Quenched Disorder and Vestigial Nematicity in the Pseudogap Regime of Cuprates

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Abstract

- We carried out a theoretical analysis of the Landau-Ginzburg-Wilson effective field theory of a **classical incommensurate CDW** in the presence of weak **quenched disorder.**
- Although the possibility of long-range CDW order is precluded in such systems, any **discrete symmetry-breaking** aspect of the charge order (**nematicity** in our case) generically survives up to a nonzero disorder strength.
- Such "**vestigial order**", which is subject to unambiguous macroscopic detection, can serve as an avatar of what would be CDW order in the zero disorder limit.

Model

charge density $\rho(r) = \bar{\rho} + [\psi_x(r)e^{iQ_x r} + \psi_y(r)e^{iQ_y r} + c.c] + \ldots$

$$H_{\text{CDW}} = -J\sum_{\langle r,r'\rangle,m}[\psi^\dagger(r,m)\psi(r',m)+h.c.] - V_z\sum_{r,m}[\psi^\dagger(r,m)\psi(r,m+1)+h.c.]$$
$$+U\sum_{r,m}[\psi_x^\dagger\psi_x + \psi_y^\dagger\psi_y - 1]^2 - \Delta\sum_{r,m}[\psi_x^\dagger\psi_x - \psi_y^\dagger\psi_y]^2 - \sum_{r,m}[h^\dagger\psi + h.c.]$$

$h(r,m)$: random field $\quad \overline{h_\alpha(r,m)h_\beta(r',m)} = \sigma^2\delta_{\alpha\beta}\delta_{m,m'}\delta(r-r')$

- Apply replica trick and integrate out h; perform Hubbard-Stratonovich transformation and solve self-consistent equations:

$$1 = T\int d^3k\left[\frac{1}{E_x(k,\mathcal{N})} + \frac{1}{E_y(k,-\mathcal{N})}\right] + \sigma^2\int d^3k\left[\frac{1}{E_x^2(k,\mathcal{N})} + \frac{1}{E_y^2(k,-\mathcal{N})}\right]$$

$$-\frac{\mathcal{N}}{\Delta} = T\int d^3k\left[\frac{1}{E_x(k,\mathcal{N})} - \frac{1}{E_y(k,-\mathcal{N})}\right] + \sigma^2\int d^3k\left[\frac{1}{E_x^2(k,\mathcal{N})} - \frac{1}{E_y^2(k,-\mathcal{N})}\right]$$

where $\mathcal{N}$ is the nematic order parameter (one of the HS fields).

Isotropic	Nematic	Stripe	Checkerboard
$\overline{\langle\psi_x\rangle} = 0,$	$\overline{\langle\psi_x\rangle} = 0,$	$\overline{\langle\psi_x\rangle} \neq 0,$	$\overline{\langle\psi_x\rangle} = \overline{\langle\psi_y\rangle} \neq 0$
$\overline{\langle\psi_y\rangle} = 0,$	$\overline{\langle\psi_y\rangle} = 0,$	$\overline{\langle\psi_y\rangle} = 0,$	$\mathcal{N} = 0$
$\mathcal{N} = 0$	$\mathcal{N} \neq 0$	$\mathcal{N} \neq 0$	

