Title: Review on Electronic Nematicity and Beyond

Date: Apr 22, 2010 11:30 AM

URL: http://pirsa.org/10040081

Abstract: In correlated electron systems, electrons can organize themselves in states that are analogous to classical liquid crystal phases. The search for such phases in solid state systems, in particular for the quantum version of an anisotropic liquid crystal state, dubbed electronic nematic phase, has been of great interest. For example, anisotropic metal bounded by two consecutive meta-magnetic transitions was reported in bilayer Ruthenates, and anisotropic neutron scattering patterns were observed in high temperature Cuprates In this talk, I will review theoretical development of the nematic phase and present relevant experimental issues. The interplay with other competing orders and avoided quantum criticality will be also discussed.

Review on Nematicity & Beyond

Canadian Institute for Advanced Research

Hae-Young Kee
University of Toronto

4-Corner Condensed Matter Symposium, April 22, 2010

- Review on Theoretical studies -- Pomeranchuk instabilities and Mean field theories

- Relevant materials -- High temperature Cuprates and Ruthenates

- Summary and Open questions

Nematicity

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under google; Did you mean: ***pneumaticity*** Top 2 results

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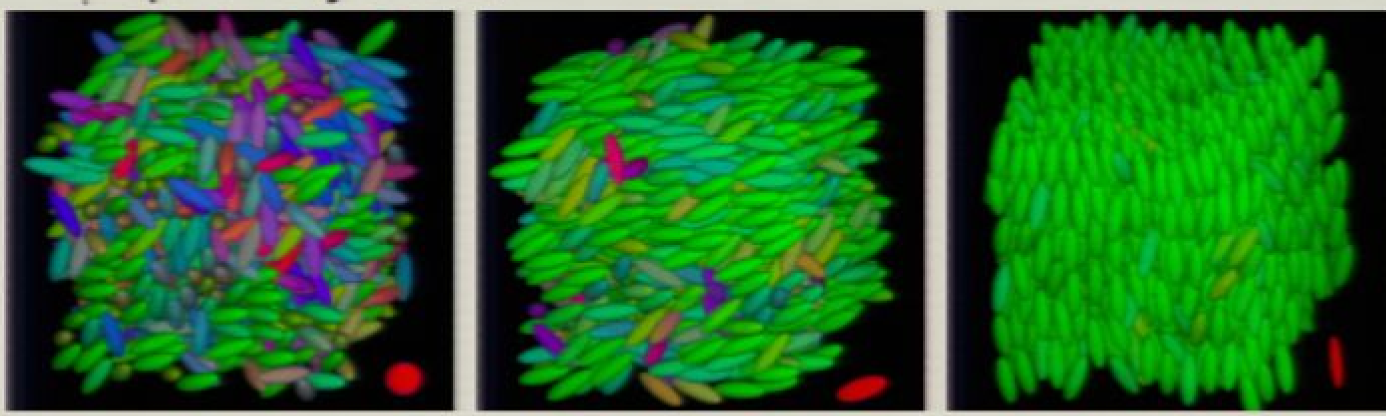
Liquid crystals;



Fluid Nematic Smectic-A

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Nematicity

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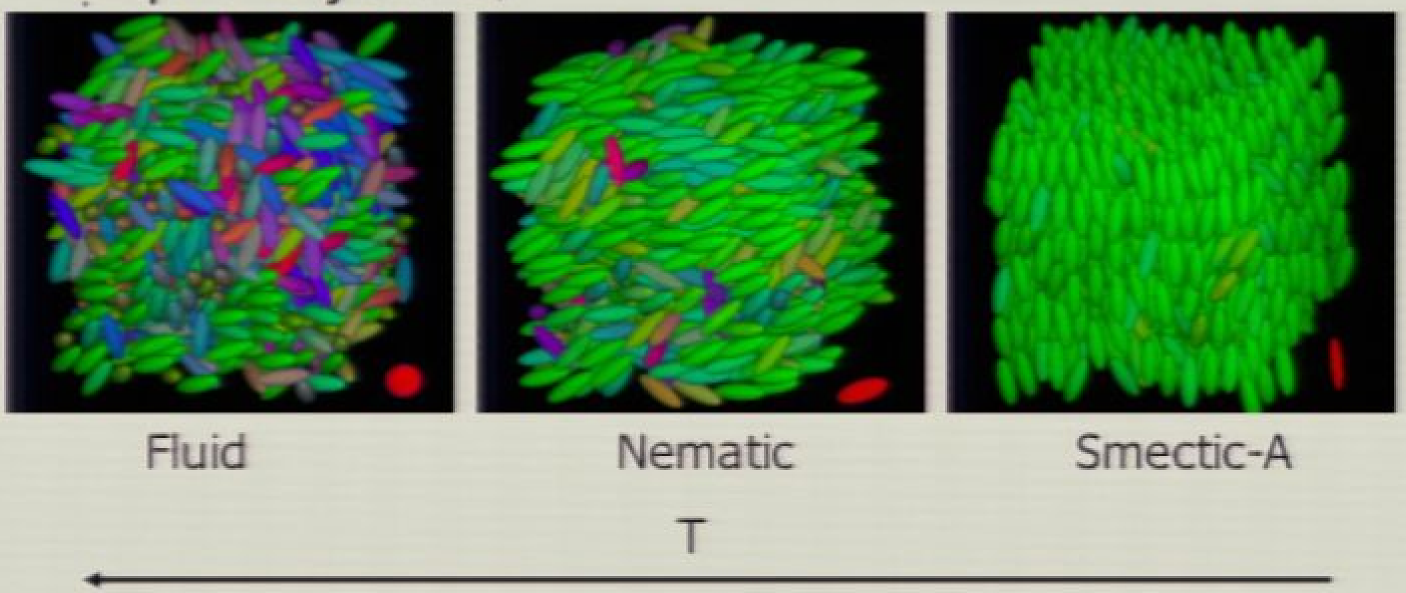
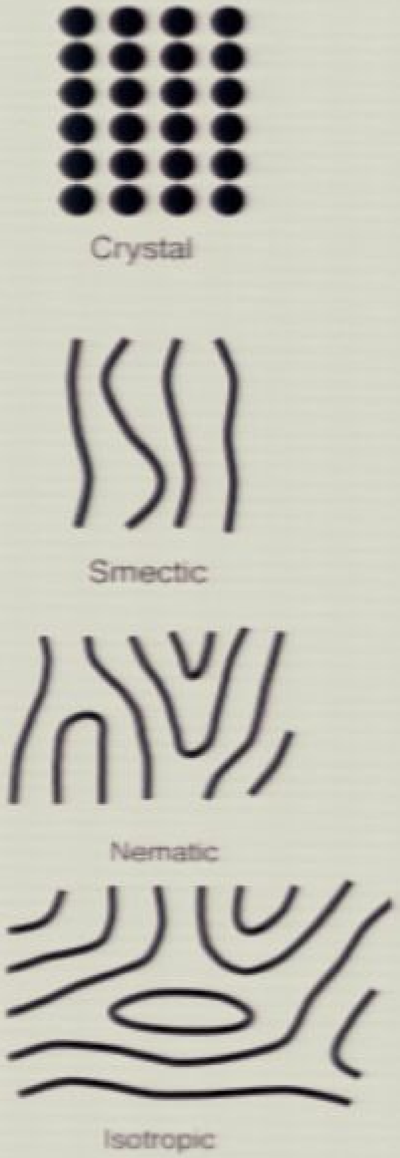


Broken Symmetry (Order parameter) characterizes different phases

Electronic Liquid Crystals



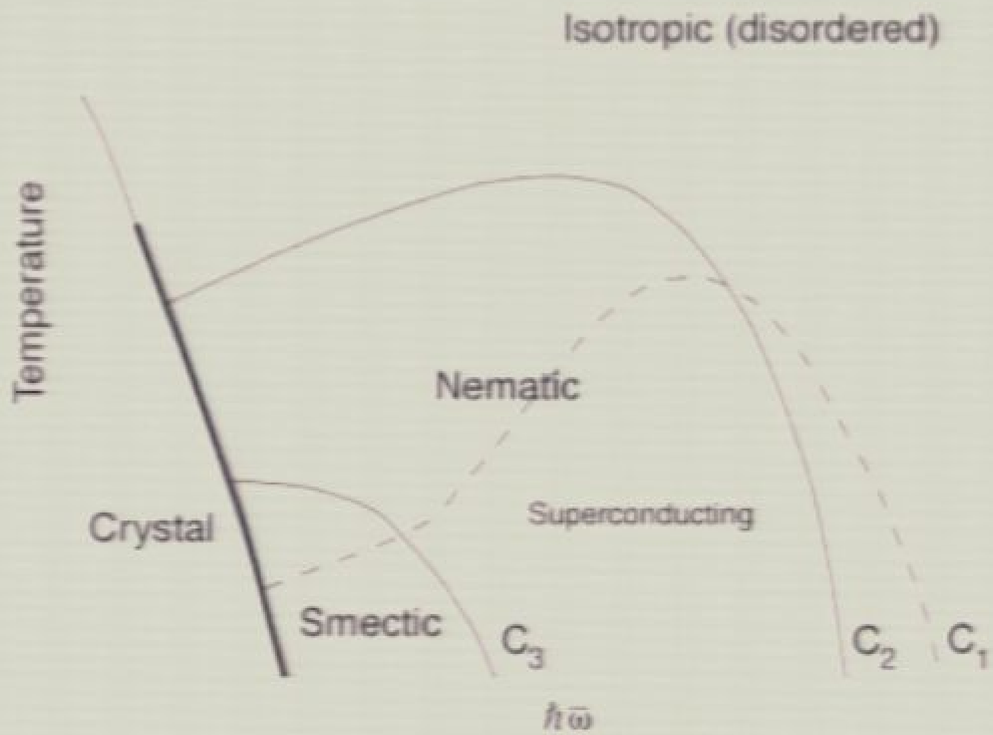
- Solid Phase – Translational symmetry (X)
  Rotational symmetry (X)
- Smectic Phase – Translational symmetry (O/X)
  Rotational symmetry (X)
- Nematic Phase – Translational symmetry (O)
  Rotational symmetry (X)
- Isotropic Liquid Phase – Translation symmetry (O)
  Rotational symmetry (O)

Possible examples for nematic phase

- 2D gas - FQH nu=9/2
- high temperature cuprates
- "new" quantum phase near the putative QCP in $Sr_3Ru_2O_7$

A doped Mott insulator

A doped Mott insulator



Kivelson et al., Nature **393**,550(1998)

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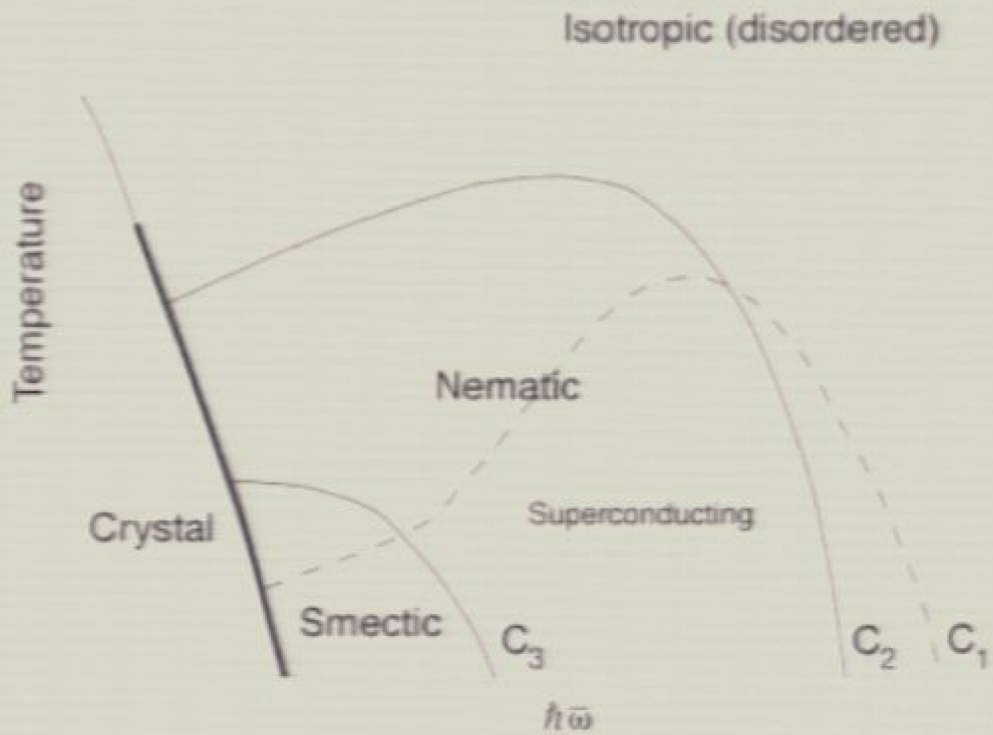

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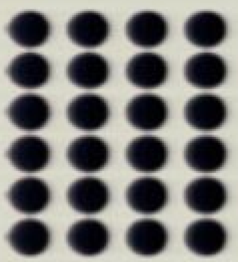
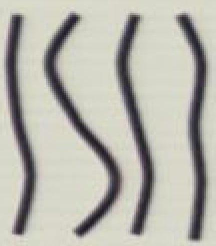
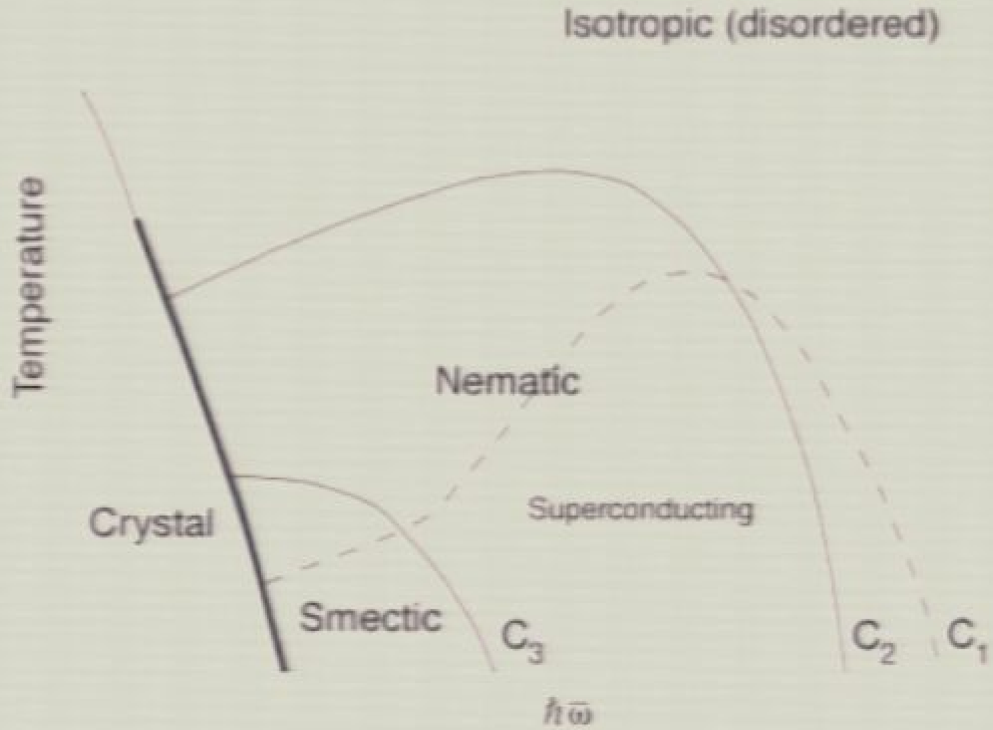


