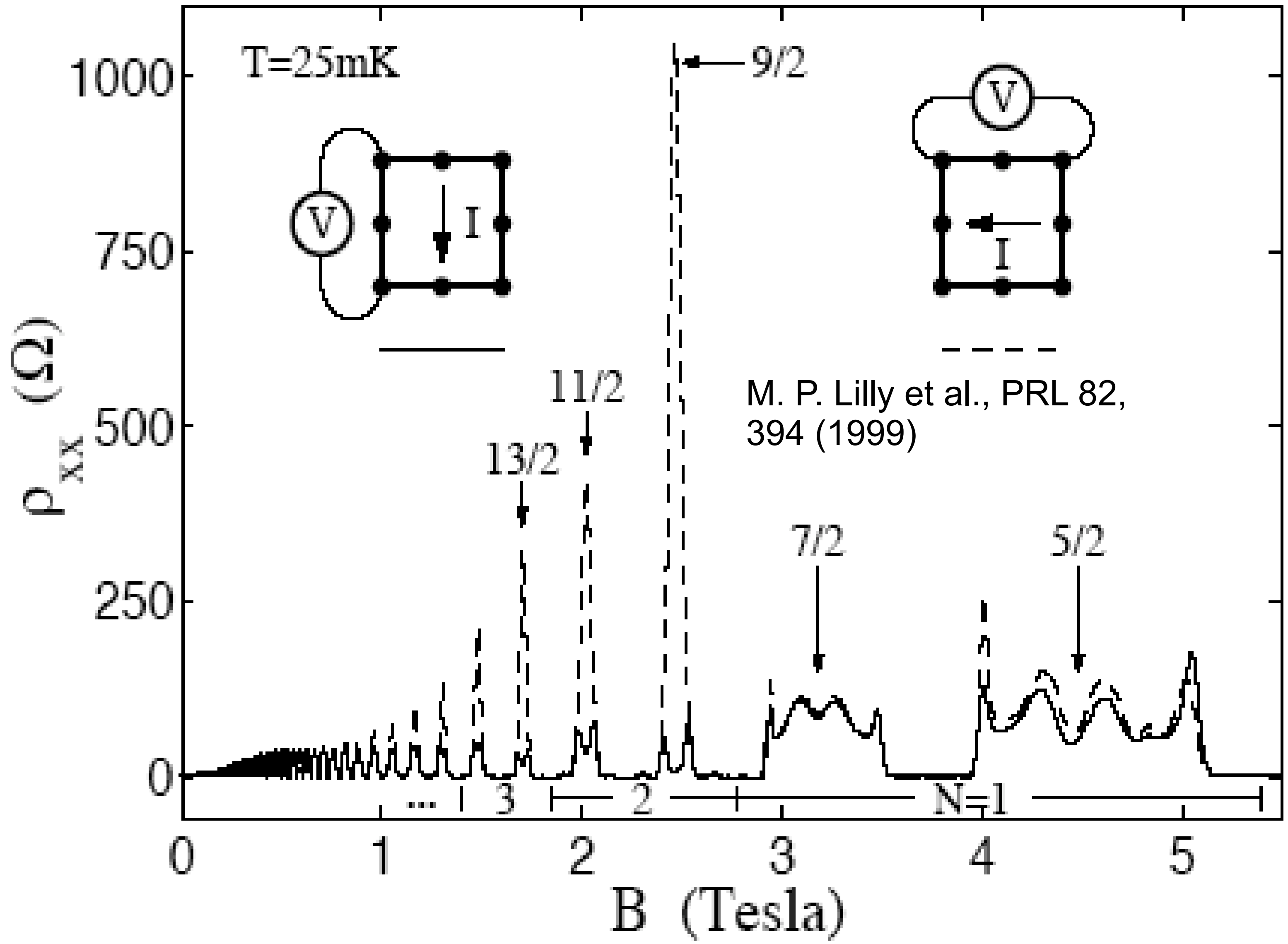
Science **315**, 214 (2007)



Order 1 resistive anisotropy
C4 symmetry reduced to C2
(no associated structural transition)

The phase has orientational order, but translational symmetry is preserved
electronic analog of nematic phase.

Similar features observed in 2DEG at high B fields



M. P. Lilly et al., PRL 82, 394 (1999)

M. M. Fogler, et al, PRL 76 ,499 (1996), PRB 54, 1853 (1996); E. Fradkin et al, PRB 59, 8065 (1999), PRL 84, 1982 (2000).

III. Microscopic model and theoretical phase diagram

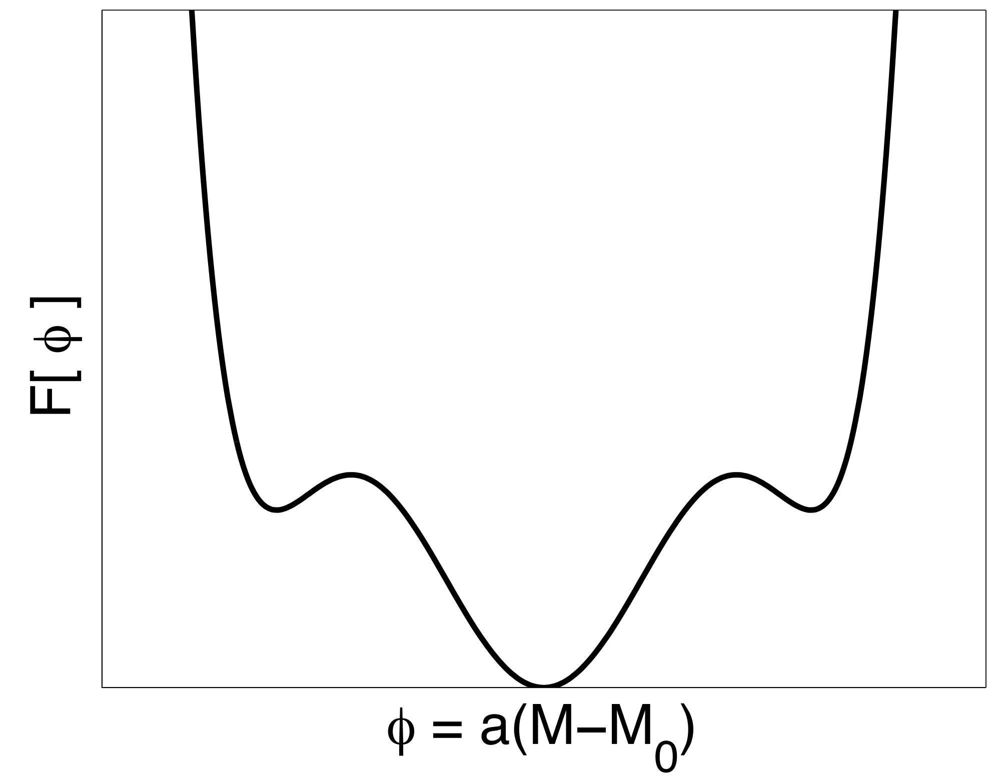
Itinerant electron metamagnetism

First consider effective theory for itinerant electron metamagnetism

$$F = \alpha\phi^2 - \beta\phi^4 + \gamma\phi^6 - H\phi$$

1. $E = \sum_\sigma \int_{-\infty}^{\mu_\sigma} d\epsilon \; \epsilon\nu(\epsilon)$

2. $M = \sum_\sigma \sigma \int_{-\infty}^{\mu_\sigma} d\epsilon \; \nu(\epsilon)$

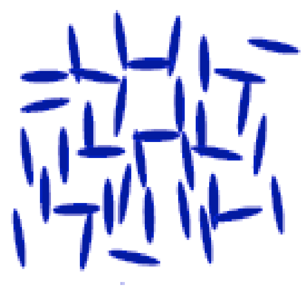


From 1,and 2, we can derive Landau coefficients.

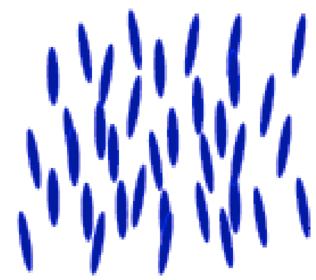
Requirement for weakly first-order metamagnetic transition:
D.O.S at the fermi level must have pronounced positive curvature.