Results

- **Zero disorder**

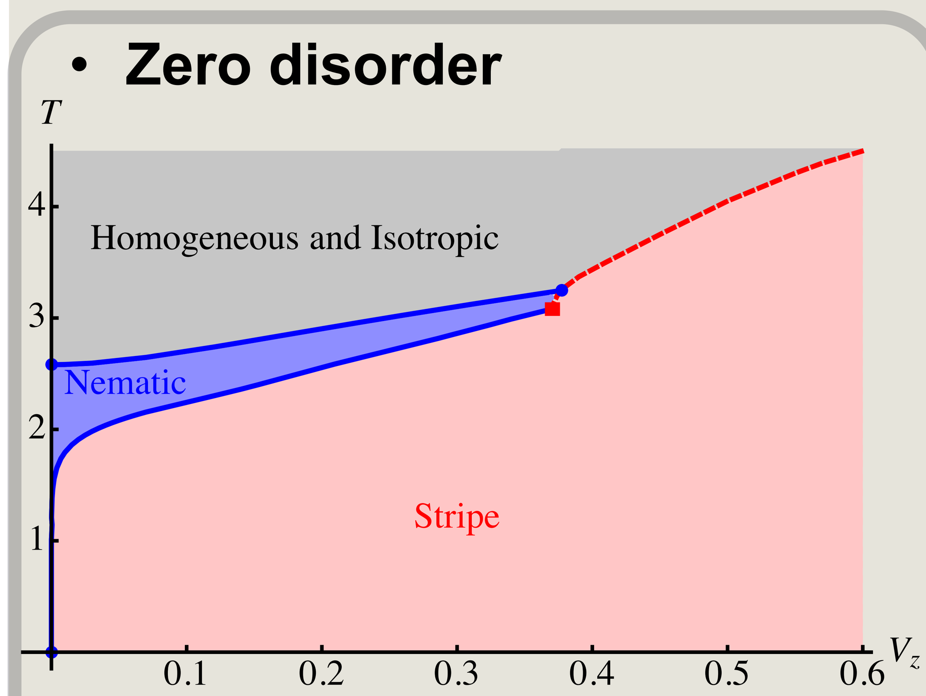

Fig. 1 Zero-disorder phase diagram. Solid and dashed lines are second and first order transitions, respectively.

- **3D finite disorder**

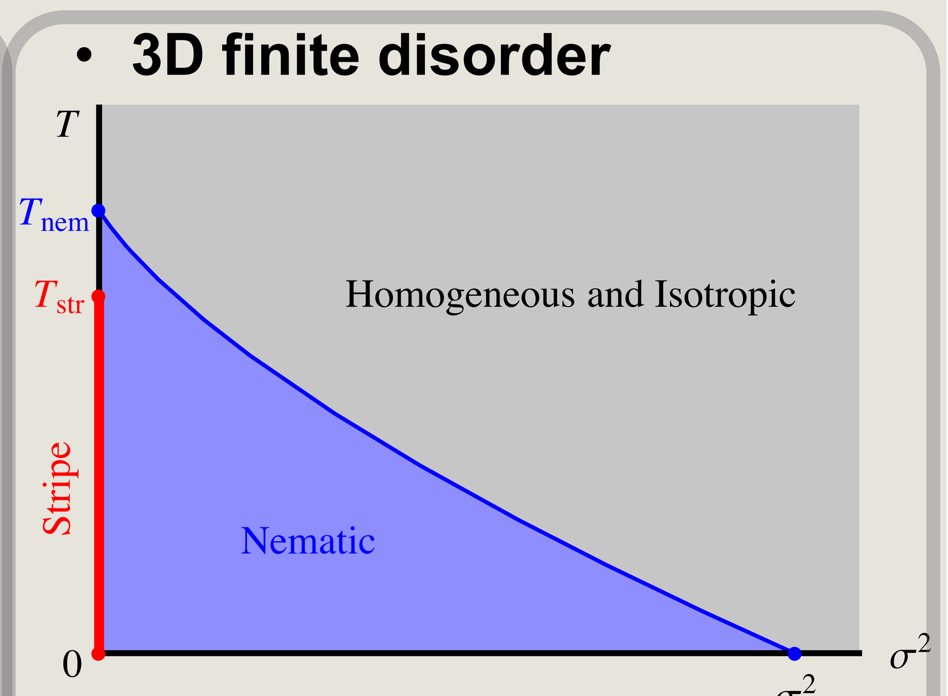

Fig. 2 Finite-disorder phase diagram at V_z=0.01J. Nematic phase survives up to a critical disorder strength.