Crystal



Smectic



Nematic

Isotropic

Kivelson et al., Nature **393**,550(1998)

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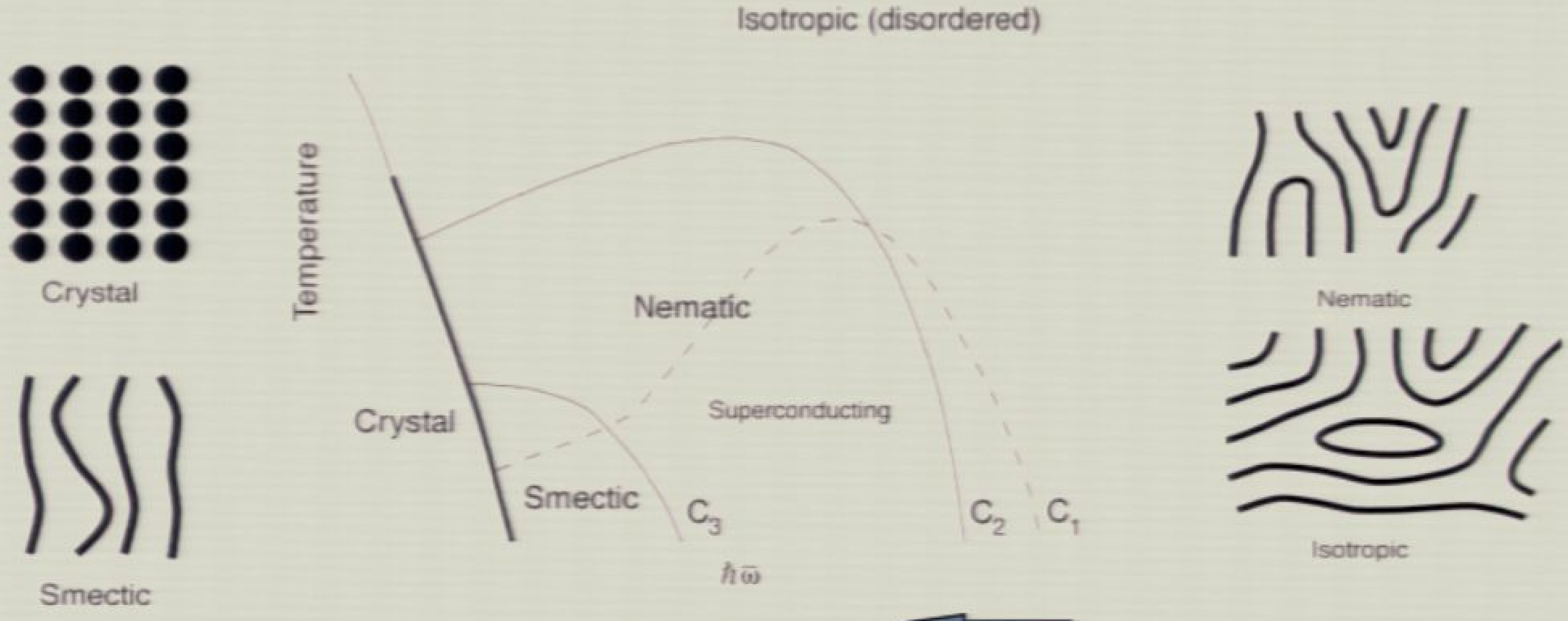

approach from Fermi liquid (weak coupling theory)

Kivelson et al., Nature **393**,550(1998)

Broken rotational symmetry

Can we define an order parameter for nematic?

Broken rotational symmetry

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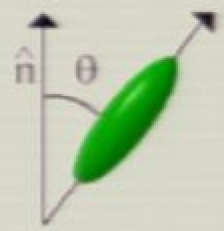
Nematic Order Parameter: quadruple density

$$\hat{\mathbf{Q}}(x) \equiv \Psi^\dagger(\vec{r}) \begin{pmatrix} \partial_x^2 - \partial_y^2 & 2\partial_x\partial_y \\ 2\partial_x\partial_y & \partial_y^2 - \partial_x^2 \end{pmatrix} \Psi(\vec{r}) + \text{c.c.}$$

$$\hat{Q}_{ij} = \hat{p}_i\hat{p}_j - \frac{1}{2}\hat{p}^2\delta_{ij}$$

Electron momentum
align/anti-align



$$Q_{ij} = \frac{1}{N}\sum_N u_i u_j - \frac{1}{3}\delta_{ij}$$

$$S = \langle \cos^2\theta - \frac{1}{3} \rangle$$

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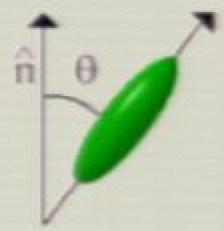

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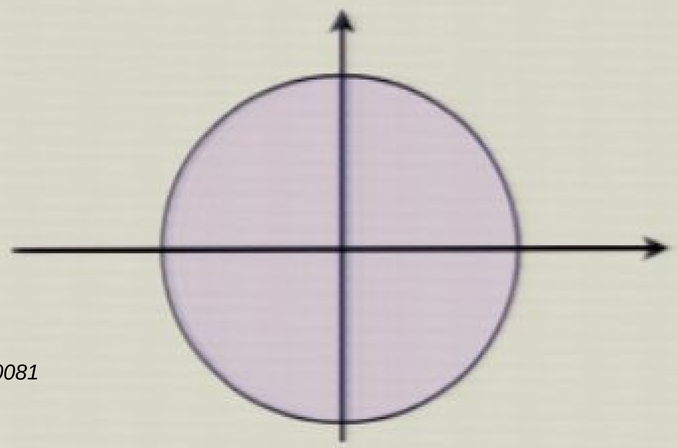
Consequences of nematic order



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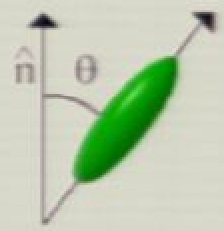

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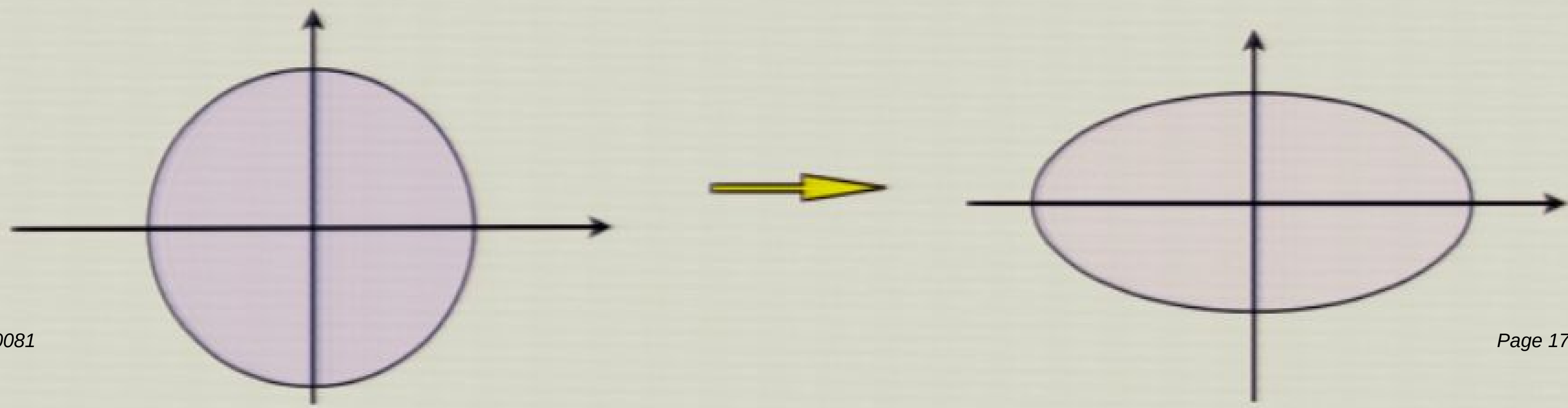

→ Fermi surface distortion

→ Fermi surface distortion

Pomeranchuk instability

ON THE STABILITY OF A FERMI LIQUID

I. Ia. POMERANCHUK

Submitted to JETP editor May 7, 1958

J. Exptl. Theoret. Phys. (U.S.S.R.) 35, 524-525 (August, 1958)

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$$E = \sum_{\sigma} \int \varepsilon(p)\, \delta n(\mathbf{p}) \frac{d^3p}{(2\pi\hbar)^3} + \frac{1}{2} \sum_{\sigma} \sum_{\sigma'} \iint f(\mathbf{p}\mathbf{p}')\, \delta n(\mathbf{p})\, \delta n(\mathbf{p}') \frac{d^3p\, d^3p'}{(2\pi\hbar)^6} \qquad (1)$$

(σ is the excitation spin).

Stability will exist for small δn if $E > 0$ for arbitrary δn. The values of p actually involved in the integrals of Eq. (1) are those close to p_0 (the temperature is zero). Therefore $\epsilon(p) = (d\epsilon/dp)_{p_0}(p - p_0) = v_0(p - p_0)$. The variations δn appearing in Eq. (1) are due to deformations of the Fermi surface, and we shall find the criterion for stability with respect to such deformations (see diagram).

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(a) unperturbed distribution (all states inside occupied). (b) perturbed distribution; in regions 1, $\delta n = -1$, in regions 2, $\delta n = 1$; inside the solid line all states are occupied.

$$E = \sum_{\sigma} \int \varepsilon(p)\, \delta n(\mathbf{p}) \frac{d^3p}{(2\pi\hbar)^3} + \frac{1}{2} \sum_{\sigma} \sum_{\sigma'} \iint f(\mathbf{p}\mathbf{p}')\, \delta n(\mathbf{p})\, \delta n(\mathbf{p}') \frac{d^3p\, d^3p'}{(2\pi\hbar)^6} \quad (1)$$

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Let us expand the momentum p corresponding to the solid line of diagram b in a series of spherical surface harmonics:

$$p = p_0 + \sum_{lm} \Phi_{lm} Y_{lm}(\theta, \varphi), \quad Y_{l0}(0) = 1. \quad (2)$$

$$E = \frac{p_0^2 v_0}{(2\pi\hbar)^3} \sum \Phi_{lm}^2 \frac{4\pi}{2l+1} \frac{(l+m)!}{(l-m)!} + \frac{2p_0^4}{(2\pi\hbar)^6} \sum_{lm} \Phi_{lm}^2 \left(\frac{4\pi}{2l+1}\right)^2 f_l \frac{(l+m)!}{(l-m)!}. \quad (6)$$

The conditions for stability are written separately for each l, m:

$$1 + \frac{8\pi}{2l+1} \frac{p_0^2 f_l}{v_0 (2\pi\hbar)^3} > 0, \quad 1 + \frac{2p_0^2}{v_0 (2\pi\hbar)^3} \int f P_l(\cos\theta)\, do > 0. \quad (7)$$

Hubbard model ;

$$H = \sum_{\mathbf{i},\mathbf{j}} \sum_{\sigma} t_{\mathbf{ij}}\, c^{\dagger}_{\mathbf{i}\sigma} c_{\mathbf{j}\sigma} + U \sum_{\mathbf{j}} n_{\mathbf{j}\uparrow} n_{\mathbf{j}\downarrow} \, .$$

d-wave superconductivity and Pomeranchuk instability in the two-dimensional Hubbard model

C. Halboth and W. Metzner, PRL (2000)

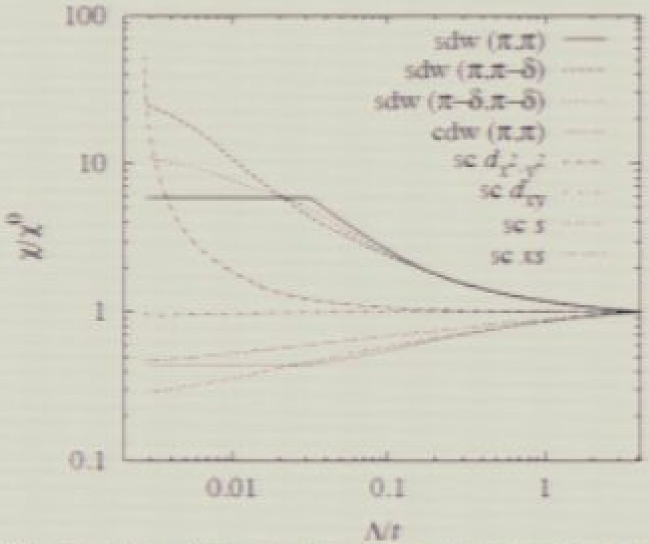
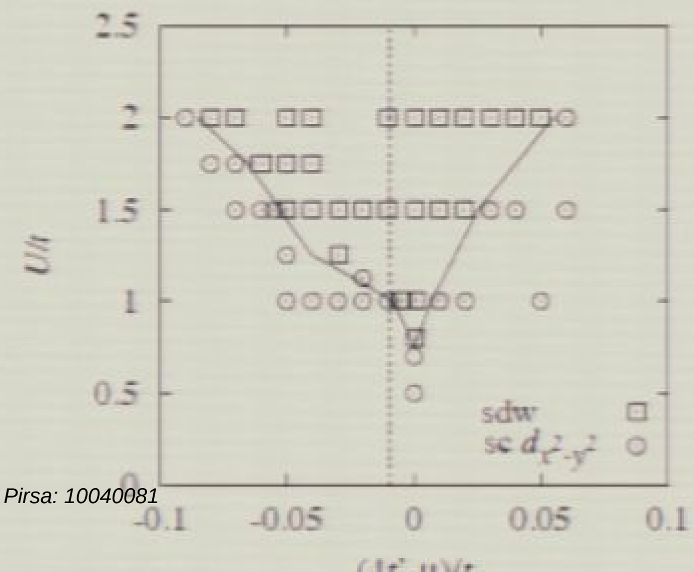


FIG. 1. The flow of the ratio of interacting and non-interacting susceptibilities for $t' = -0.01t$, $U = t$ and $\mu = -0.055t$.



