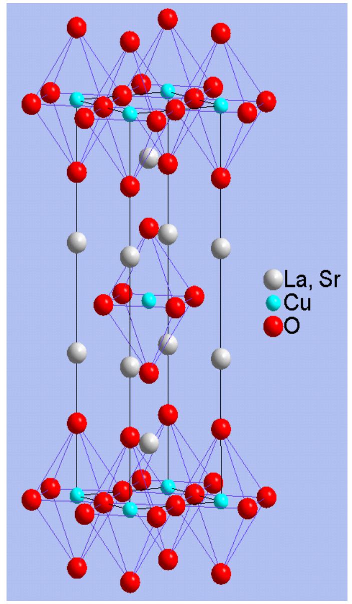
Ferronematic order in underdoped Cuprates

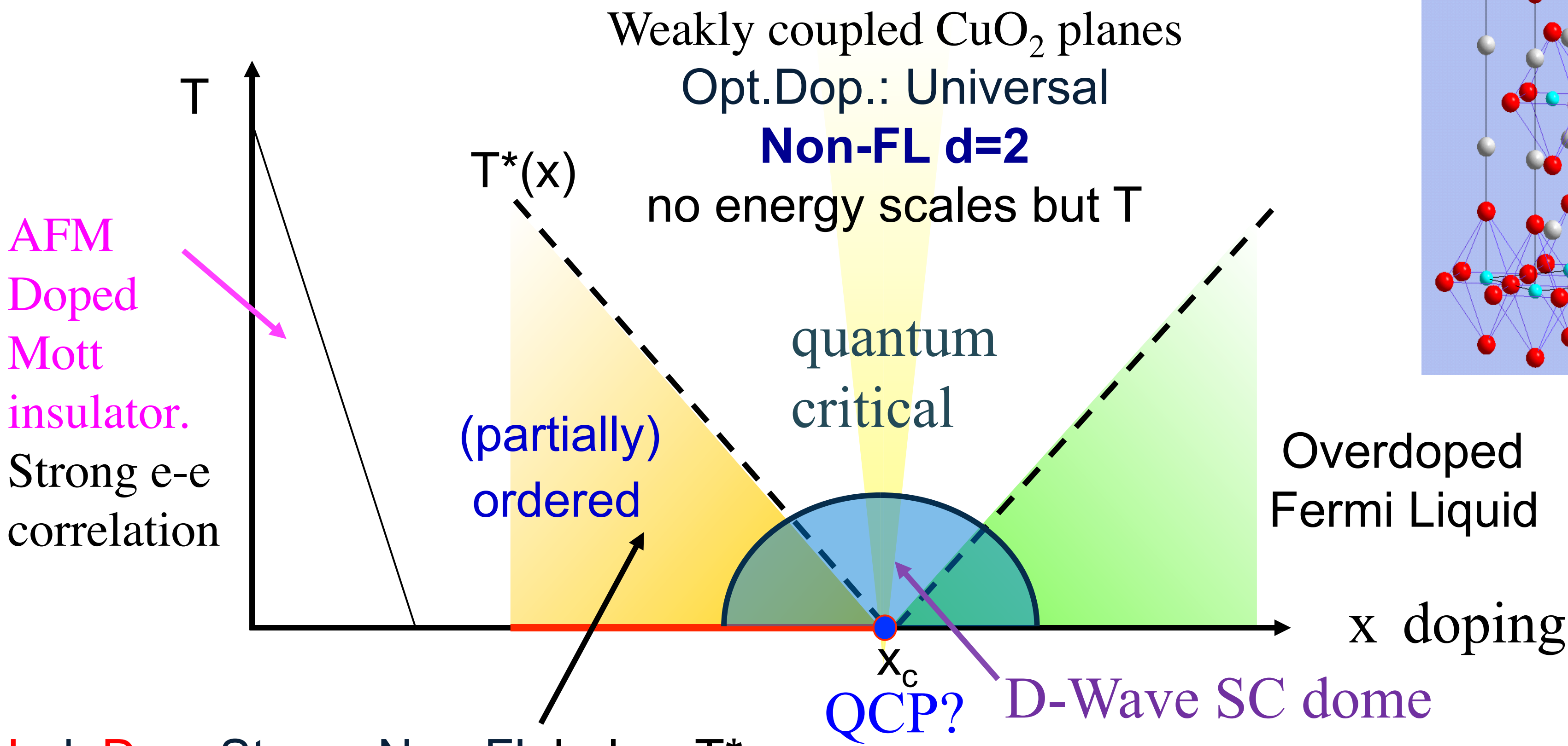
Collaborators: G. Seibold, M. Capati, M. Grilli and J. Lorenzana.