Electronic nematic phases

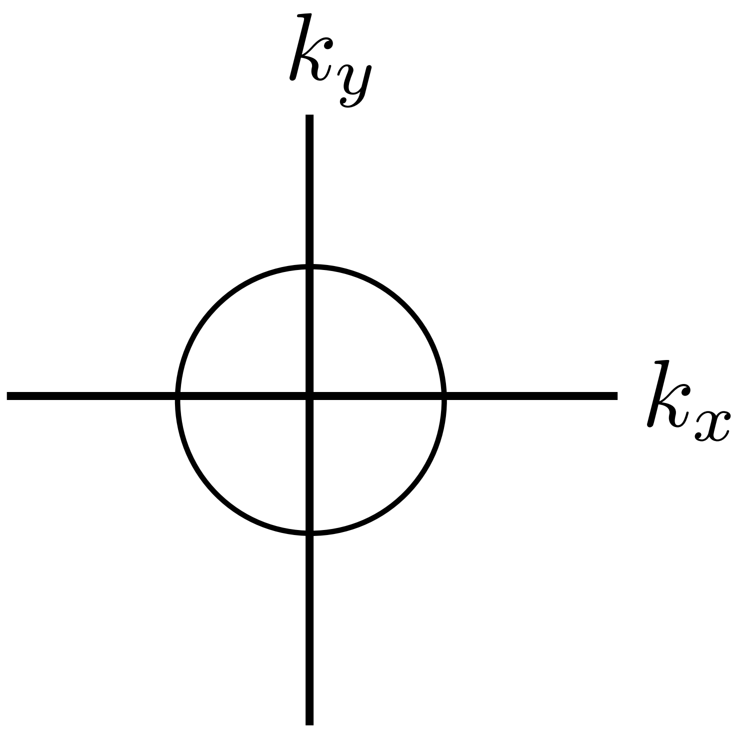
Isotropic

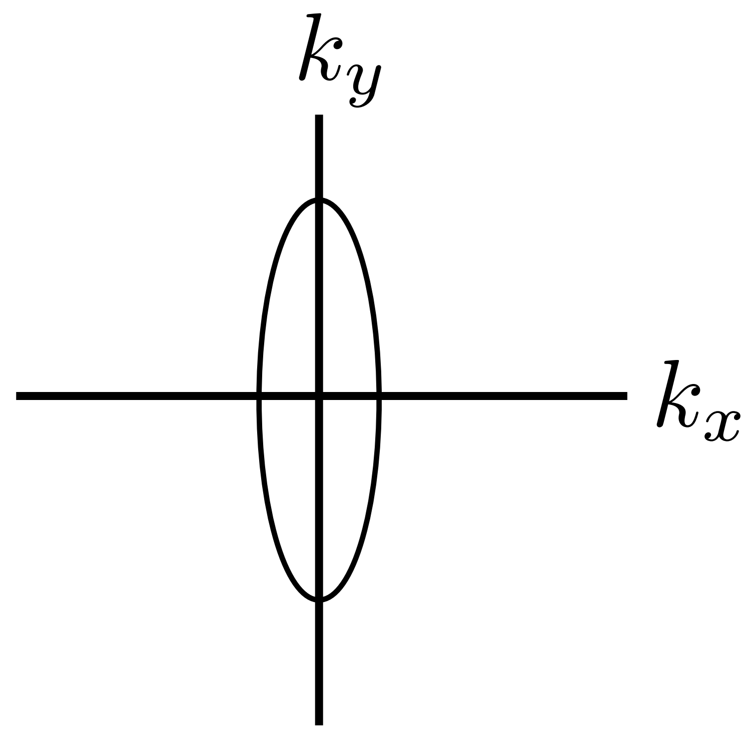


Nematic



Classic nematic liquid crystal: preserves translation breaks rotation symmetry.





Electronic analog: Fermi surface breaks underlying rotational symmetry.

effective theory of the nematic transition: L=2 Fermi-liquid instability.

$$V_{eff} = \sum_{\boldsymbol{k},\boldsymbol{k}'} f_2 P_2(\hat{k} \cdot \hat{k}') \delta n_{\boldsymbol{k}\sigma} \delta n_{\boldsymbol{k}'\sigma'}$$

Formulating a microscopic theory

Problems with a microscopic formulation:

1) Both metamagnetism and nematic order arise as intermediate to strong-coupling effects: difficult to treat theoretically. Stoner mean-field theory: $N(E_f)U \sim 1$ not a well-controlled method.

2) Difficult to imagine why metamagnetism and nematicity should be tied together.

Critical insight into both of these issues: H.-Y. Kee *et al.* PRB (2005).
Consider *effective* models close to van Hove singularities.

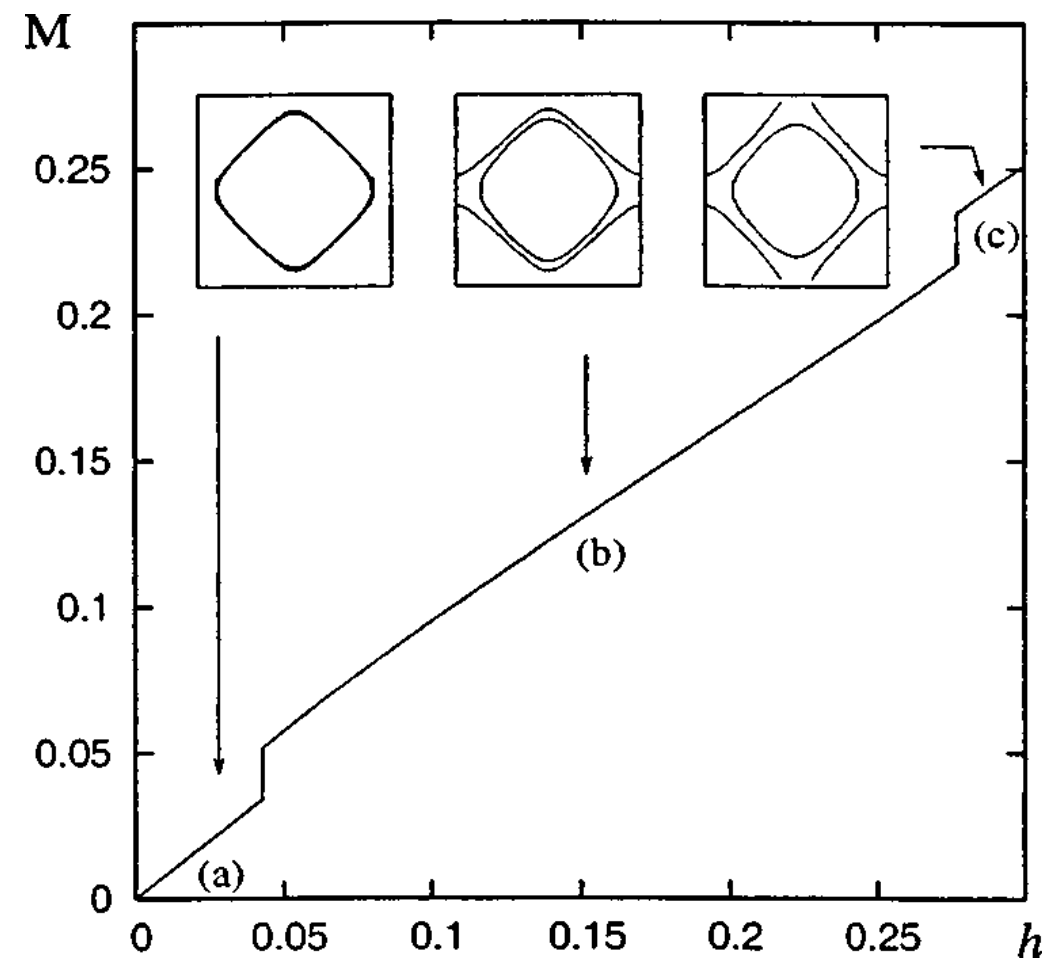
Proposal of H.-Y. Kee *et al.*

PRB **71**, 184402 (2005)

$$H = \sum_{\boldsymbol{k}\sigma} (\epsilon_{\boldsymbol{k}} - \mu)\, c^{\dagger}_{\boldsymbol{k}\sigma} c_{\boldsymbol{k}\sigma} + \sum_{\boldsymbol{q},\sigma} F_2(q) \mathrm{Tr}[\hat{Q}_\sigma(\boldsymbol{q})\hat{Q}_\sigma(-\boldsymbol{q})] + \mathrm{H.c.}$$

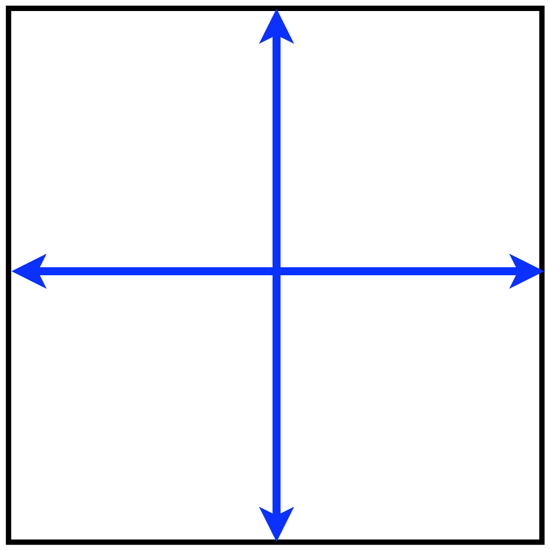
V_{eff}

$$\hat{Q}^{ij}_{\alpha}(\boldsymbol{q}) \sim \sum_{\boldsymbol{k}} c^{\dagger}_{\boldsymbol{k}+\boldsymbol{q}\alpha} \left(\hat{k}^i \hat{k}^j - \frac{1}{2}\hat{k}^2 \delta^{ij} \right) c_{\boldsymbol{k}\alpha}$$



effective model of single band near vHS

V_{eff}



Attractive

Proposal of H.-Y. Kee *et al.*

PRB **71**, 184402 (2005)