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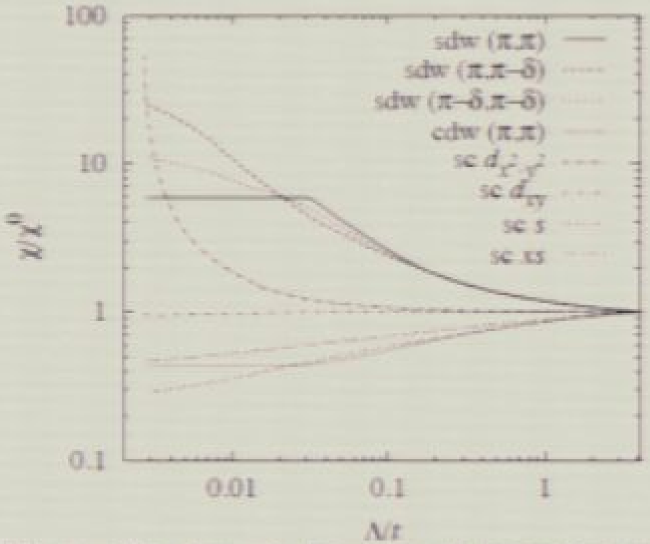

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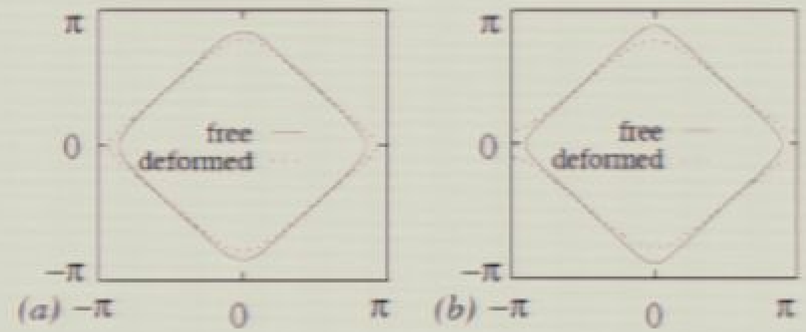

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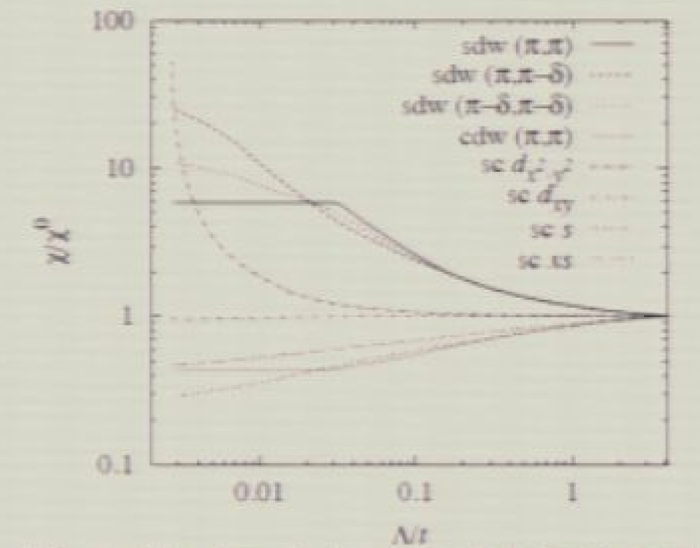

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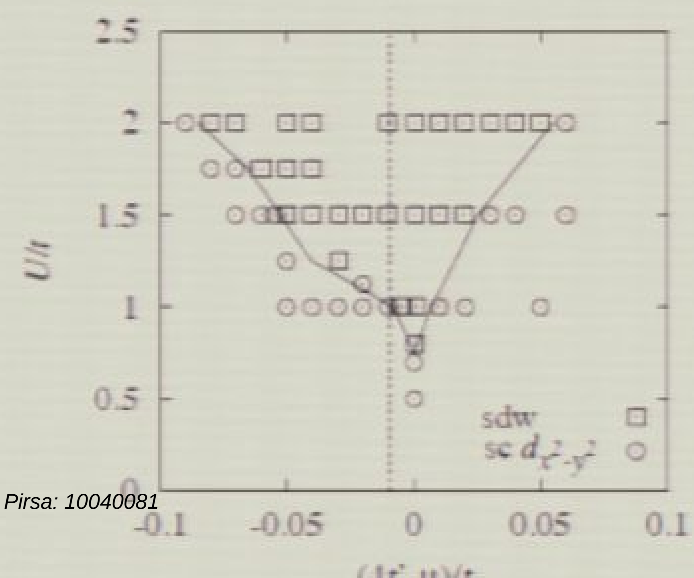

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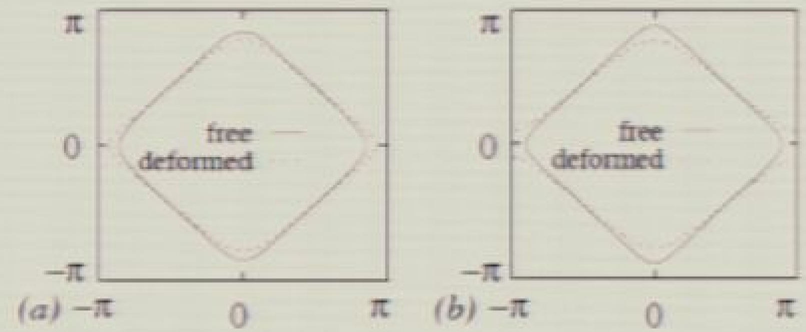

to analyze the stability of FS shape, introduce

$$\kappa_{\mathbf{k}_F \mathbf{k}'_F} = \frac{\delta s_{\mathbf{k}_F}}{\delta \mu_{\mathbf{k}'_F}}$$

measure of the size of Fermi surface shifts
for small momentum dependent chemical potential shift
; FS is stabile if all eigenvalues are positive

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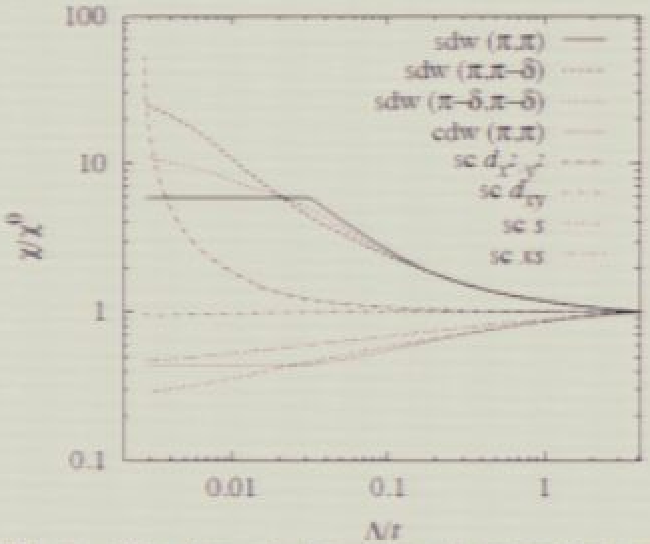

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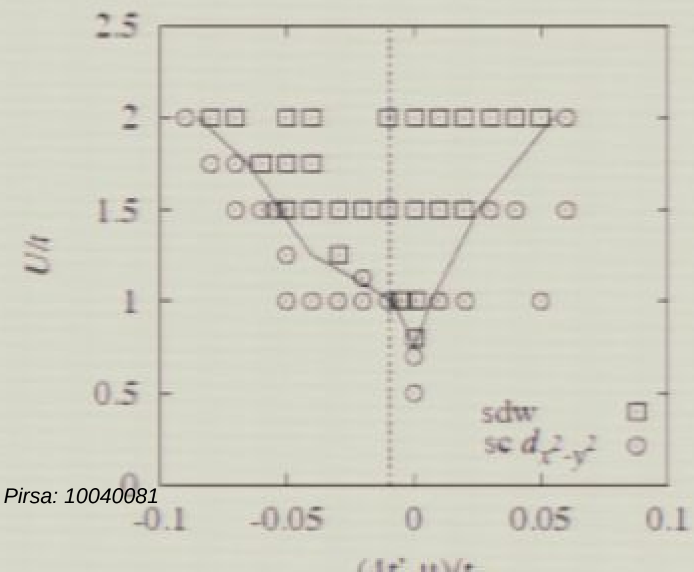

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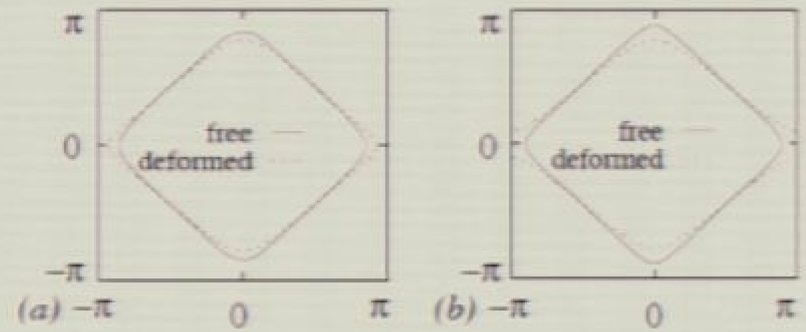

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measure of the size of Fermi surface shifts
for small momentum dependent chemical potential shift
; FS is stabile if all eigenvalues are positive

PI competes with SC and magnetic order
; needs further study to find their interplay

Ginzburg- Landau Analysis

model Hamiltonian : $$H = \int d^2r \hat{\Psi}^\dagger(\mathbf{r})\epsilon(-i\nabla)\hat{\Psi}(\mathbf{r}) + \int d^2r d^2r' F_2(\mathbf{r}-\mathbf{r}')\mathrm{Tr}[\hat{Q}(\mathbf{r})\hat{Q}(\mathbf{r}')]$$

$$\hat{\mathrm{Q}}(x) \equiv \Psi^\dagger(\vec{r}) \begin{pmatrix} \partial_x^2 - \partial_y^2 & 2\partial_x\partial_y \\ 2\partial_x\partial_y & \partial_y^2 - \partial_x^2 \end{pmatrix} \Psi(\vec{r}) + \text{c.c.}$$

$$\hat{\Delta} = \langle \hat{Q}(\mathbf{r}) \rangle = \begin{pmatrix} \Delta & \Delta' \\ \Delta' & -\Delta \end{pmatrix}$$

- Landau-Ginzburg Free Energy

$$\mathcal{F}(\Delta) = r\mathrm{Tr}[\widehat{\Delta}^2] + v\mathrm{Tr}[\widehat{\Delta}^4] + \cdots,$$

$r < 0$ ($v > 0$) if $F_2 < -2/N_0$ $\longrightarrow \Delta \neq 0$

where $r = F_2 + 1/(2N_0)$ and $v = 3aN_0|F_2|^3/(8E_F^2)$; a is from $\epsilon(\mathbf{k}) = v_F q(1 + a(q/k_F)^2)$

: second order transition

V. Oganesyan *et al.* Phys. Rev. B 64, 195109 (2001)

On a two-dimensional lattice

$$\hat{Q}(\mathbf{q}) = \frac{1}{N}\sum_{\mathbf{k}} c^{\dagger}_{\mathbf{k}+\mathbf{q}} \begin{pmatrix} \cos k_y - \cos k_x & \sin k_x \sin k_y \\ \sin k_x \sin k_y & \cos k_x - \cos k_y \end{pmatrix} c_{\mathbf{k}}$$

$$H = \sum_{\mathbf{k}} (\varepsilon_{\mathbf{k}} - \mu) c^{\dagger}_{\mathbf{k}} c_{\mathbf{k}} + \sum_{\mathbf{q}} F_2(\mathbf{q}) \,\mathrm{Tr}\left[\hat{Q}^{\dagger}(\mathbf{q})\hat{Q}(\mathbf{q})\right]$$

where

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Mean Field Analysis

$$\Delta = F_2 \langle \hat{Q}_{xx}(0) \rangle \qquad \text{and} \qquad \Delta' = F_2 \langle \hat{Q}_{xy}(0) \rangle$$

$$\begin{aligned} \bar{\varepsilon}_{\mathbf{k}} = & -2t(\cos k_x + \cos k_y) - 4t' \cos k_x \cos k_y \\ & + \Delta(\cos k_x - \cos k_y) - \Delta' \sin k_x \sin k_y . \end{aligned}$$

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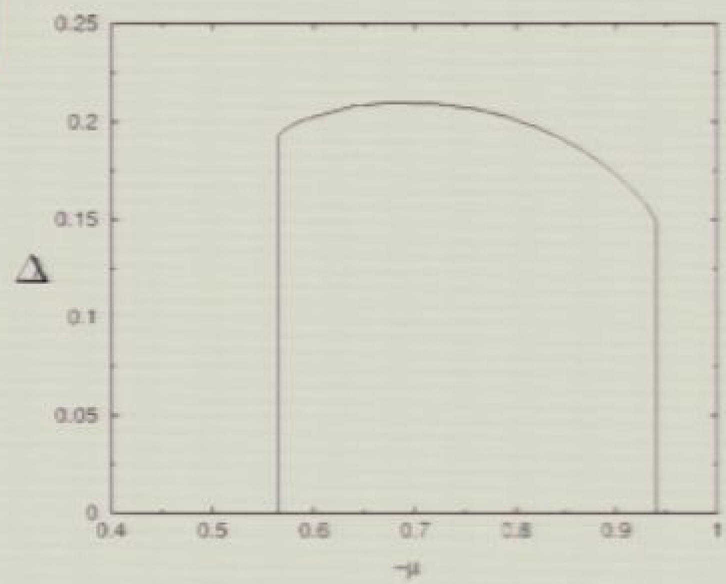

FIG. 1. The nematic order λ as a function of chemical potential μ for $|F_2|/(2t)=0.55$ and $t' = -0.4t$ $(2t=1)$ at $T=0$. $\mu=-0.4$ corresponds to the half filling, $x=0$.

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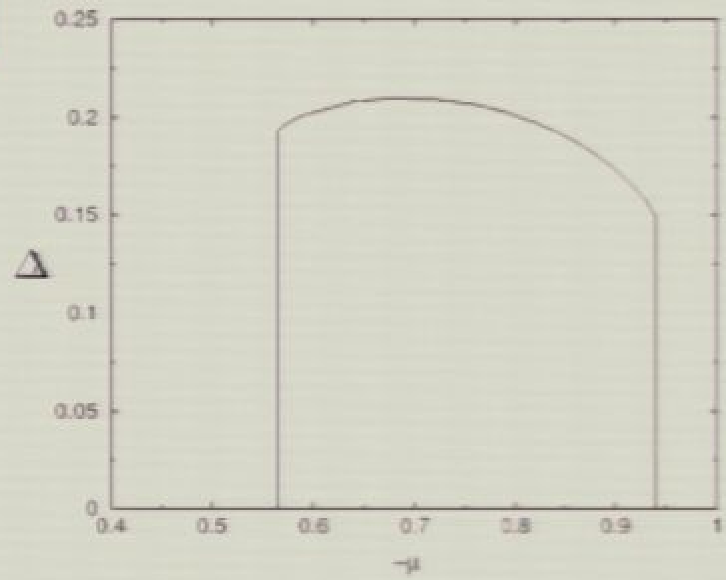

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1st order transition - Mean field study

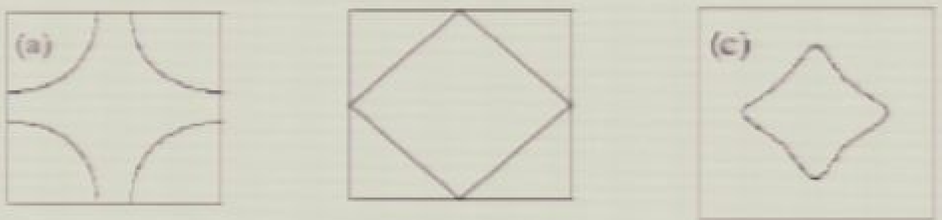
Free energy analysis

Khavkine, Chung, Oganesyan, HYK, PRB (2004).