- **CDW correlation length**

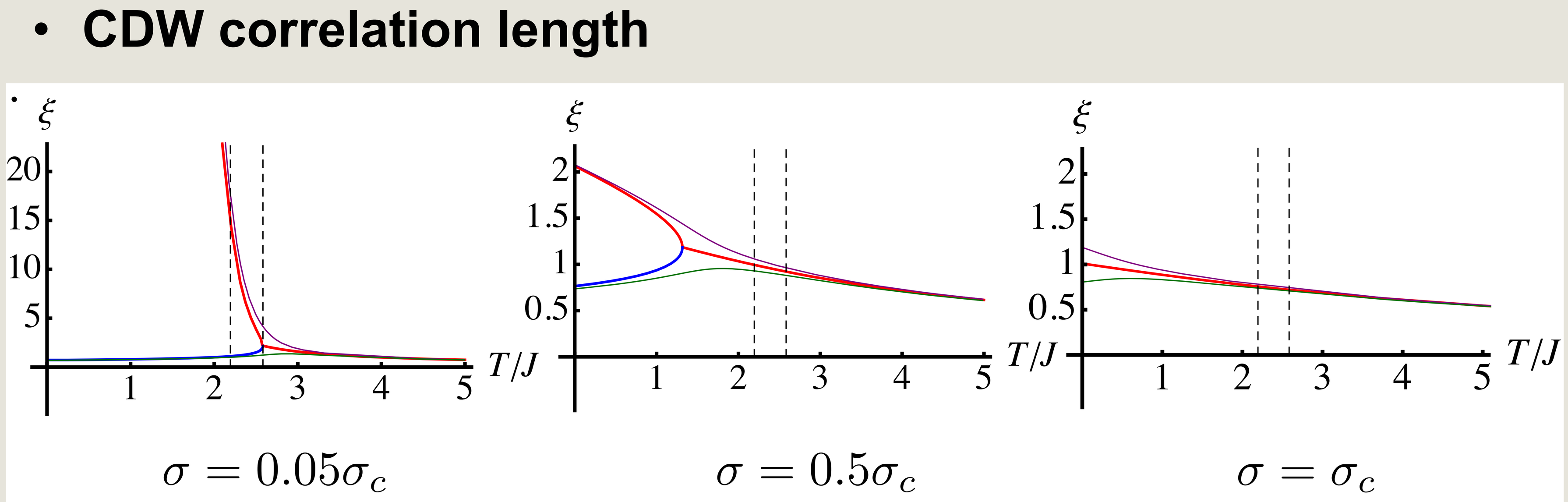

Fig. 3 T-dependence of CDW correlation length under various disorder strengths, with (thin lines) or without (thick lines) an explicit symmetry breaking field.

QCP around doping 0.19?

- Various experiments have indicated a possible quantum critical point in cuprates at around doping 0.19[1,2].
- With disorder taken into account, the QCP (if exists) cannot be incommensurate-CDW type.
- Discrete symmetry breaking QCP is possible, e.g., nematic or time reversal symmetry breaking.

Ongoing work (in collaboration with Prof. Subir Sachdev)

$$H_{\text{SC-CDW}} = H_{\text{CDW}} + g\sum_{r,m}|\psi(r,m)|^2 + g'\sum_{r,m}|\psi(r,m)|^4$$
$$-K\sum_{\langle r,r'\rangle,m}[\psi_{\text{sc}}^\dagger(r,m)\psi_{\text{sc}}(r',m)+h.c.] - V_z'\sum_{r,m}[\psi_{\text{sc}}^\dagger(r,m)\psi_{\text{sc}}(r,m+1)+h.c.]$$

ψ_{sc} : superconductivity order parameter $\quad$ constraint : $|\psi_x|^2 + |\psi_y|^2 + |\psi_{\text{sc}}|^2 = 1$