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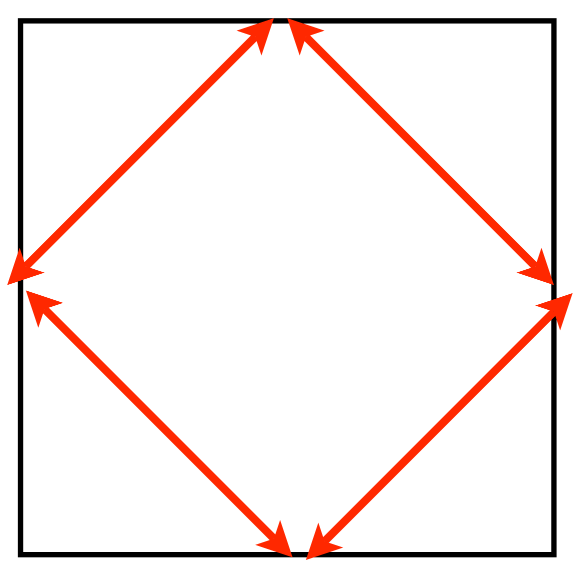
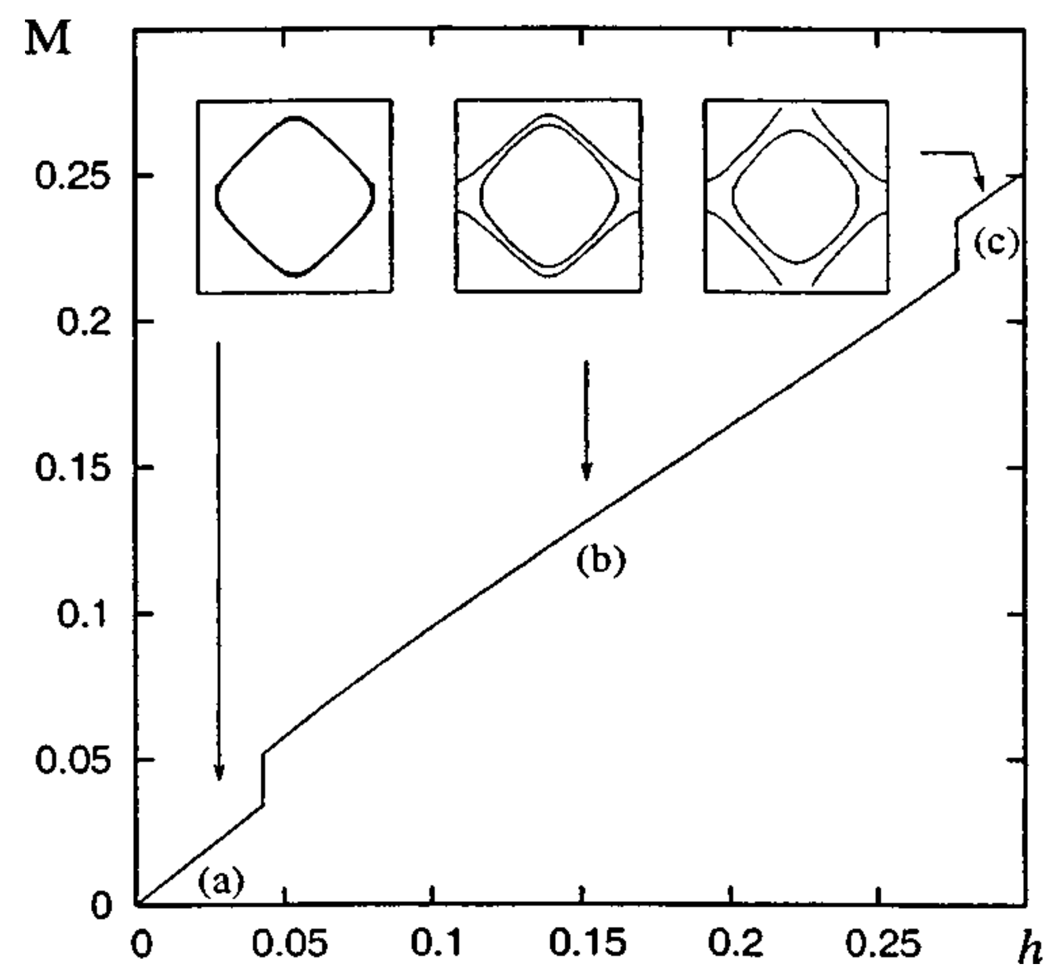


Repulsive



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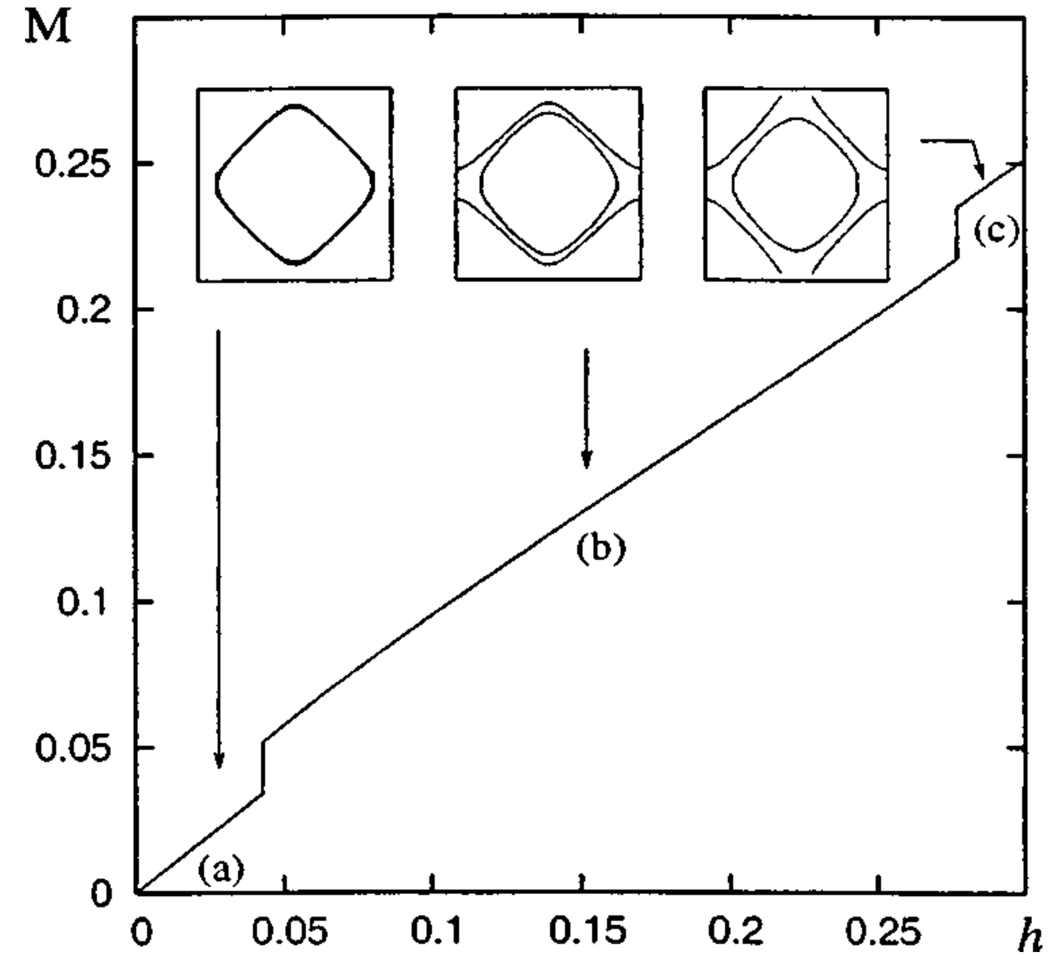

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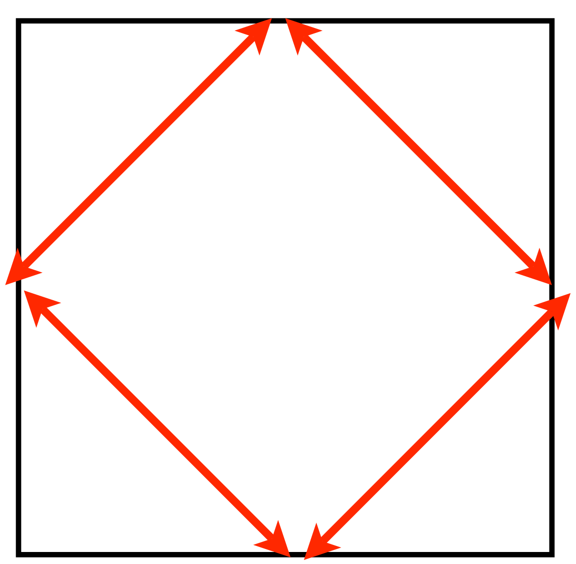


Repulsive

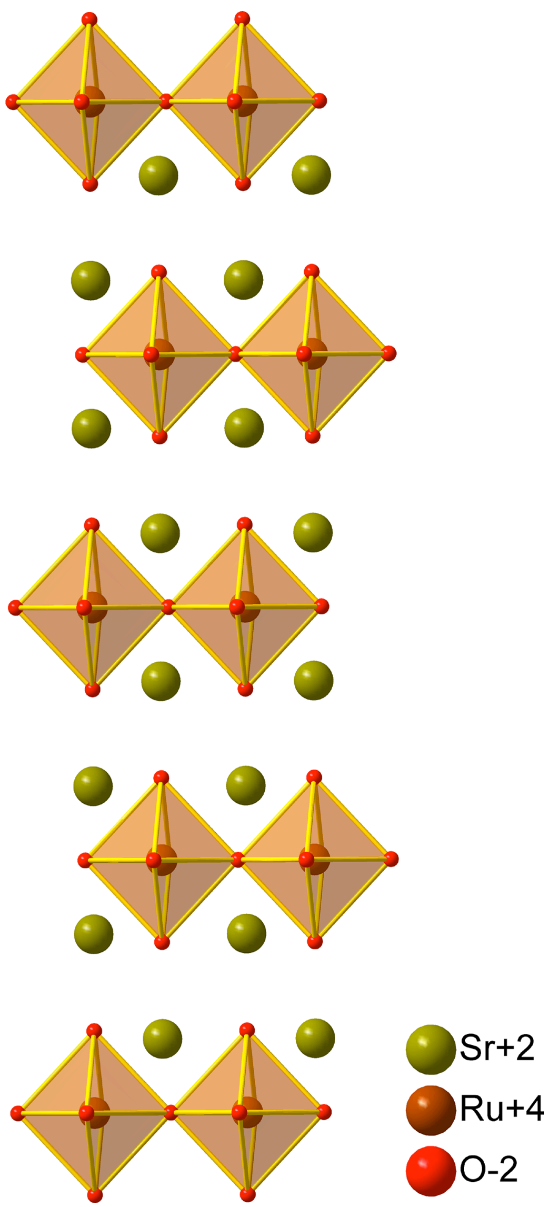
Although the phenomena can be “engineered”,

Microscopic origins of this is still unclear.