Hidden Ferronematic order in underdoped cuprates.
arH1v:1204.2119v1 [cond-mat.supr-com]

Carlo Di Castro
Dipartimento di Fisica Università di Roma
“La Sapienza”

Generic phase diagram of Cuprates, e.g. $La_{2-x}Sr_xCuO_4$





Und. Dop. Strong Non-FL below T*.
Pseudogap associated with a variety of spin and charge ordered structures:
stripe-like (dynamical with smectic order) (LSCO, YBCO)
checkerboard or droplets (Bi2212)

Non-FL in d>1? Competing Order?
The critical fluctuations of the competing order can be the glue for d-wave pairing and the cause of the Non-FL behavior.
Hidden QCP (many proposals)➔

QCP for the formation of ICDW.

Strong correlations reduces double occupancy

Why ICDW?

Phase Separation is easy

Generic of all models for CuO_2 planes

Add Coulomb forces → Frustrated PS on local basis

From the high doped correlated Fermi Liquid (Rome):
Local (Hubbard) repulsion reduces the homogenizing kinetic energy term, favoring PS in the presence of phonon mediated (*Holstein*) *attraction*.
Frustrate with Coulomb

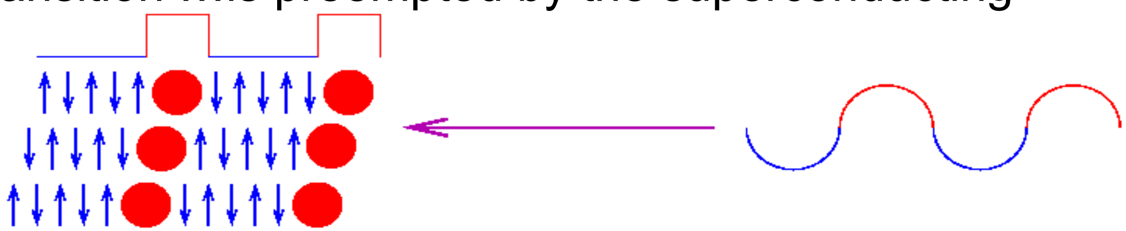
STRIPES

From low doping (Emery, Kivelson): Expulsion of holes from AF background; Zaanen,Tranquada,… antiphase stripes.

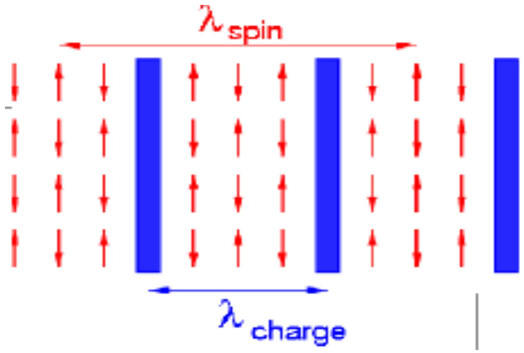
ICDW instability with finite q_c modulating wave vector [(0,1), (1,0) direction], QCP (x_c=0.19), end-point of a critical line $T_{CDW}(x) \approx T^*$

Indeed new resonant x-ray scattering experiments in YBCO [Ghiringhelli et al; Chang et al 2012] identify a 2D-ICDW as the order competing with superconductivity at intermediate doping. "The incipient CDW phase transition …is preempted by the superconducting transition,…".

