Nodal nematic quantum criticality and quasiparticle interference

Eun-Ah Kim
Cornell University

References

E.-A. Kim et al., PRB 77, 184514 (2008)
E.-A. Kim and M.J. Lawler, in preparation

Collaborators

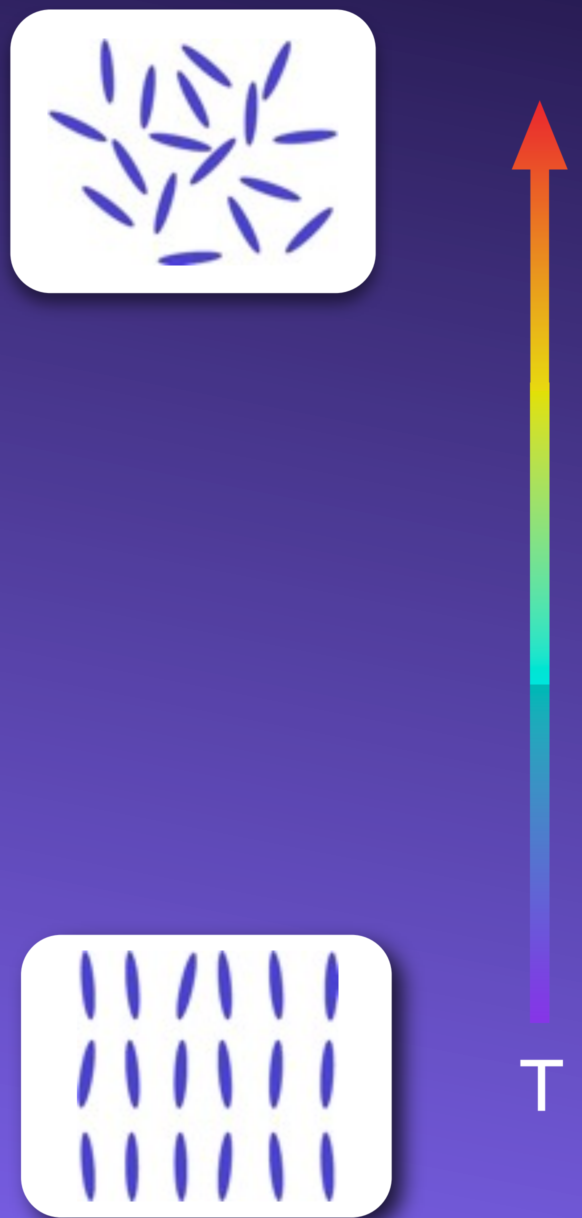
M.J. Lawler(SUNY Binghamton, Cornell)
P. Oreto(Stanford)
S. Kivelson(Stanford)
E.Fradkin(UIUC)
S.Sachdev(Harvard)

Nodal nematic quantum criticality and quasiparticle interference

- <u>Introduction: electronic LC</u>
- Nodal nematic quantum criticality
- Quasiparticle interference
- Outlook

Liquid Crystal

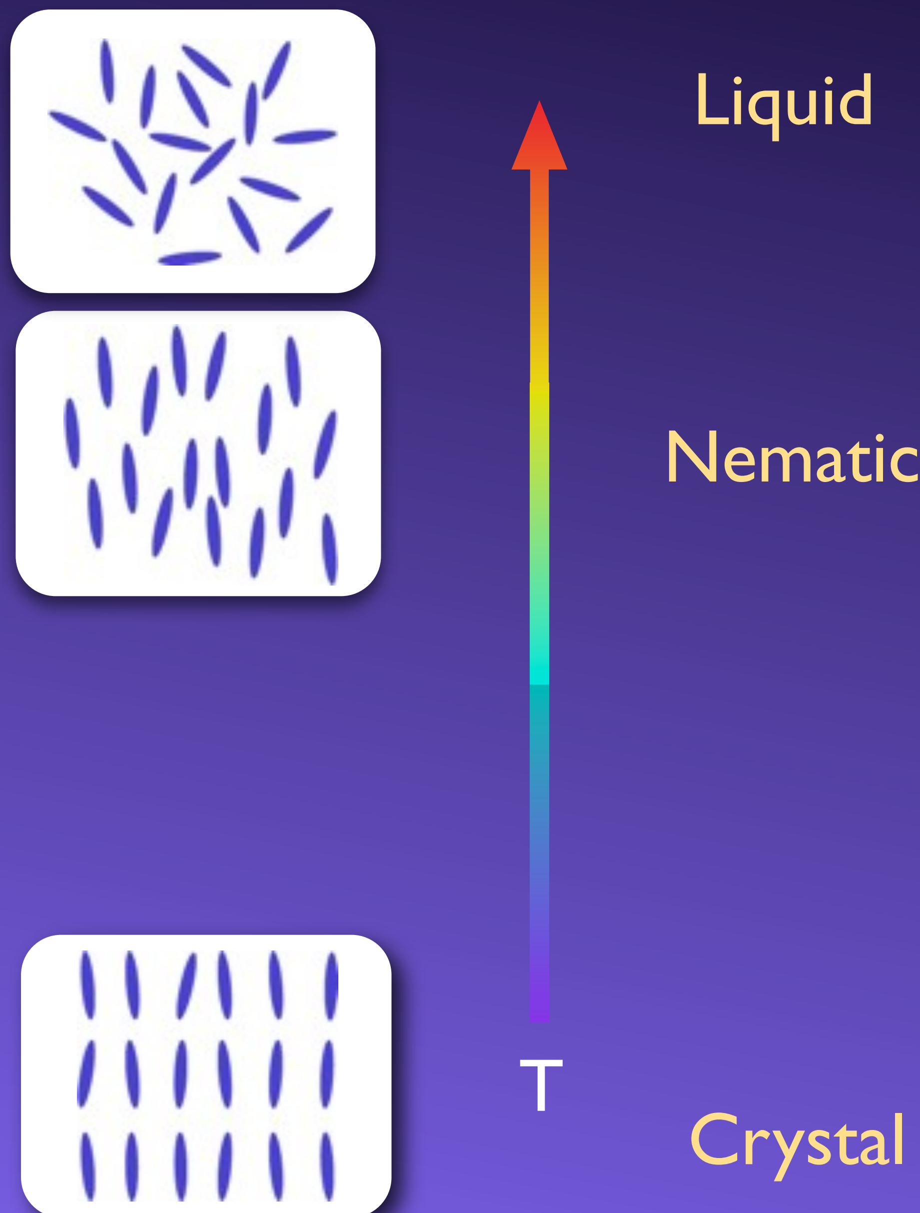
Liquid Crystal



Liquid

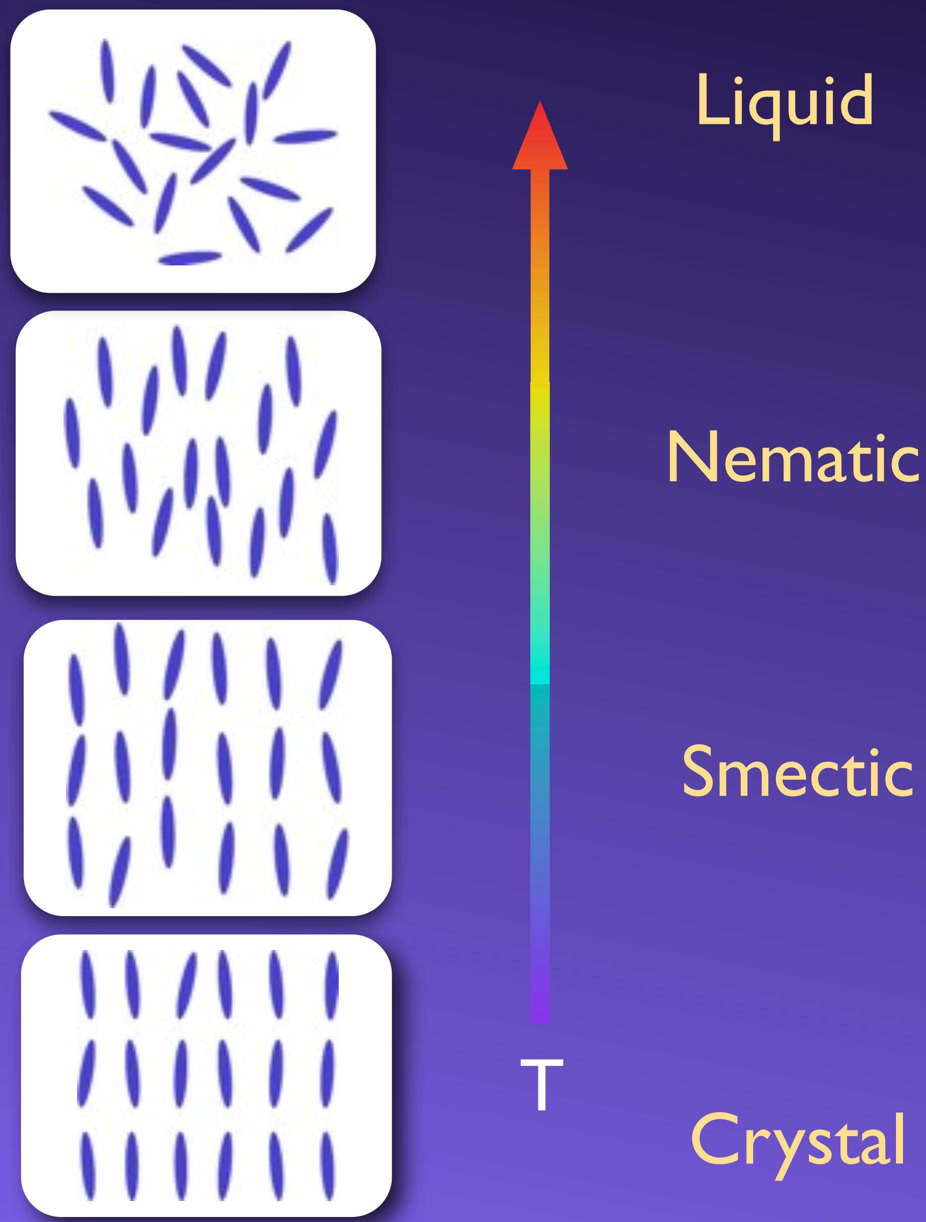
Crystal

Liquid Crystal



Reinitzer(1888)

Liquid Crystal



Reinitzer(1888)

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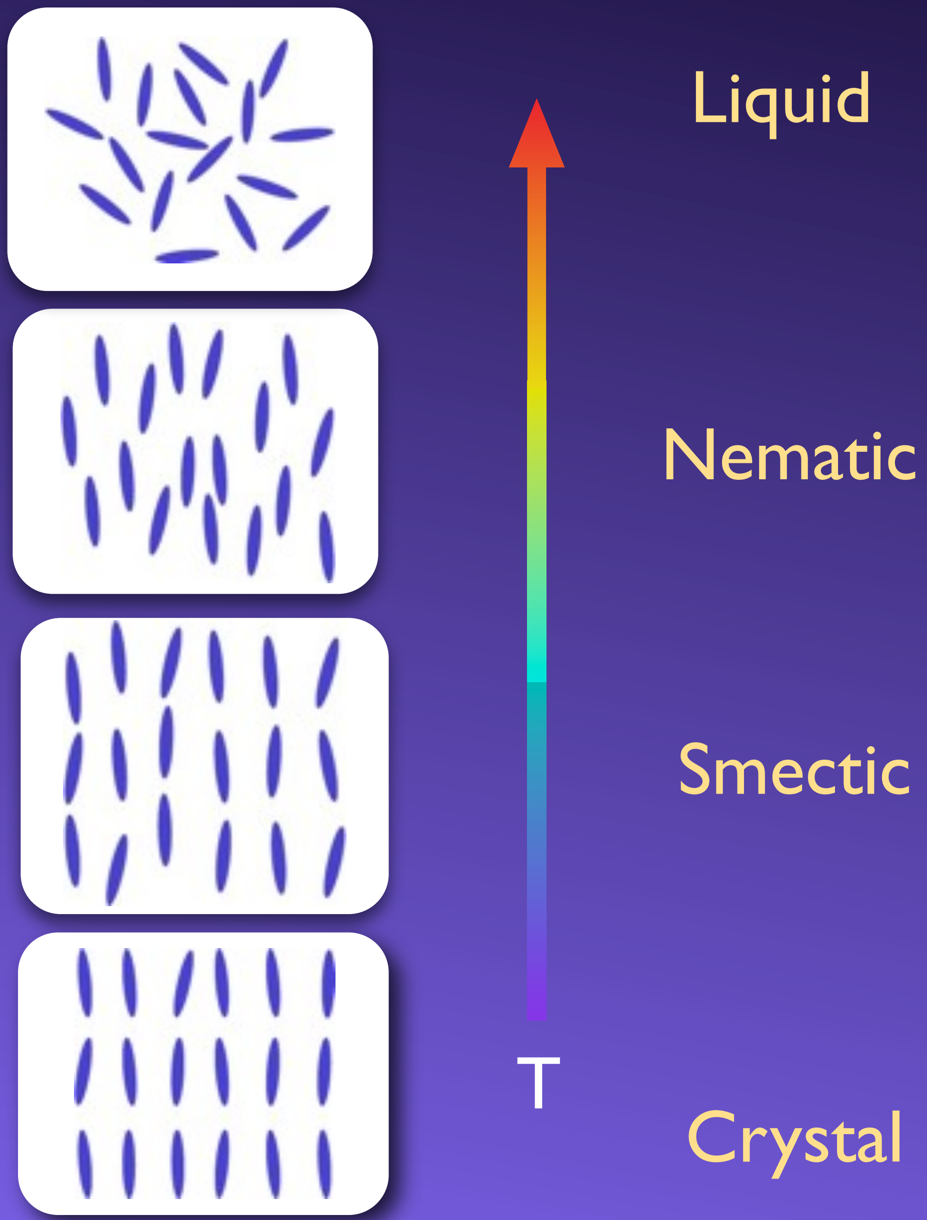

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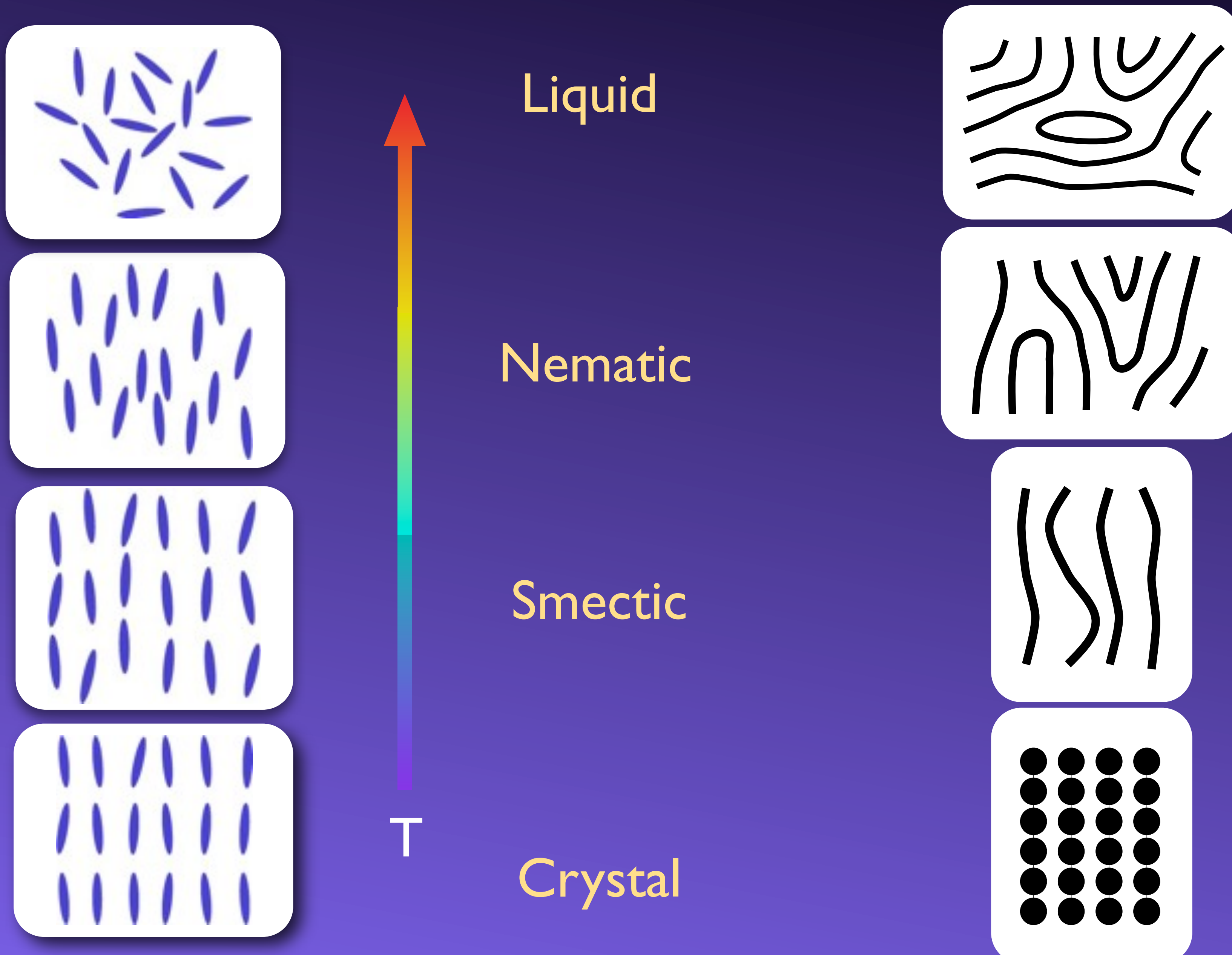

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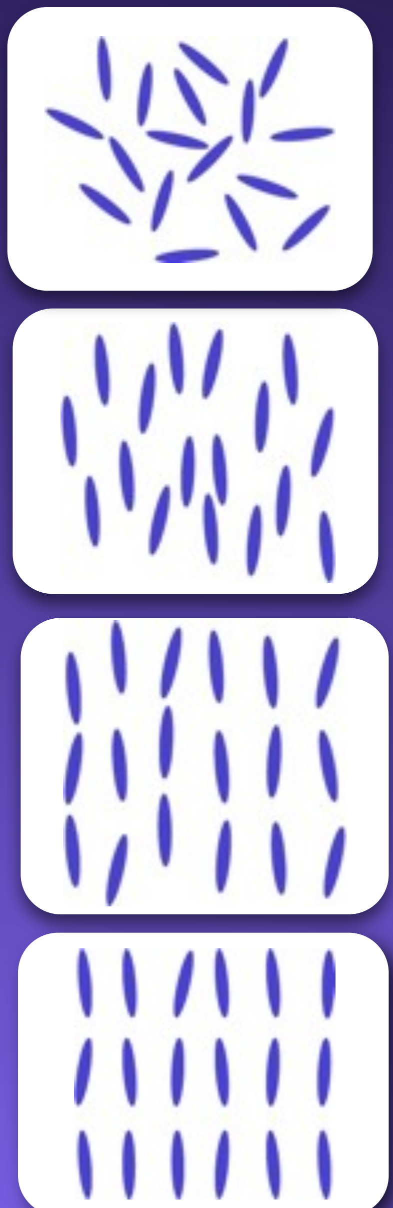
Kivelson, Fradkin, Emery, Nature (1998)

Electronic Liquid Crystal

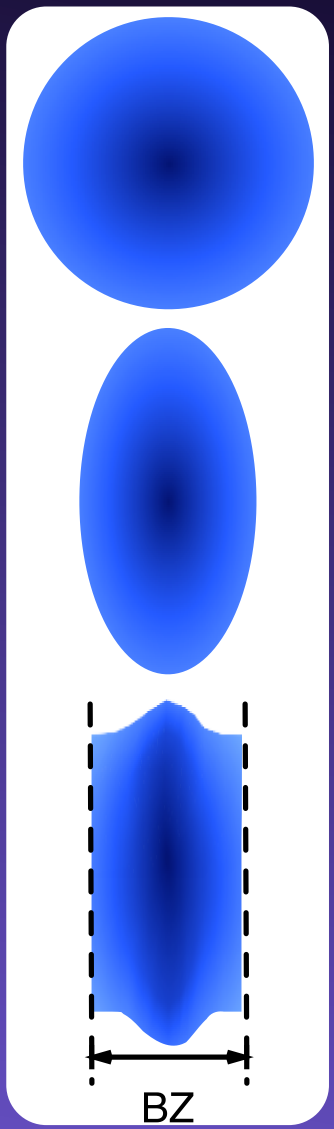


Liquid

Nematic

Smectic

Crystal



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Electronic Liquid Crystal

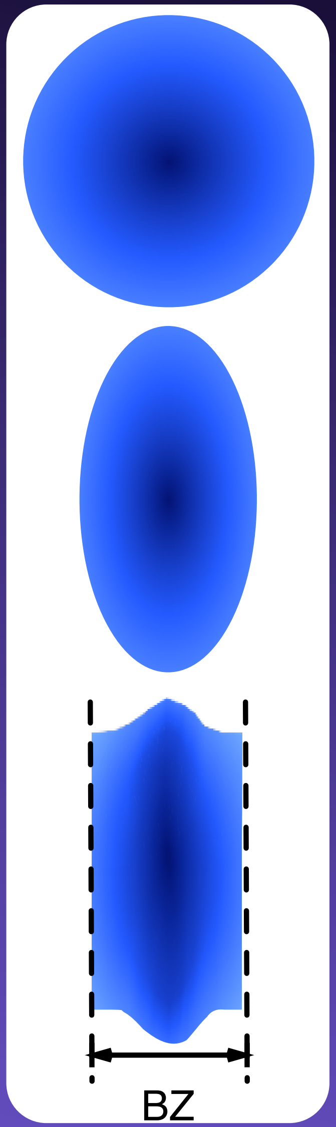
Liquid

Nematic

Smectic

T

Crystal



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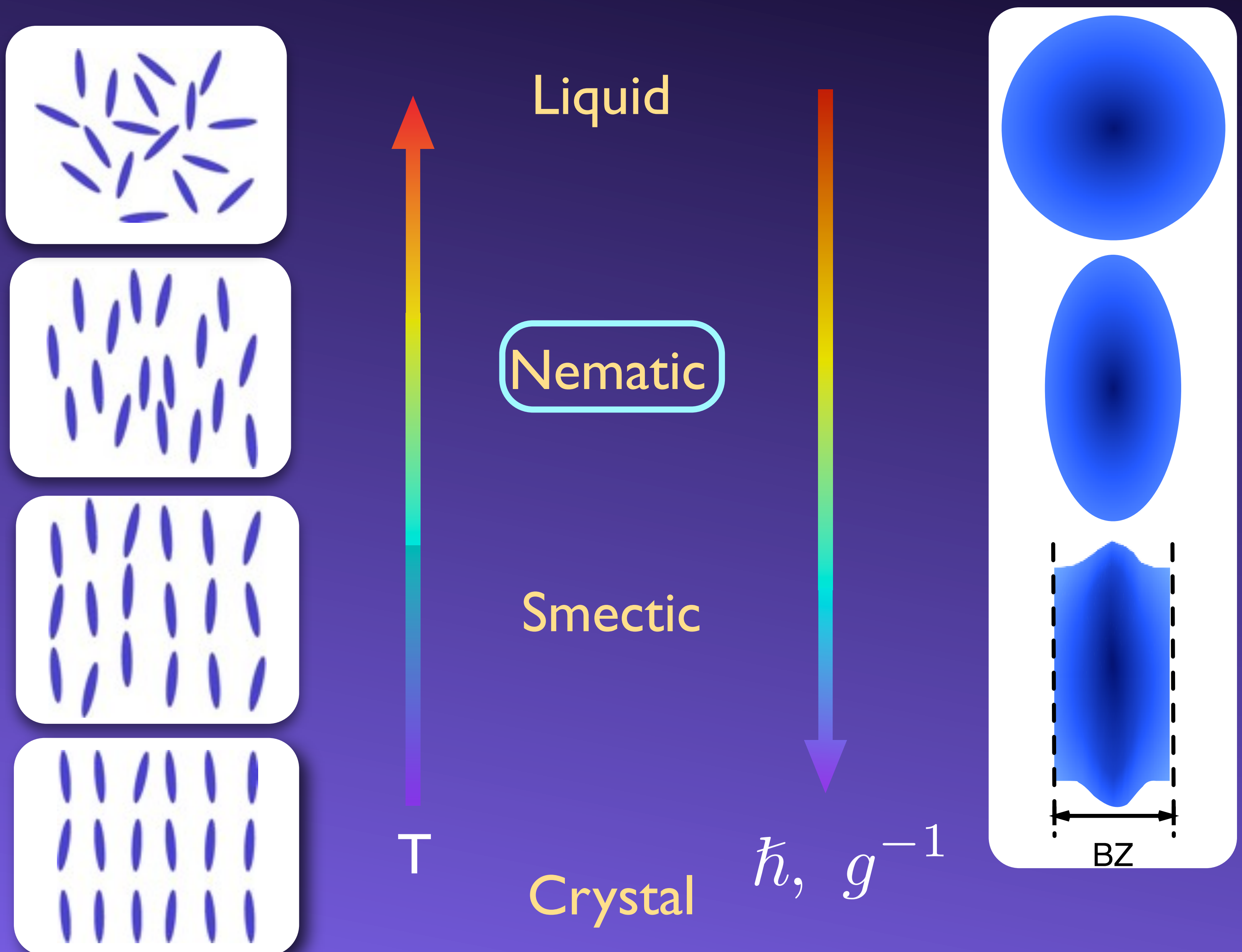