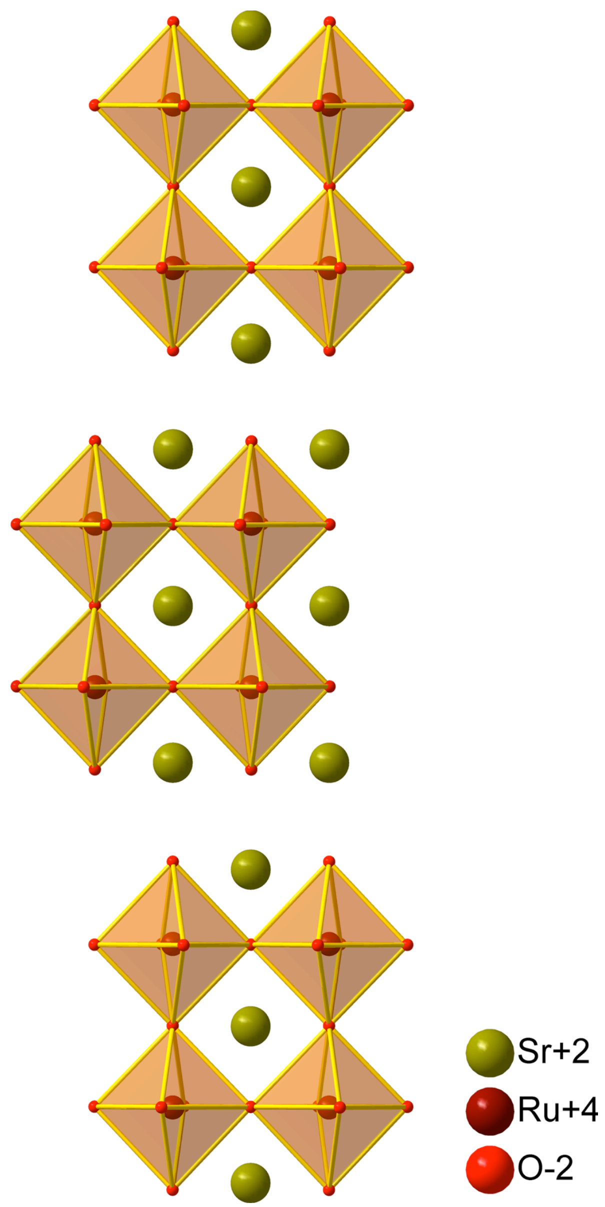
Our proposal: metamagnetic and nematic transitions here are both driven by orbital-ordering tendency.

Monolayer vs. bilayer ruthenate compounds

Sr_2RuO_4



$Sr_3Ru_2O_7$

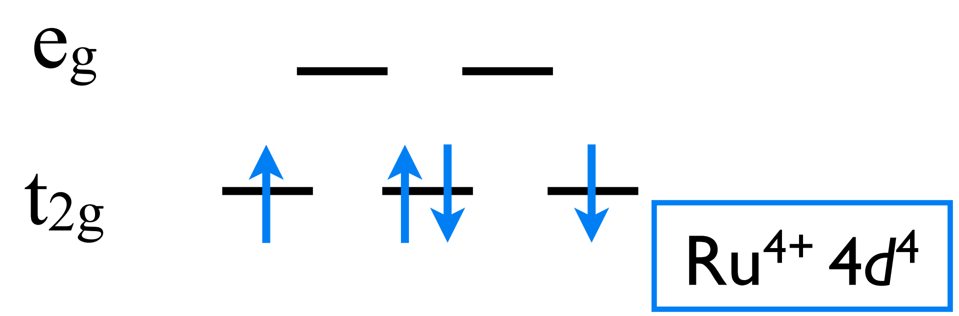


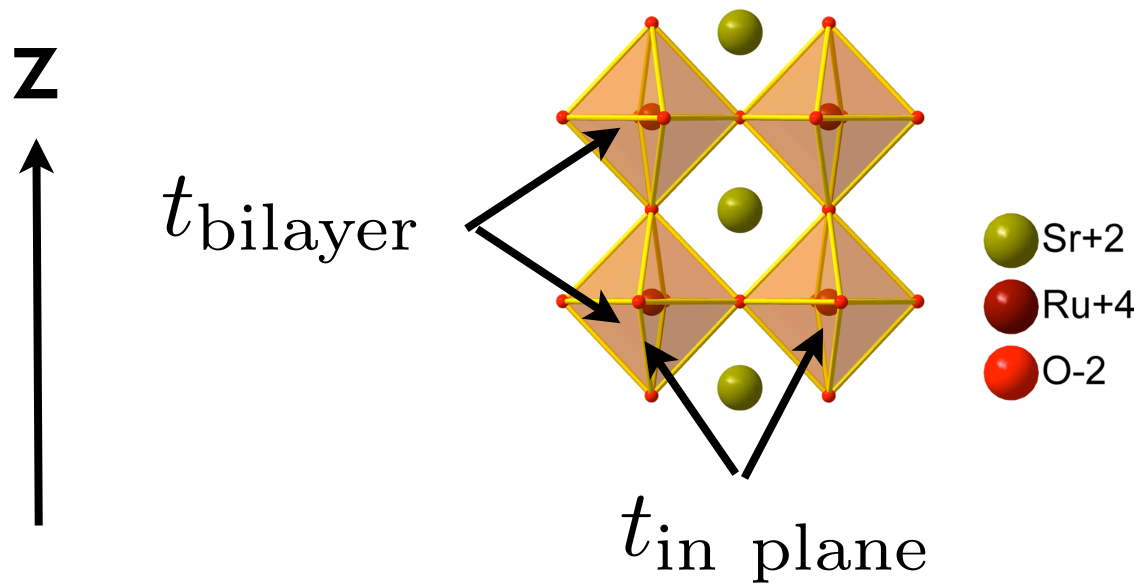
What are the microscopic origins of the low temperature physics of $Sr_3Ru_2O_7$?

i.e. why do Sr_2RuO_4 and $Sr_3Ru_2O_7$ have such different physical properties?

Monolayer vs. bilayer ruthenate compounds

In both of these materials, degeneracy of Ru t_{2g} (d_{xz},d_{yz},d_{xy}) orbitals plays a crucial role.

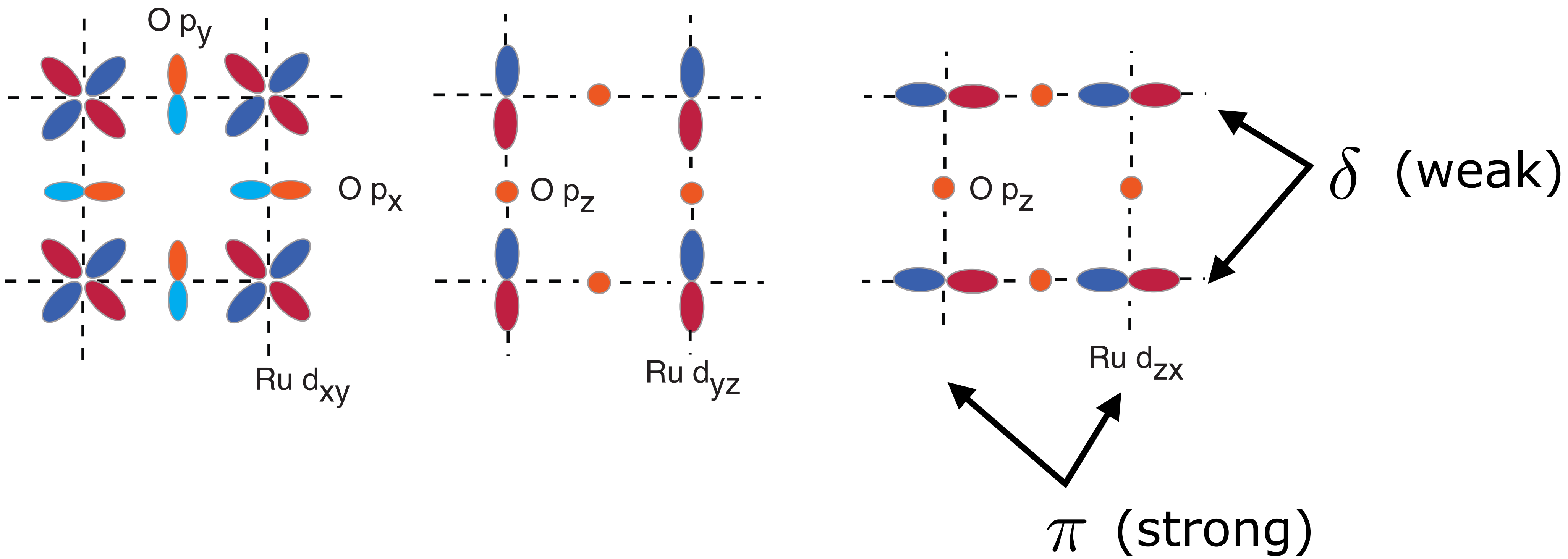




The strong bilayer splitting in $Sr_3Ru_2O_7$ is the primary difference between the two materials.

$$t_{\text{in plane}} \approx t_{\text{bilayer}}$$

Which of the t_{2g} orbitals are most affected by the bilayer splitting?