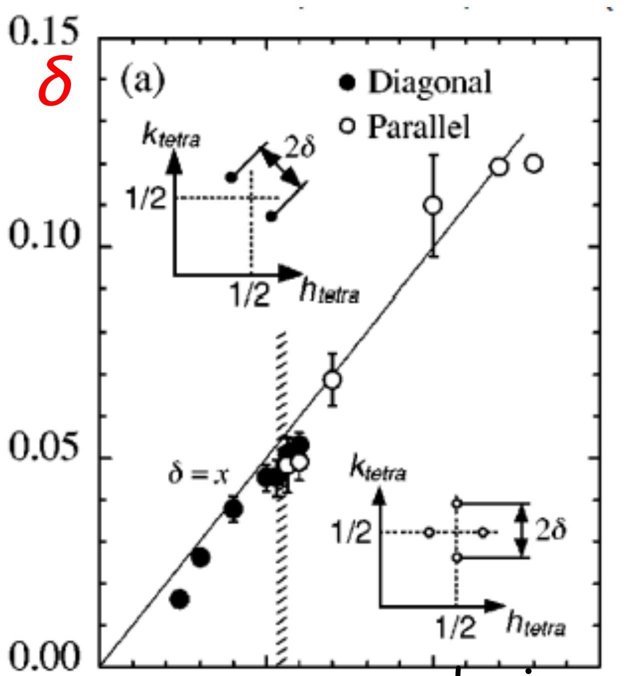
ICDW smoothly evolving into anharmonic stripes



However **long range *stripe order*** observed *in codoped LSCO only* (e.g. $La_{1.48}Nd_{0.4}Sr_{0.12}CuO_4$)
Elastic neutron scattering: Splitting of magnetic and superlattice peaks denotes periodic spin and charge modulation (q_s=q_c/2)