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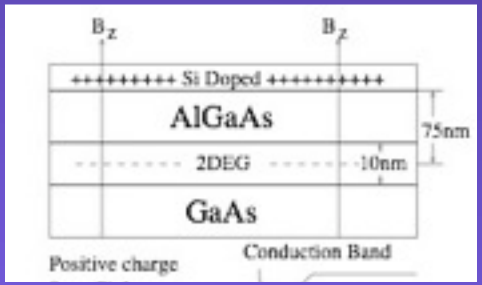
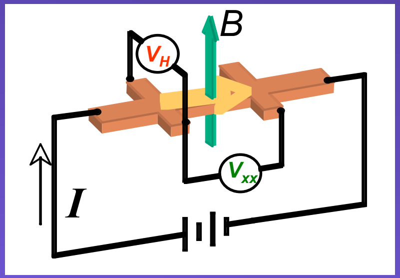
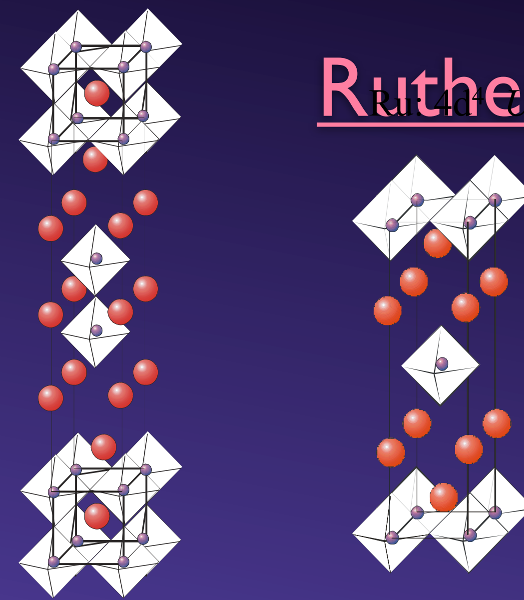
Electronic Liquid Crystal

Electronic Liquid Crystal

2DEG under $\vec{B}$







Ruthenates

Electronic Liquid Crystal

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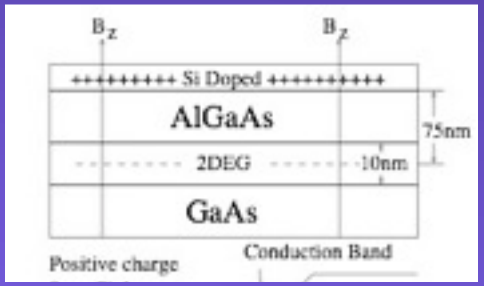
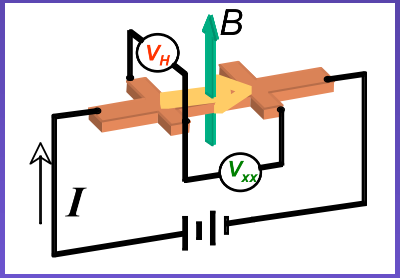
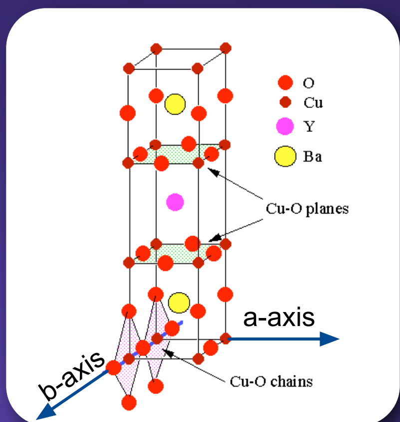
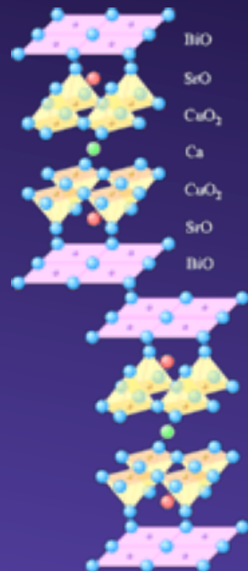




Cuprates





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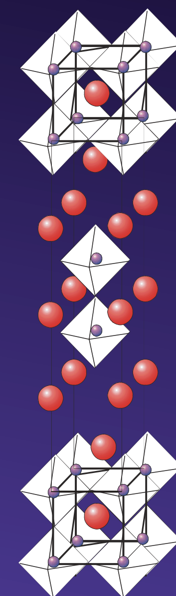
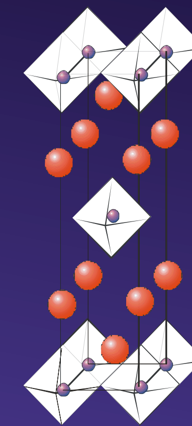
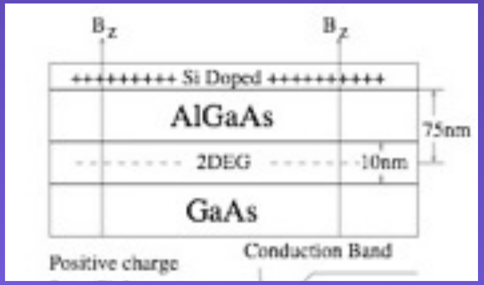
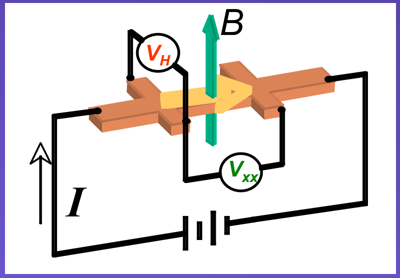




Electronic Liquid Crystal

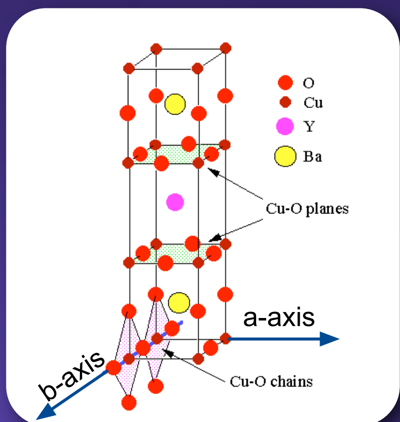
2DEG under $\vec{B}$

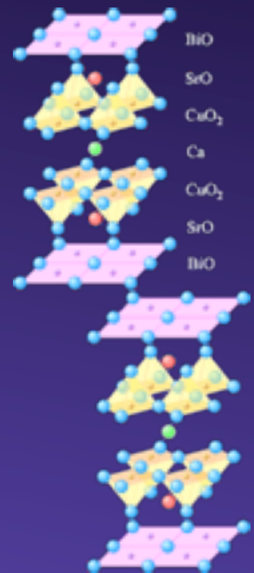




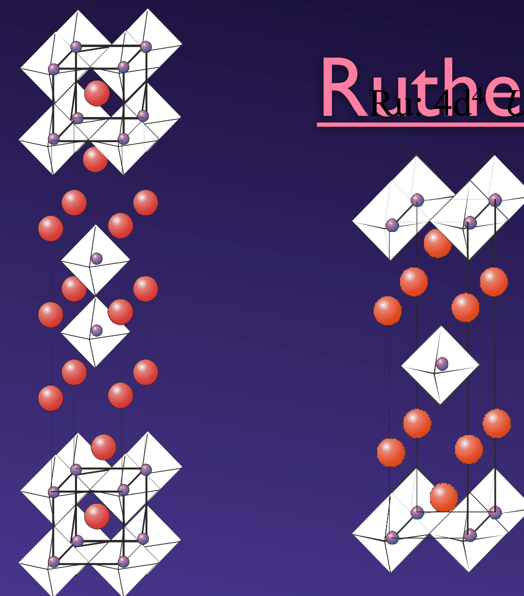
Strongly correlated systems

Cuprates



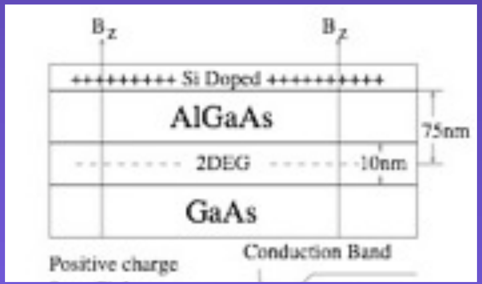


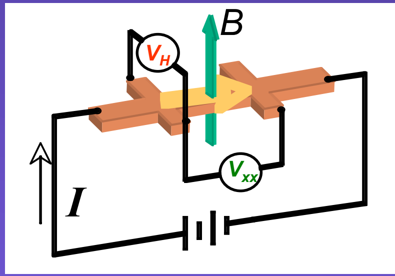
Ruthenates



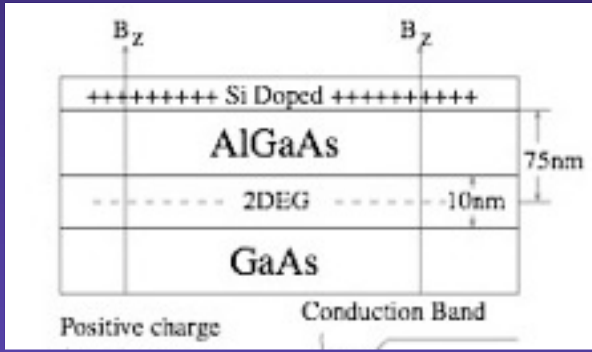
Electronic Liquid Crystal

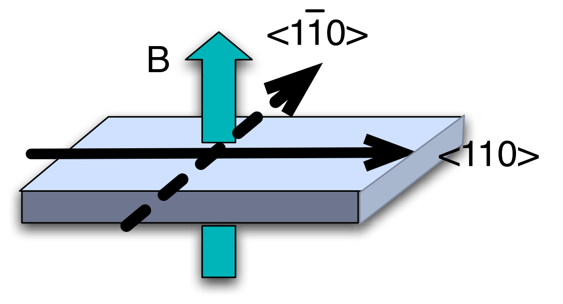
2DEG under $\vec{B}$

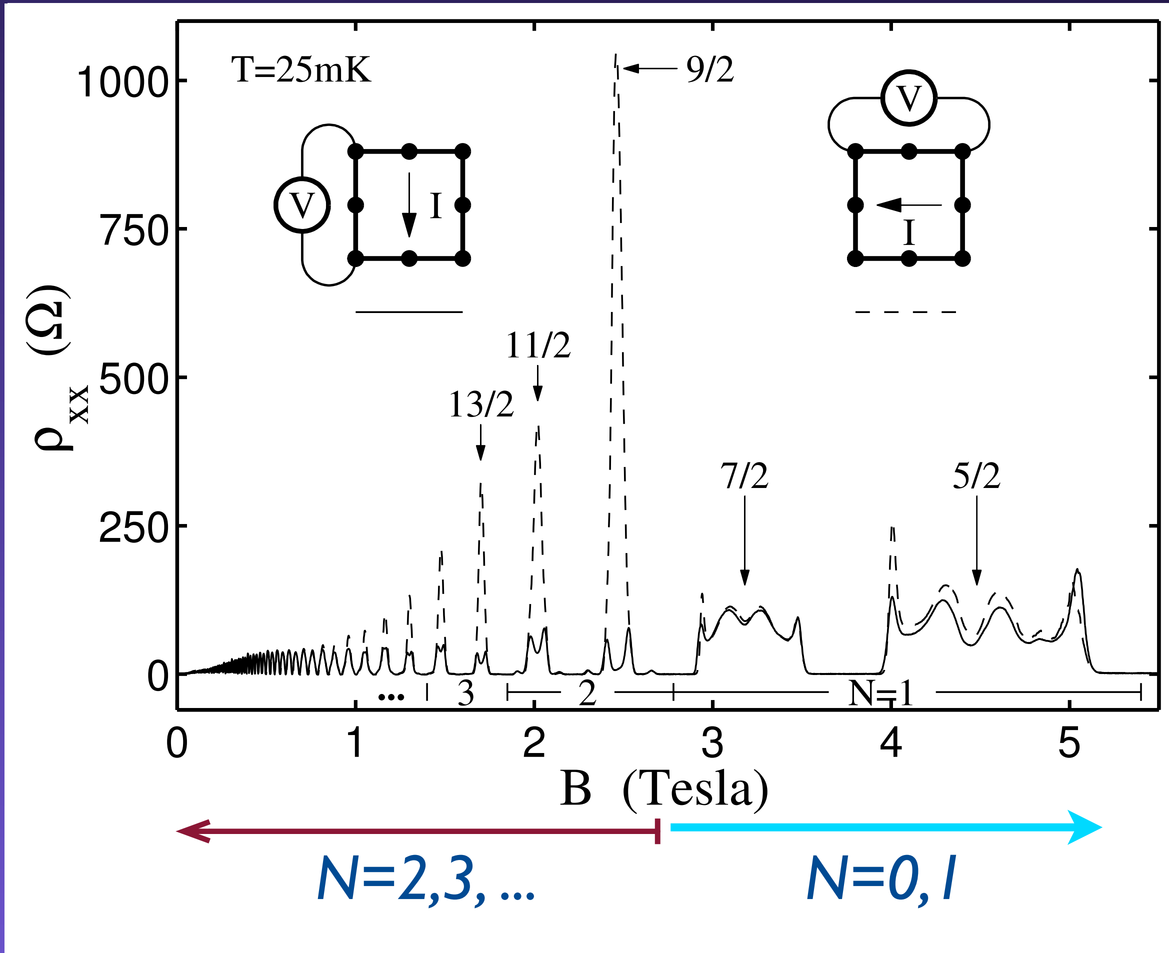




Anisotropic phase in high Landau Levels:
Quantum Hall nematic

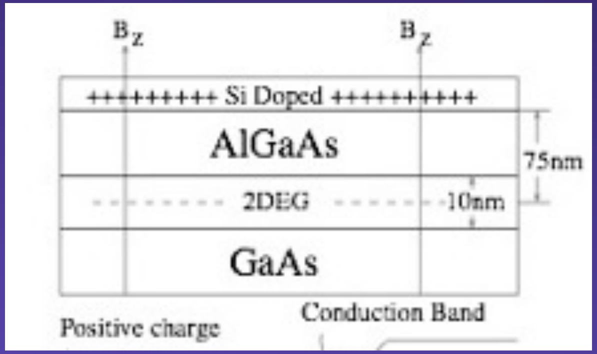


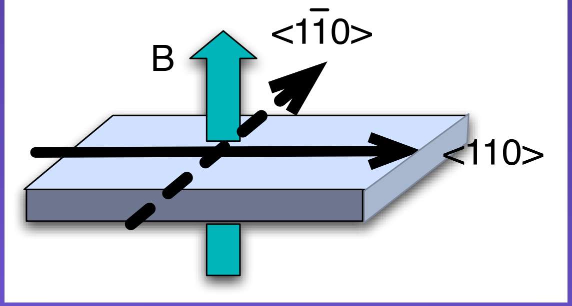


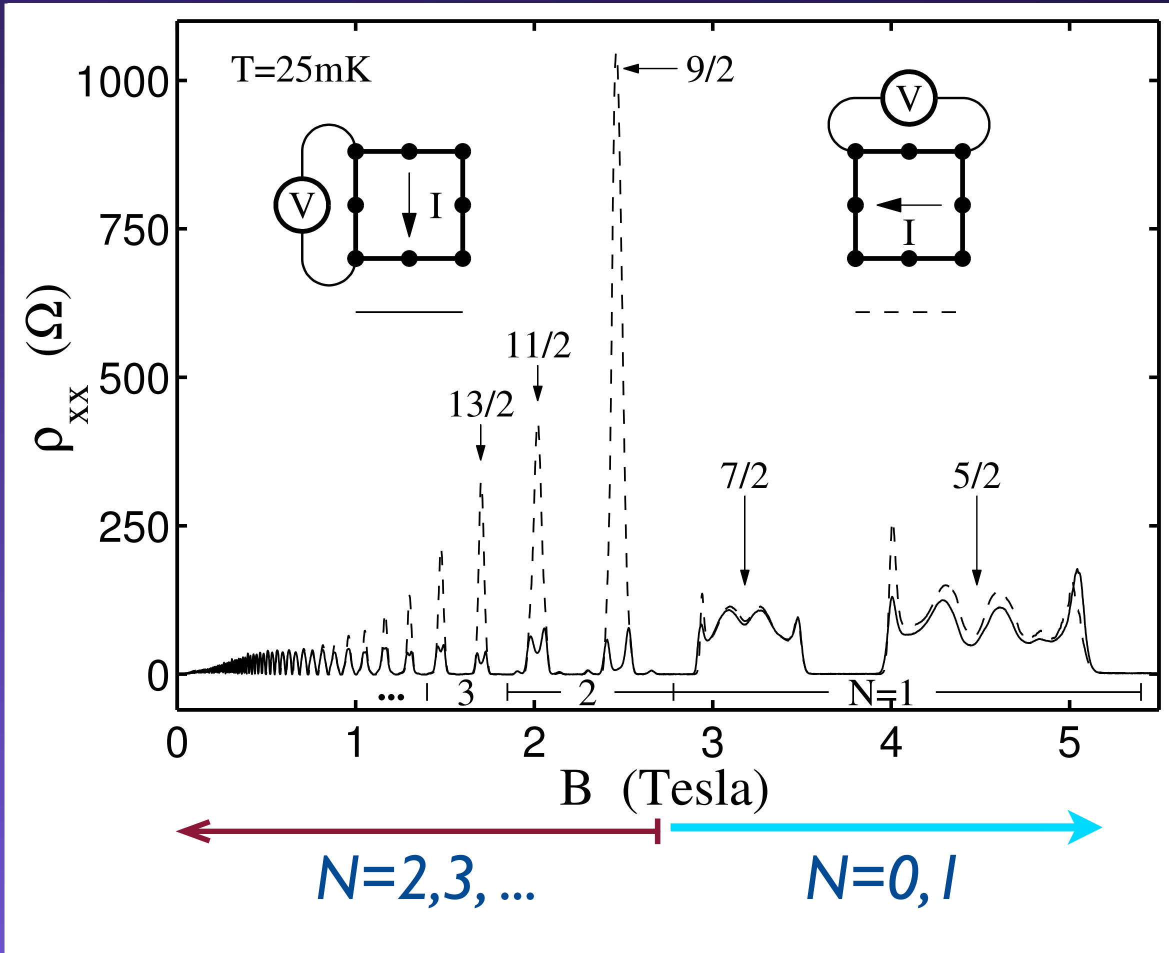


Lilly et al, PRL 83, 824, (1999).

Anisotropic phase in high Landau Levels: Quantum Hall nematic



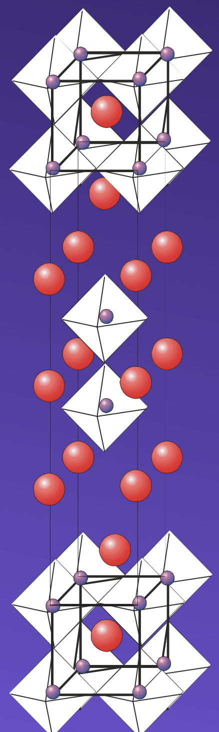


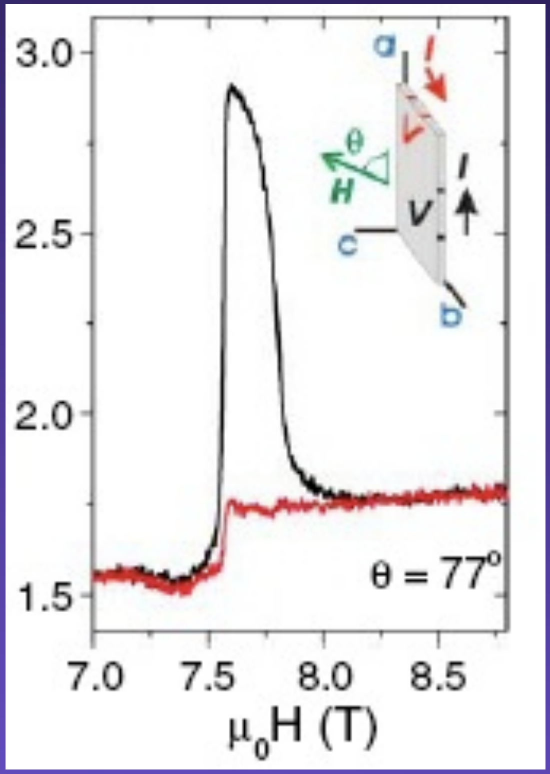


T_N=100mK

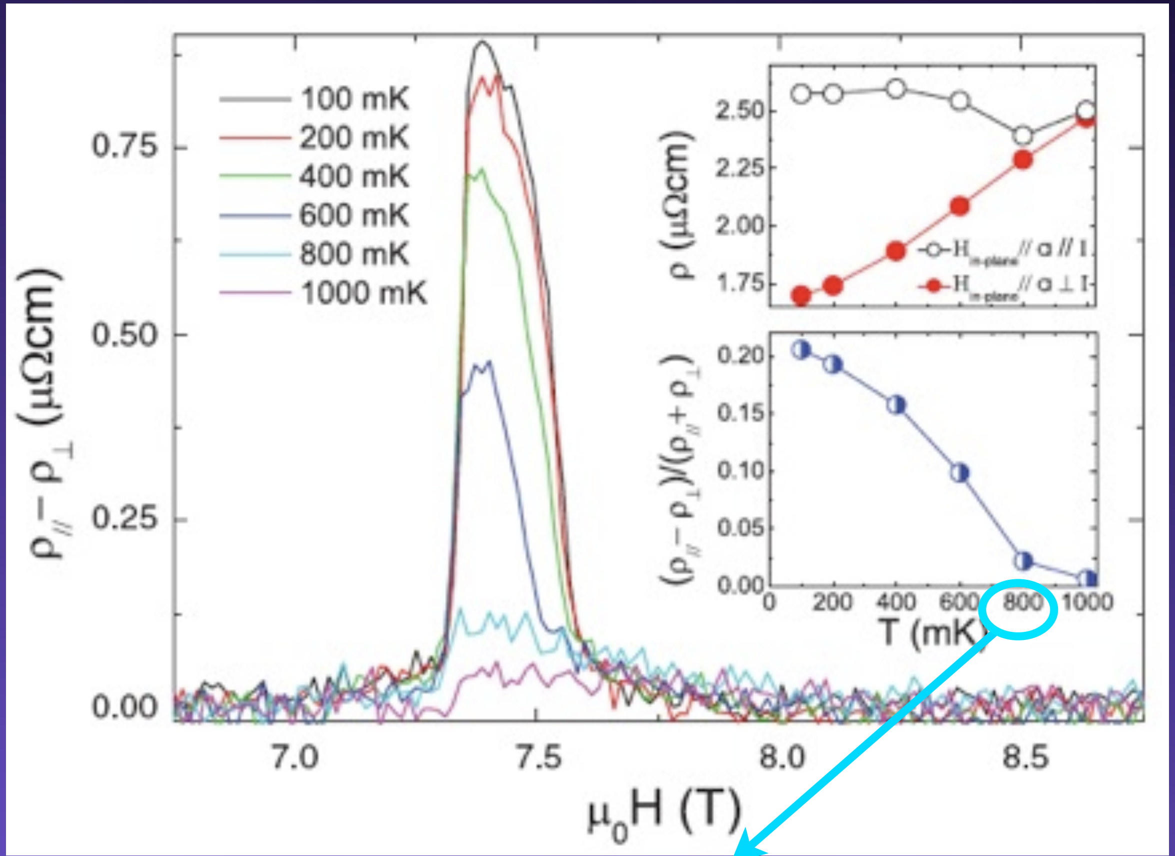
Lilly et al, PRL 83, 824, (1999).