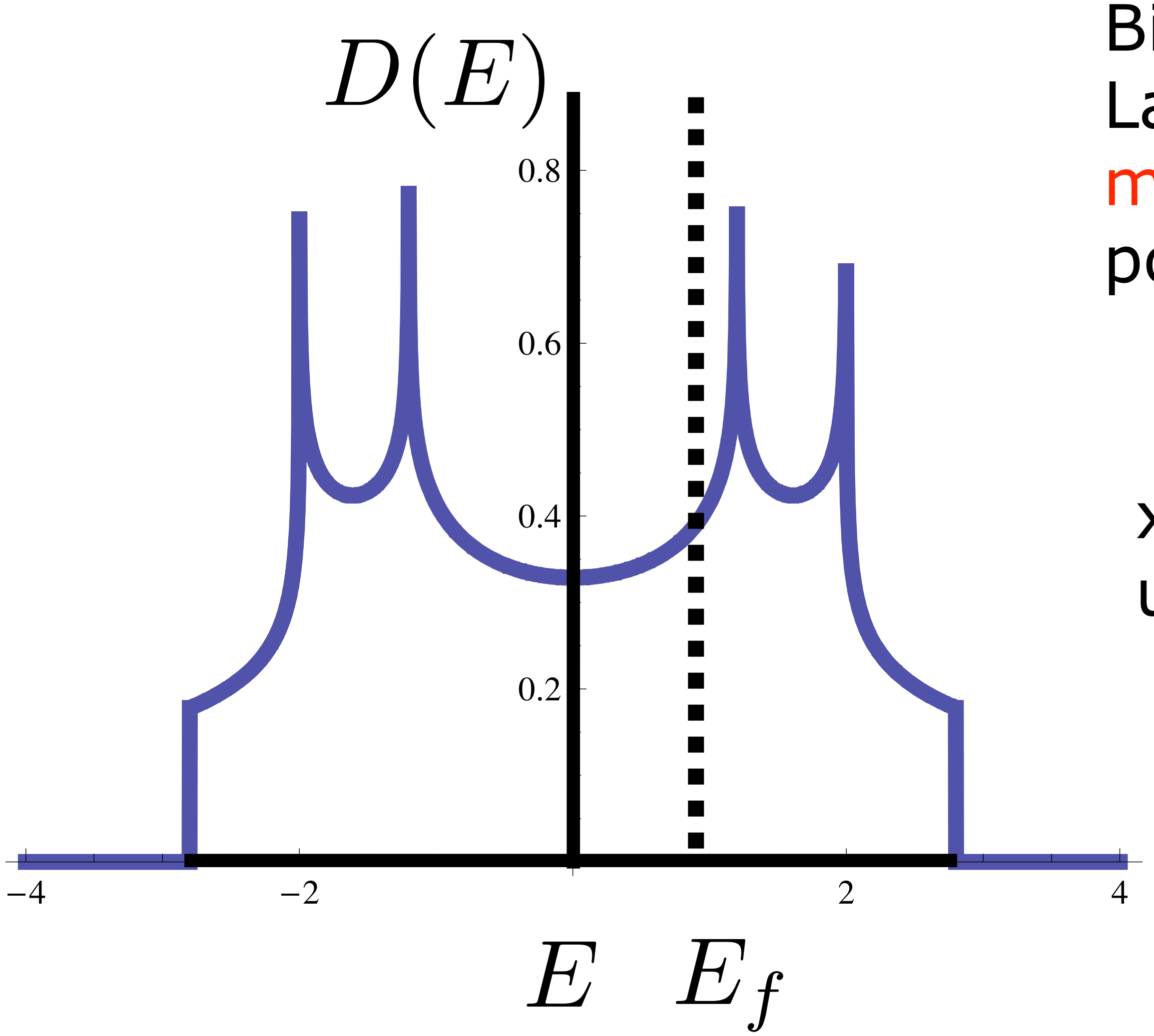
Electrons "hopping" between two adjacent Ru sites make use of intervening oxygen p-orbitals.

xz,yz: quasi-1D bands, *strongly* affected by bilayer splitting.

xy: quasi-2D band, *weakly* affected by bilayer splitting.

Primary difference between Sr_2RuO_4 (n=1) and $Sr_3Ru_2O_7$:
bilayer-split quasi-1D bands in $Sr_3Ru_2O_7$.

Metamagnetism and nematicity in quasi-1D bands



Bilayer-split quasi-1D bands satisfy Landau theory of weakly-first order metamagnetism: $D(E_f)$ has pronounced positive curvature

xz,yz orbitals also transform as a doublet under C_4:

$$\begin{pmatrix} xz \\ yz \end{pmatrix} \rightarrow \begin{pmatrix} yz \\ -xz \end{pmatrix}$$

Orbital-ordering among xz,yz: breaks C_4, producing nematic order. Proximity of Fermi level to a van Hove singularity of the quasi 1D dispersion enables a weak-coupling treatment of this problem.

Metamagnetism and orbital-ordering: weak-coupling

$$H = H_{kin} + U \sum_{i,\alpha} n_{i\alpha\uparrow} n_{i\alpha\downarrow} + \frac{V}{2} \sum_{i\alpha \neq \alpha'} n_{i\alpha} n_{i\alpha'}$$

H_{kin}: strongest hybridizations among t_{2g} orbitals

U term: Intra-orbital repulsion

V term: Inter-orbital repulsion

$$\sum_i \langle \vec{M}_{xz,i} + \vec{M}_{yz,i} + \vec{M}_{xy,i} \rangle$$

Total magnetic moment: breaks T.

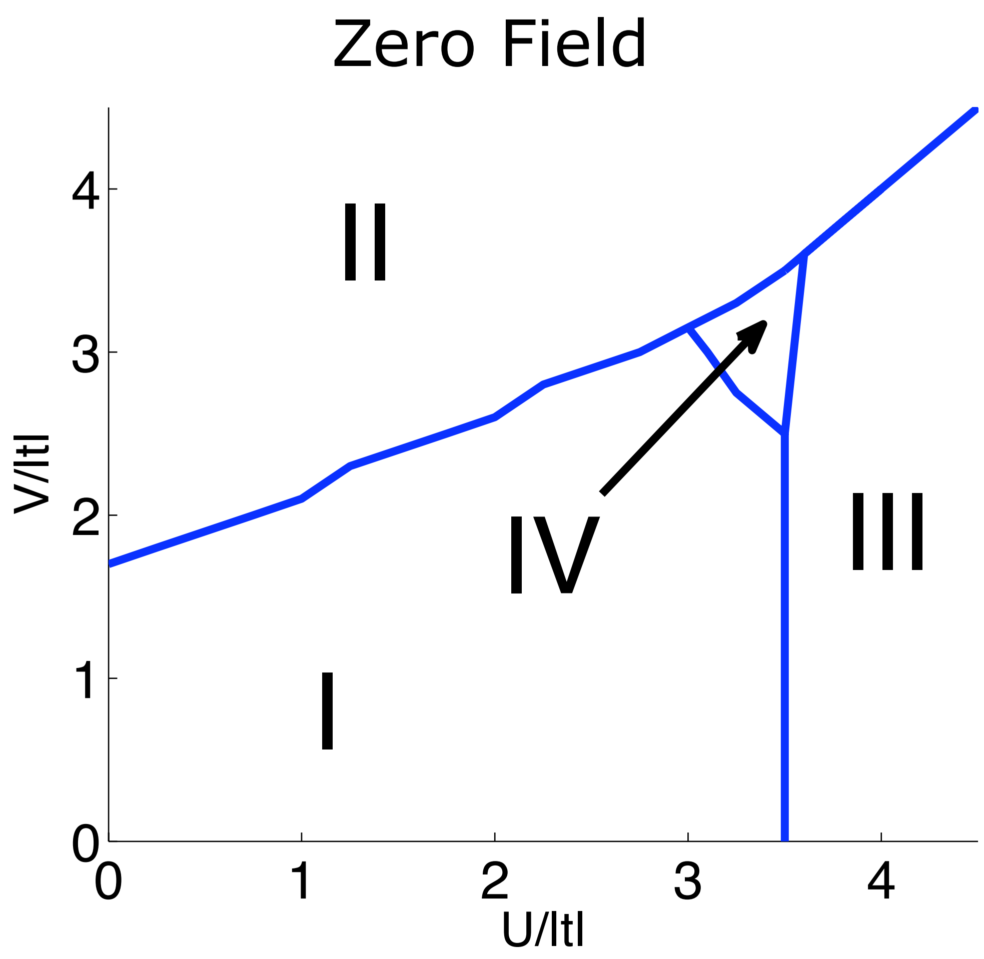
$$\sum_i \langle n_{xz,i} - n_{yz,i} \rangle$$

Nematic: breaks orbital degeneracy, C_4.

$$\sum_i \langle \vec{S}_{xz,i} - \vec{S}_{yz,i} \rangle$$

Spin nematic: breaks orbital degeneracy, C_4. T, SU(2), but preserves (C_4 x T).