- Lifshitz transition in non-interacting systems ; Fermi surface topology change
  -- van Hove singularity

$F \propto \mu^2 \ln|\mu|$

a singularity at $\mu \to 0$



I. M. Lifshitz, JETP **38**, 1569 (1960)

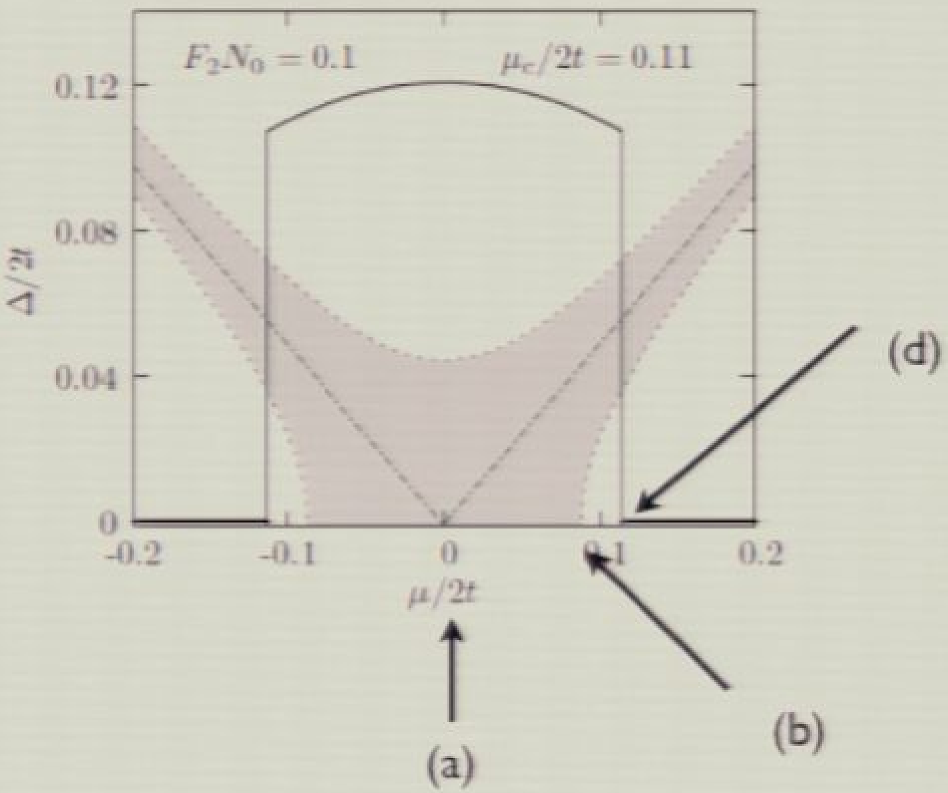
- for small $\mu < 2t$ and $\Delta < 2t$

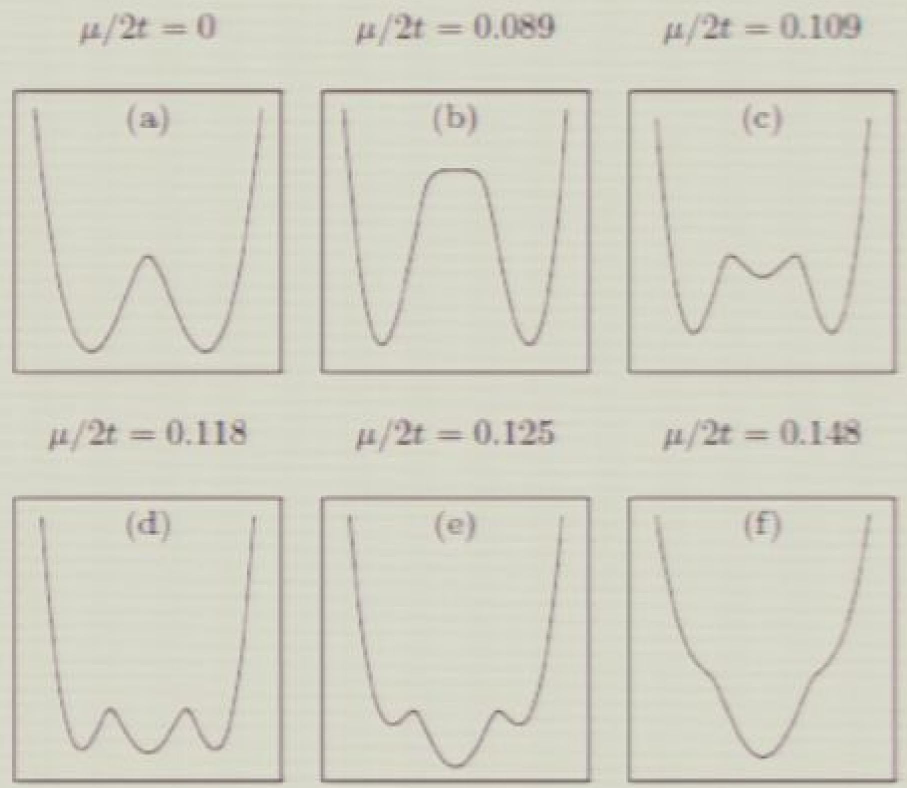
$$F = \frac{\Delta^2}{2|F_2|} + N_0 \left[\Delta^2 + (\Delta + \mu/2)^2 \ln\left|\frac{\Delta + \mu/2}{4}\right| + (\Delta - \mu/2)^2 \ln\left|\frac{\Delta - \mu/2}{4}\right| \right]$$

Non-analyticity moved to $\mu = \pm 2\Delta$

Does nematicity hinder Lifshitz transition?

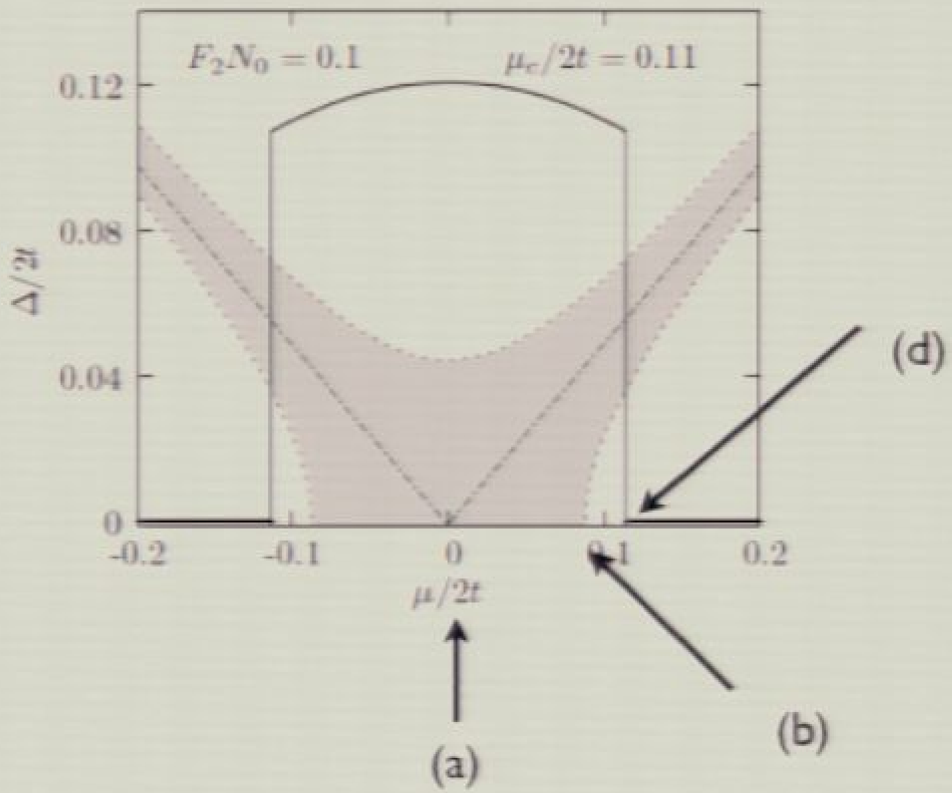
Free energy analysis (continued)

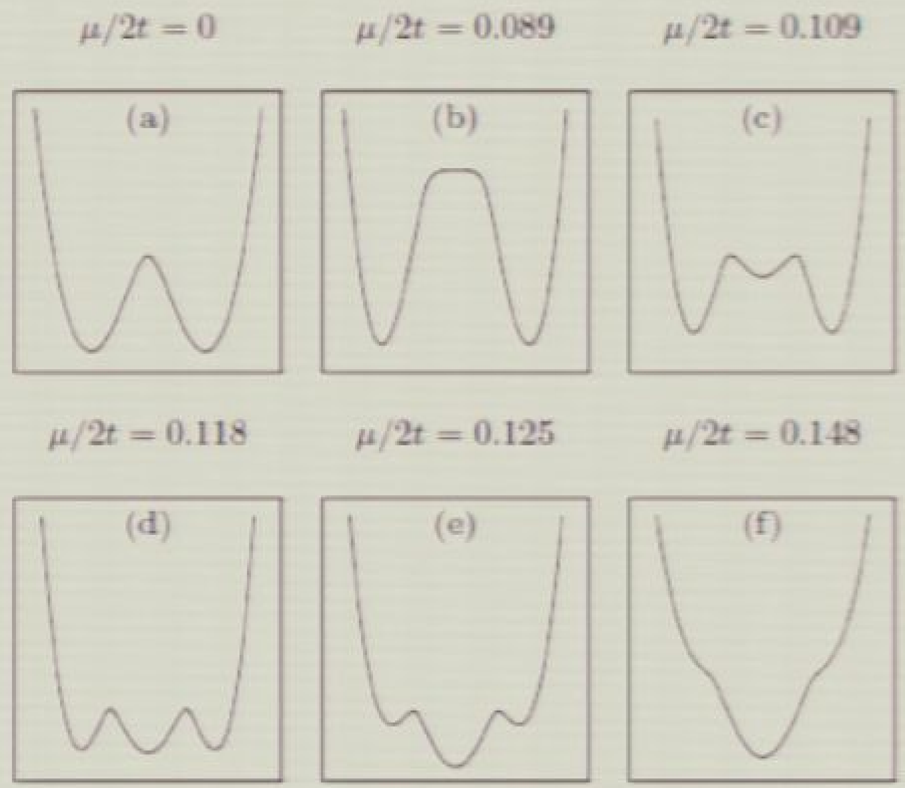




shaded area; negative curvature near zero-order

Free energy analysis (continued)





shaded area; negative curvature near zero-order

- Landau-Ginzburg Free Energy

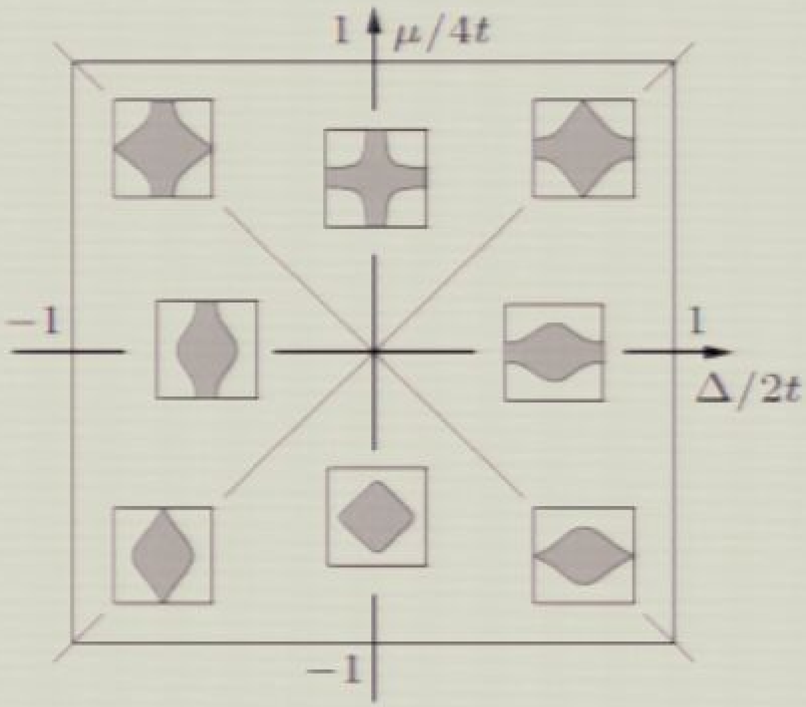
$$\mathcal{F}(\Delta) = r\,\mathrm{Tr}[\Delta^2] + v\,\mathrm{Tr}[\Delta^4] + \cdots,$$

$v > 0$, and expend higher orders (6th order) ; 1st order

Density of states

$$D(\varepsilon) = N_0 \mathrm{Re}\left\{ \frac{1}{\sqrt{1-(\varepsilon/2)^2}} K\left(1 - \frac{\Delta^2 - (\varepsilon/2)^2}{1-(\varepsilon/2)^2}\right)\right\}$$

where $N_0 = 1/(\pi^2 t)$ and set $t' = 0$.



Lines $(\mu/2)^2 = \Delta^2$ mark the vH singularities

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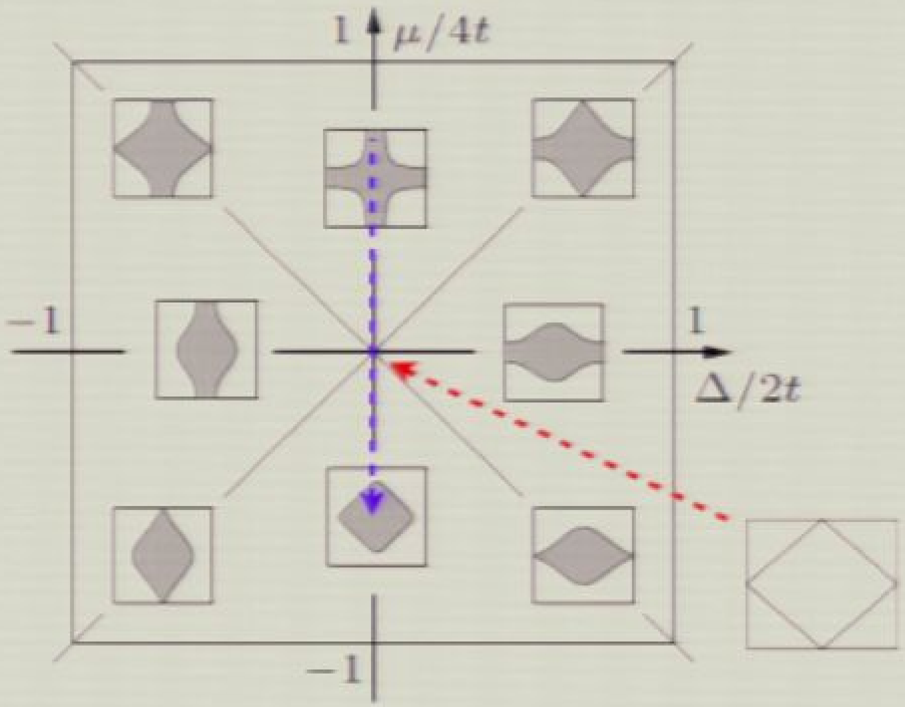

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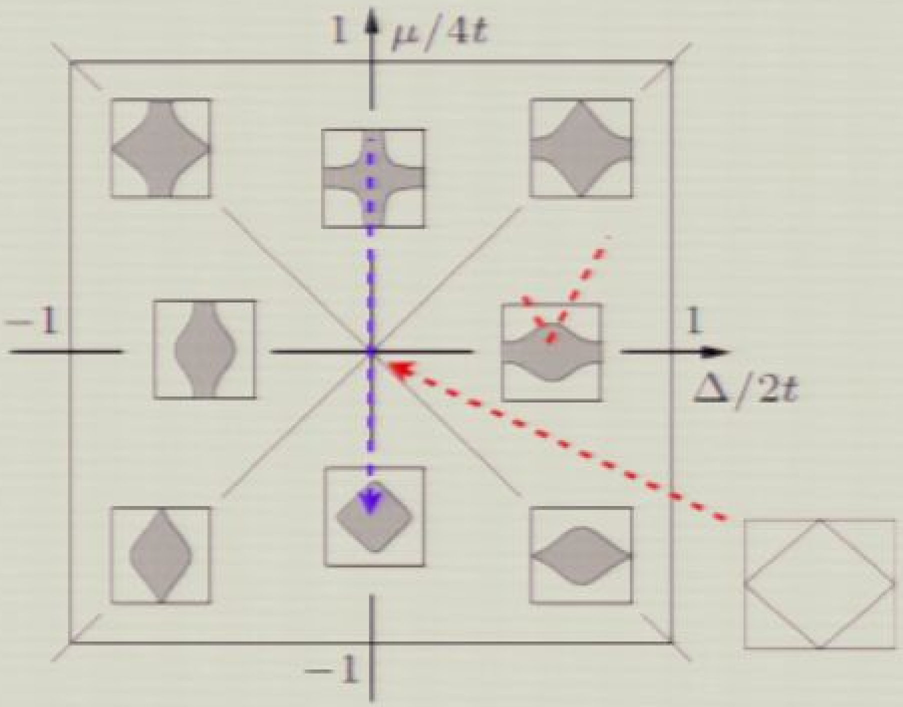
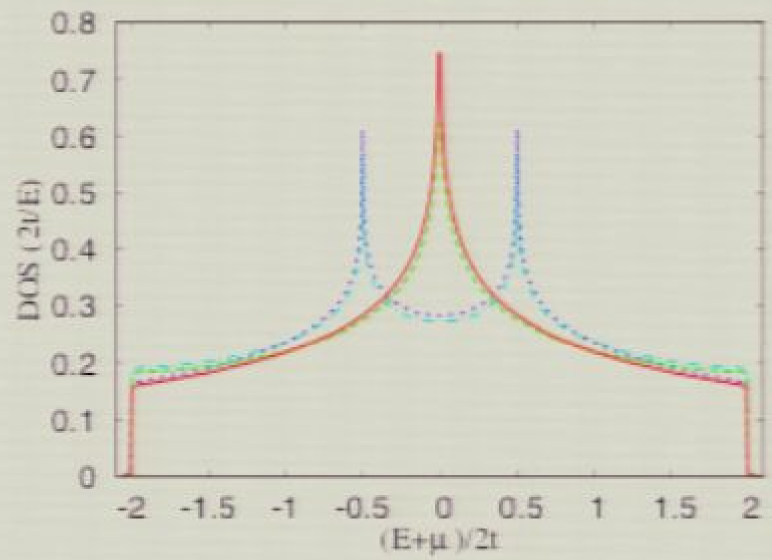


supression of Liftshitz transition
(van Hove singulairty is avoided)