Anisotropic phase in an itinerant metamagnet $Sr_3Ru_2O_7$





$\rho\ (\mu\Omega cm)$

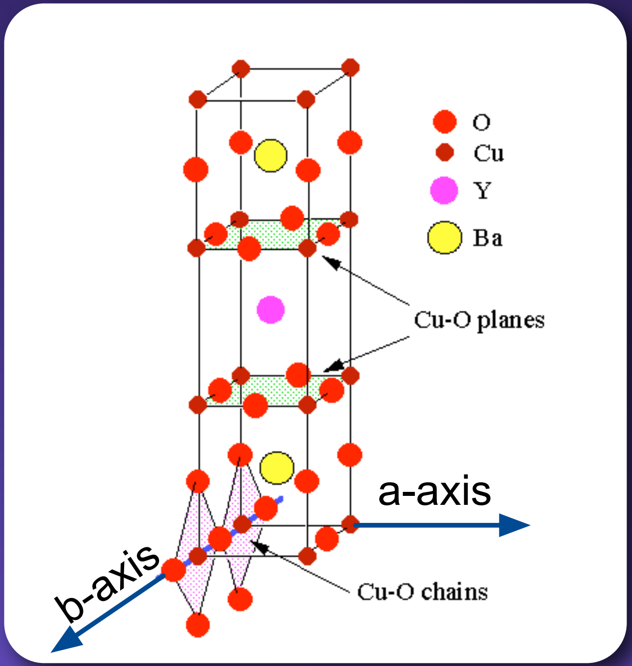


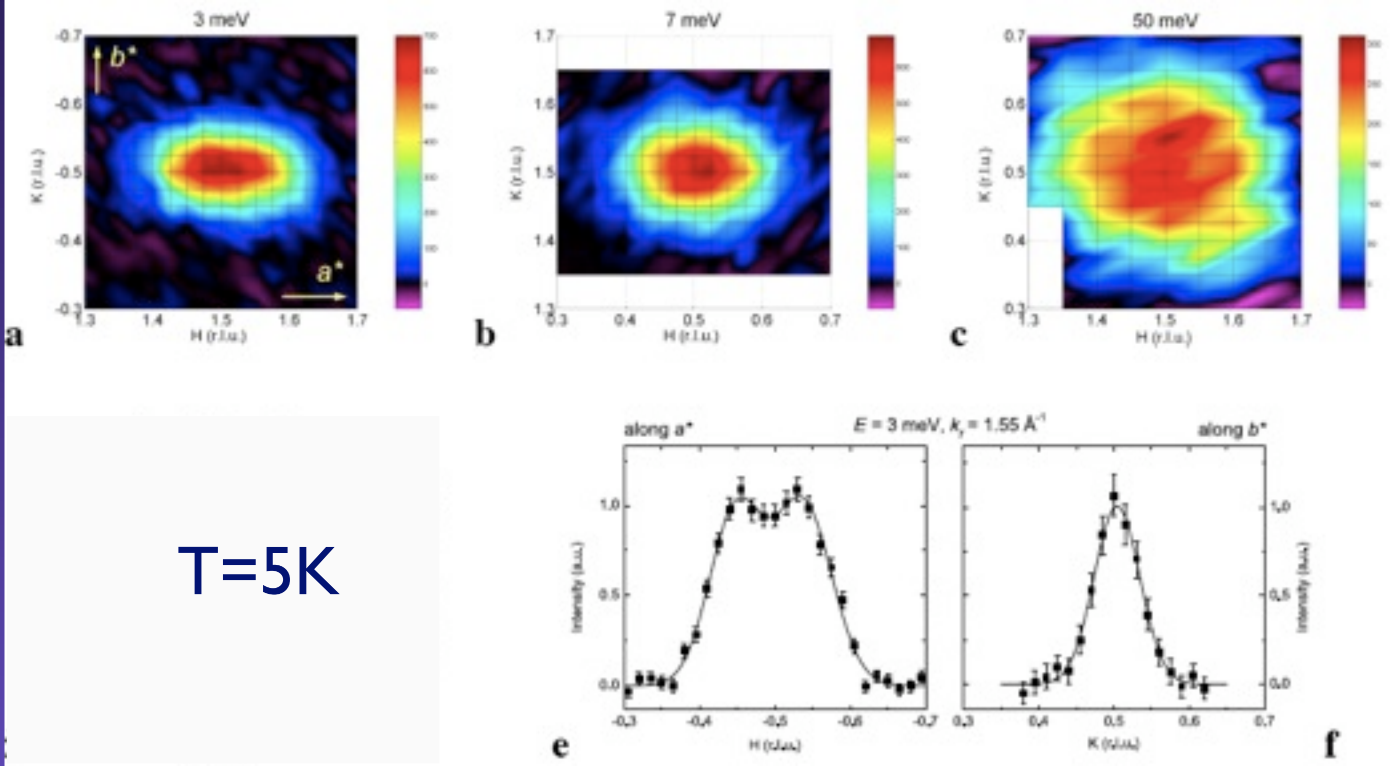
T_N=800mK

Magnetoresistive anisotropy exposed by modest in-plane field

Borzi et al, science 2007.

Anisotropic phase in superconducting (T_c=35K) underdoped $YBa_2Cu_3O_{6.45}$





Anisotropy in magnetic (π/a,π/b) neutron scattering peak

Hinkov et al, Science, Jan 2008

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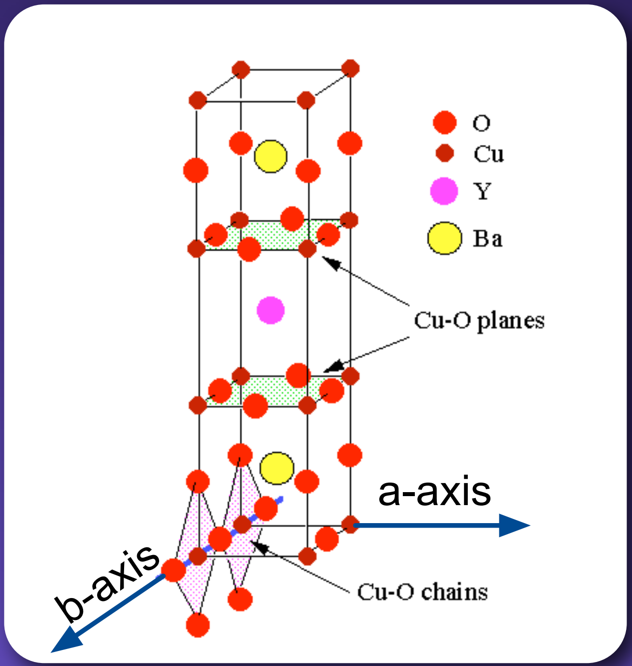

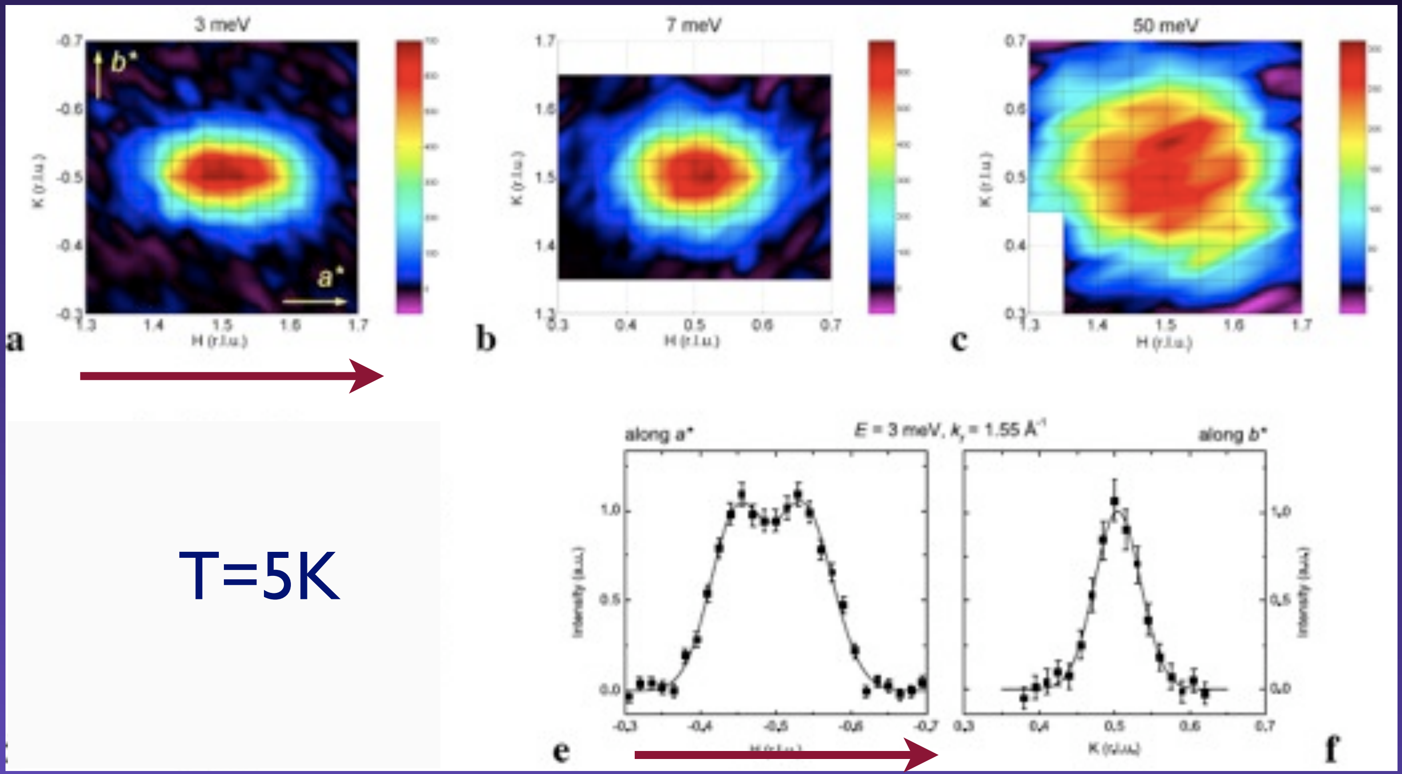

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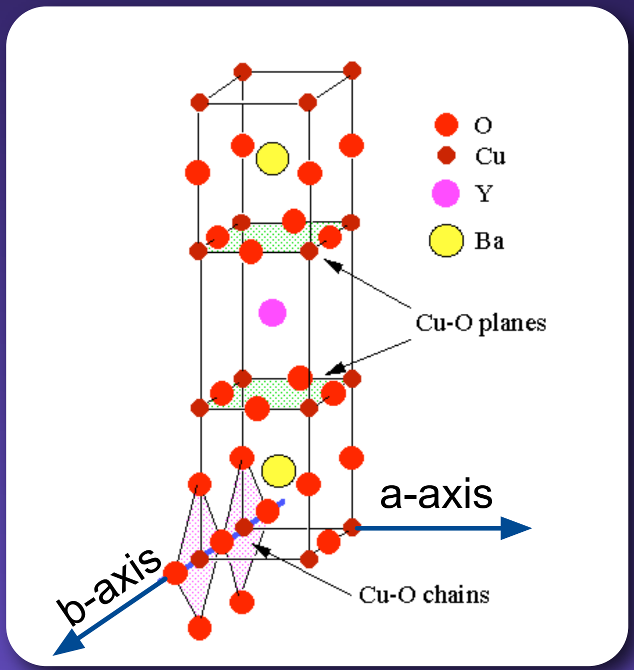

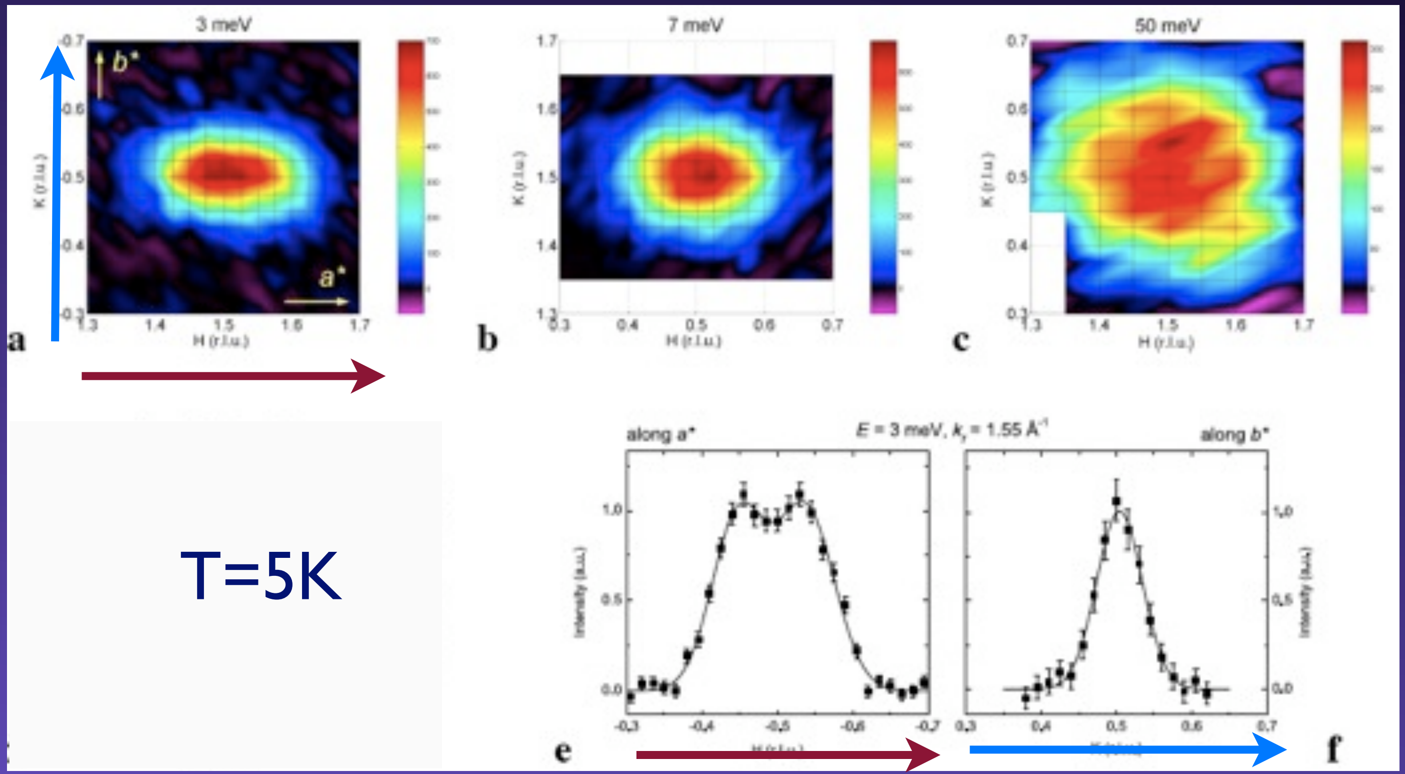

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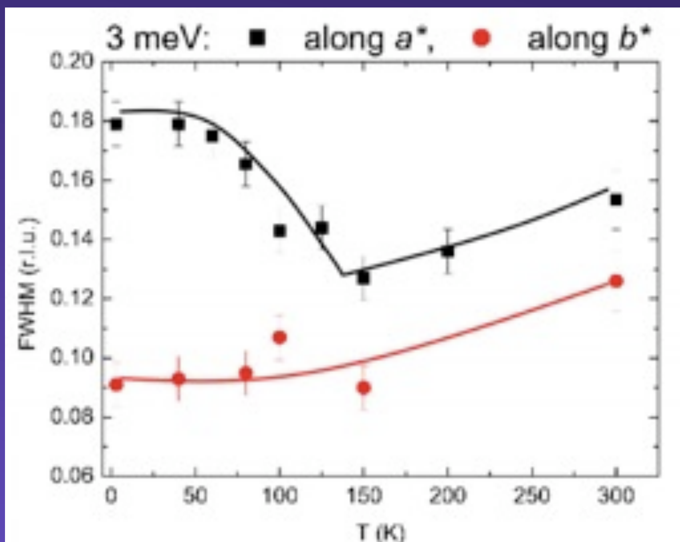
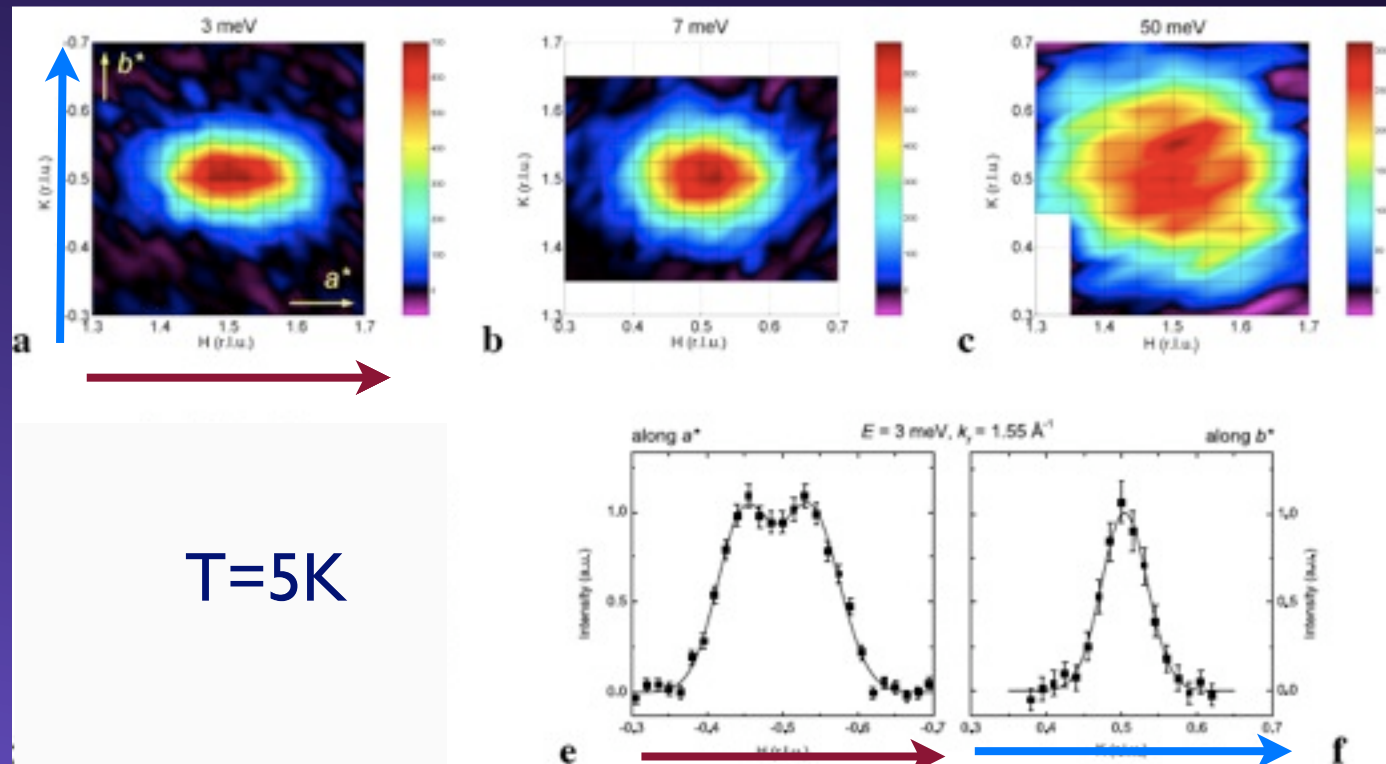




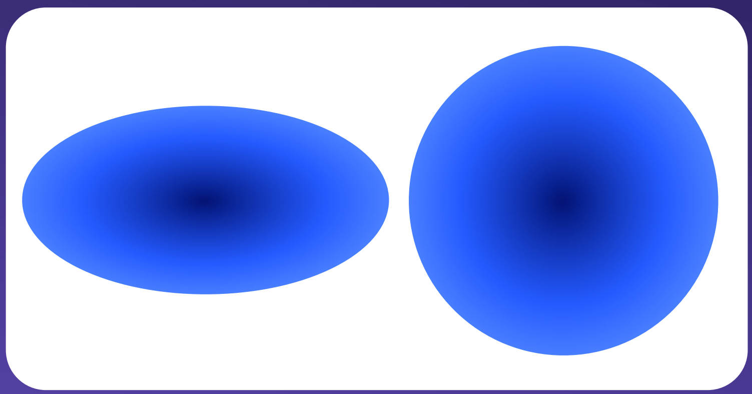
T=5K

T_N~150K

Anisotropy in magnetic ($\pi/a,\pi/b$) neutron scattering peak

Hinkov et al, Science, Jan 2008

Nematic QPT as FS instability



Pomeranchuk's instability

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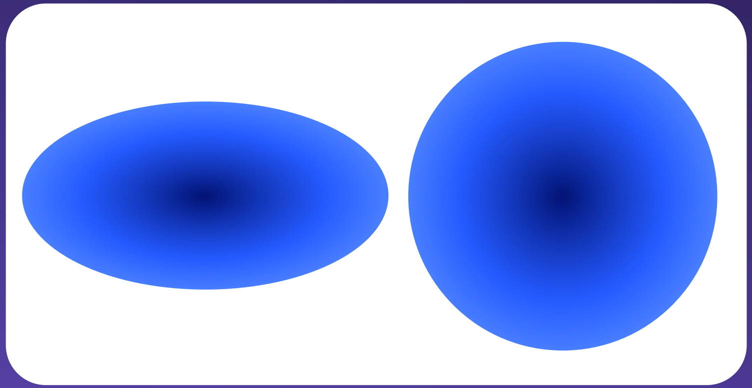

Pomeranchuk's instability

H. Yamase and W. Metzner, PRB (2006).
L. Dell'Anna and W. Metzner, PRL (2007)

V. Oganesyan et al. PRB (2001)
M. Lawler et al. PRB (2006)

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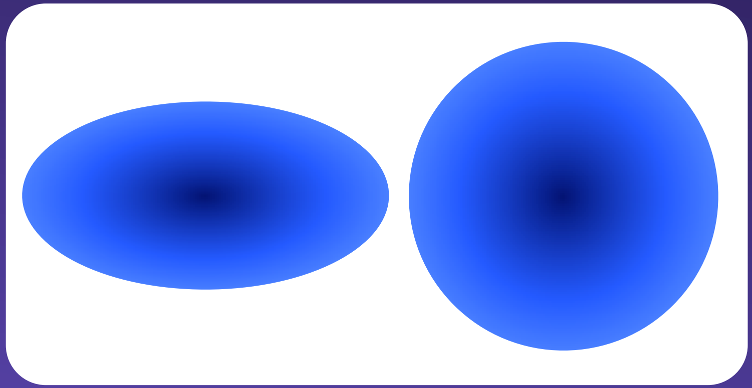

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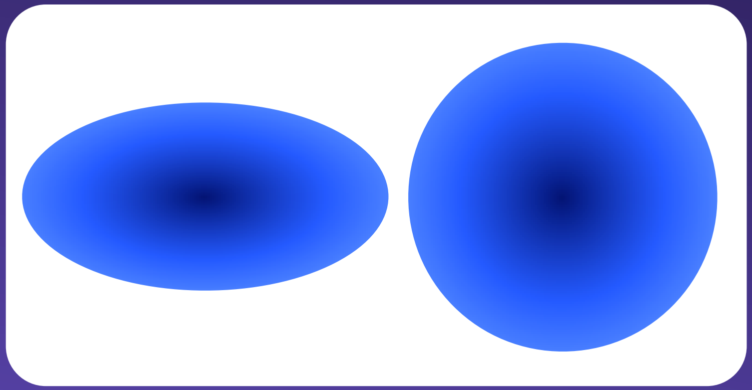