Phase diagram



I: Paramagnet

II: Nematic order

III: Ferromagnet degenerate with spin-nematic

IV: Ferromagnet, nematic and spin-nematic

Physical regime: $U \approx V$

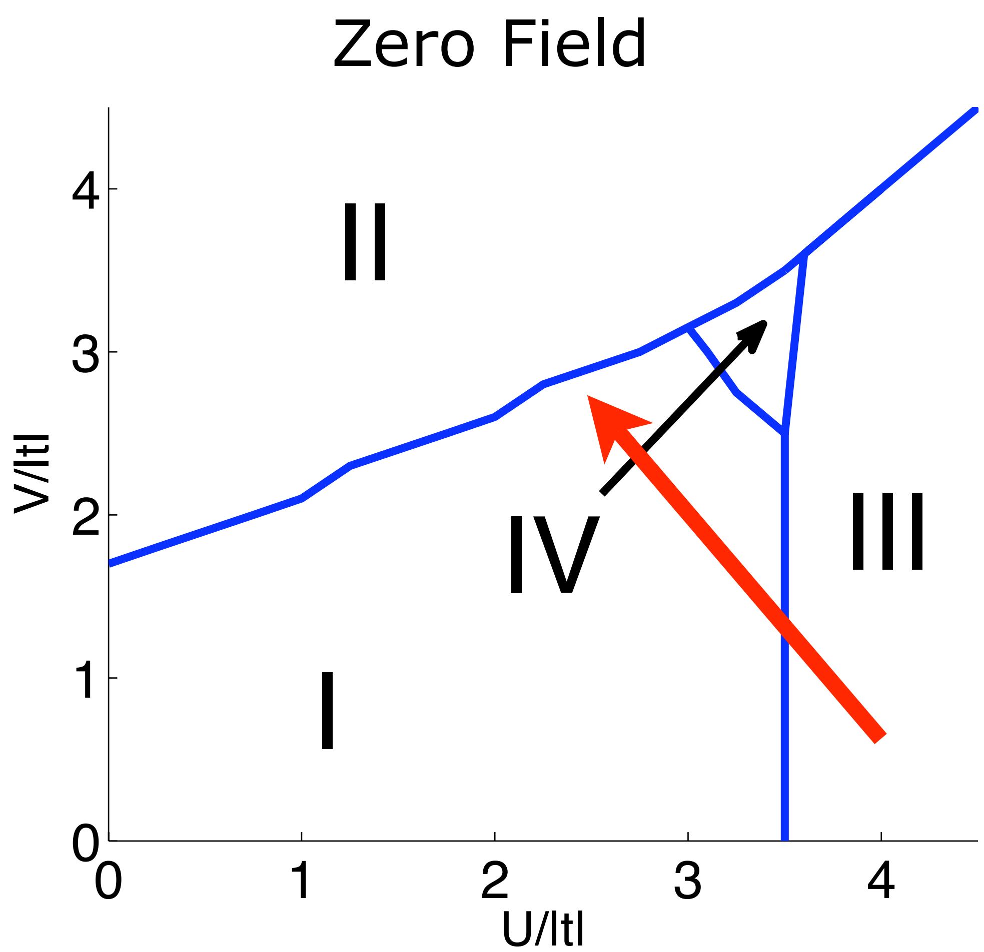
All phase boundaries here mark 1st order transitions.

Landau theory contains trilinear coupling:

$$c(\rho) N_o \vec{M} \cdot \vec{N}_s$$

relative weight of this term determines if phase IV wins.

Phase diagram



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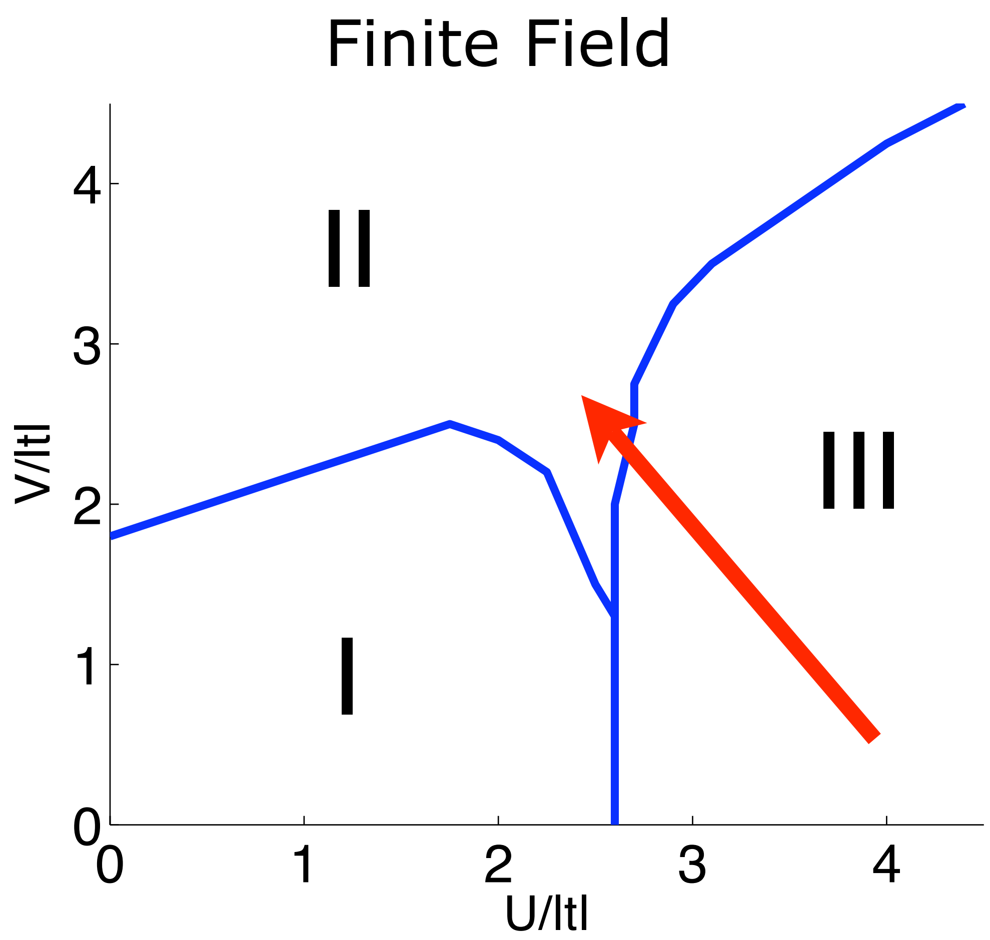


I: Small moment

II: Intermediate moment, Nematic

III: Large moment

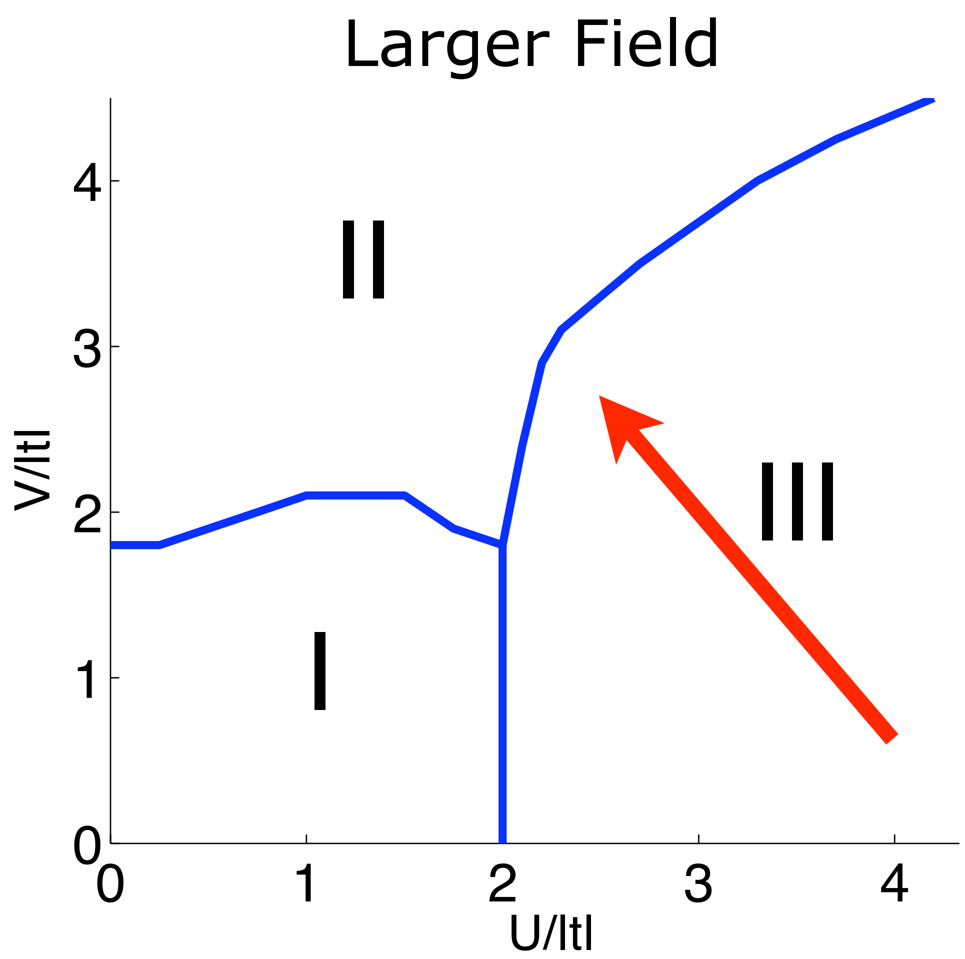
System crosses first metamagnetic boundary into nematic phase.

Physical regime: $U \approx V$

There is no distinction between nematic and spin-nematic in a finite field.

All phase boundaries here mark 1st order transitions.