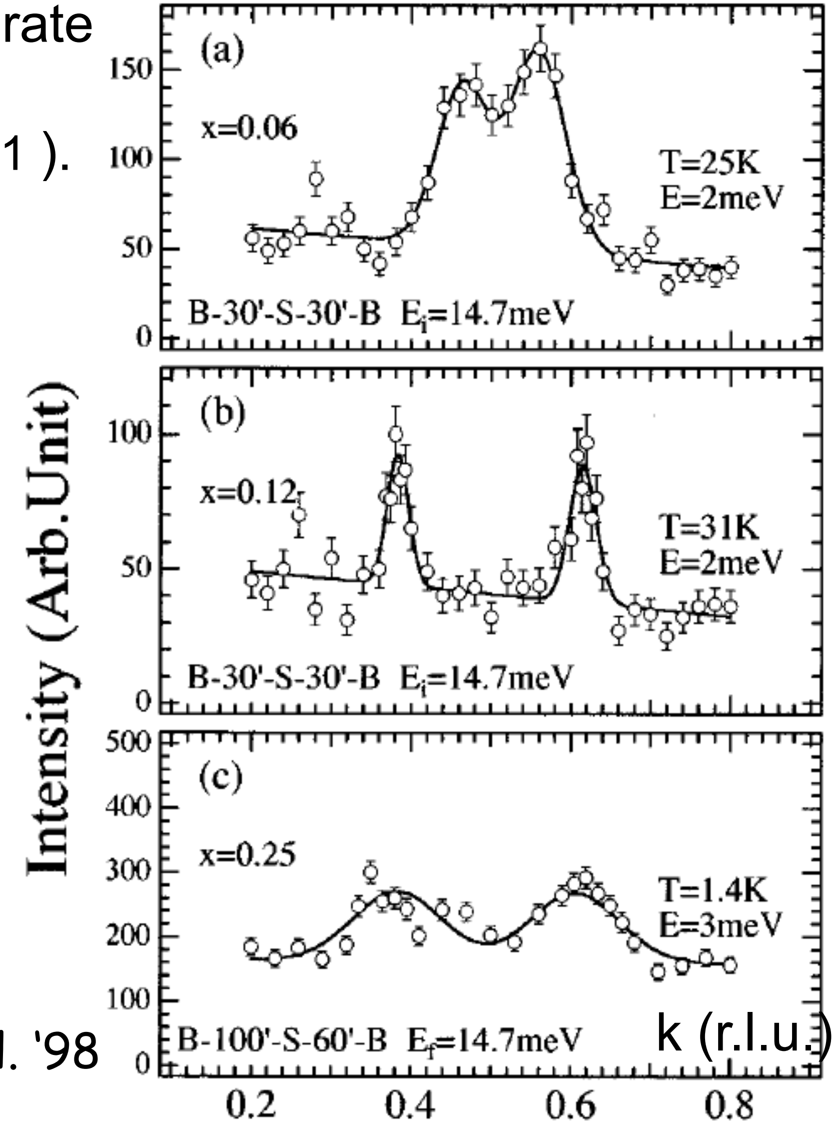


Generally,YBCO,LSCO, Bi2201: - Incommensurate spin scattering (q_s *//* Cu-O bond in YBCO;
$\boldsymbol{q_s=(\pi/a)\delta}$ diagonal for x< 0.06 in LSCO, Bi2201).
-No signature of charge modulation.
-Breaking of rotational symmetry



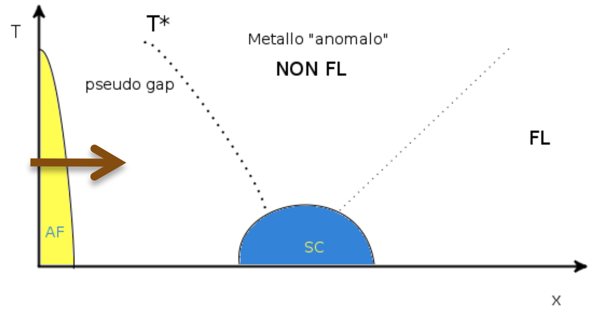
Fujita et al. 2002 doping x

$La_{2-x}Sr_xCuO_4$



Yamada et al. '98

Therefore from low doping



LSCO, Bi2201, YBCO:
-Incommensurate spin modulation, smectic like, response.
-No Charge modulation
-Evidence of four field rotational symmetry breaking
Nematic charge order also in $Bi_2CaCu_2O_{8+y}$, (Lawler et al. 2010 [STM])

By doping the AF background we will answer the questions:

Can incommensurate spin correlations arise without charge *modulation as instead required by the stripe model?*

Is nematicity a sign of fluctuating spin and charge density wave order, as it would be given by *dynamic melted stripes, or has it an independent origin?*

Doped holes form Vortex-Antivortex (V-A) segments, nematic seeds (random in space) for incommensurate spin smectic like structure,
a new phase, dubbed by us “ferronematic”.

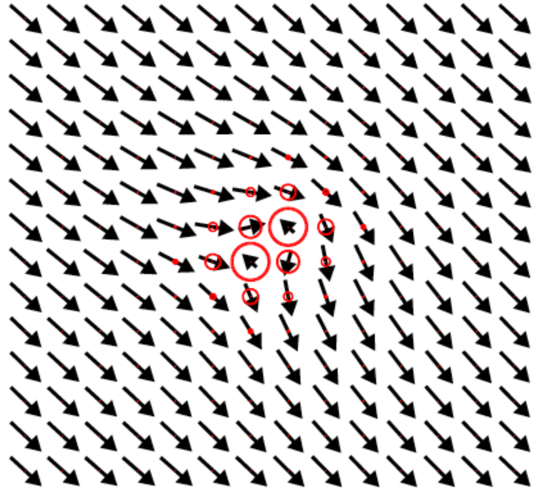
(G. Seibold et al. . **arXiv:12042119**)

See also Berciu and John 2004, Timm and Bennemann 2000.