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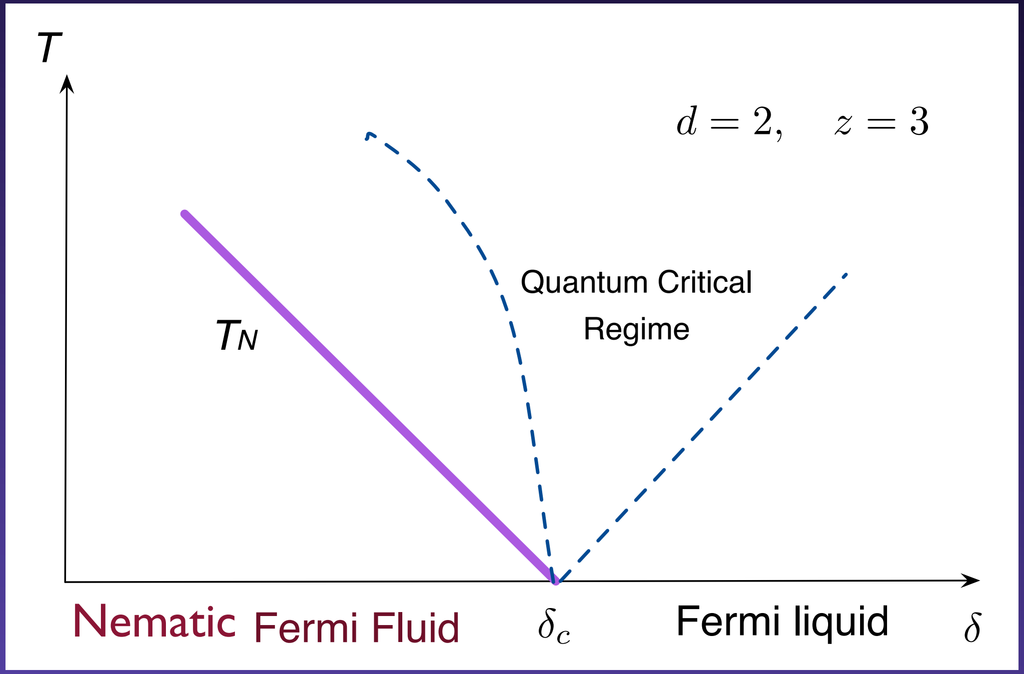

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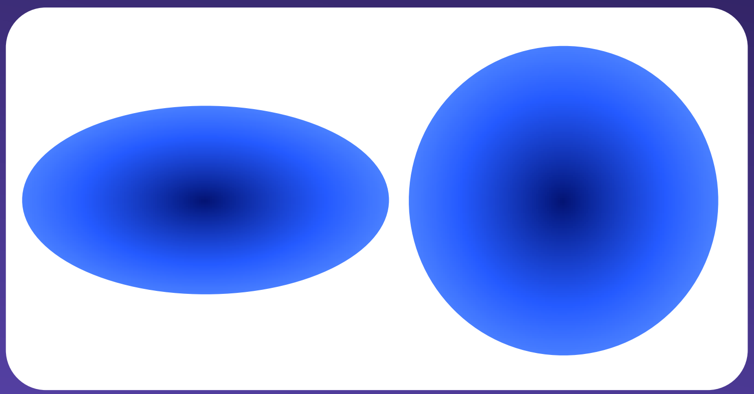
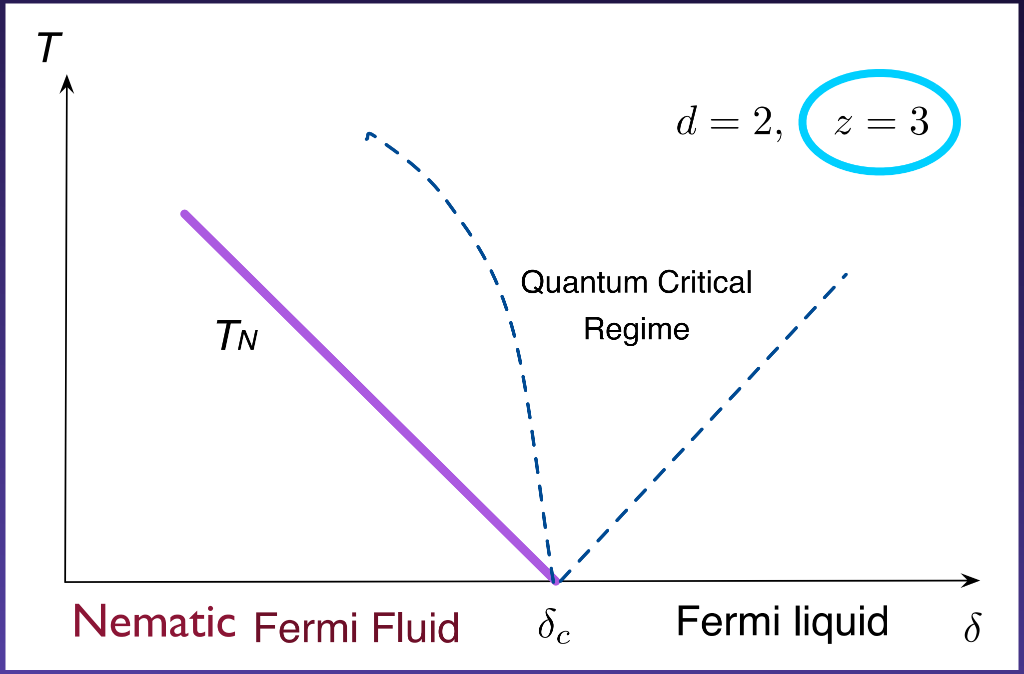


Pomeranchuk's instability



V. Oganesyan et al. PRB (2001)
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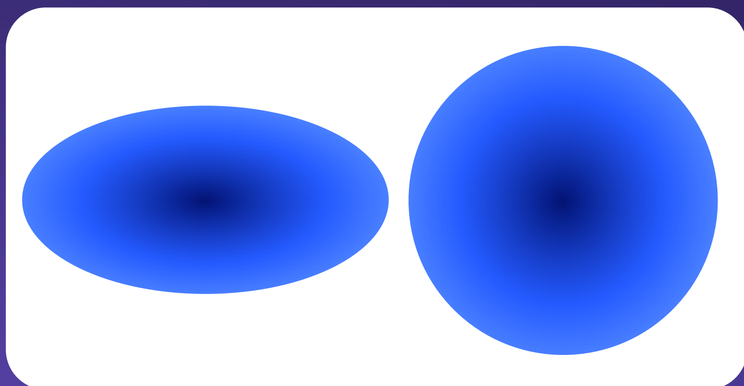

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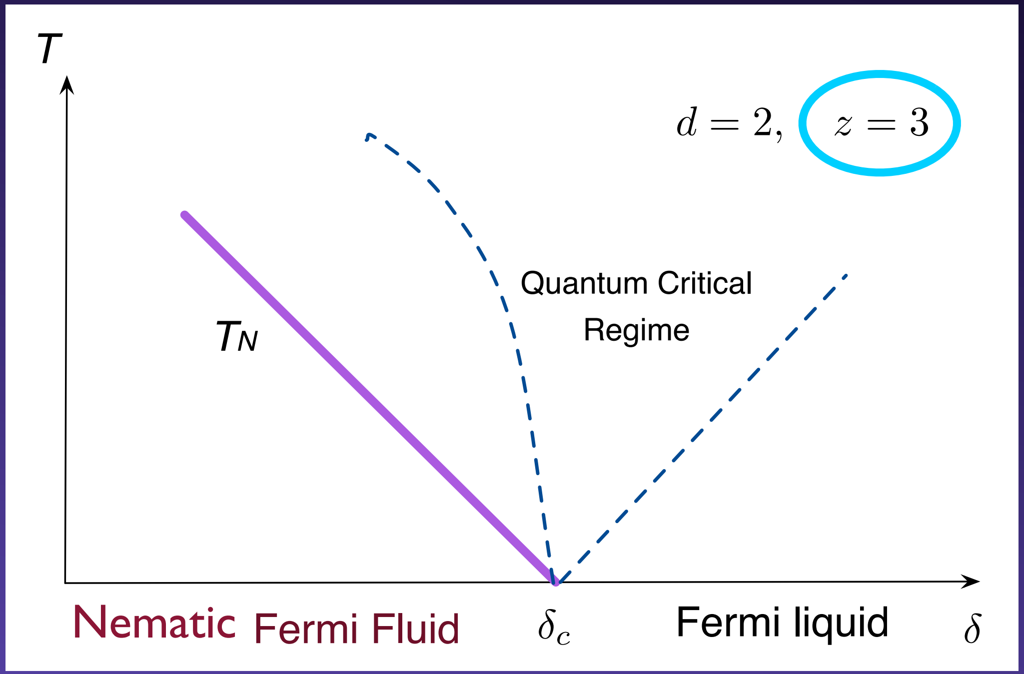
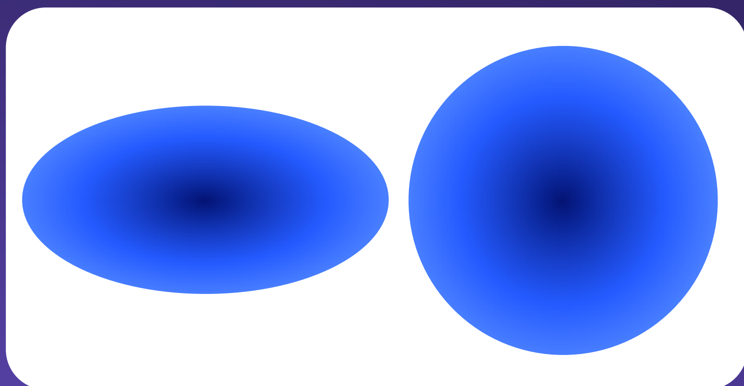


Fermi liquid breaks down

V. Oganesyan et al. PRB (2001)
M. Lawler et al. PRB (2006)

Nematic QPT as FS instability



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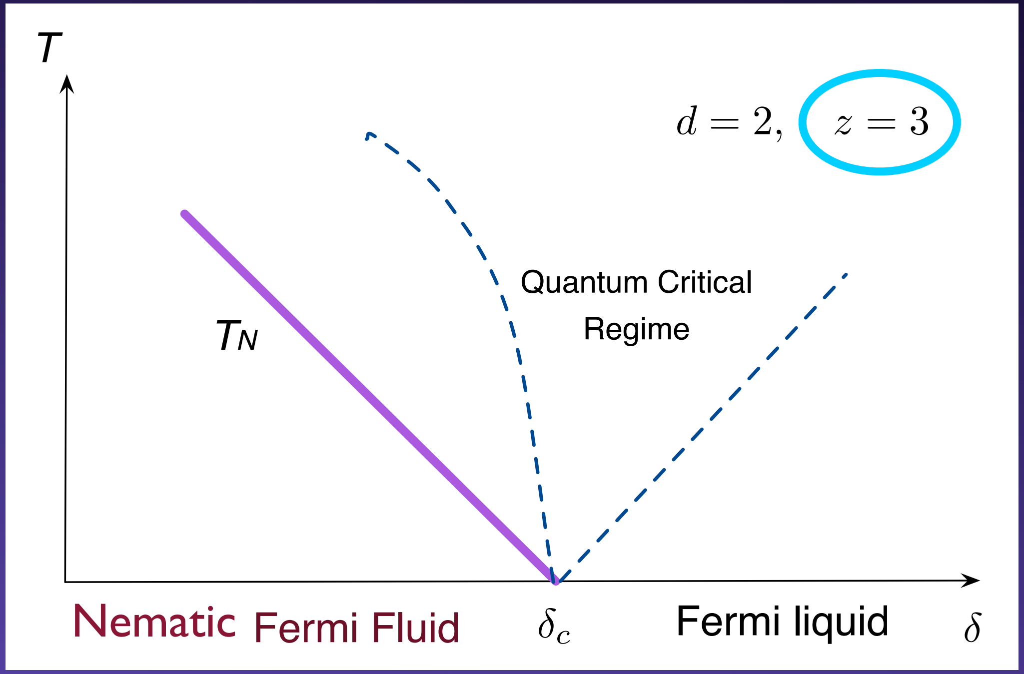


- Fermi liquid breaks down
  ➡some controversy over what is left

V. Oganesyan et al. PRB (2001)
M. Lawler et al. PRB (2006)

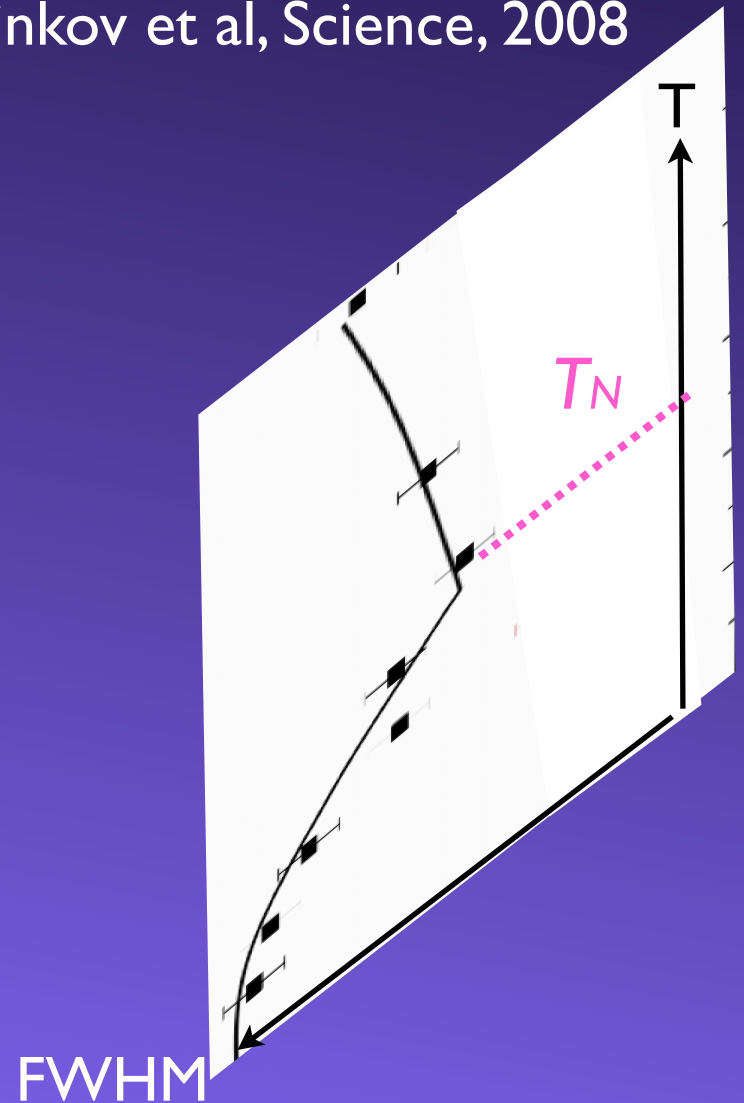
Cuprate: simplified life ?

The theory of nodal nematic quantum criticality

- Introduction: electronic nematic
- <u>Nodal nematic quantum criticality</u>
- Quasiparticle interference
- Outlook

Nematic QCP in the SC dome?

Hinkov et al, Science, 2008



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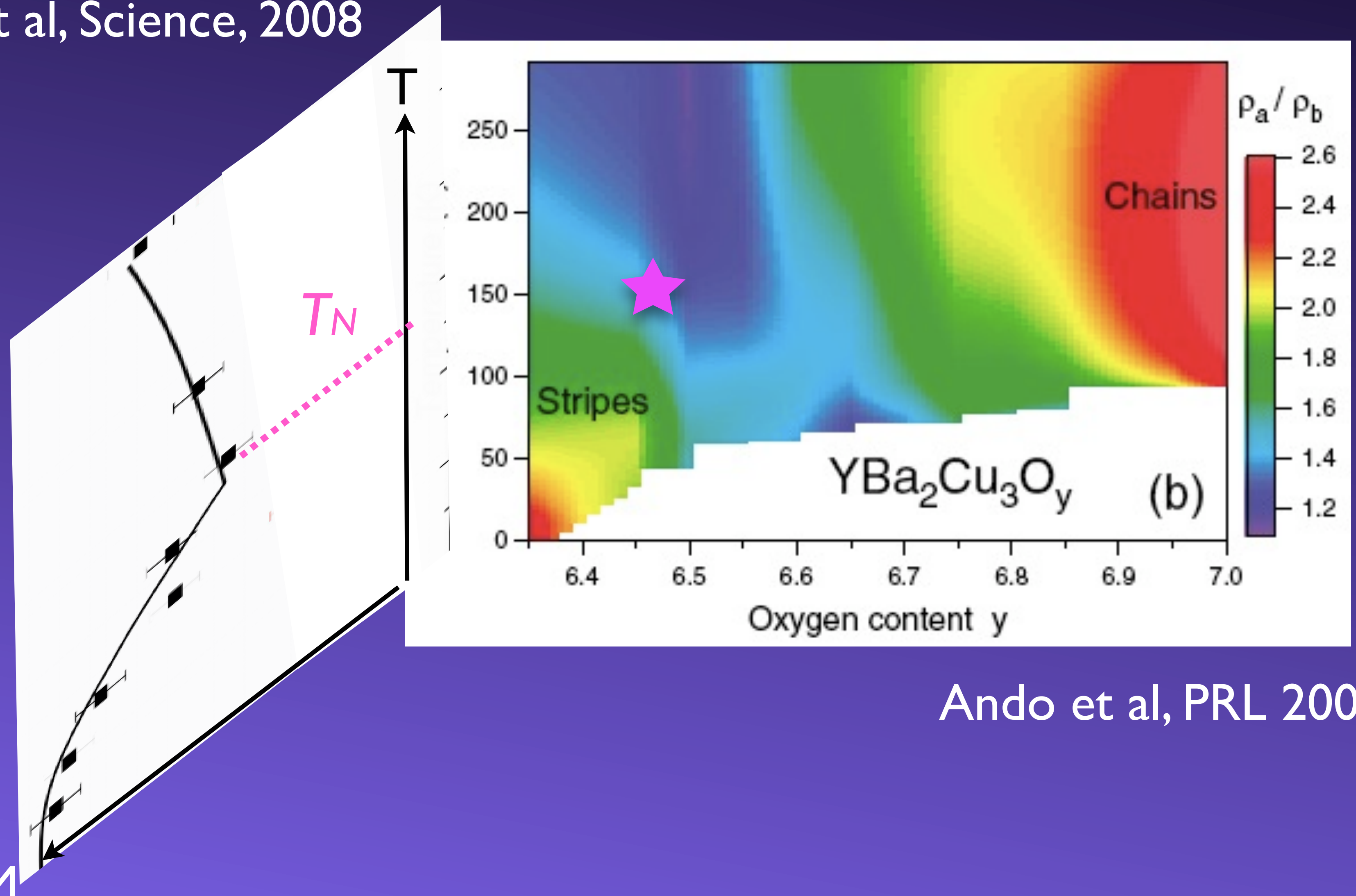
Hinkov et al, Science, 2008



Ando et al, PRL 2002

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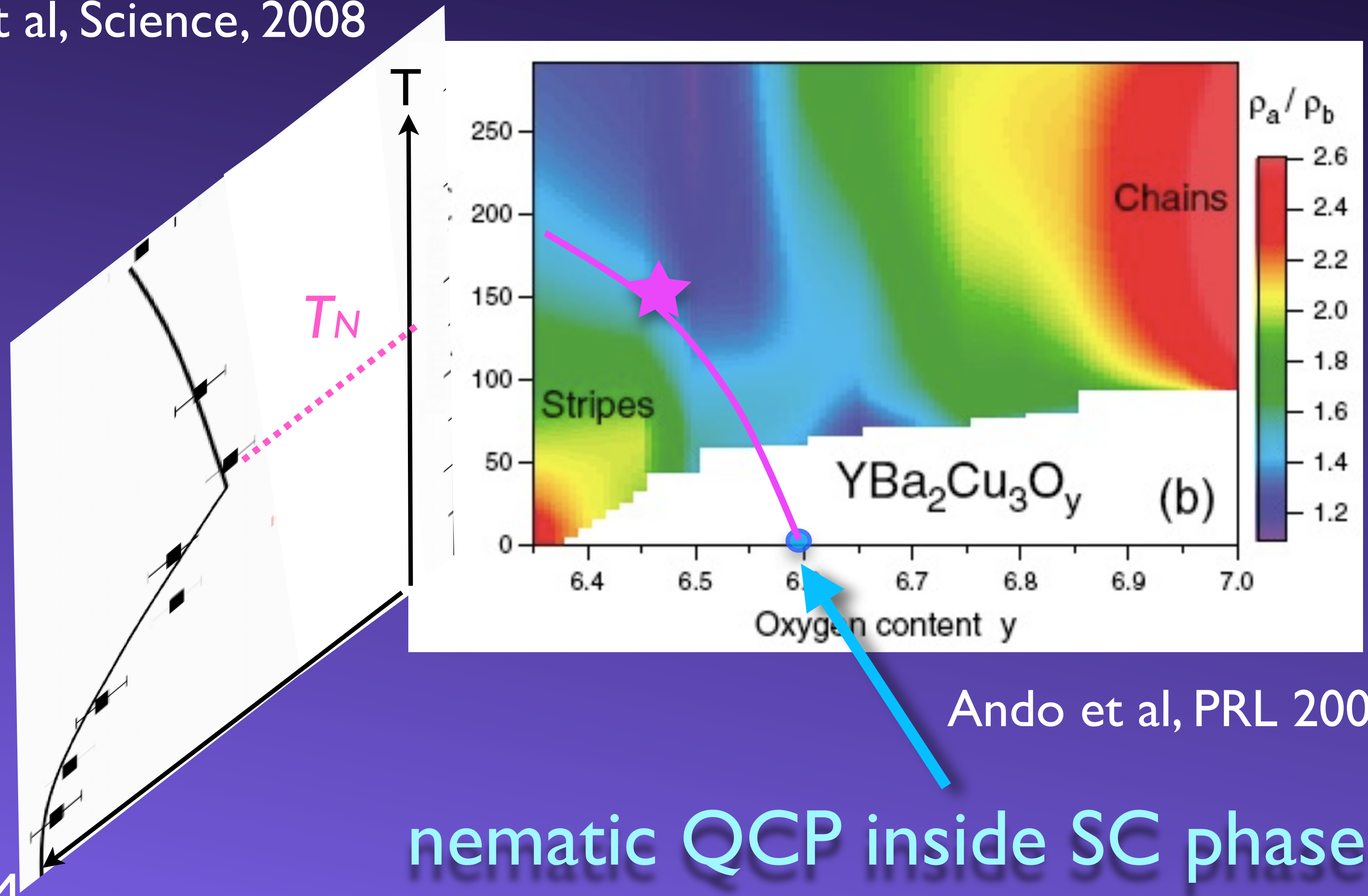
Hinkov et al, Science, 2008

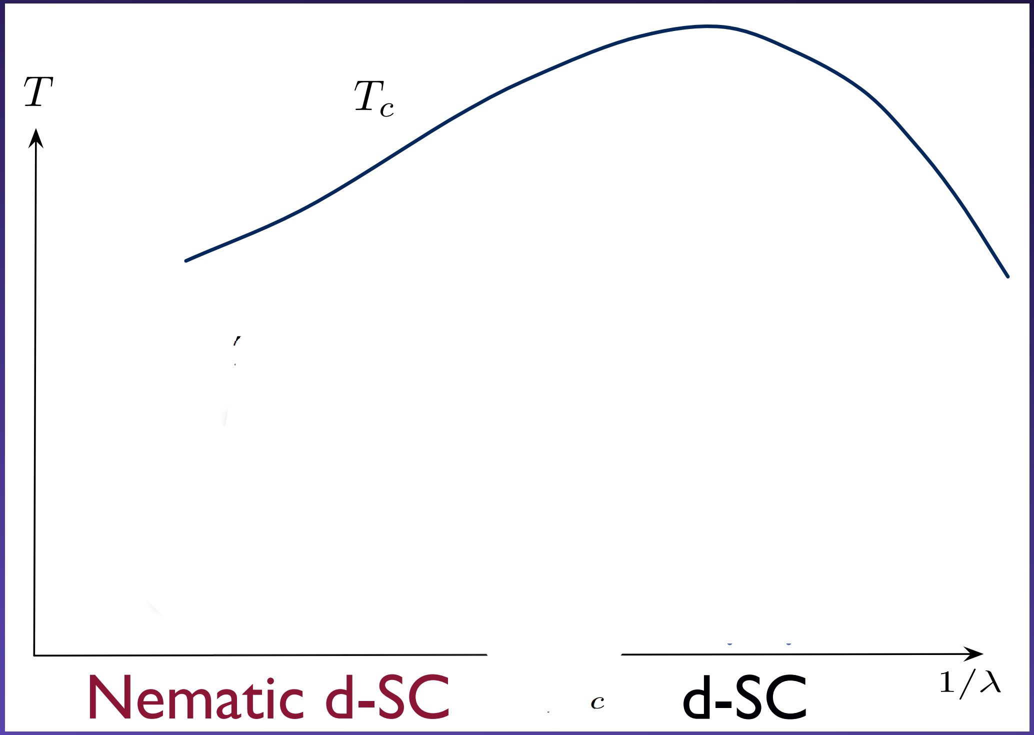


Ando et al, PRL 2002

nematic QCP inside SC phase?