Phase diagram



I: Small moment

II: Intermediate moment, Nematic

III: Large moment

Physical regime: $U \approx V$

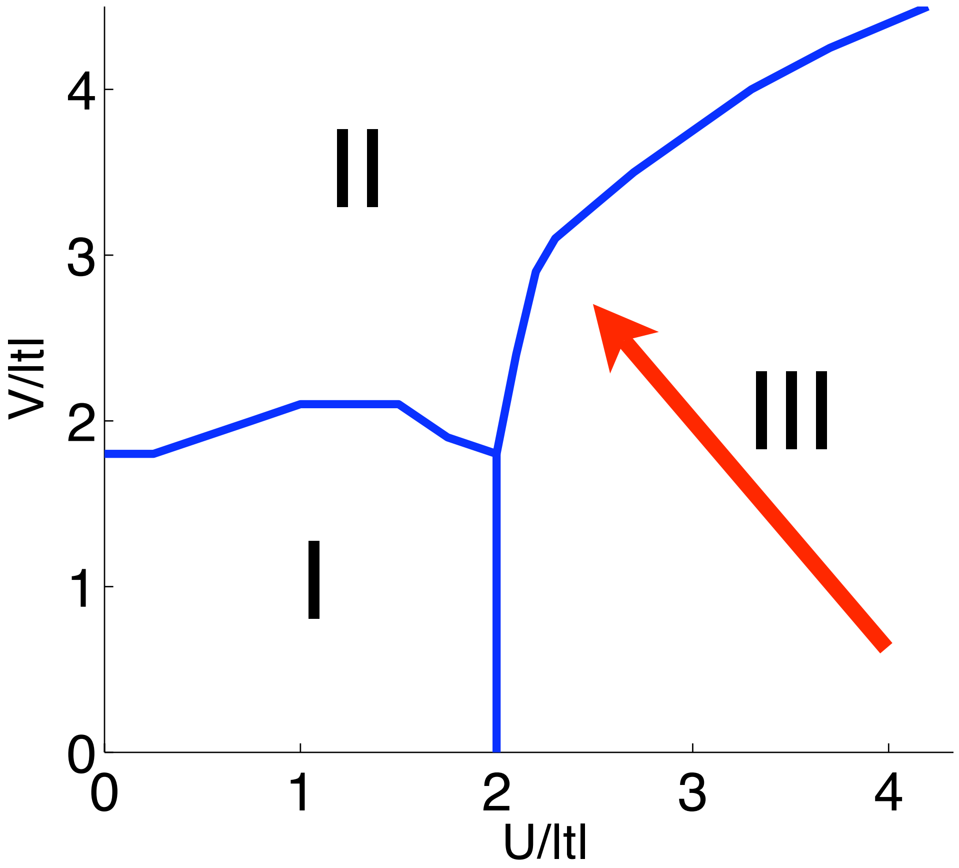
All phase boundaries here mark 1st order transitions.

System crosses second metamagnetic boundary into large moment phase.

There is no distinction between nematic and spin-nematic in a finite field.

Phase diagram

Larger Field



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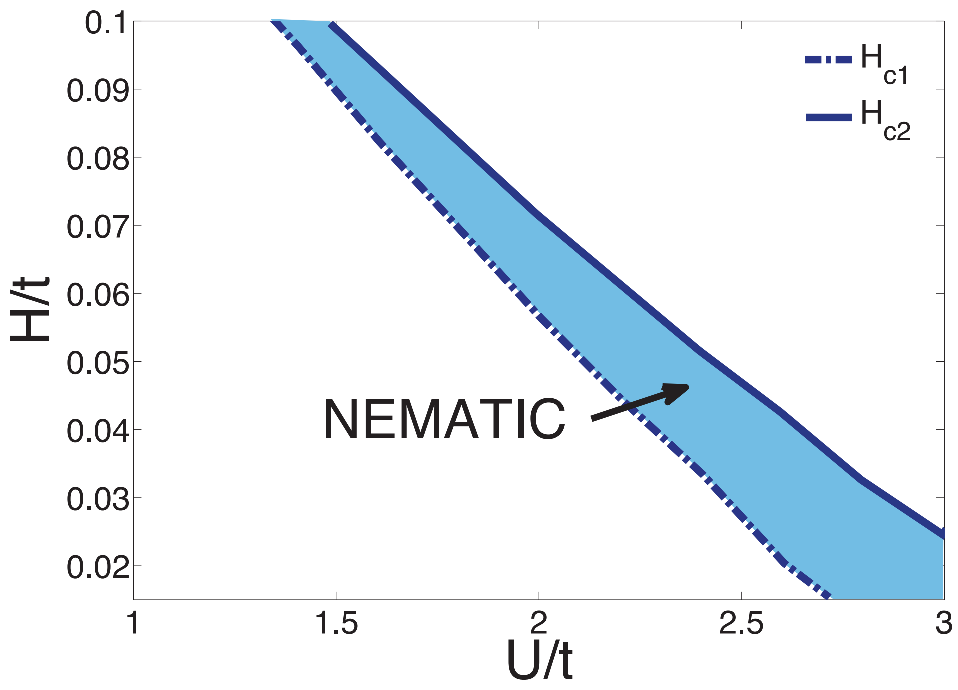
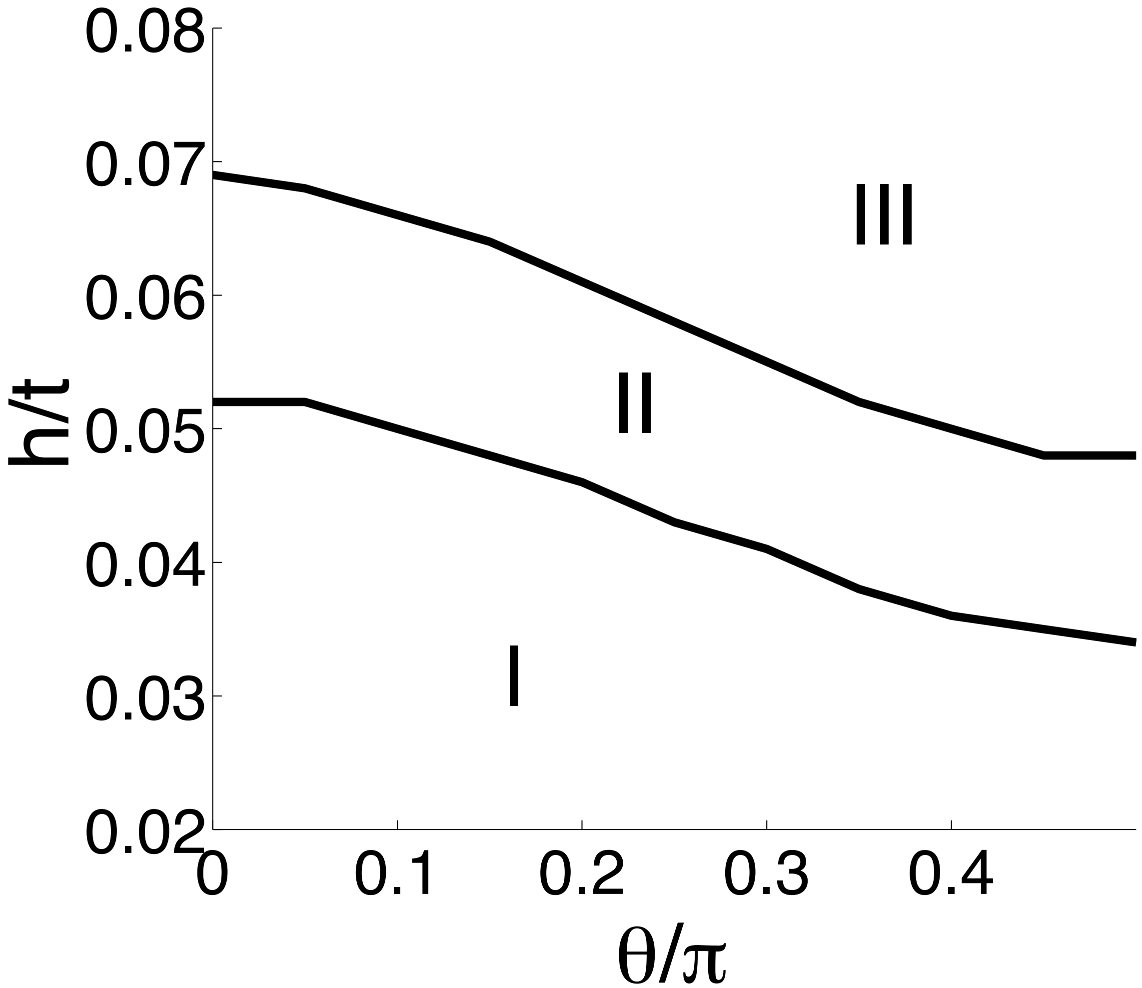


All phase boundaries here mark 1st order transitions.

Effect of spin-orbit coupling

SOC changes Fermi surface topology, and therefore plays an important qualitative role.



$$H_{s.o}(\theta) = \lambda \vec{L} \cdot \vec{S}(\theta)$$

Angle-dependent "metanematic" transitions.

Phase I: small nematic order, small moment.

Phase II: large nematic order, intermediate moment.

Phase III: small nematic order, large moment.

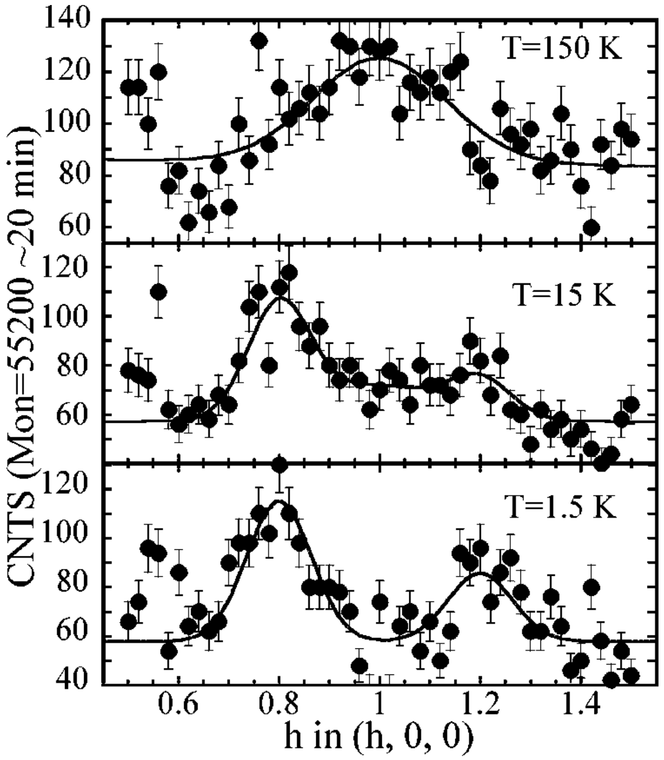
All phase boundaries mark 1st order transitions.