- **Zero disorder, zero temperaure phase diagram**

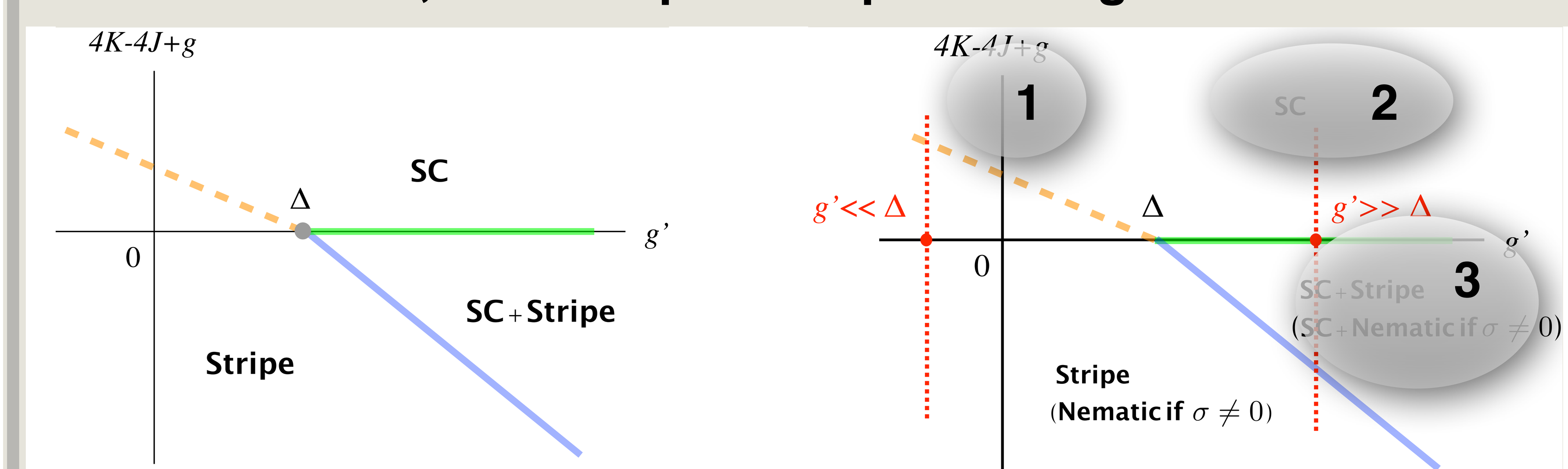

Fig. 4 **Left**: solid and dashed lines are second and first order transitions, respectively. The stripe (SC+stripe) phase becomes nematic (SC+nematic) at finite disorder. **Right**: Different parameter regions. Region 1 is the same as the parameters in ref[3].

- **CDW structure factor in Region 1**

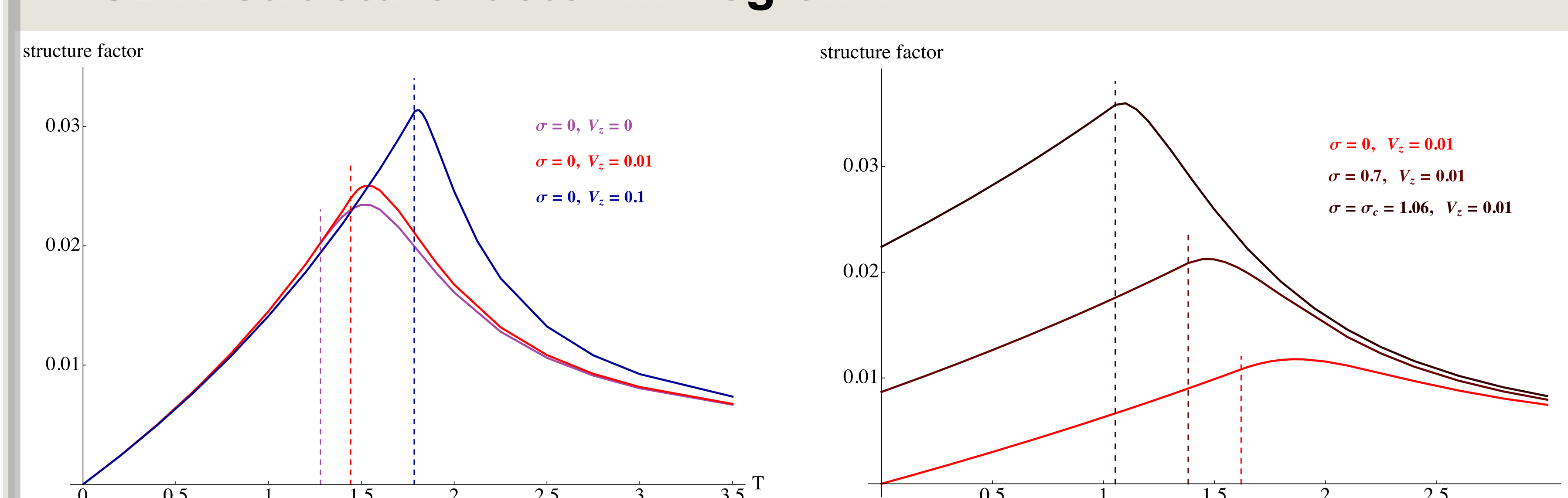

Fig. 5 CDW structure factor as a function of temperature with input parameters from Region 1. **Left:** under increasing V_z with zero disorder. **Right**: under increasing disorder with fixed V_z=0.01J. Dashed lines mark superconductivity transitions.