Nodal nematic QCP?

- Nematic QPT deep inside d-wave SC



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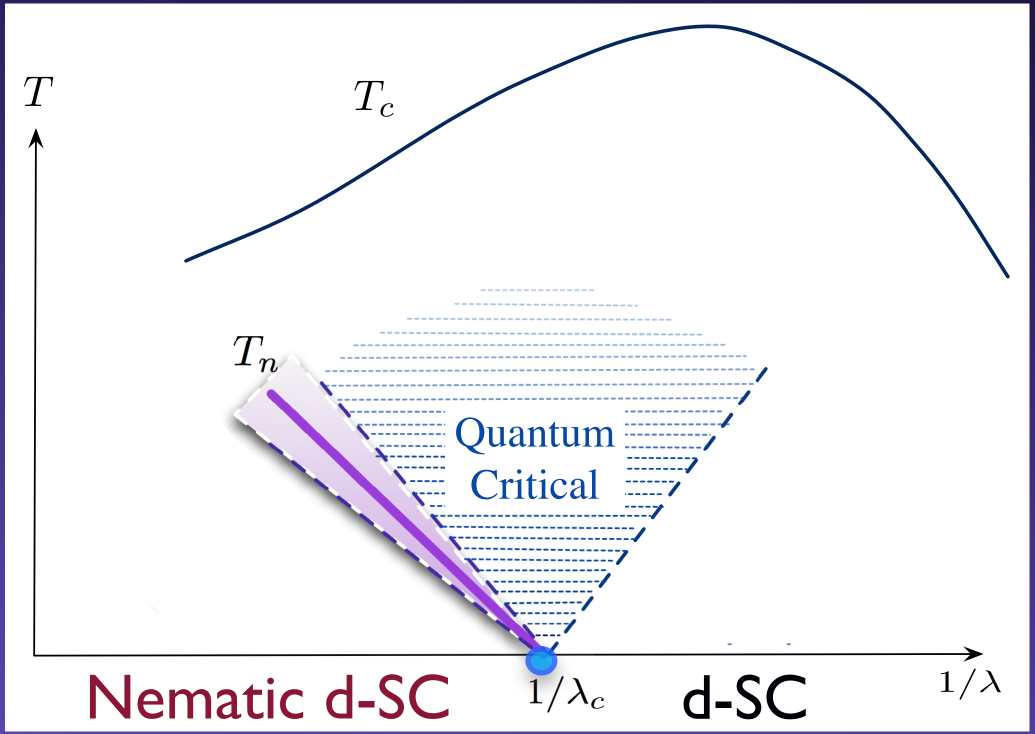
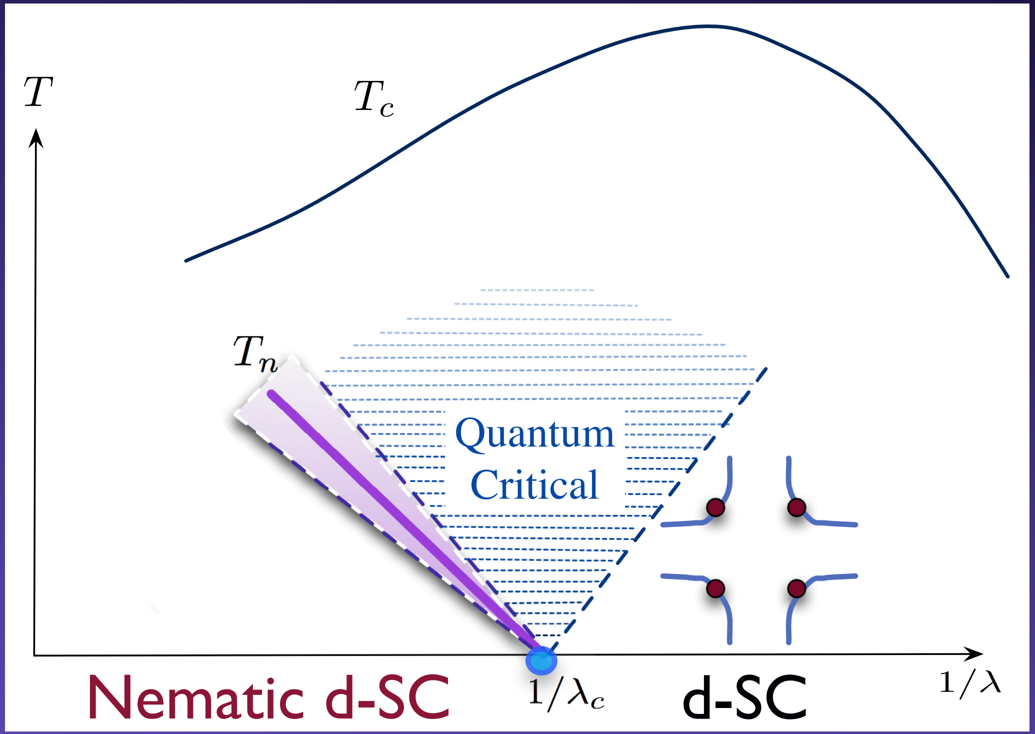


Nodal nematic QCP?

- Nematic QPT
  deep inside d-wave SC

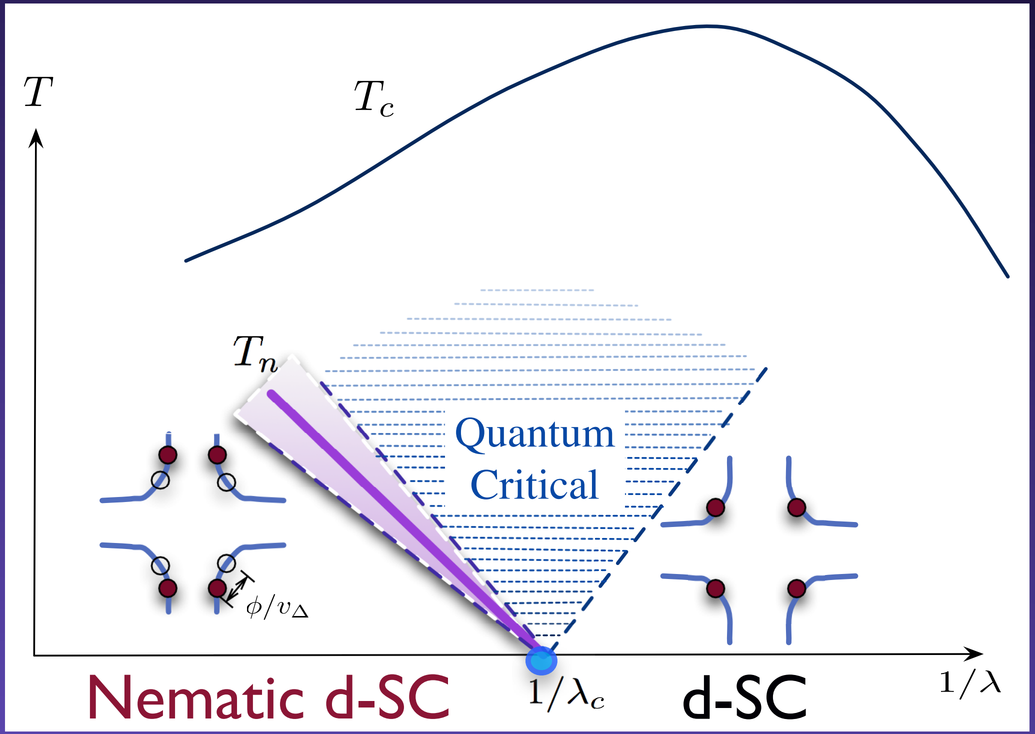
- QPT of nodal qp's



Nodal nematic QCP?

- Nematic QPT
  deep inside d-wave SC
- QPT of nodal qp's
- Nematic d-SC:
  d-SC + small s-component

$$\Delta_d\,(\cos k_x - \cos k_y) + \lambda\phi$$



nodal nematic QCP?

Nodal nematic QCP?

- Nematic QPT deep inside d-wave SC
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- Nematic d-SC: d-SC + small s-component

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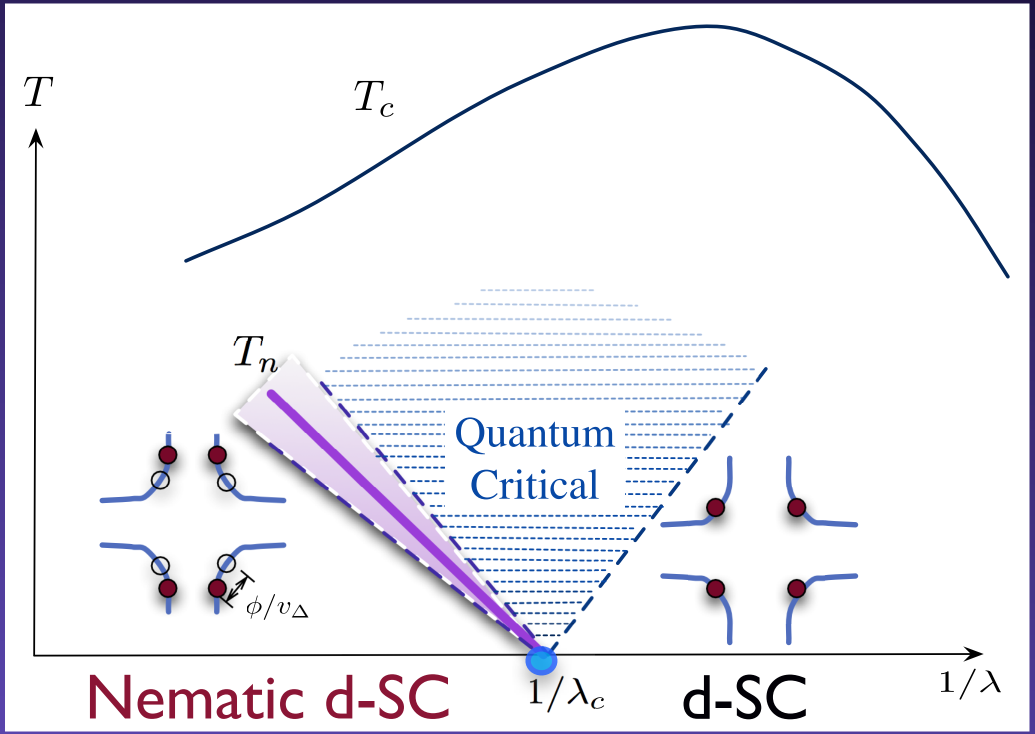
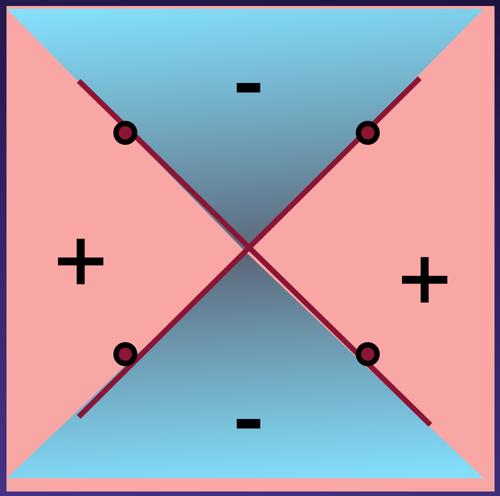


nodal nematic QCP?

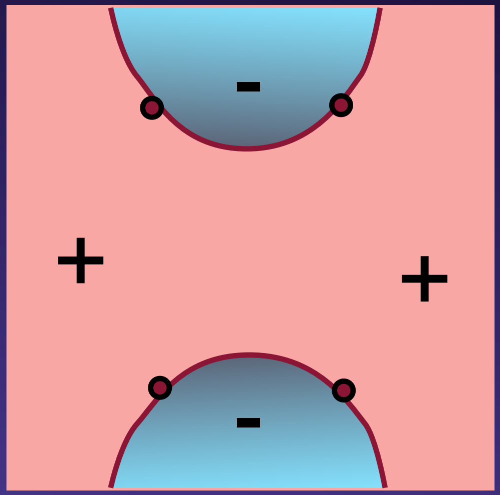
Vojta, Zhang, Sachdev, PRL (2000)

The nematic mode ϕ



The nematic mode ϕ

- Nematic ordering: $C_{4v} \rightarrow C_{2v}$
  $\Leftrightarrow$ small s-wave component



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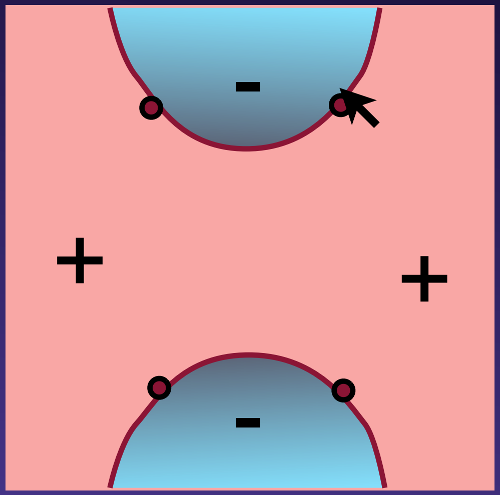

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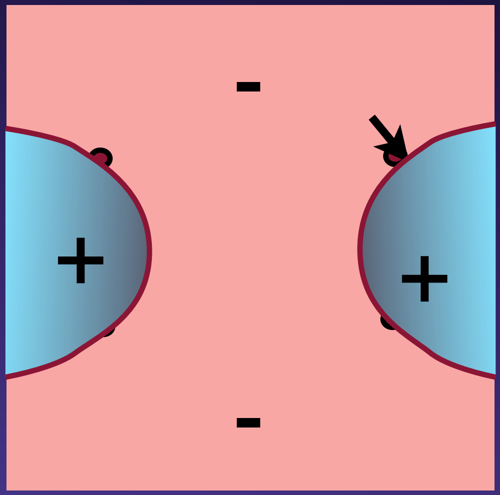

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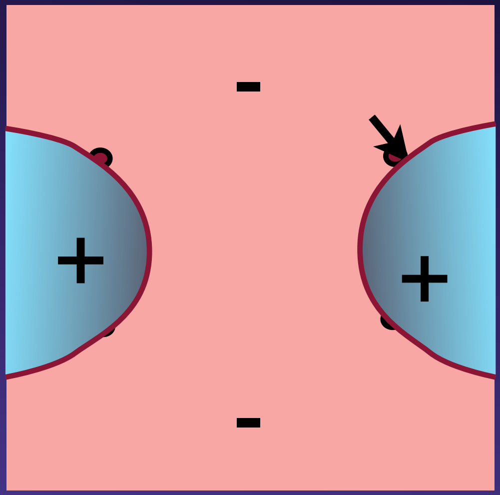
➡ couple strongly to nodal fermions



The effective field theory

- The nodal fermions

$$\mathcal{L}_\Psi = \sum_\alpha \Psi^\dagger_{1,\alpha}(\vec{p}) \begin{pmatrix} -i\omega + v_F p_x & v_\Delta p_y \\ v_\Delta p_y & -i\omega - v_F p_x \end{pmatrix} \Psi_{1,\alpha}(\vec{p})$$

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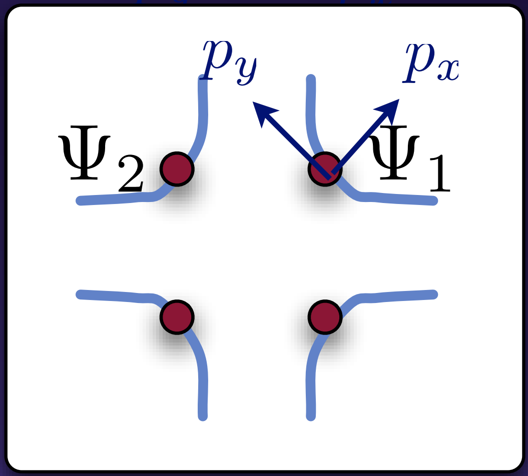

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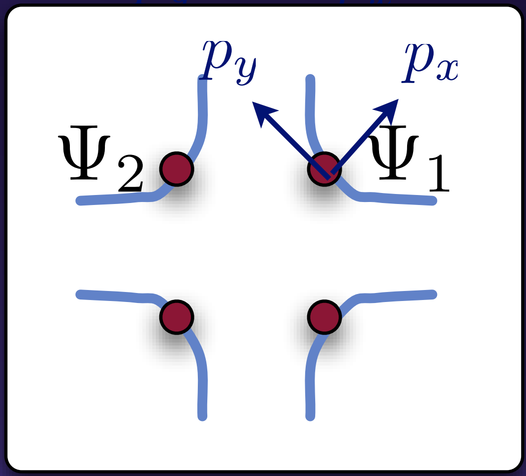

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$$\mathcal{L}_{\rm int} = \lambda \sum_\alpha \Psi^\dagger_{1,\alpha} \begin{pmatrix} 0 & \phi \\ \phi & 0 \end{pmatrix} \Psi_{1,\alpha} + (1 \leftrightarrow 2)$$

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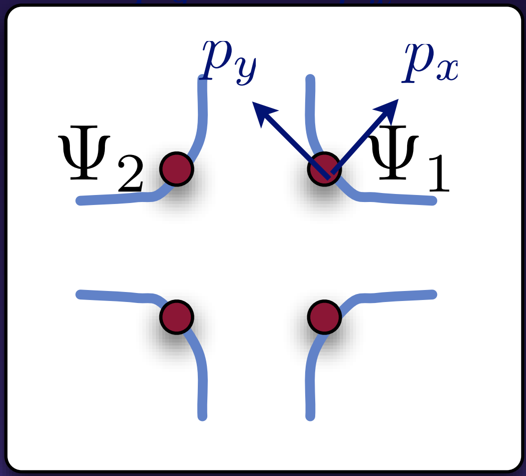

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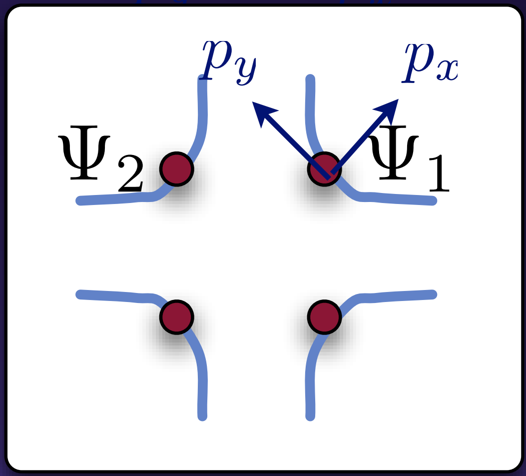

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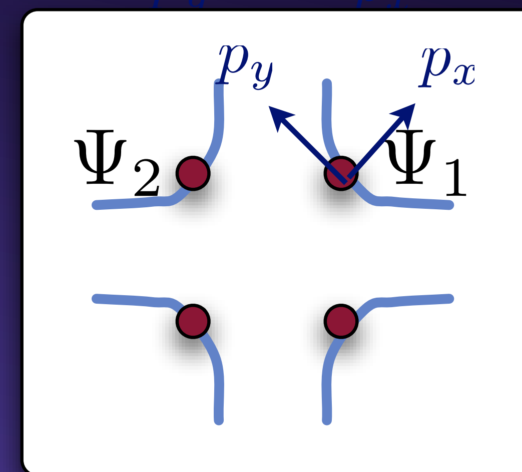

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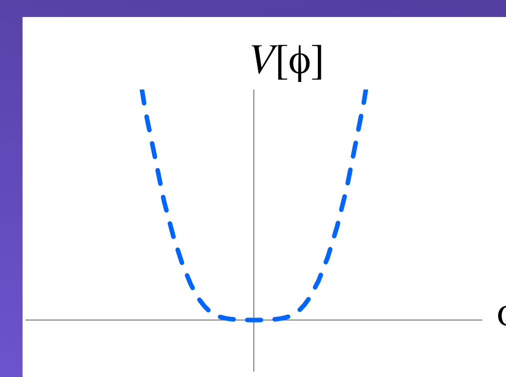

- Symmetry: $\Psi \to \hat{\tau}_2 \Psi$, $\vec{p} \to -\vec{p}$, $\phi \to -\phi$

$$\mathcal{L} = \frac{2N}{2}\varphi^2 + \sum_{\alpha}^{N} \Psi^{\dagger}_{1,\alpha} \left[-i\omega + \hat{\tau}_3 v_F p_x + \hat{\tau}_1 (v_\Delta p_y + g\varphi) \right] \Psi_{1,\alpha}$$

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The $\phi - \Psi$ coupling

: irrelevant in the massive (disordered) side

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(RG analysis confirmed the validity of this apporach Y. Huh and S. Sachdev (2008))

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- Integrate out fermions

$$\mathcal{L}_{\text{eff}}[\varphi] = \frac{N}{2}\varphi^2 - \frac{N}{2}\int \frac{d\vec{p}d\omega}{(2\pi)^2} \log\left[\omega^2 + (v_F p_x)^2 + (v_\Delta p_y + g\varphi)^2\right] + (v_F \leftrightarrow v_\Delta)$$

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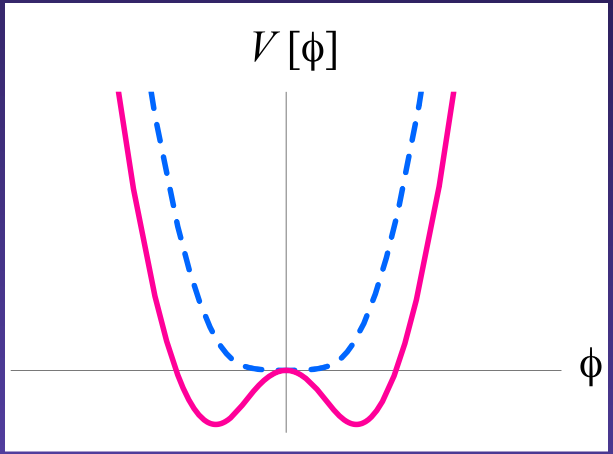

➡ 2nd order QPT at $\boxed{g=g_c}$

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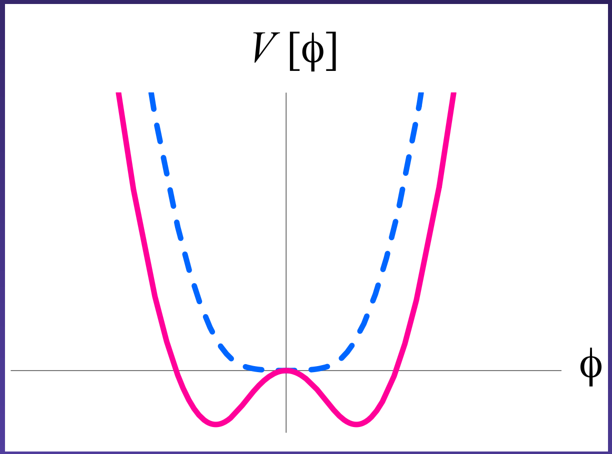
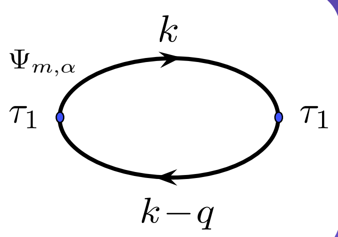


- Gaussian fluctuation

$$\Pi(\vec{q},\omega) = \sum_{m,\alpha}$$



nematic mode dynamics

- Fluctuations: non-analytic action

$$S^{(2)}[\varphi] = \int \frac{d^2p d\omega}{(2\pi)^3} \, \frac{1}{2} \left[\gamma\sqrt{\omega^2 + E_1(\vec{p})} \left(1 - \frac{v_\Delta^2 p_y^2}{\omega^2 + E_1(\vec{p})}\right) + [p_x \leftrightarrow p_y]\right] |\varphi(p)|^2$$