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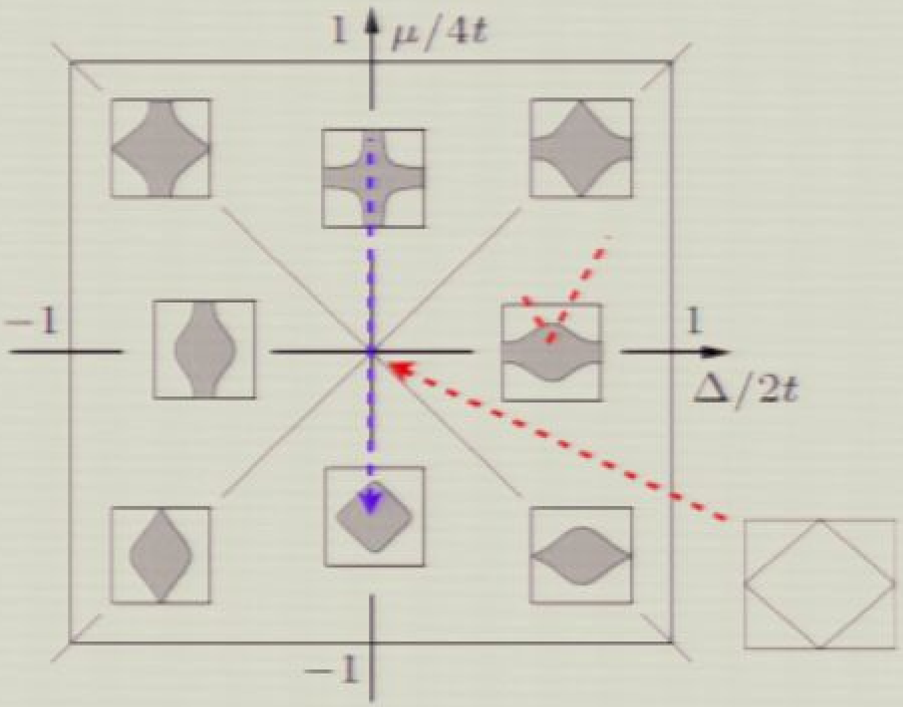

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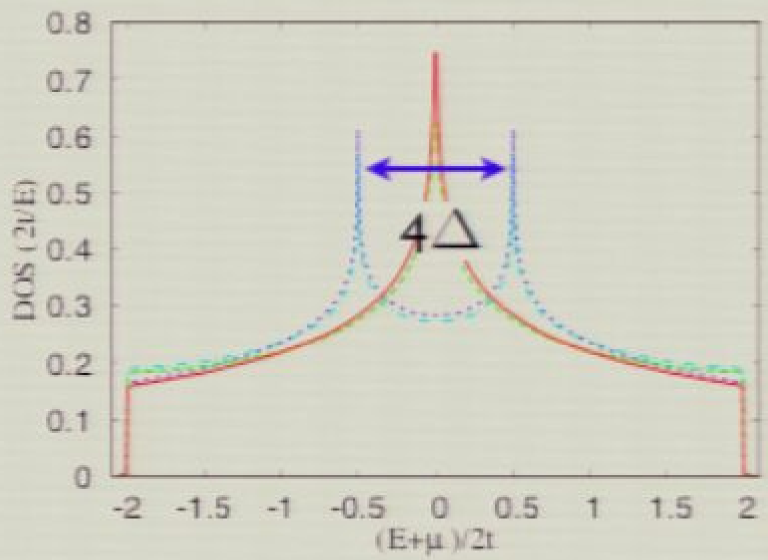
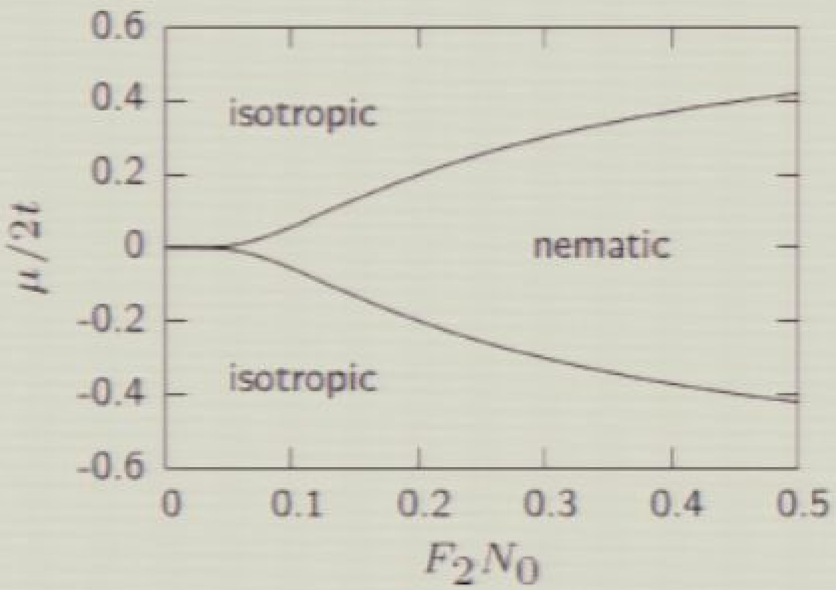


Lines $(\mu/2)^2 = \Delta^2$ mark the vH singularities

Phase diagram at T=0



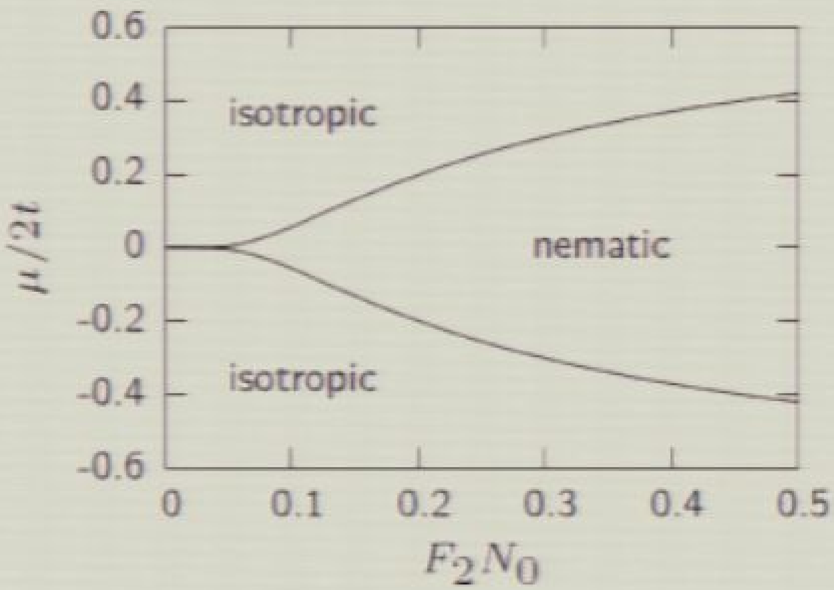
The isotropic state becomes unstable for $\mu < \mu_*$

$$\mu_* \propto \exp\left[-1/(F_2N_0)\right]$$

; it preempts the sus. divergence (2nd order)

$\rightarrow$ a nematic transition occurs for "arbitary small" interaction at Van Hove band filling, $\mu = 0$.

Phase diagram at T=0



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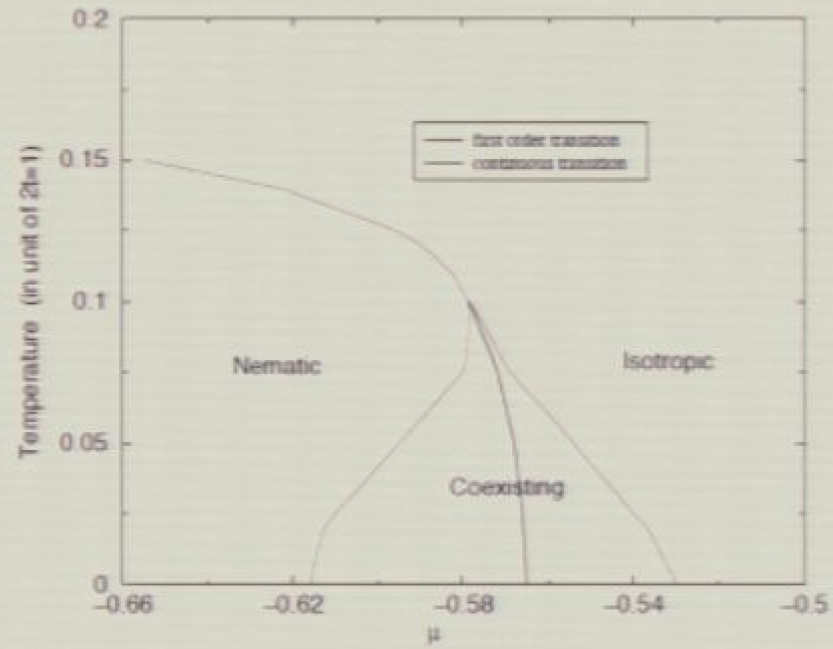
→ a nematic transition occurs for "arbitary small" interaction at Van Hove band filling, $\mu = 0$.

Phase diagram at finite T

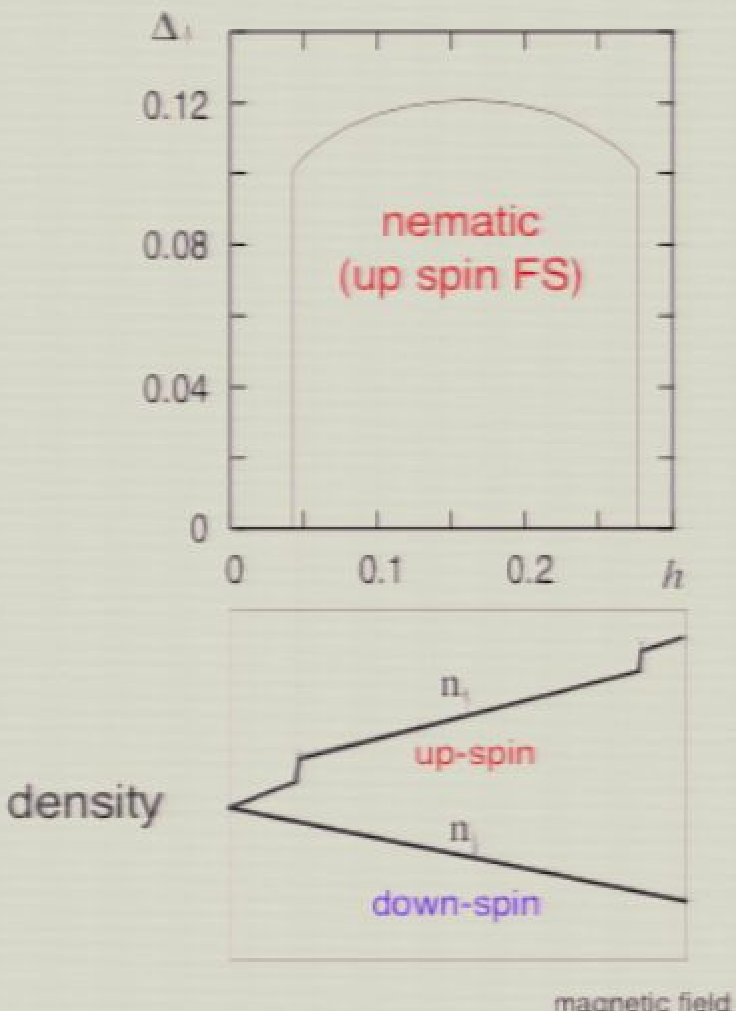
for finite $t' = -0.4t$ and $|F_2|N_0 = 0.2$



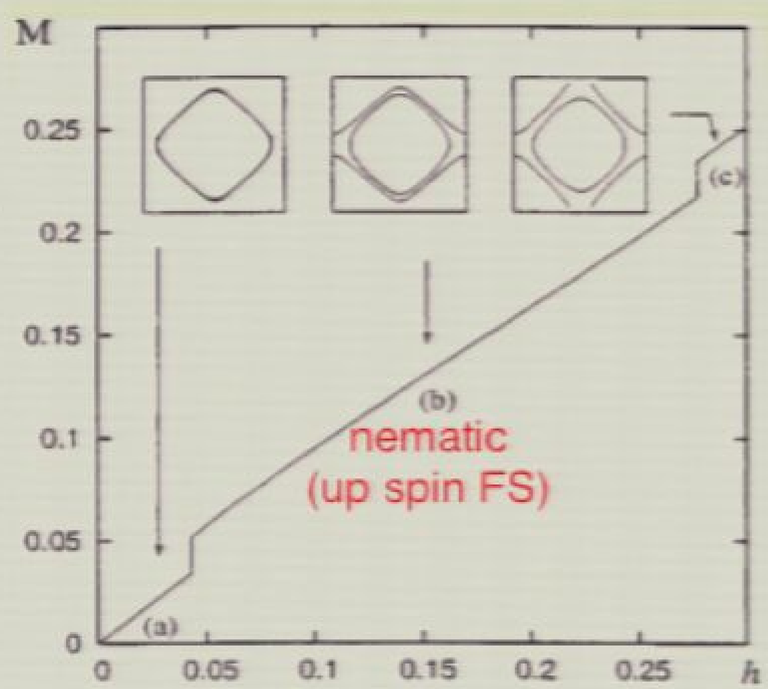
The transition becomes second order at finite temperature.