Spin-orbit coupling captures the O(1) anisotropy of critical fields as the field angle is varied.

Comparison to finite-q order

How does the nematic phase here compare with SDW, etc?

PRB **67**, 012504 (2004)



Inelastic neutron scattering: incommensurate fluctuations for T < 20K. Wave-vectors are consistent with FS nesting. However, no static SDW order is present (for h=0).

Spin-orbit coupling destroys near-perfect nesting of Fermi surface.

one-loop spin susceptibility

$$\left[\chi^{ij}(\boldsymbol{q})\right]^{st}_{ba} = \int_0^\beta d\tau \sum_{\boldsymbol{pp'}} \sum_{\alpha\beta\gamma\delta} \sigma^i_{\alpha\beta}\sigma^j_{\gamma\delta} \times \langle T_\tau d^\dagger_{s\boldsymbol{p}\alpha}(\tau) d_{t\boldsymbol{p}+\boldsymbol{q}\beta}(\tau) d^\dagger_{a\boldsymbol{p'}\gamma}(0) d_{b\boldsymbol{p'}-\boldsymbol{q}\delta}(0)\rangle$$

RPA: $\frac{U_{c,sdw}}{2}\mathrm{Max}\left(\mathrm{eig}\left[\chi\right]\right) = 1$

close to critical coupling for FM. SOC provides a natural explanation for why SDW order is not formed.

Summary

1) We have considered the microscopic origins of metamagnetism and nematicity, making use of interplay b/w orbital, spin ordering.

2) Relatively small interval over which nematic phase occurs:

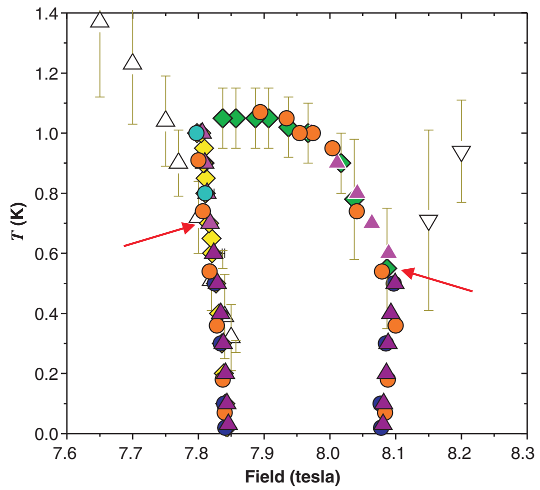
3) Asymmetry present in the problem (and experimental data). Nematic order decreases monotonically from Hc1 to Hc2.

4) Moderate spin-orbit coupling consistent with bandstructure estimates produce an O(1) decrease in critical fields as field angle varies.

5) Quasi-1D bands contribute to spin-fluctuations and account for INS peaks. However, spin-orbit coupling efficiently spoils their nesting, plausibly explaining why SDW order does not occur at h=0.

6) Our model predicts that nematic order should occur for all field orientations (this has not yet been detected experimentally).

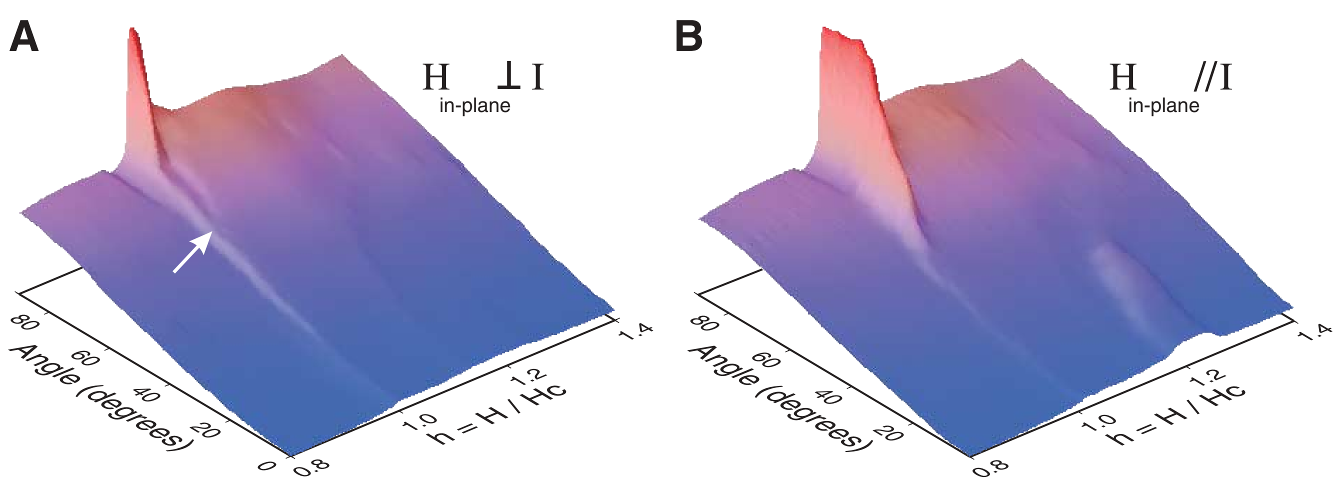
Current and future work



Nematic phase has a *higher* entropy than the surrounding isotropic phases.

Our model does not provide an answer for large resistive anisotropy (just a symmetry argument).

Plausible explanation: scattering off of nematic domains.



average resistivity decreases with angle as domains get aligned.

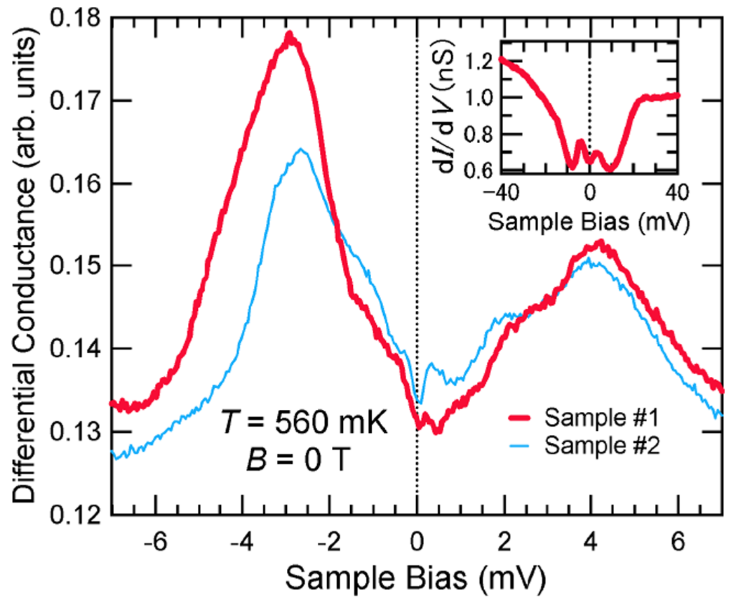
Science **315**, 214 (2007)

Nematic domains could also account for why the phase has higher entropy

Current and future work

Effects of quantum fluctuations

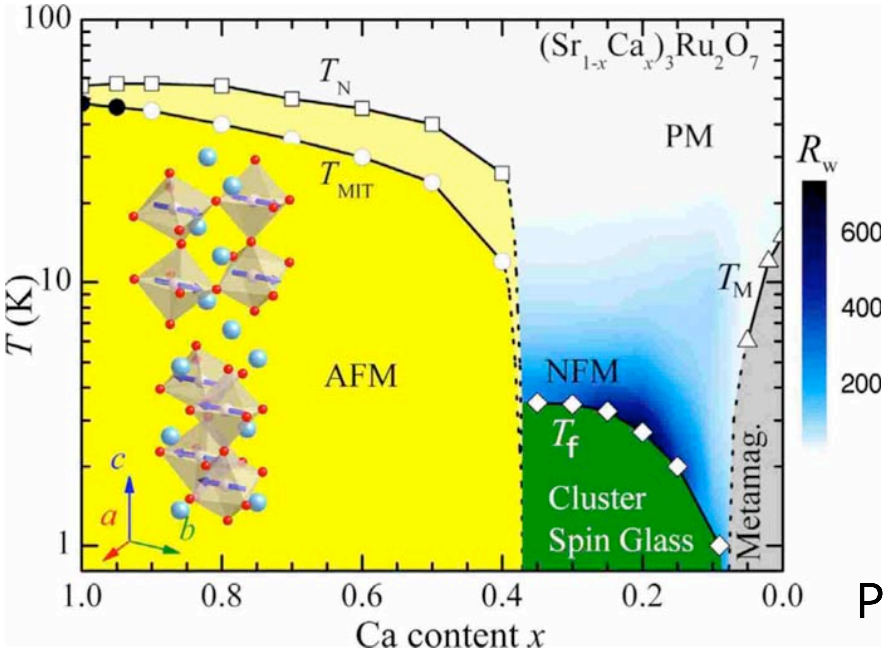
PRL **99**, 057208 (2007)



STM experiments have revealed a “pseudogap” in LDOS which persists at zero field.

Can this feature be explained due to local nematic quantum fluctuations?

This feature could also occur due to incommensurate spin-fluctuations



PRB **78**, 180407(R) (2008)

Calcium doping studies suggest a metamagnetic QCP occurs with doping. Nematic fluctuations might also persist here and could be the basis of a fluctuational theory.