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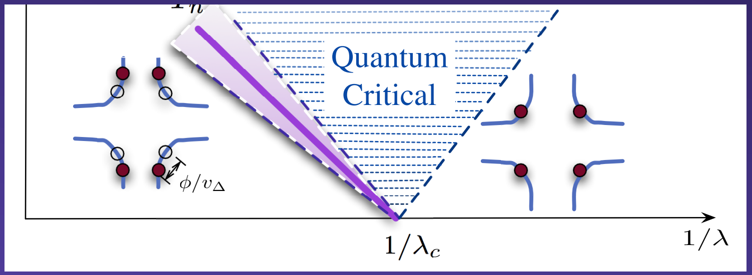

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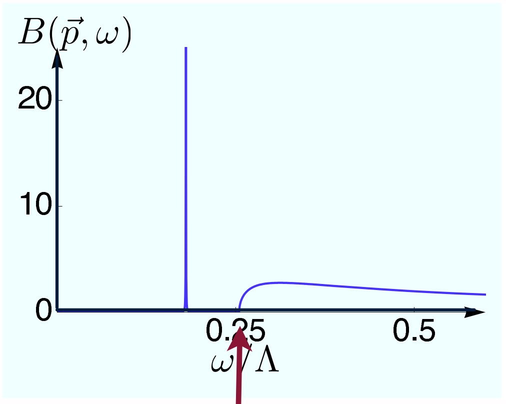

$\omega = v|\vec{p}|$

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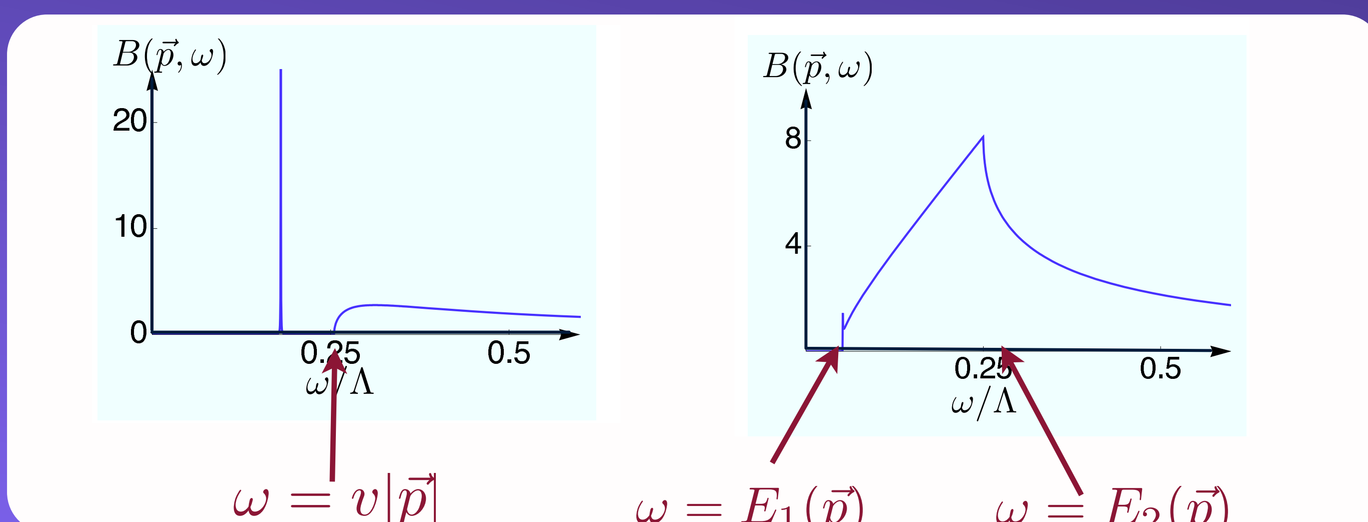

The theory of nodal nematic quantum criticality

- Introduction: electronic nematic
- Nodal nematic quantum criticality
- <u>Quasiparticle interference</u>
- Outlook

Fermion Spectral Function

- Probability of finding a fermion at given energy ω

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- Probability of finding a fermion at given energy ω

  -momentum space

  $$A_{\vec{p},\omega} \equiv -2\mathrm{sgn}(\omega) Im\mathcal{G}_{11}(\vec{p},\omega)$$ ➡ARPES

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  ➡STM

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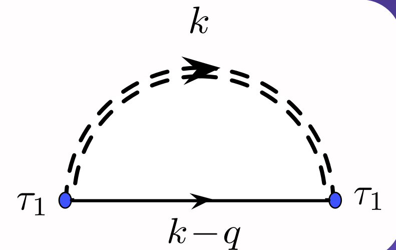
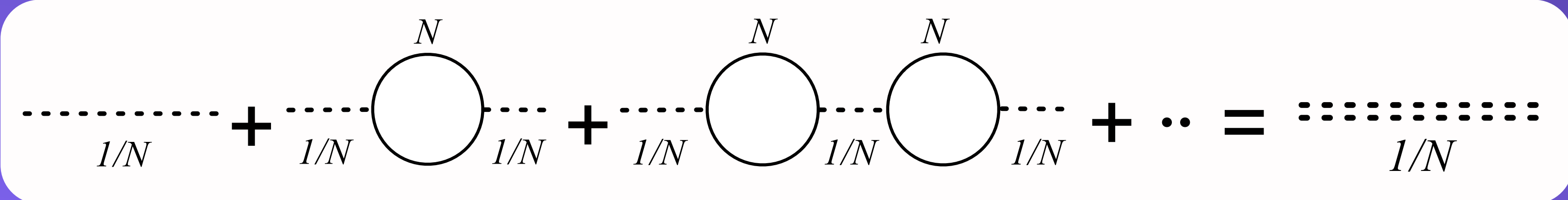
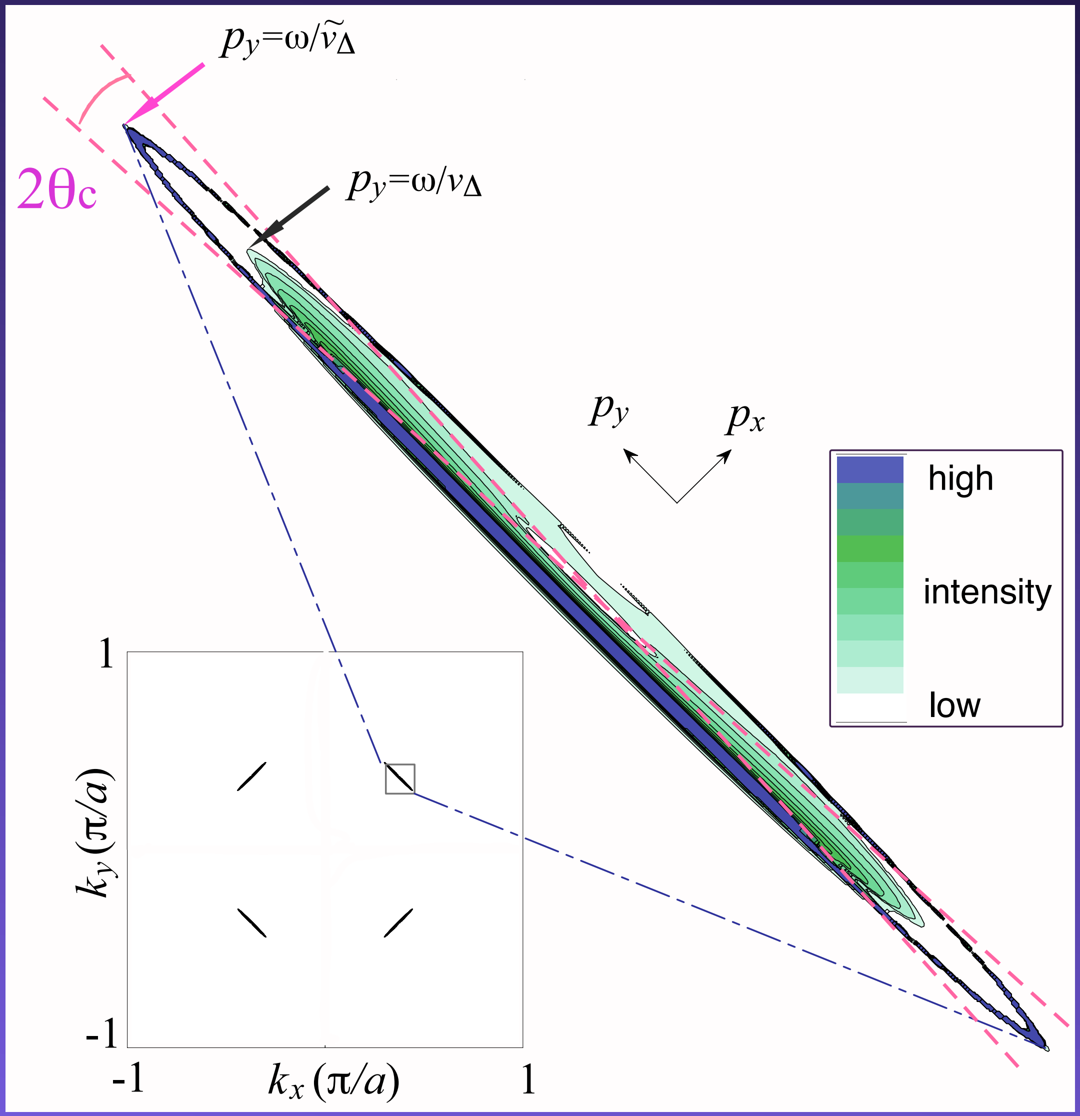
$$\hat{\mathcal{G}}_0(\vec{p},\omega) = \frac{1}{\omega\mathbb{I} - v_F p_x \tau_3 - v_\Delta p_y \tau_1}$$

$\Sigma_{\Psi_i}(\vec{q},\omega) =$





Momentum Distribution



MDC at $\omega = 9meV, v_F/v_\Delta = 19.5$

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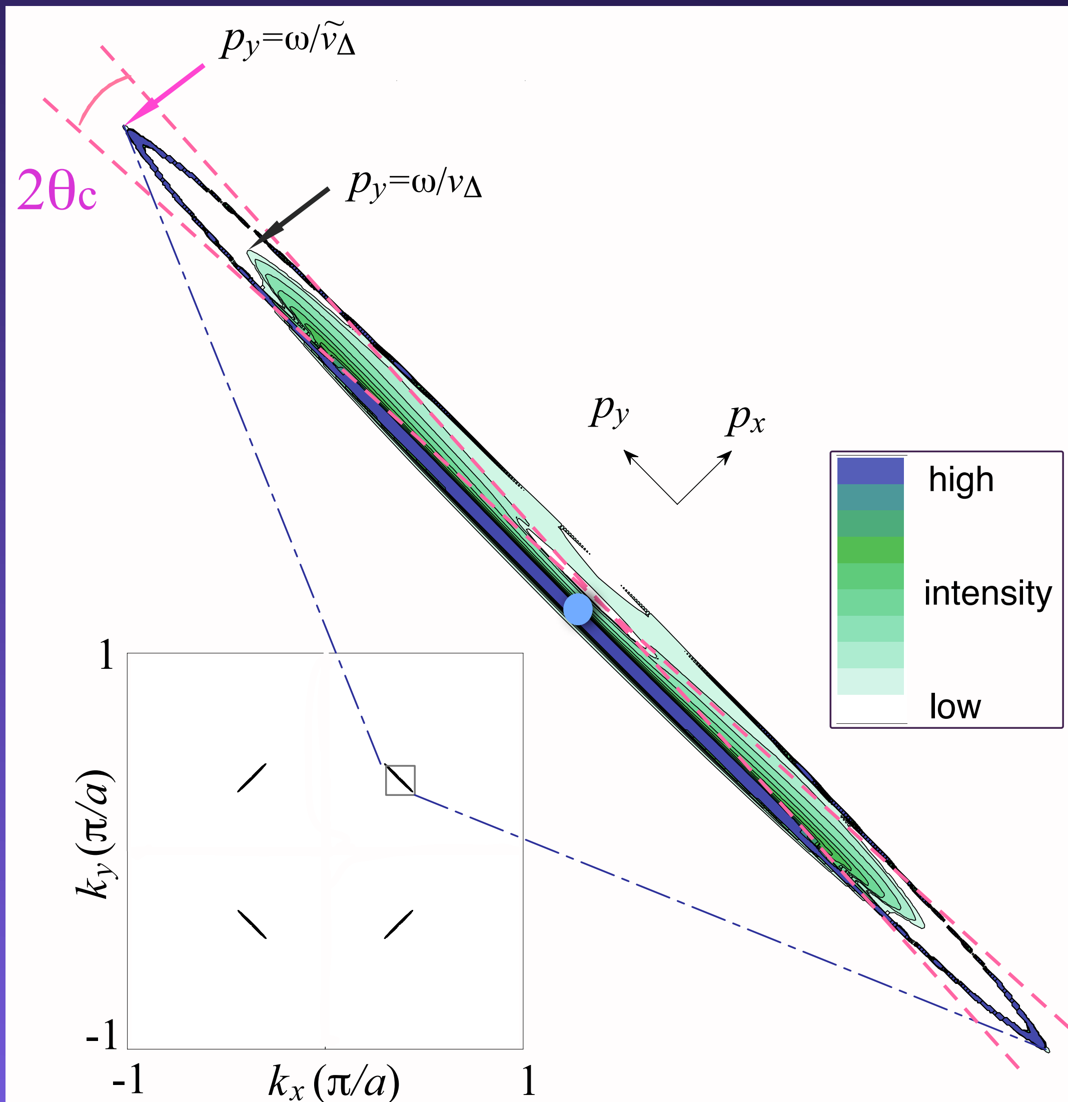

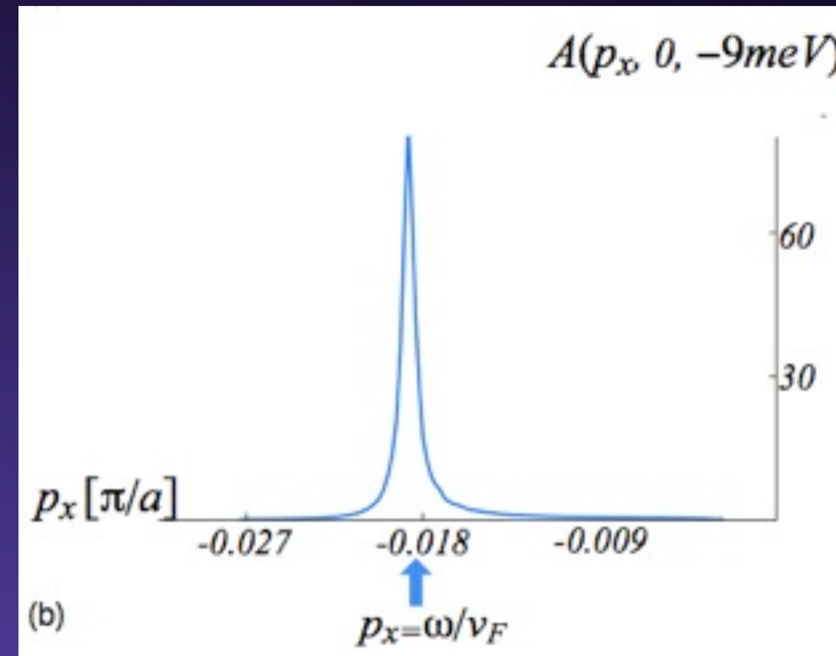

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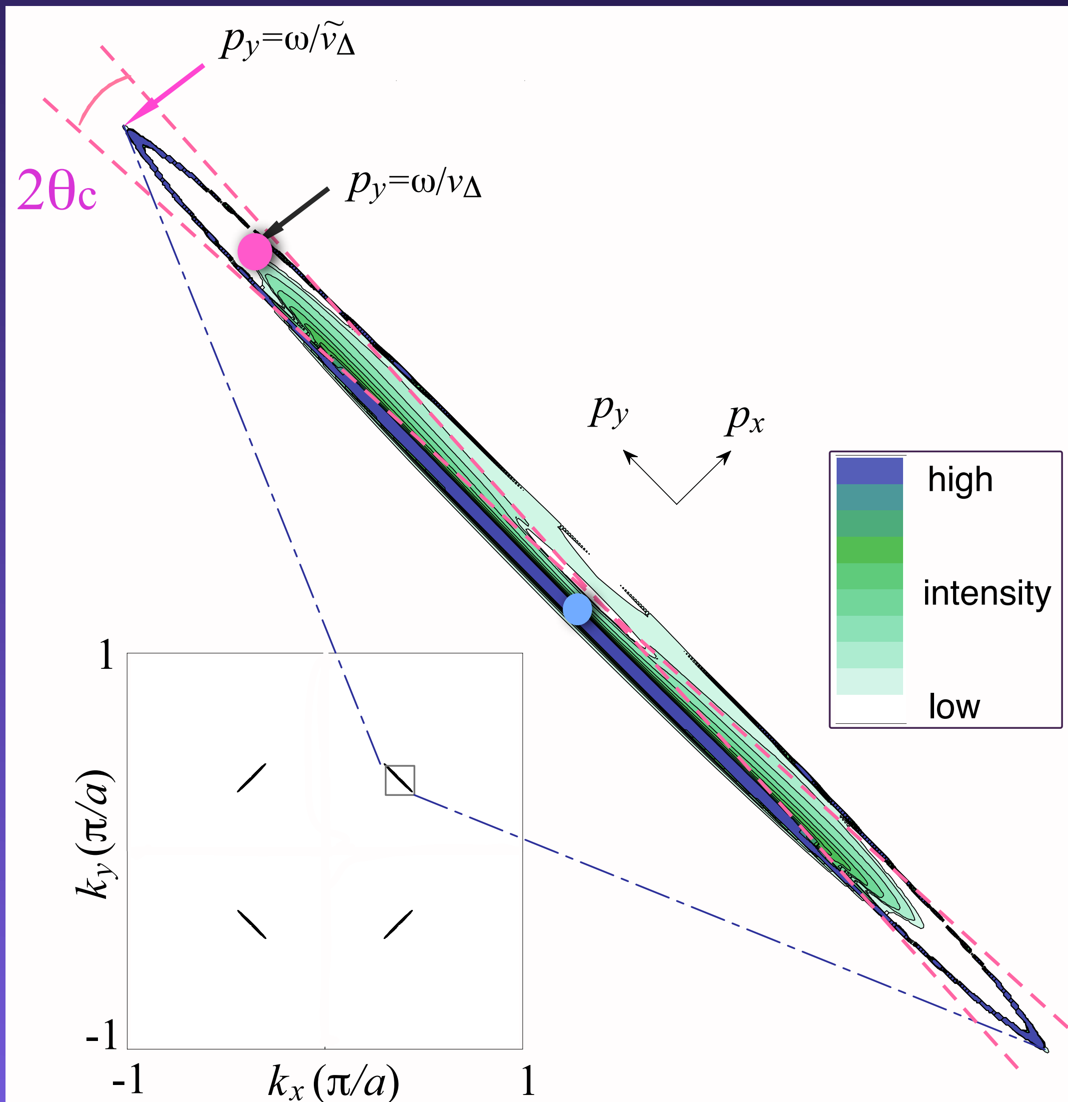
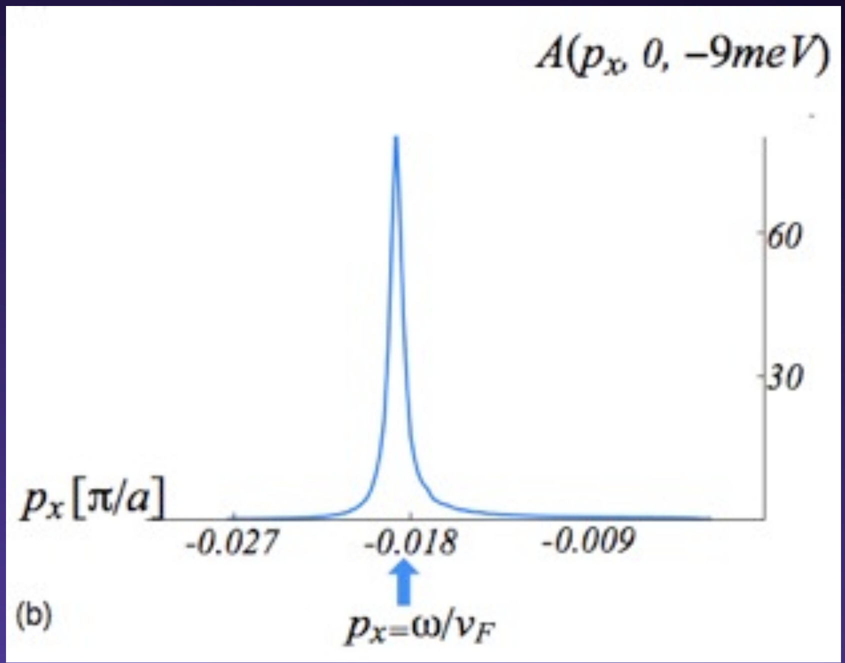
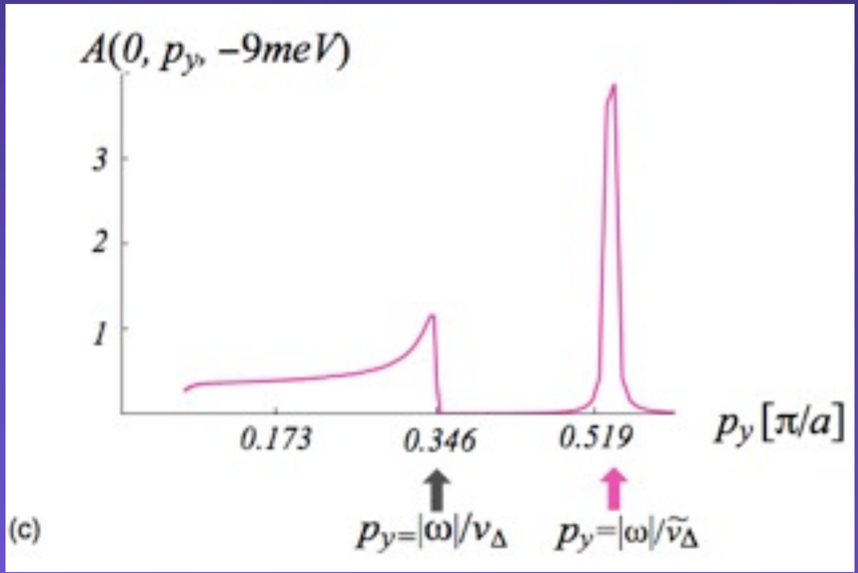
MDC line cuts

Momentum Distribution







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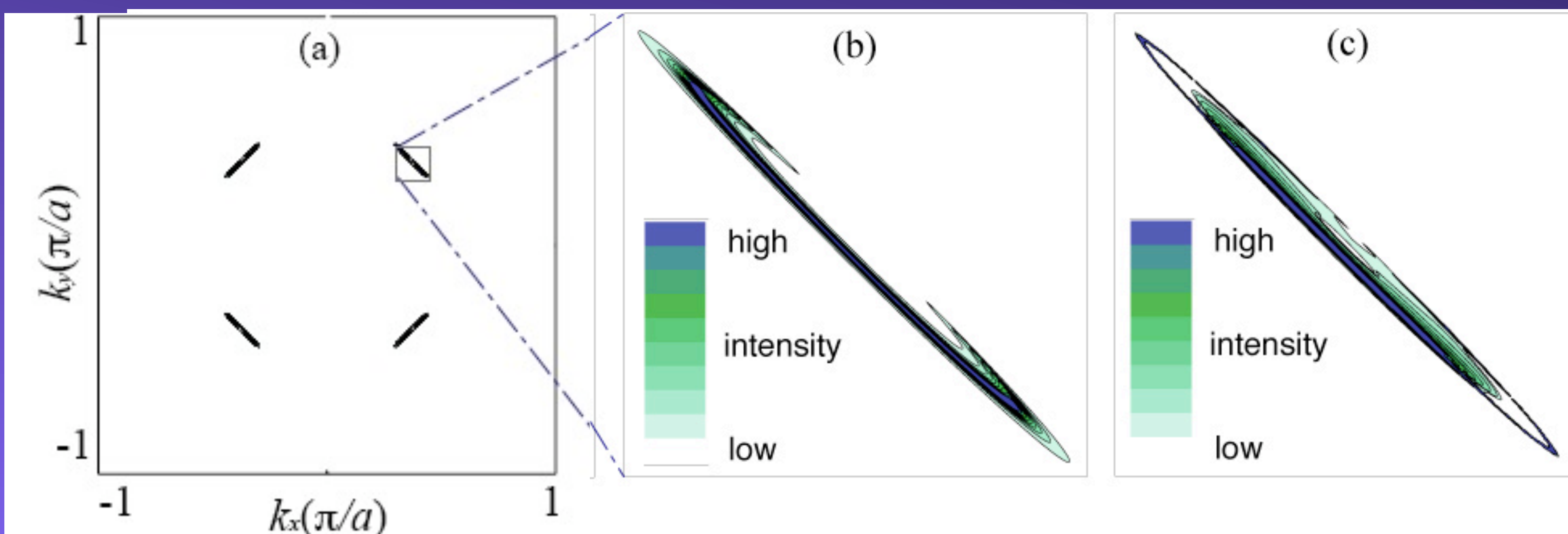
MDC line cuts