In the presence of a magnetic field

$$H_{MF} = \sum_{k\sigma} \left(\epsilon_k - \epsilon'_k - \mu + \Delta_\sigma (\cos k_x - \cos k_y)\right) c^\dagger_{k\sigma} c_{k\sigma} - h \sum_k \left(c^\dagger_{k\uparrow} c_{k\uparrow} - c^\dagger_{k\downarrow} c_{k\downarrow} \right) + \sum_\sigma \frac{\Delta_\sigma^2}{2F_2}$$



$\Delta_\downarrow = 0.$



magnetization jumps at isotropic-nematic transitions

HYK and Y.B. Kim, PRB (2005)

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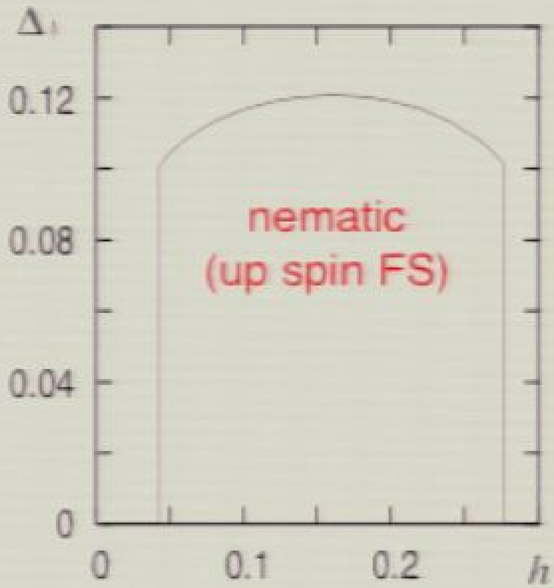

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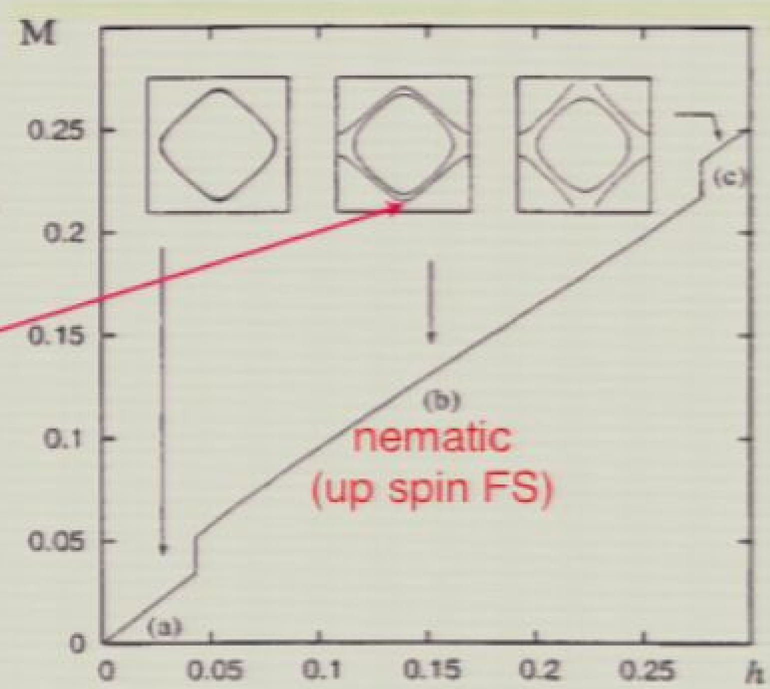

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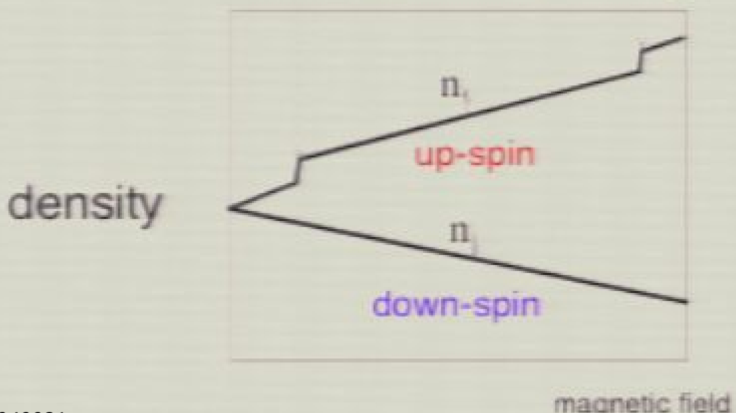

HYK and Y.B. Kim, PRB (2005)

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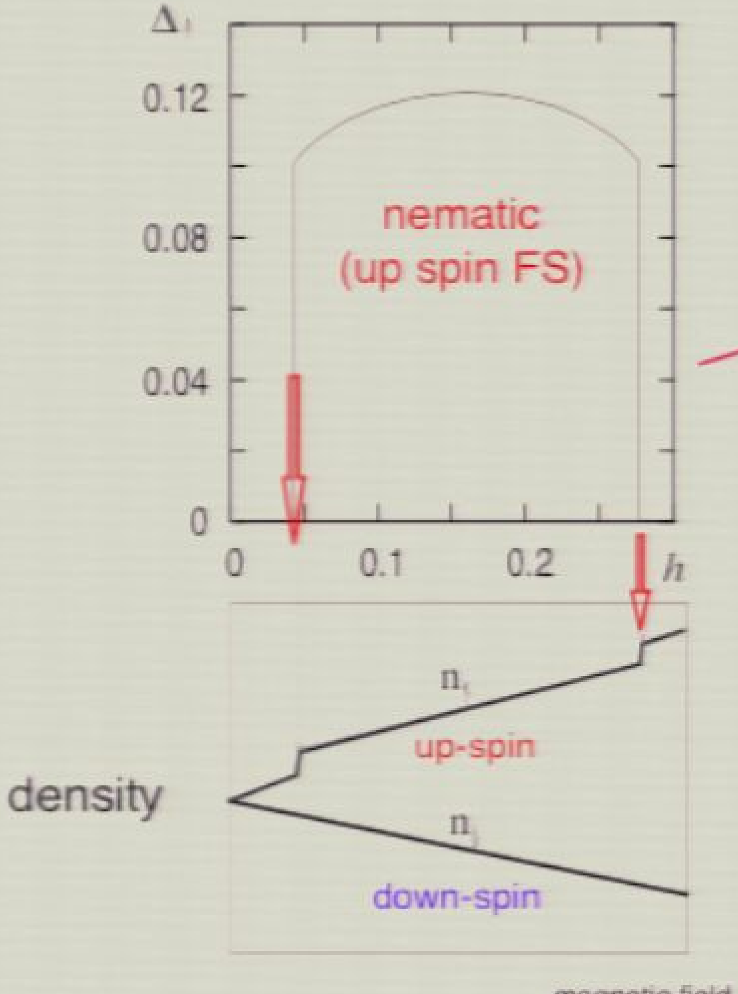

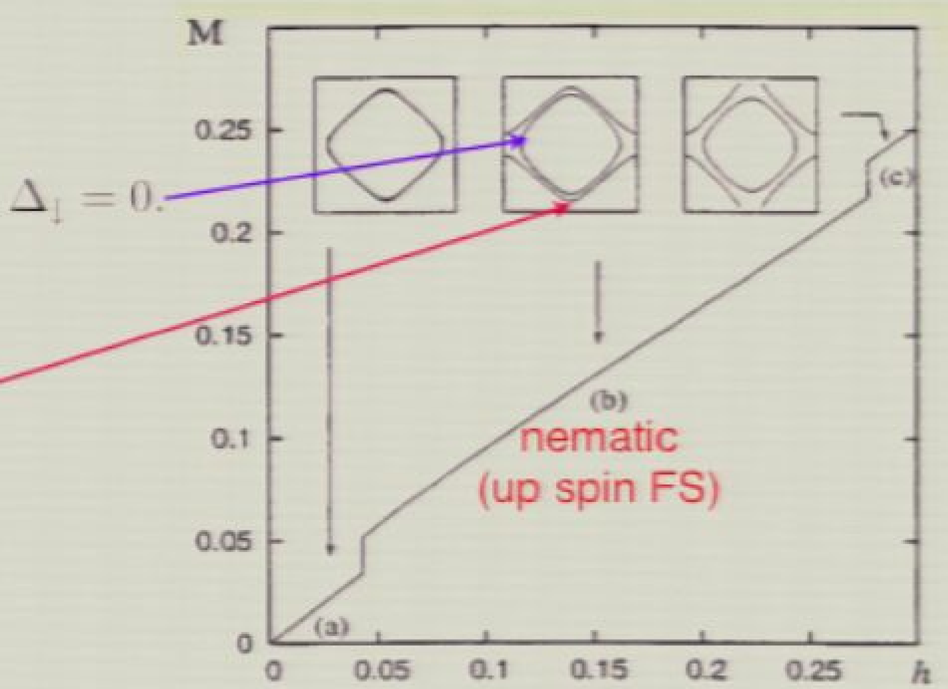

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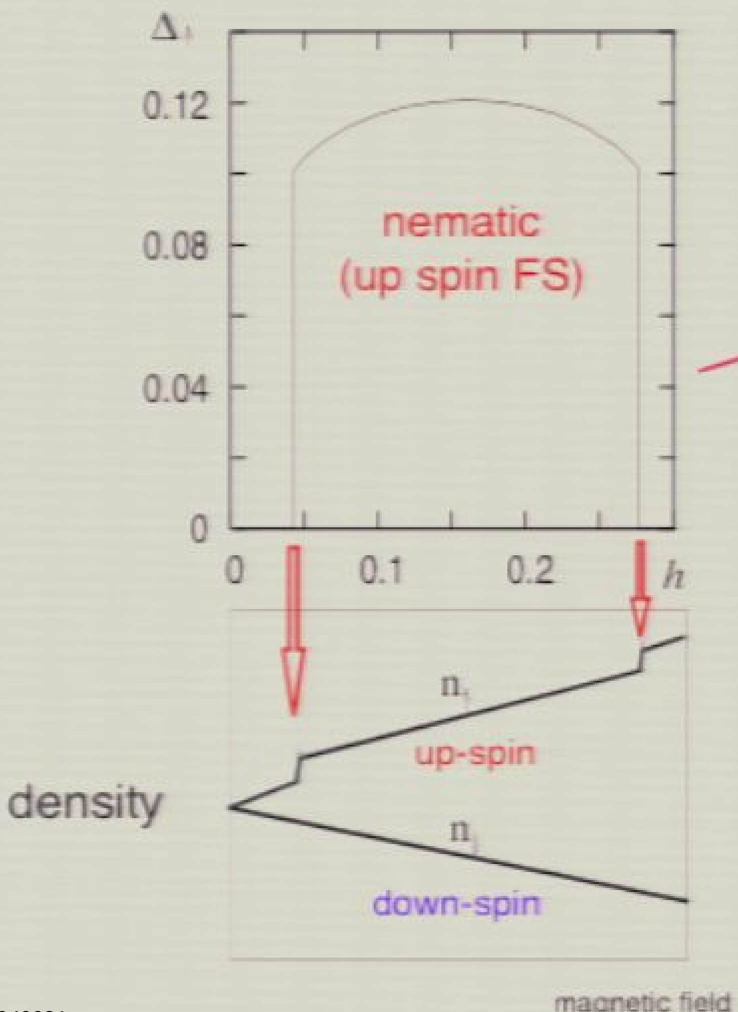

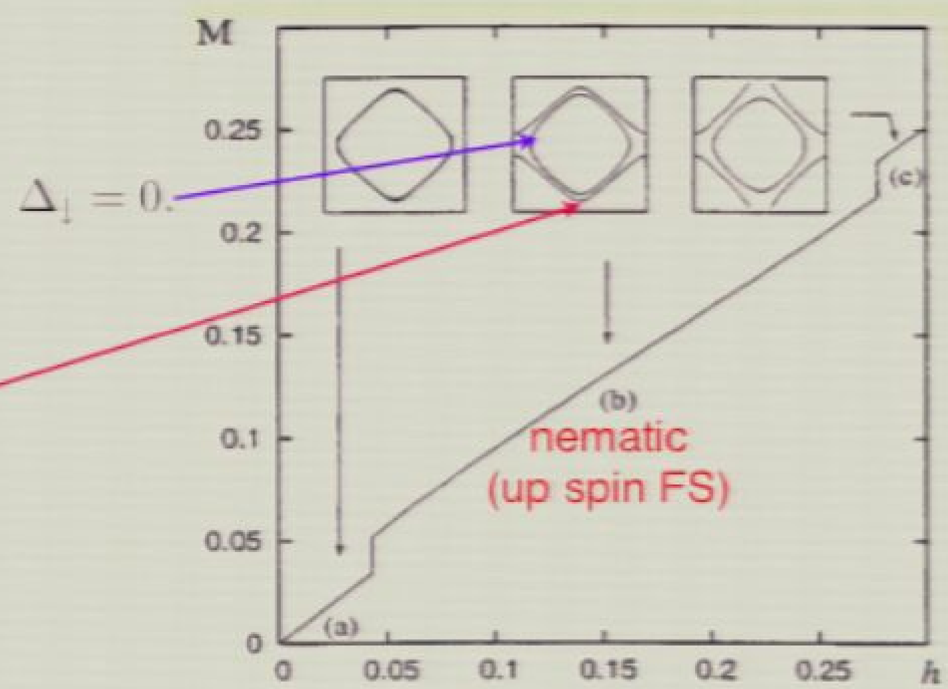

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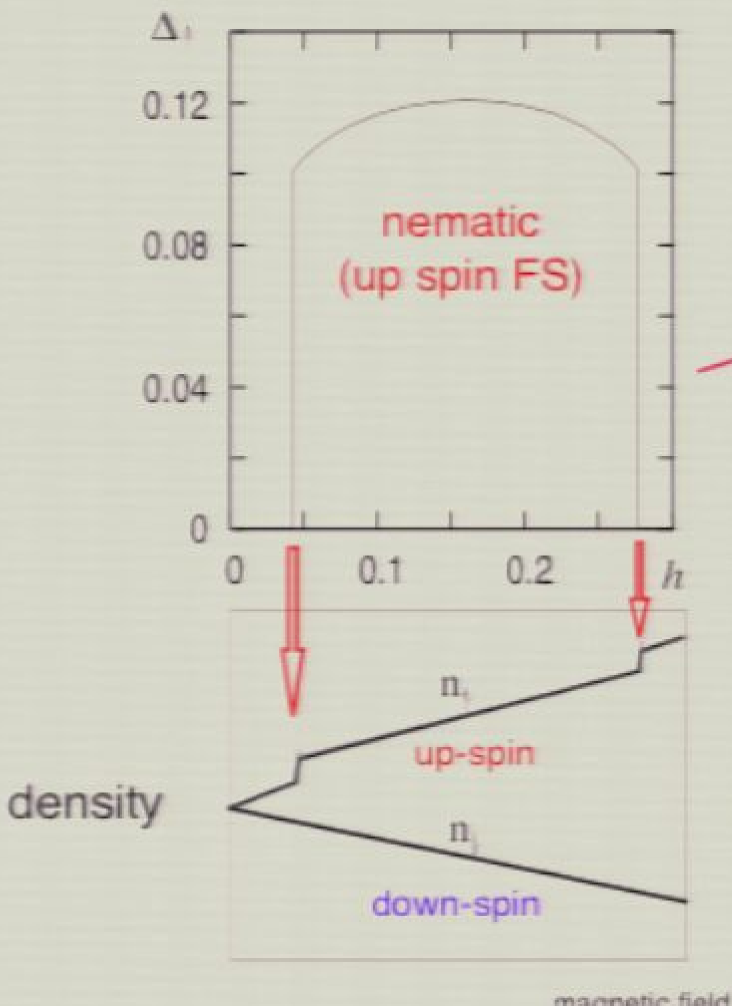
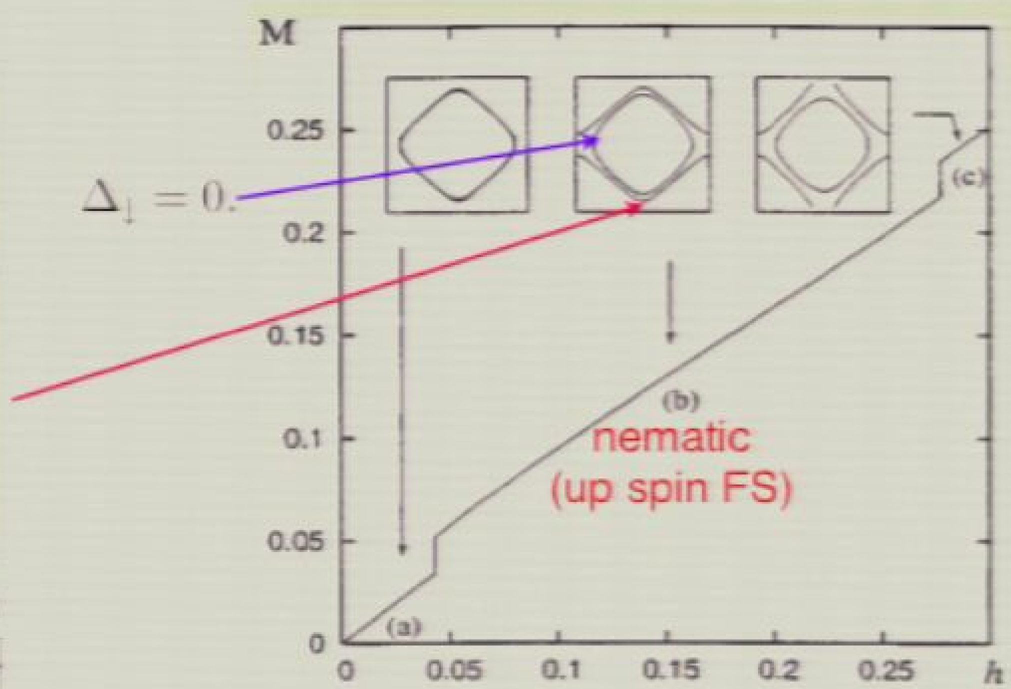