- **Region 2**

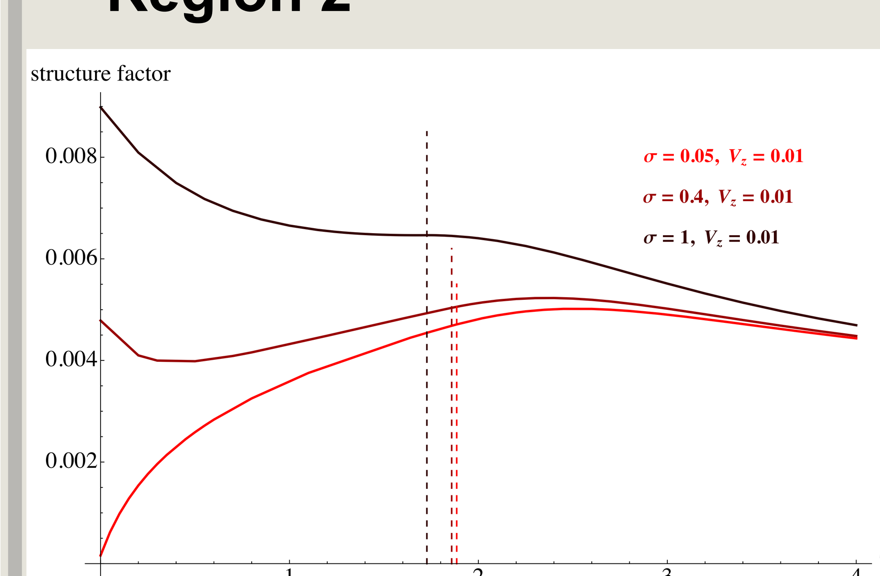

Fig. 6

- **Region 3**

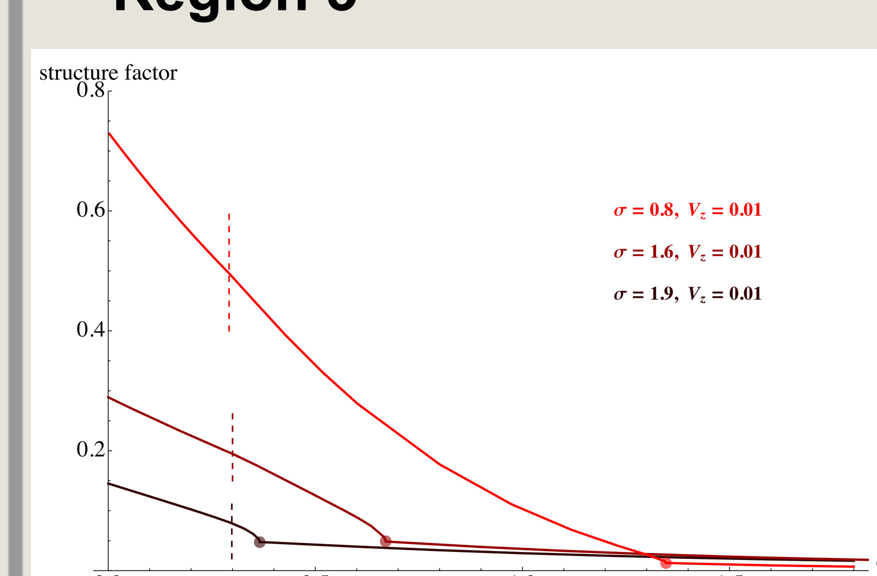

Fig. 7 Dots mark nematic transitions.

- Nematic transition greatly enhances the CDW structure factor.
- SC transition suppresses CDW correlation.
- Nematicity always wins when the two factors compete, resulting in a constantly increasing CDW structure factor as temperature decreases (no peak structure).

References

[1]K. Fujita et al., Science 344, 612 (2014) [2]B. Ramshaw et al., *arXiv* 1409.3990 (2014) [3]L. Hayward et al., Science 343, 1336 (2014)