Momentum space: ARPES

$$A(\vec{q},\omega) = -2Im\left[\frac{(\omega-\Sigma^{(0)})+(v_F q_x-\Sigma^{(1)})}{(\omega-\Sigma^{(0)})^2-[(v_F q_x-\Sigma^{(1)})^2+(v_\Delta q_y+\Sigma^{(2)})^2]}\right]$$



Real space: qp interference

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- Modulation in LDOS due to impurity

$$n(\vec{r};\omega) \equiv -2\text{sgn}(\omega) Im\left[\mathcal{G}_{11}(\vec{r},\vec{r};\omega)\right]$$

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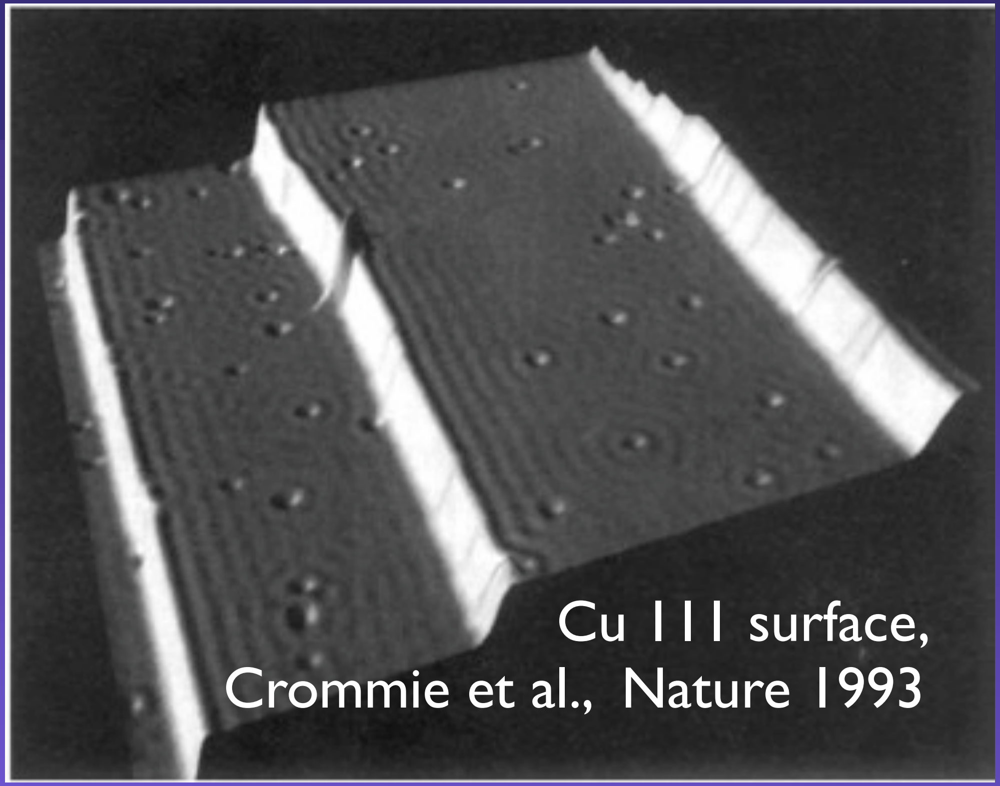

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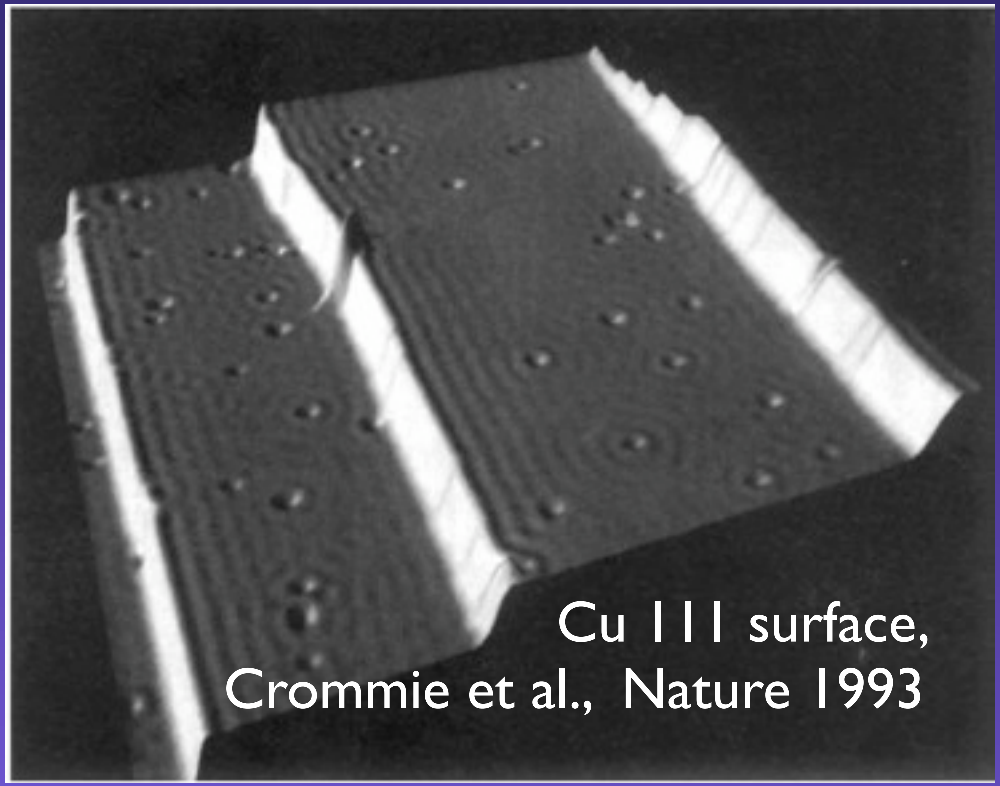

LDOS modulation of nematic QC fermions?

Real space: qp interference

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LDOS modulation of nematic QC fermions?

Real space: qp interference

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$$= n_0(\omega) - 2\mathrm{sgn}(\omega) Im\left[\hat{\mathcal{G}}(\vec{r},0;\omega)\,\widehat{\mathbf{T}}\,\hat{\mathcal{G}}(0,\vec{r};\omega)\right]_{11}$$

LDOS modulation of nematic QC fermions?

$n(\vec{q};\omega)$ as an interference

$$n(\vec{q};\omega) = -2\mathrm{sgn}(\omega)\int d\vec{k} Im\left[\hat{\mathcal{G}}(\vec{k}+\vec{q};\omega)\hat{T}\hat{\mathcal{G}}(\vec{k};\omega)\right]_{11}$$

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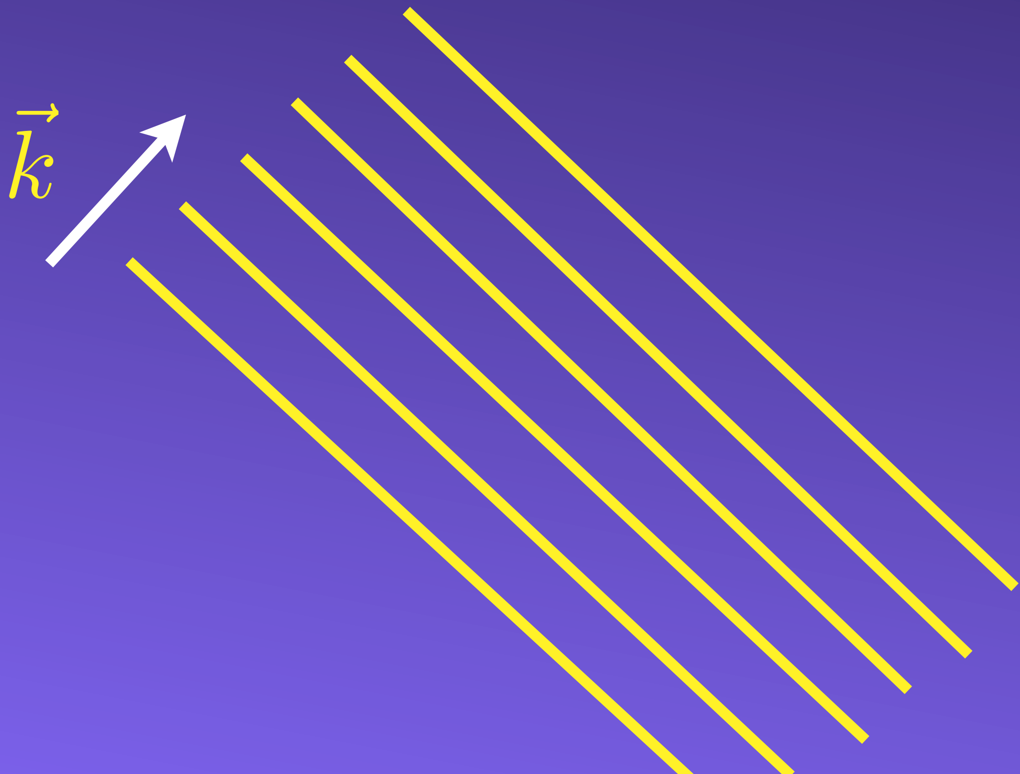

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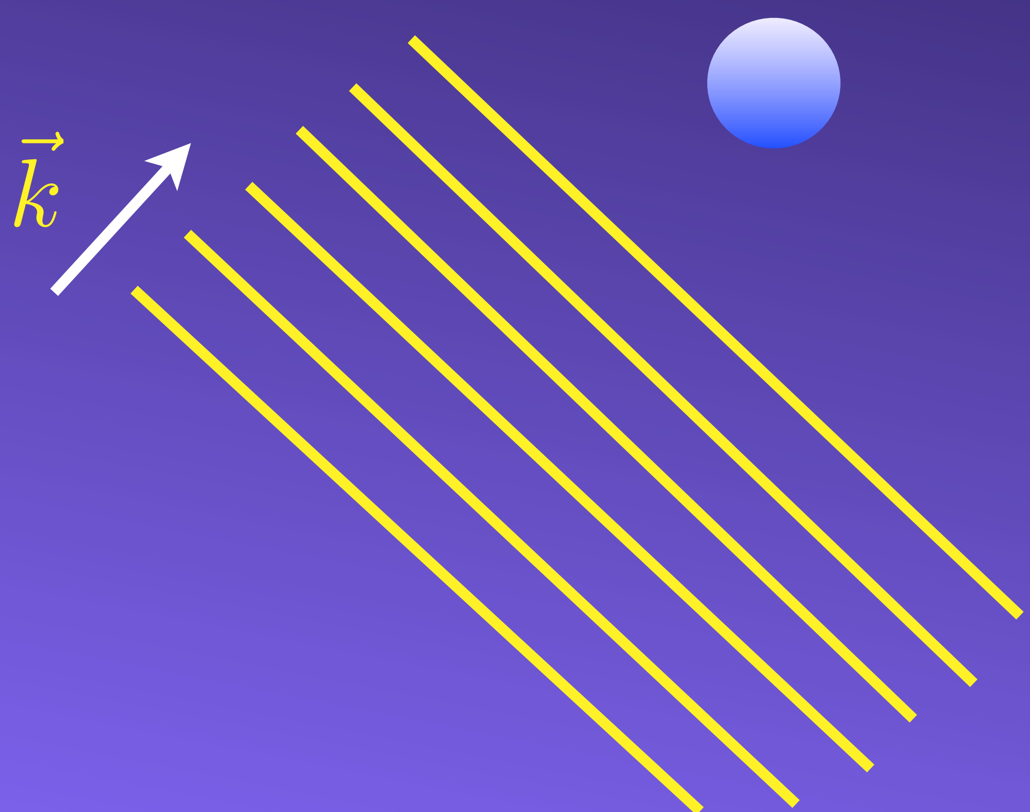
Impurity $\hat{T}$



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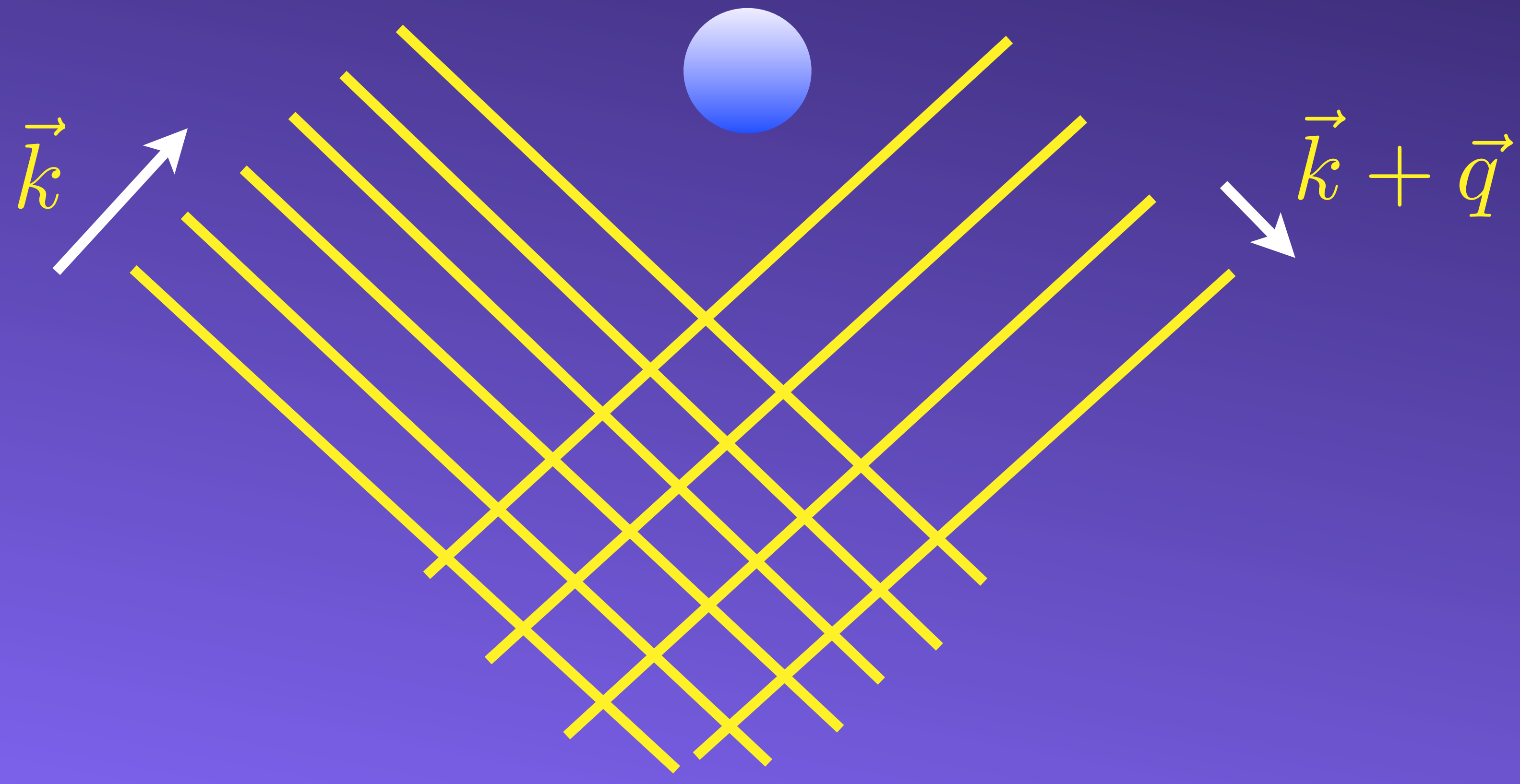

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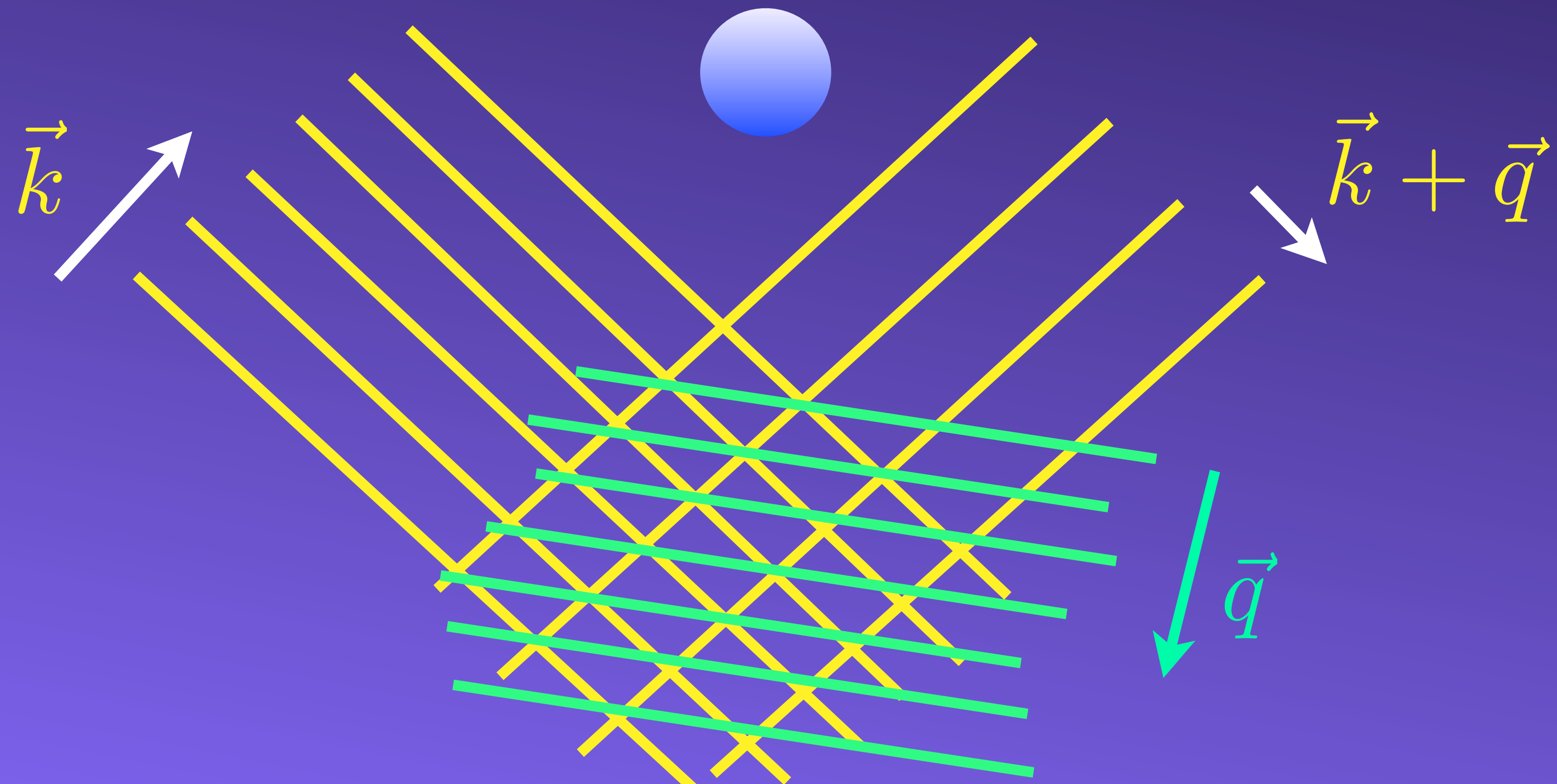

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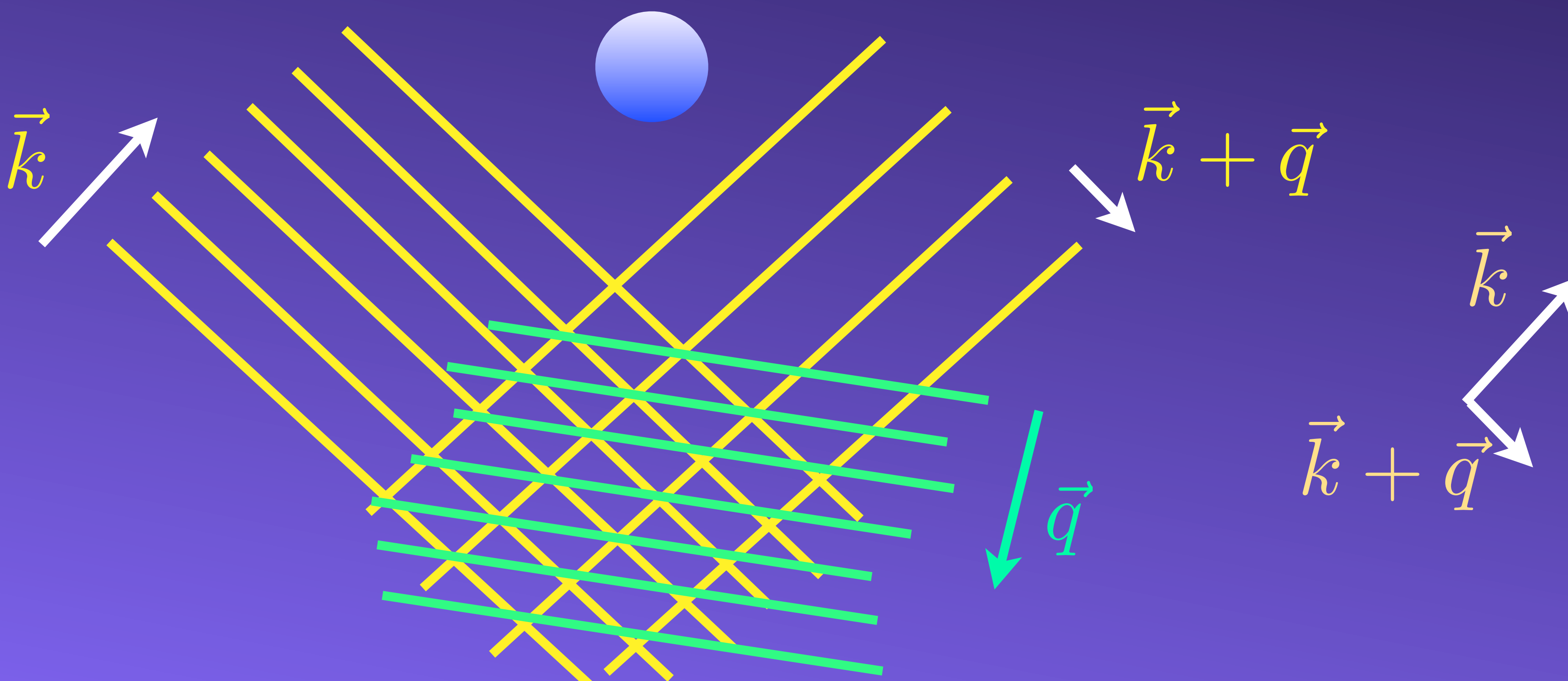