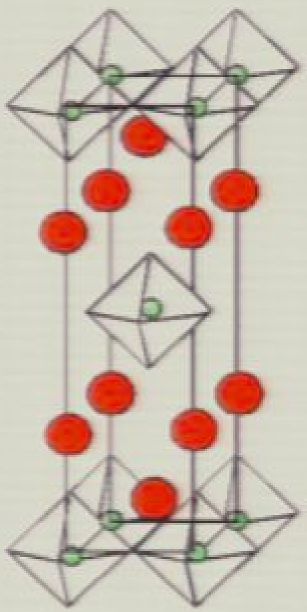
magnetization jumps at isotropic-nematic transitions

Nematic phase is bounded by meta-magnetic transitions

HYK and Y.B. Kim, PRB (2005)

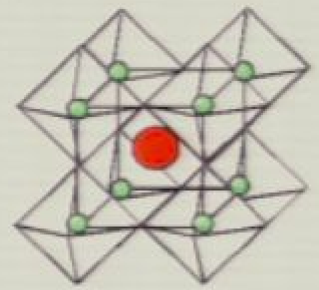
Experimental evidence of nematicity

The Ruddlesden-Popper Series: $Sr_{1+n}Ru_nO_{1+3n}$



n=1

quasi-2d
Paramagnetic Fermi liquid
Triplet superconductor

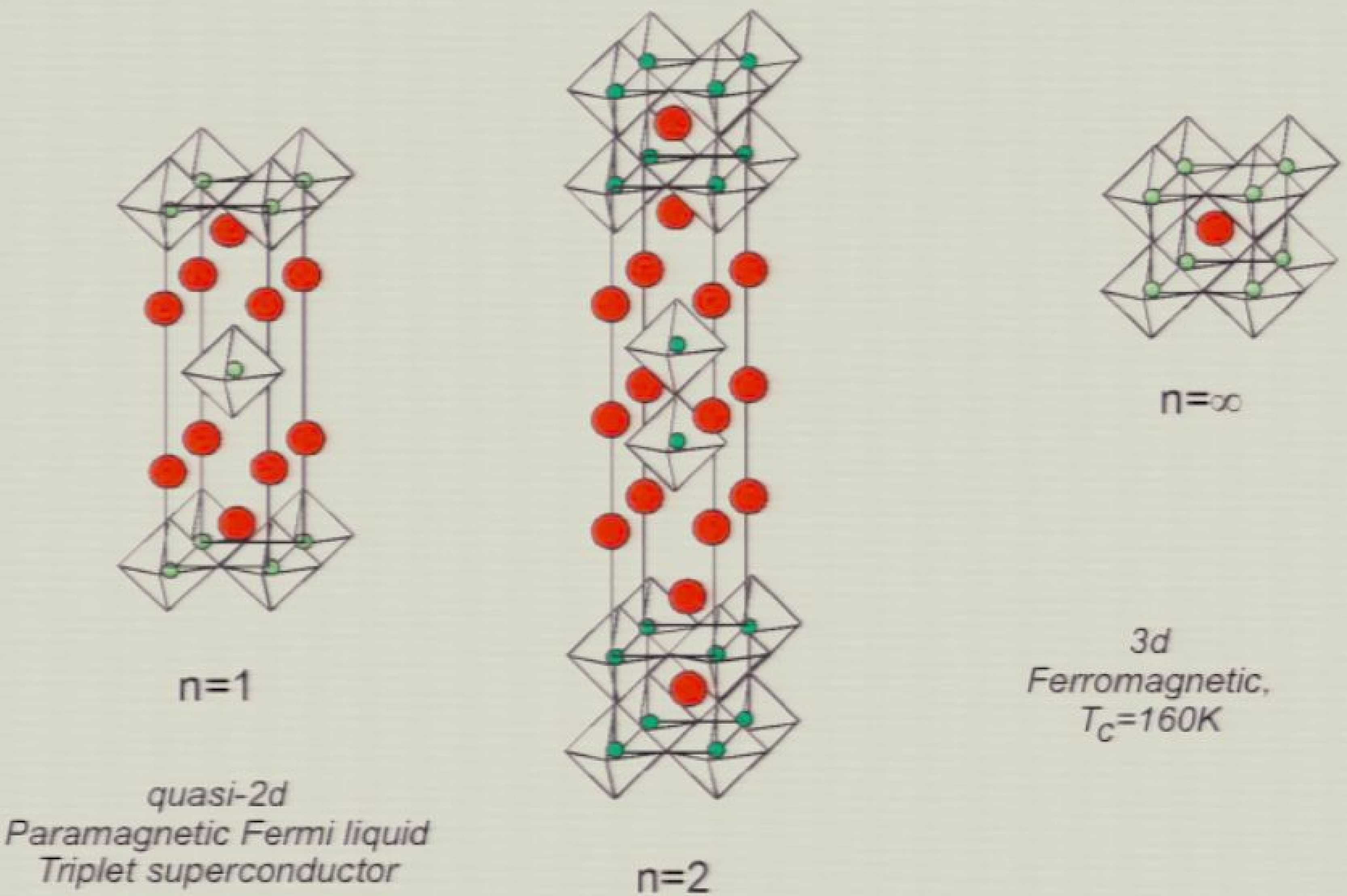


n=∞

3d
Ferromagnetic,
T_c=160K

Experimental evidence of nematicity

The Ruddlesden-Popper Series: $Sr_{1+n}Ru_nO_{1+3n}$



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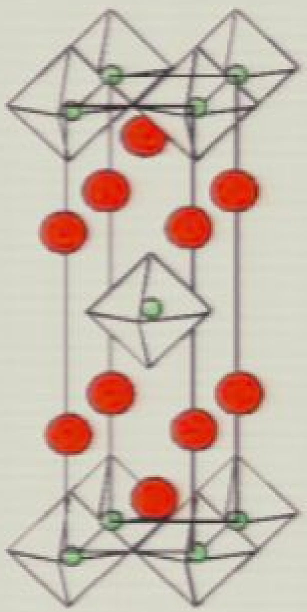

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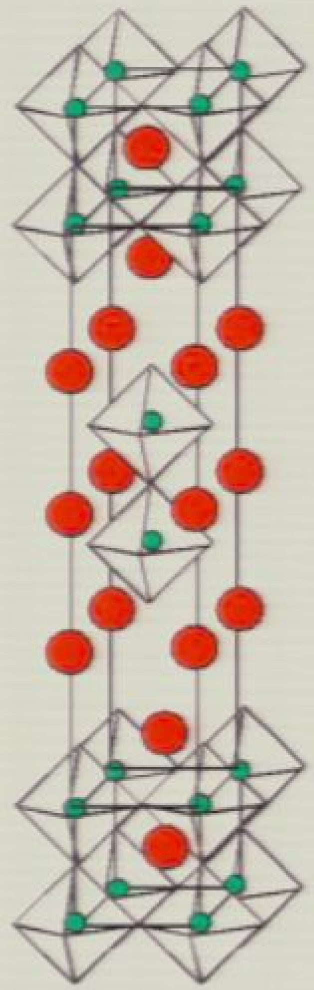
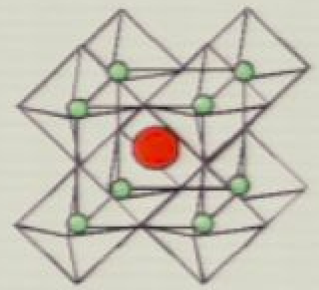
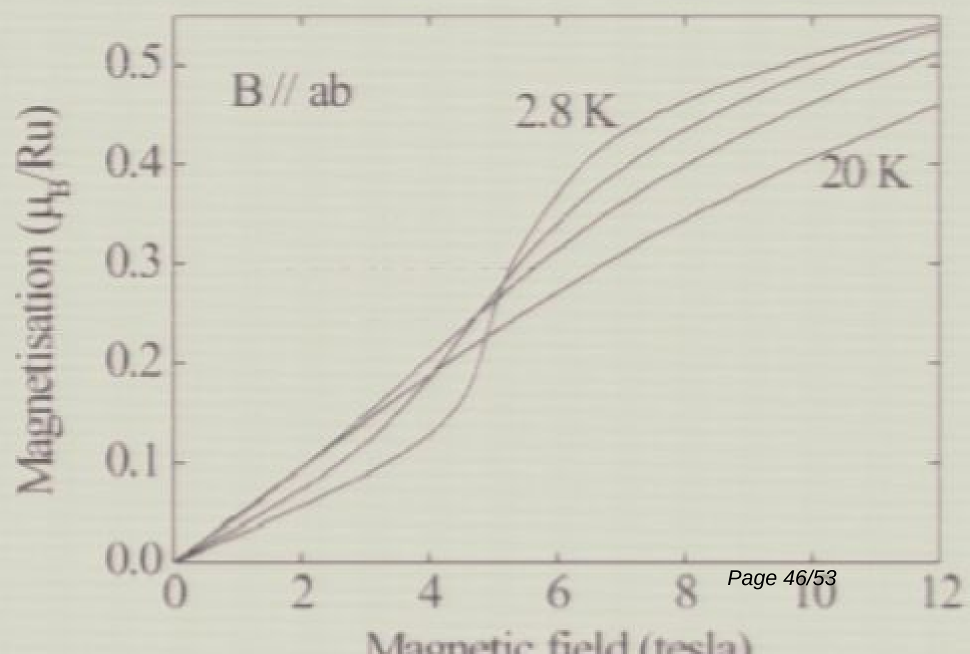


n=2

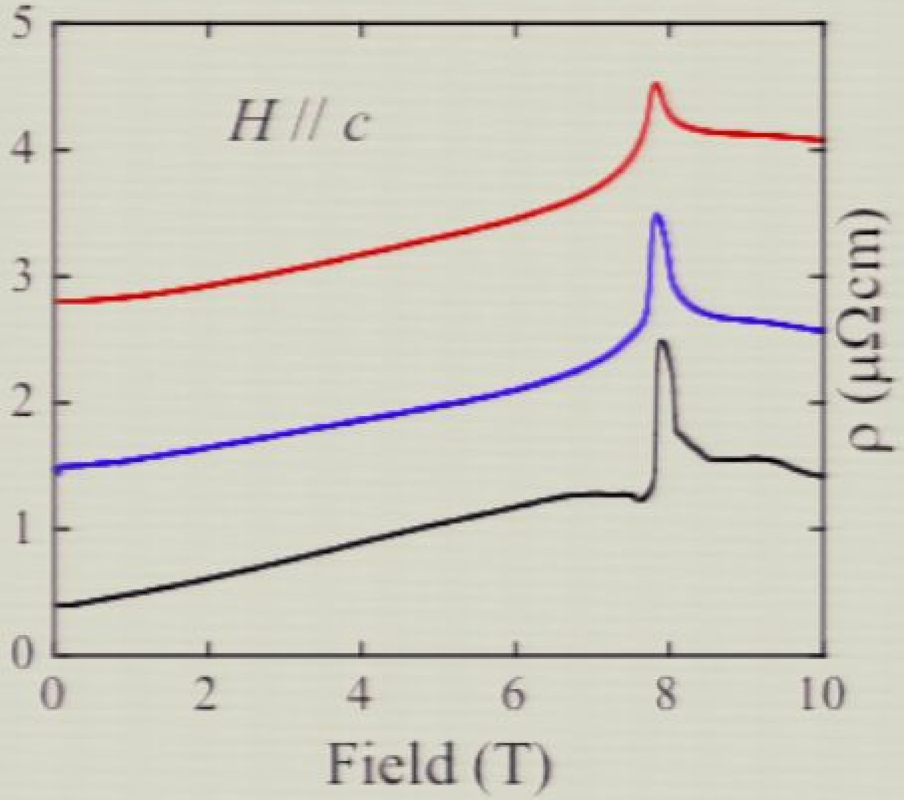


n=∞



ultra-clean

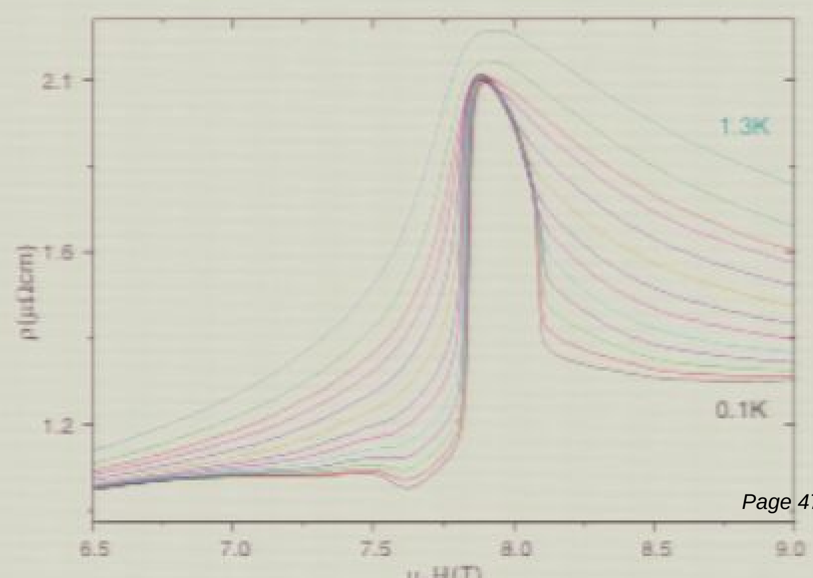
increase sample purity by order of magnitude