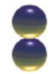
Dilute limit

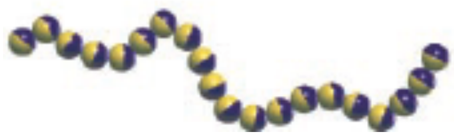
1-band extended Hubbard model (U,t,t', U/t=8, t'/t =…)
Variational calculations based on Gutzwiller approxim.
Doped charged holes in the anti-ferro background form Vortex-Antivortex (V-A) pairs which, then, tend to arrange in 1D V-A segments.

V-A pair: staggered spin/charge structure; *t'/t=-0.1*

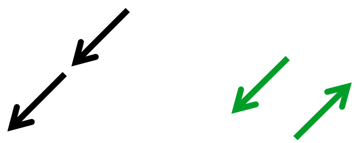


Analogy with dipolar fluids

In 3D, the maximal dipole-dipole attraction is when two dipole spheres touch each other  *nose-to-tail,* favoring an endless alignment (as for stripes).



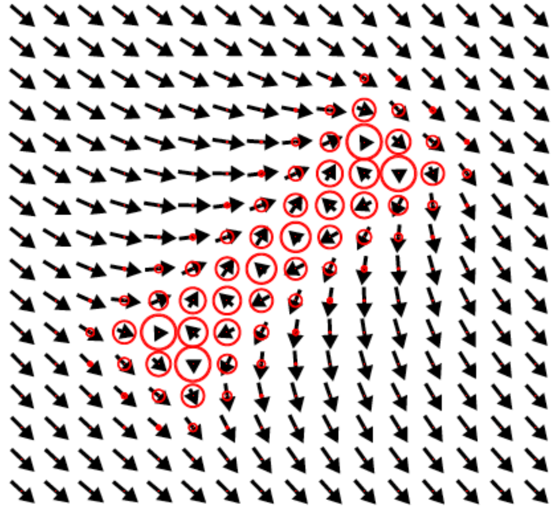
In 2D, the dipole-dipole interaction does not distinguish between the *nose-to-tail* and the antiparallel side-by side quadrupolar alignment



$$V_{dip-dip} = \frac{p_1 p_2}{l^2} - 2\frac{(p_1 l)(p_2 l)}{l^4} = -|p_1||p_2|/l^2$$

However in our variational approach short range interaction is important and the V-A pairs gain energy for nose-to-tail alignment (as in dipolar fluid) due to the local distribution of holes in magnetically ordered environment.

16x16lattice sites,
t'/t=-0.2
4 V-A pairs
staggered spin/charge



Direction is determined by t'/t.
For -0.3<t'/t<-0.2 crossover from diagonal to vertical-horizontal configuration.

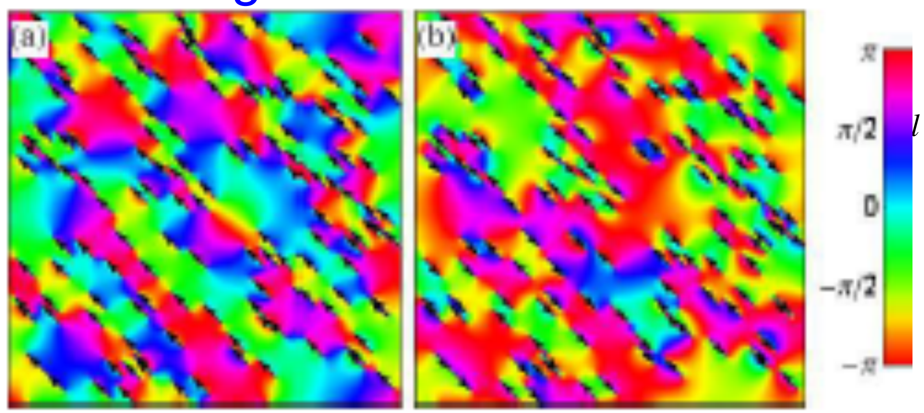
Each segment of N_{pairs} and length l has N_{ch} $(=2N_{pairs})$ charges immersed in a compensating charged background: Long range Coulomb interaction (Coulomb charge energy is increasing as $N_{ch} \ln N_{ch}$) limits chain's length l to few lattice constants.