Disorder-Sensitive Phase Formation Linked to Metamagnetic Quantum Criticality

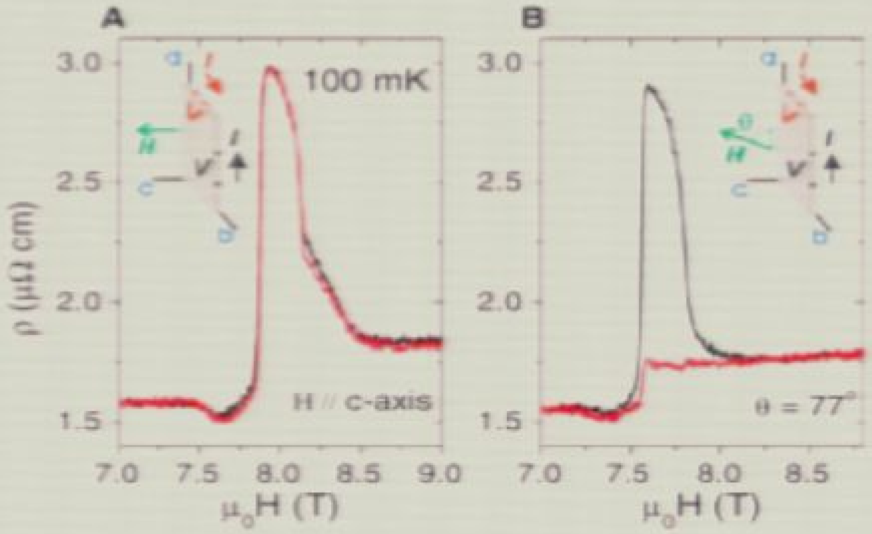
S. A. Grigera,[1*] P. Gegenwart,[1,2] R. A. Borzi,[1] F. Weickert,[2] A. J. Schofield,[3] R. S. Perry,[1,4,5] T. Tayama,[6] T. Sakakibara,[6] Y. Maeno,[4,5] A. G. Green,[1] A. P. Mackenzie[1*]

SCIENCE VOL 306 12 NOVEMBER 2004

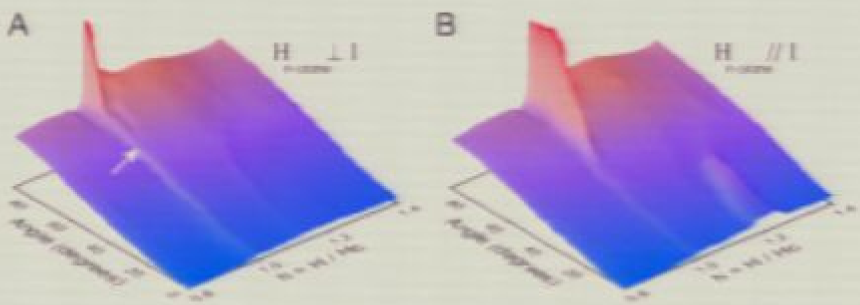


Anisotropic metal

Ruthenates (Sr3Ru2O7)



Field-current anisotropy in the presence of an in-plane magnetic field component



Borzi et al., Science 315, 214 (2007)

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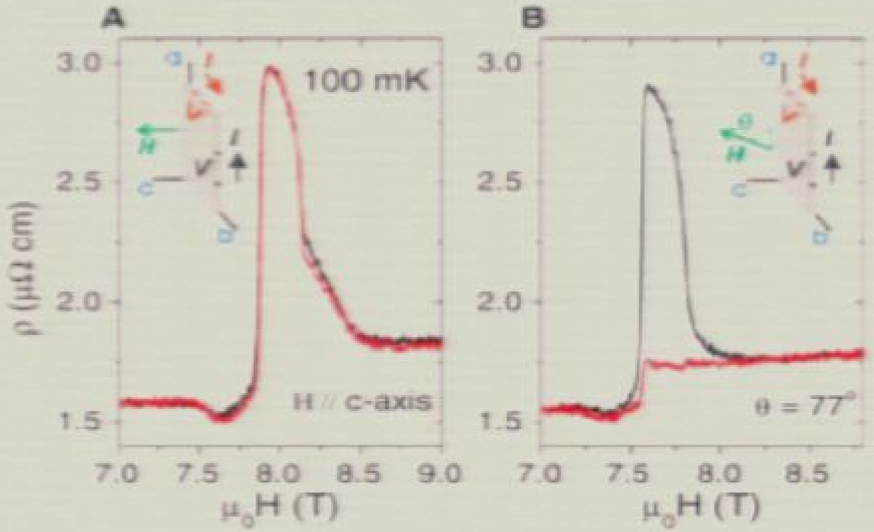

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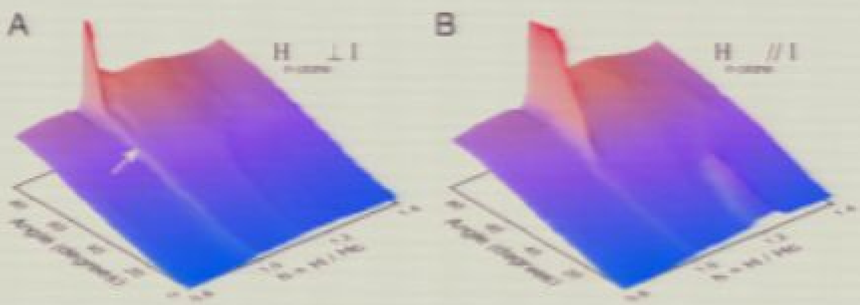
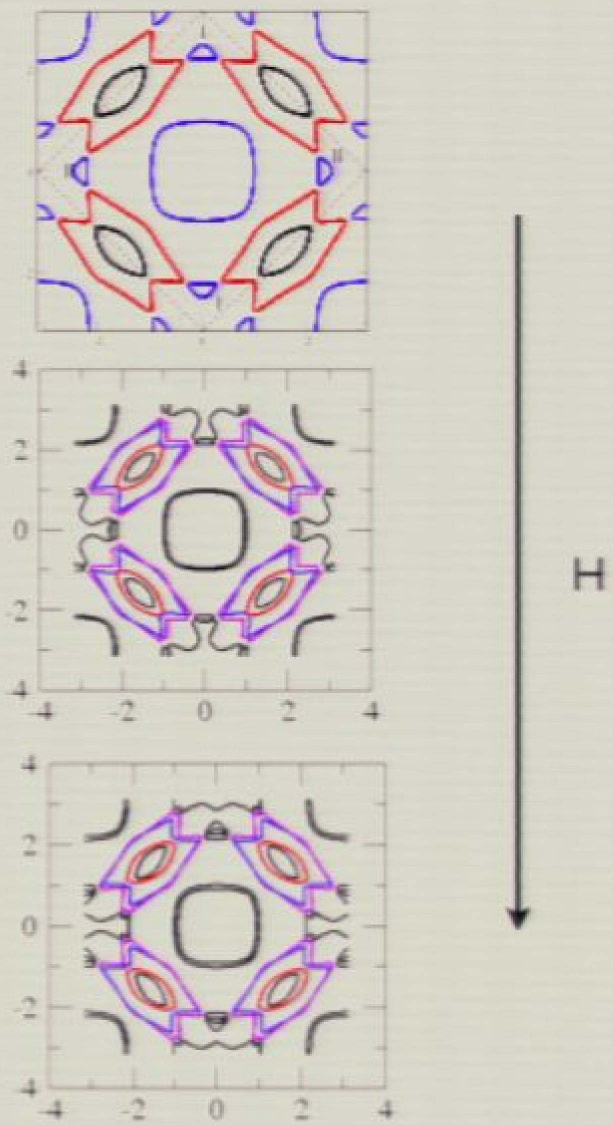


Borzi et al., Science 315, 214 (2007)

Microscopic theory



C. Puetter, J. Rau, HYK, PRB (2010)

High temperature Cuprates

Electronic Liquid Crystal State in the High-Temperature Superconductor YBa 2Cu3O6.45
V. Hinkov, *et al.*
Science **319**, 597 (2008);

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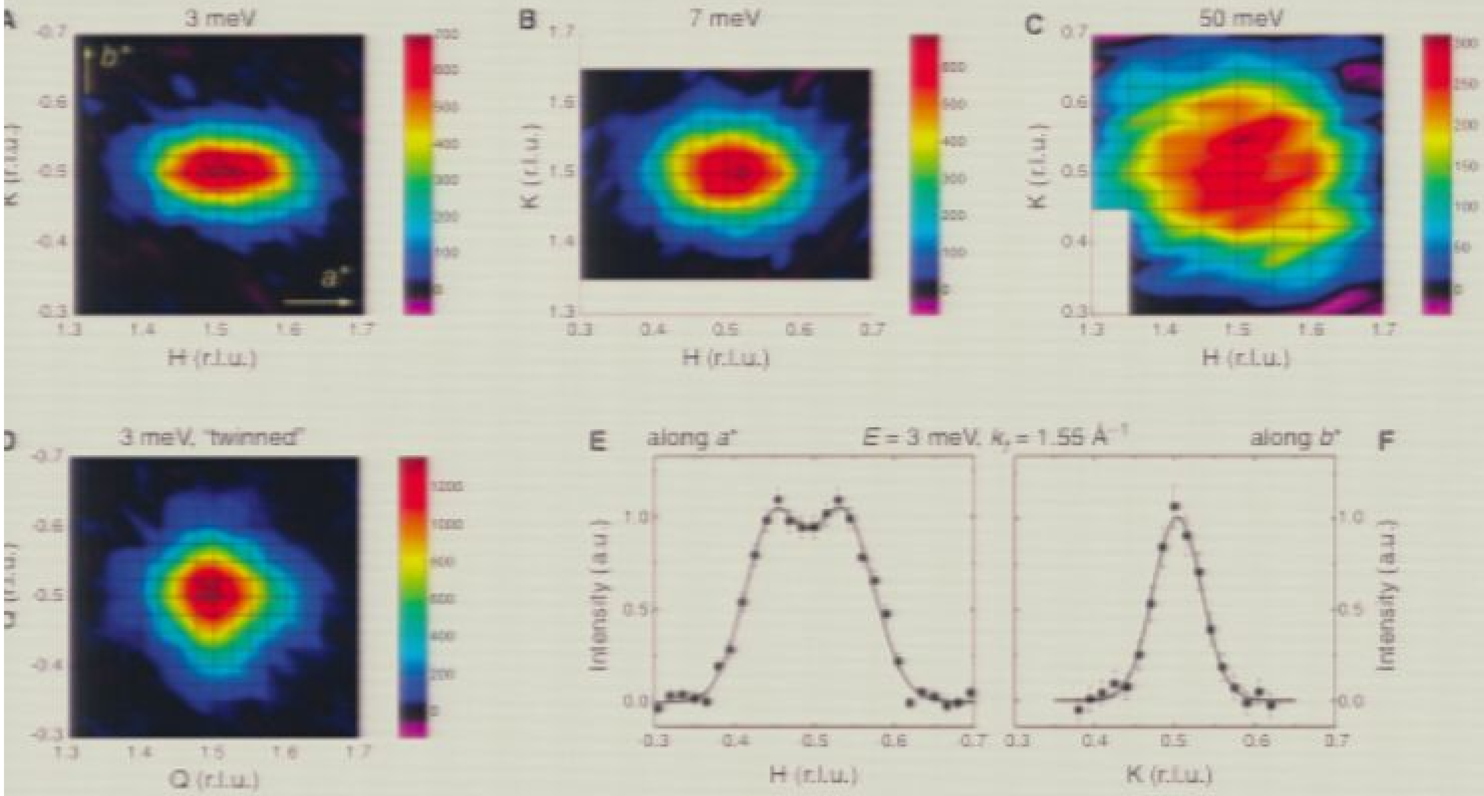

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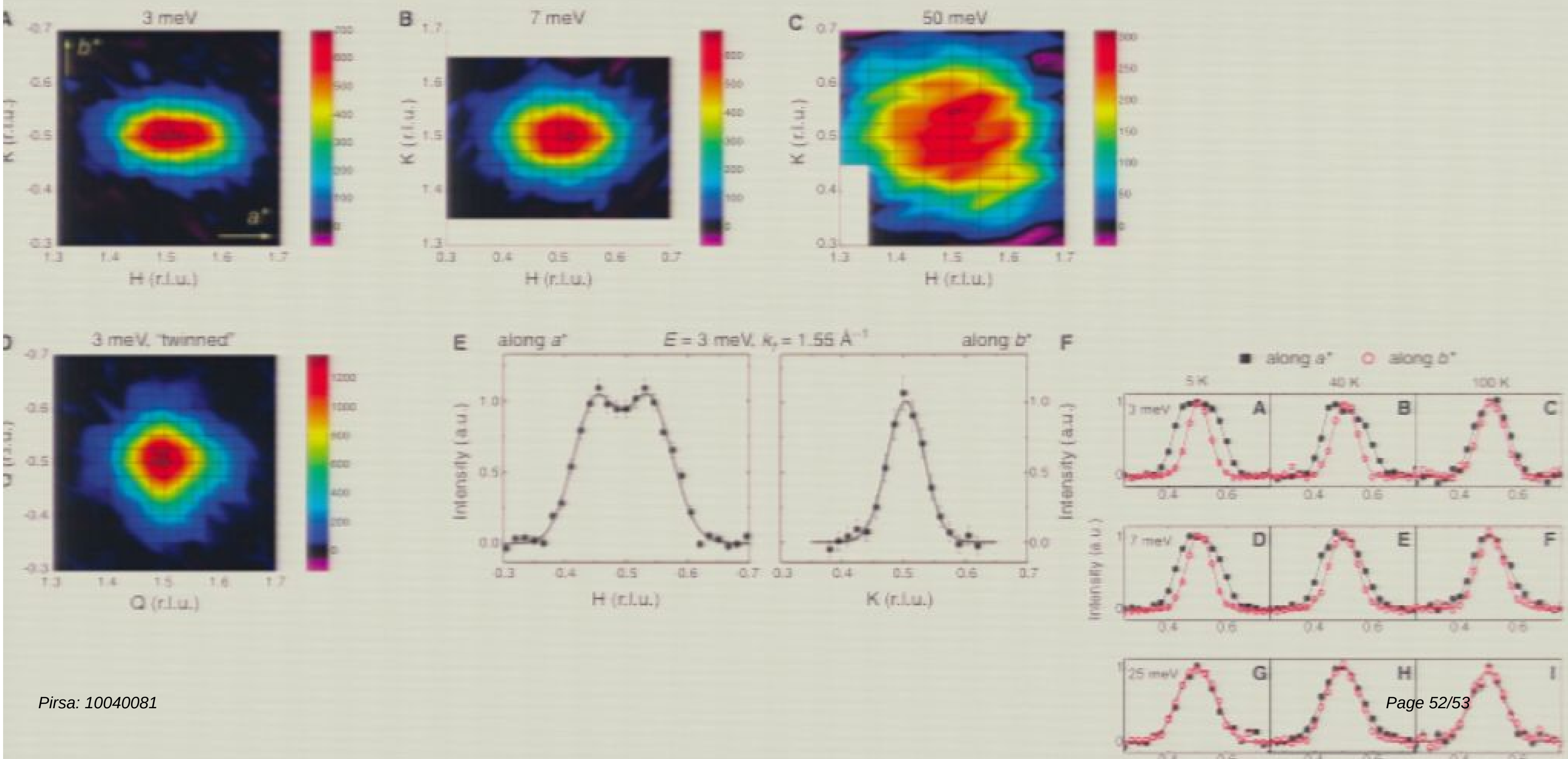

Summary and Open questions

Nematic ; Fermi surface distortion -- anisotropic metal

; accompanies meta-magnetic transitions in the presence of a magnetic field

Competition/interplay with other ordered states

--- superconductivity, spin density and charge density wave,....

--- symmetry group ; SO(6) and nematicity, HYK, Annals of physics (2010)

Microscopic mechanism of nematicity

--- $Sr_3Ru_2O_7$; C. Puetter et al, PRB (2010); S. Raghu et al PRB (2009)

--- Cuprates ; ???

Relation to quantum criticality?