For N_{seg}, the magnetic short range interaction favors, as for two V-A pairs, a ferronematic alignment.

Distribution of N_{seg} segments each of length l and charge N_{ch}:
effect of orientation

A classical XY-model is used (variational GA is too limited in sizes). Segments are chains of vacancies, alternately centers of vortex and antivortex. Parameters obtained by comparing the phase change across a single segment. Minimization of classical energy.

Oriented segments random orientation



Spin phase distribution is obtained at given doping $x=N_{ch}N_{seg}/L^2=0.03$ on a lattice of 160x160 sites,, segment sites $l+1=8$, filling factor $\nu=N_{ch}/(l+1)$ =0.7.

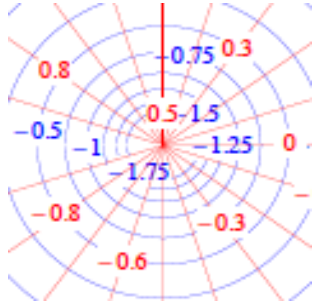
In fig.a, with macroscopic polarization, phase modulation (stripe-like in the spin sector) appears, but with random space distribution of oriented segments.

Fig.b, instead, disaggregates in large areas of equal phase.

The influence of a collection of equally oriented V-A segments on spins at each point ***r*** *is obtained by evaluating* the total phase change *Φ* at point ***r***

$$S^x(\mathbf{r})=S_0 exp(i\mathbf{Q}\cdot\mathbf{r})cos\Phi(\mathbf{r}), \quad S^y=S_0 exp(i\mathbf{Q}\cdot\mathbf{r})sin\Phi(\mathbf{r}), \quad \mathbf{Q}=(\pi,\pi),$$

gradΦ gives the *incommensuration of* spin response.

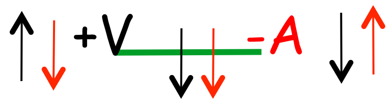


-In a single vortex, Φ is the velocity potential and coincides with the radial angle *φ*.

The (spin) velocity *v* , tangential to the streamlines, is

v=gradφ=1/r .

-Pair of Vortex and Antivortex at distance l



The velocities add to the value v=2/*l*/2 between V and A and tend to cancel outside. **v** is orthogonal to the dipole ***l***

The phase disturbance, averaged on a square (L^2), extends on a circle of radius *l*/2:

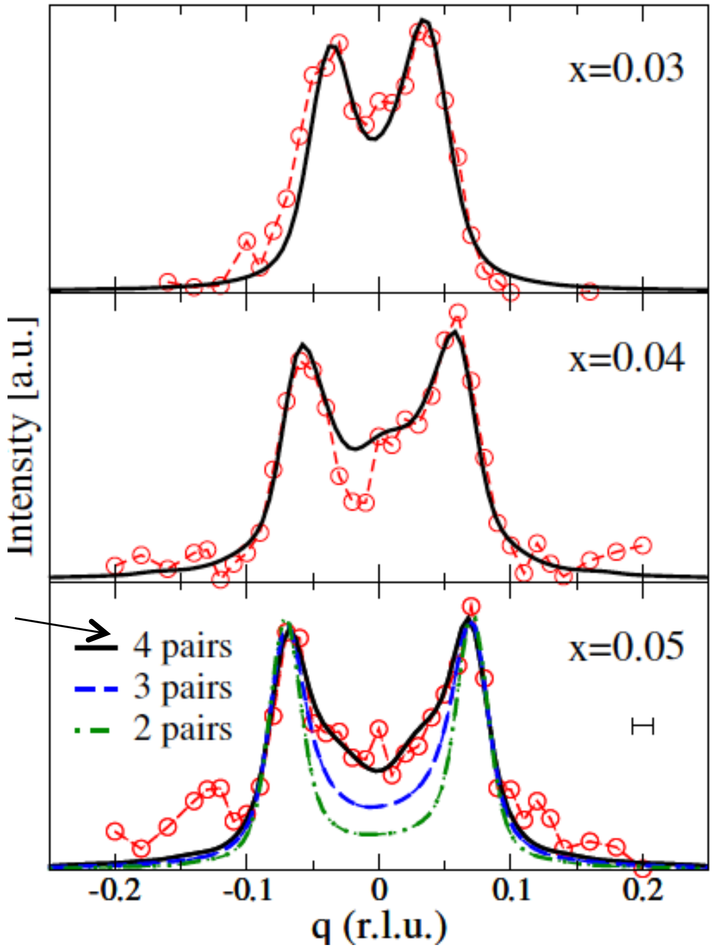
$$\langle grad\Phi\rangle \approx \pi(l/2)^2/L^2\, \mathbf{v}=\pi l \times (versz)/L^2.$$

-**For a segment** of V-A pairs, the dipole is the length ***l*** .

-Distribution of N_{seg} macroscopically polarized segments, random in space, length l, doping $x=N_{seg}N_{ch}/L^2$, filling factor $\nu=N_{ch}/(l+1)$ ($l+1$ sites):

$<grad\Phi> \approx N_{seg} <grad\Phi>_{segm} = N_{seg} \pi l x(versz)/L^2 = q$

$q = \pi \frac{x}{\nu}\frac{l}{l+1} \equiv \pi P$ is the incommensurate modulation vector of spin response (as in the stripes); q determines peak position



q perpendicular to the dipole segments and to their macroscopic polarization $P=N_{seg}l/L^2$, the "ferronematic" order parameter, (incommensurability in YBCO? Hinkov et al 2009)

Fits of the experiments (Wakimoto et al. 2000) on spin structure factor for doping x=0.3, 0.4, 0.5, $l+1=8$, no smectic order.

Average over 20≈30 configurations of 160x160 lattice

Conclusion

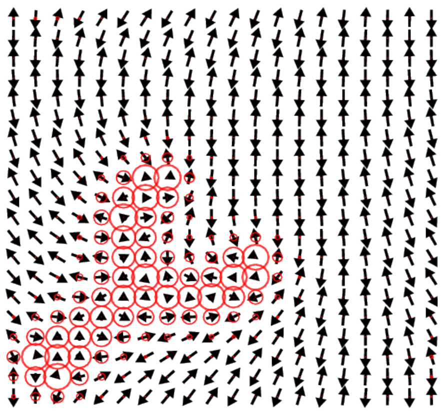
Inhomogeneous State as a bridge between FL and doped AFM separated by a hidden QCP, which, coming from high doping, arises as a correlated-Fermi-liquid instability :

At low doping glass of nematic V-A chain segments gives rise to spin smectic like correlations with the polarization of the segments as an order parameter of a phase, dubbed ferronematic by us.

Open problems: -how the two topologically different phases (stripes and ferronematic segments) are interconnected?
-T≠0? Nematic and polarization transition? Simultaneous or which first?

Increasing doping and T, branching is favored: more complex structures (checkerboard, bubbles,…) and a gas of topological excitations (ends, junctions, edge dislocations) should appear out of the nematic glass.

junctions:
20x20 lattice
14 holes,
U/t=8,
t'/t=-0.1



junction in
dipolar fluid