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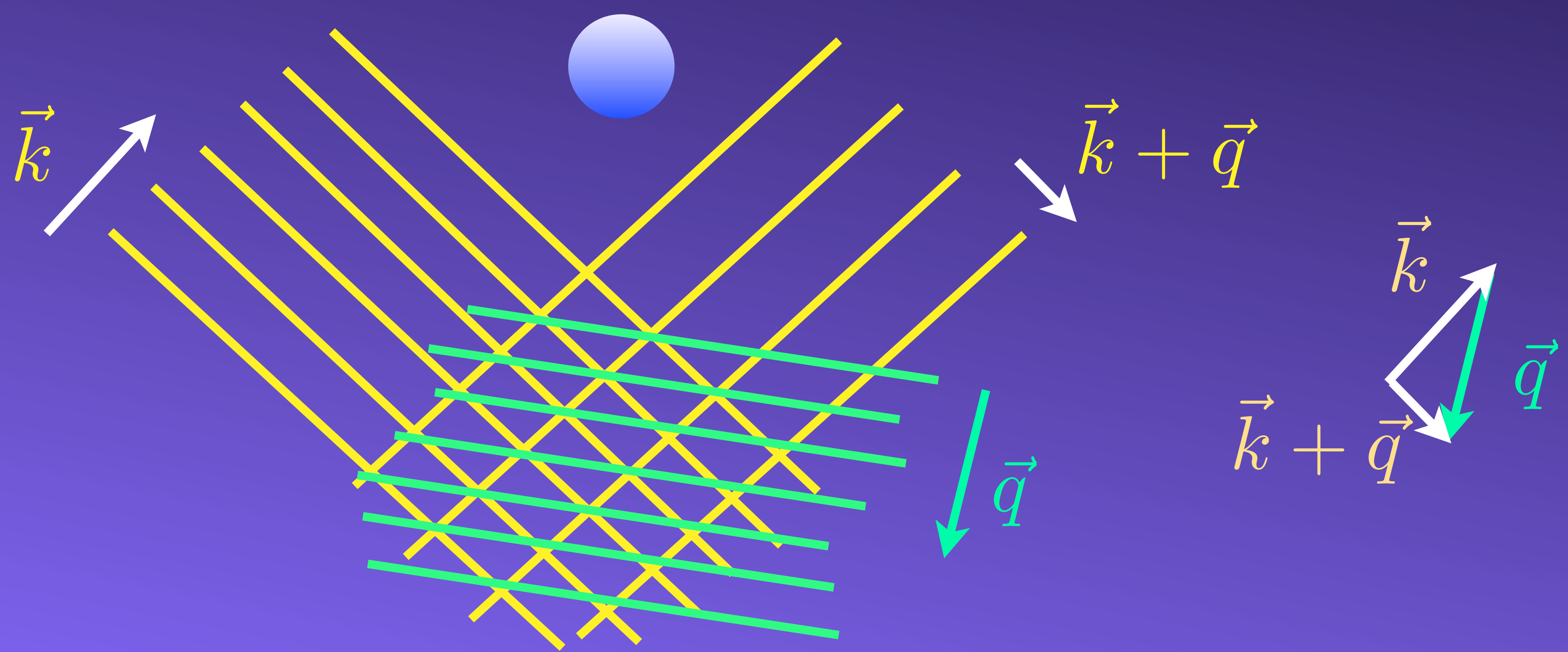
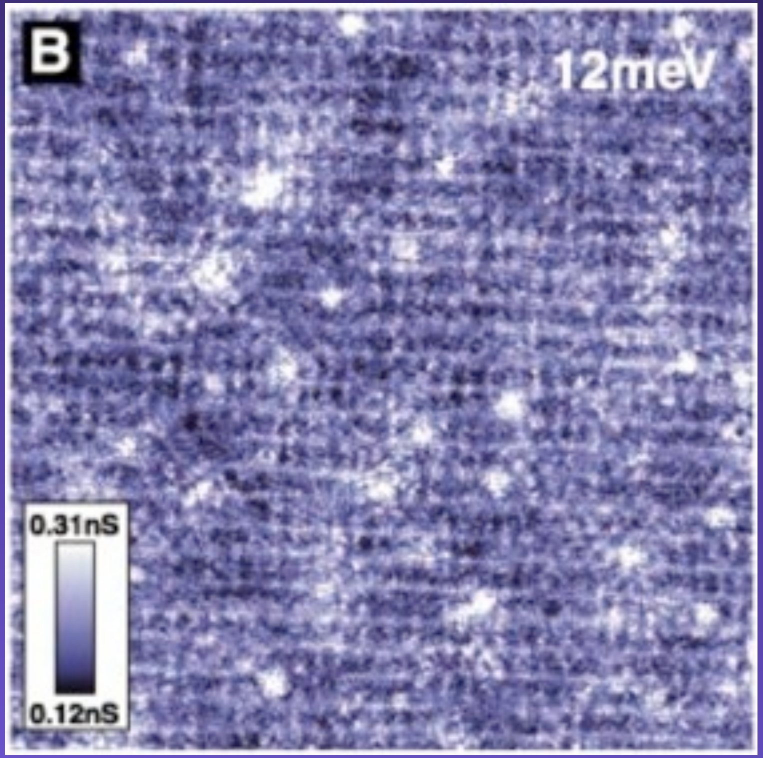


Experimental test

- qp interference: well defined octet points



FT - STS

Experimental test

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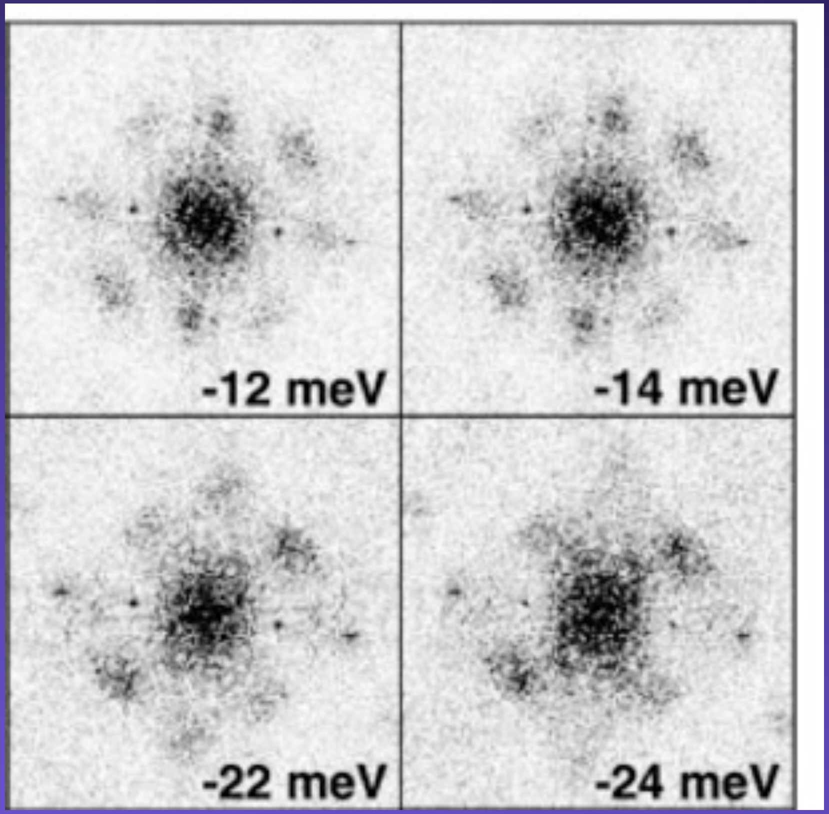

FT - STS

Hoffman et al., Science 2002

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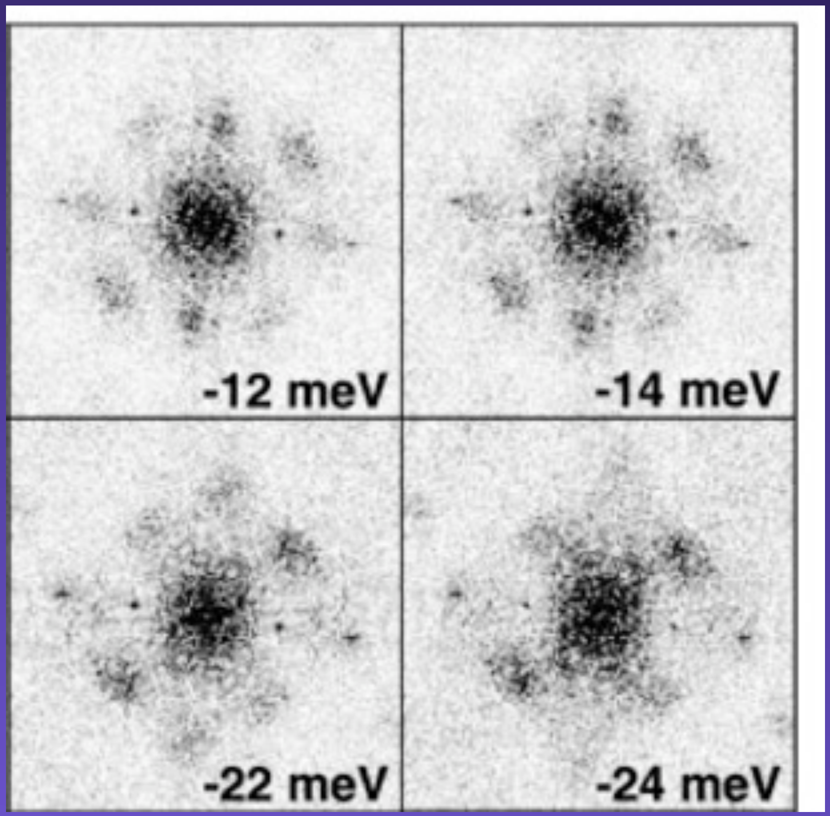

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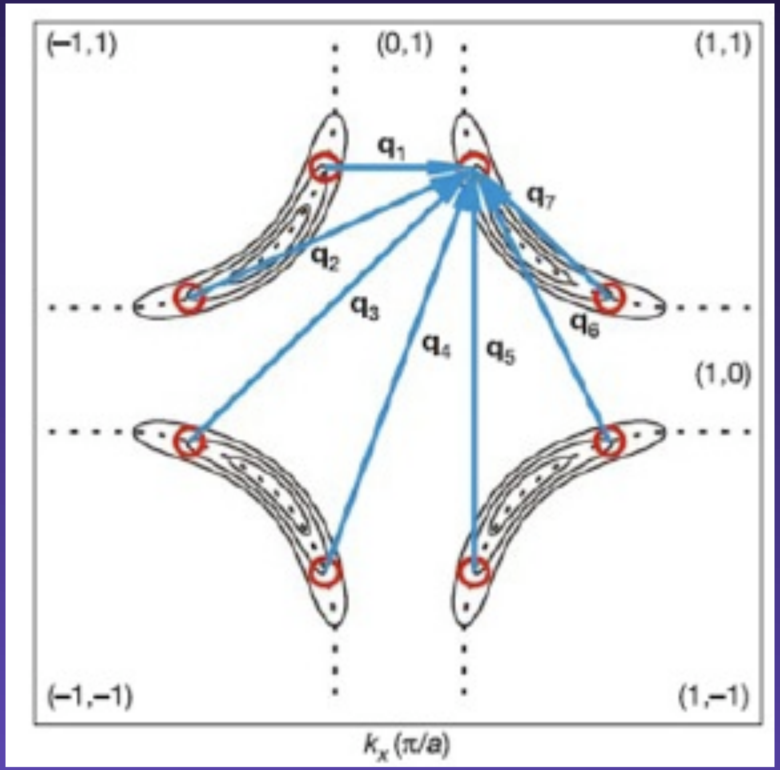
Hoffman et al., Science 2002



McElroy et al., Nature 2003

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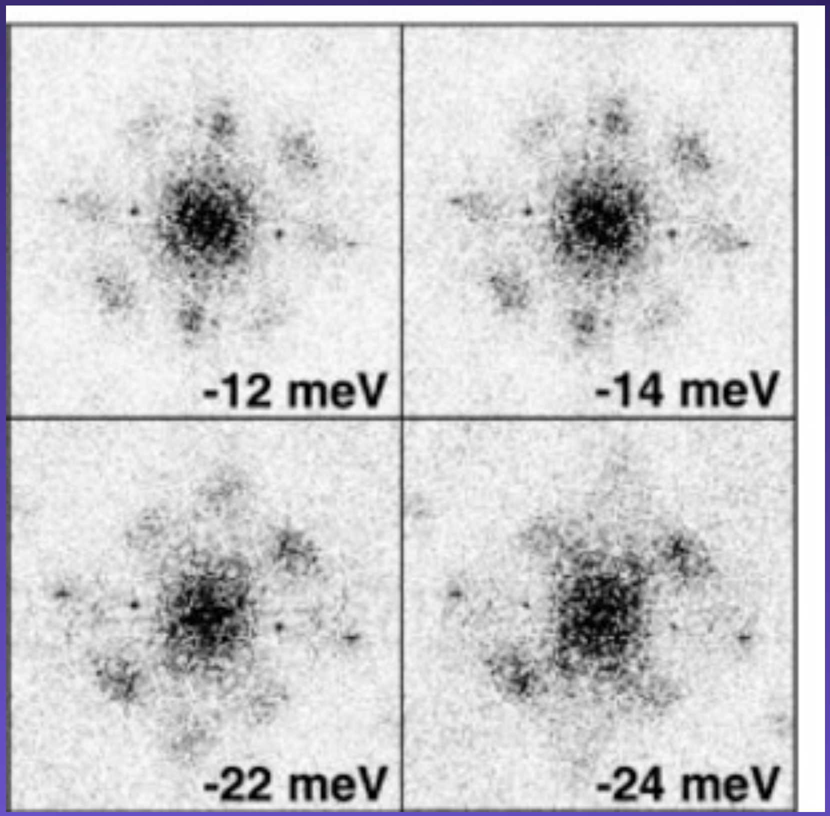

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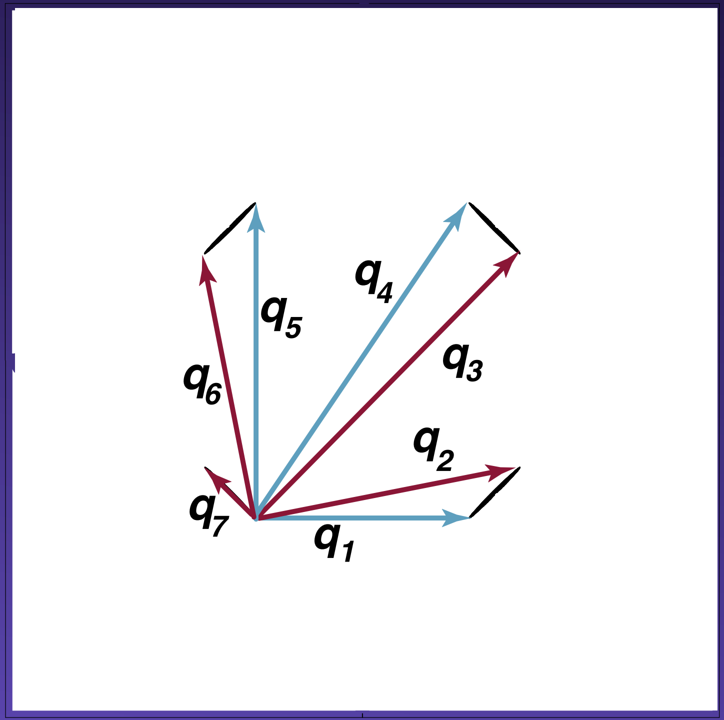

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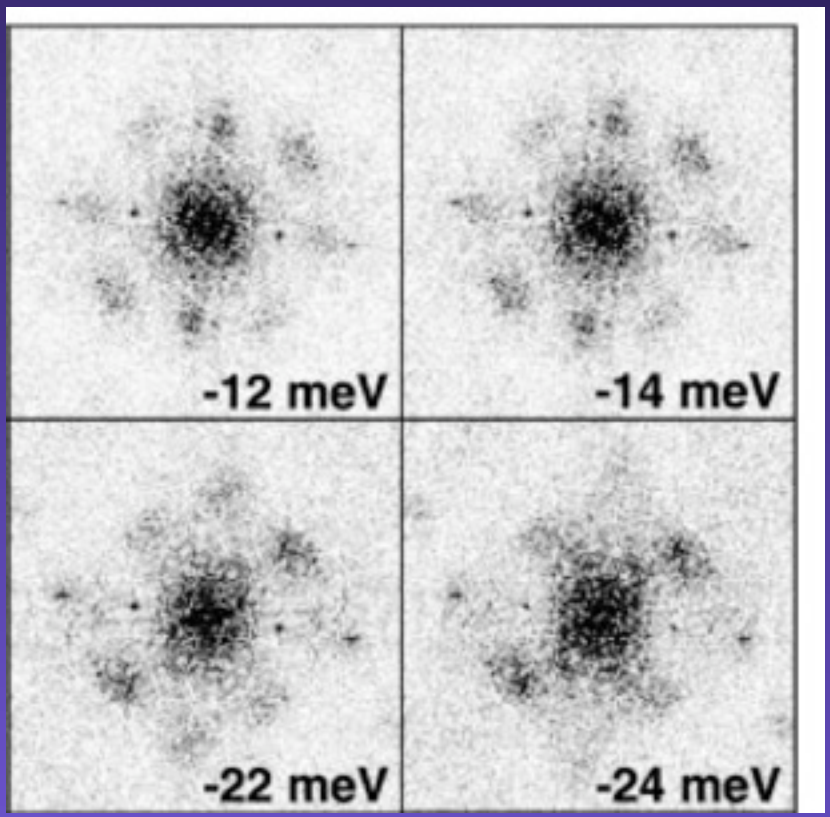
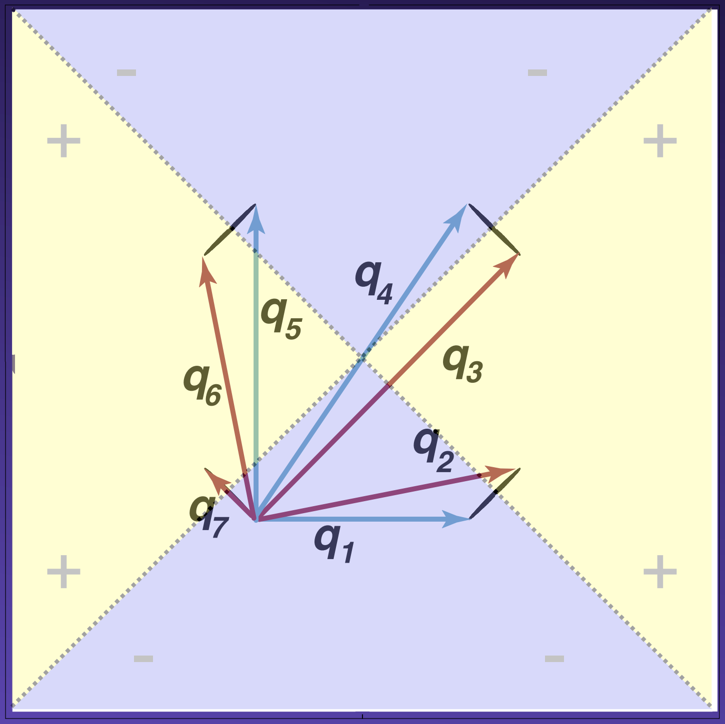
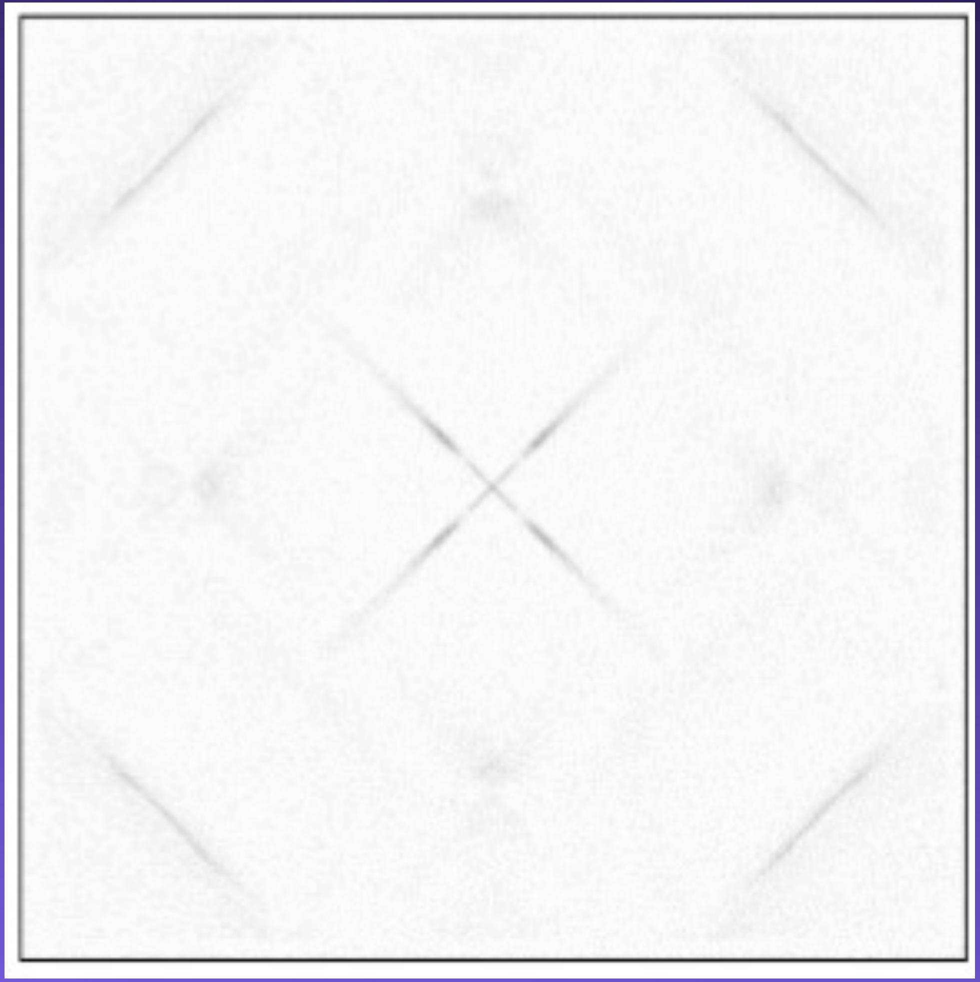




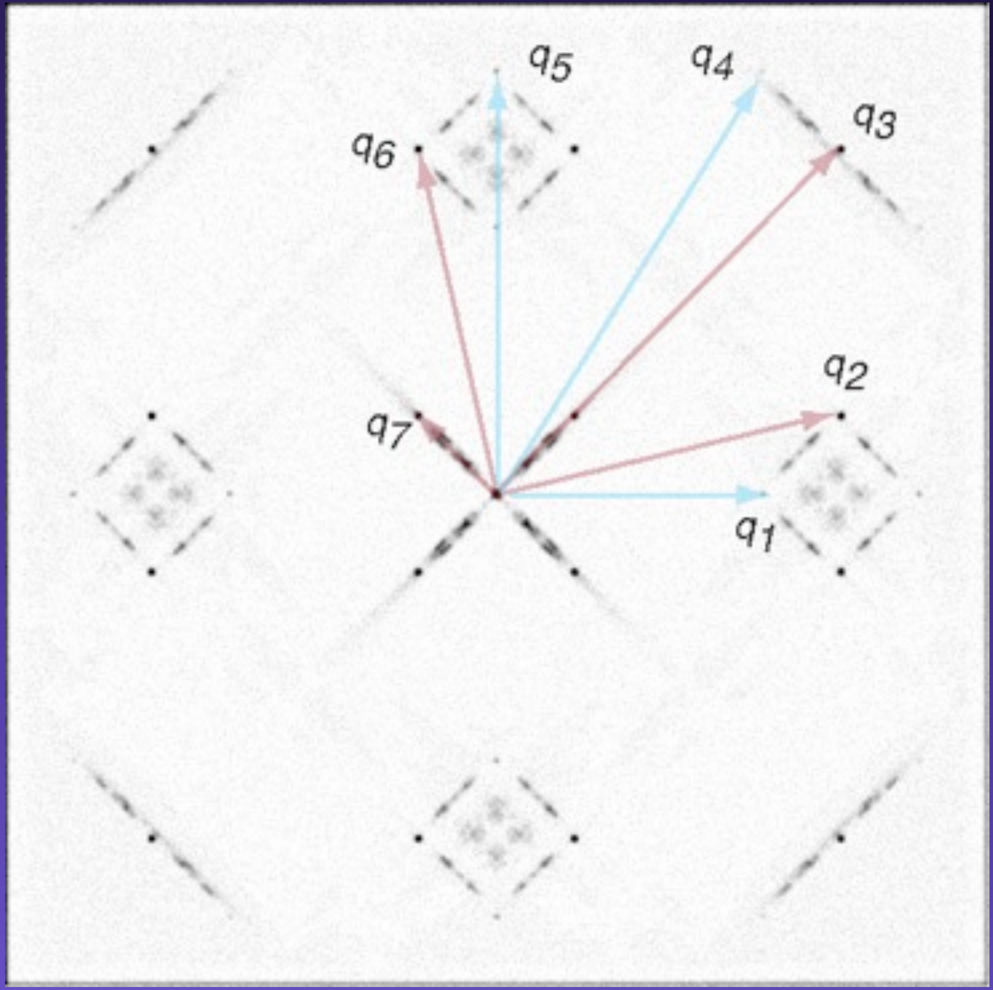
FT - STS

Hoffman et al., Science 2002

QPI intensity map (charge impurity)



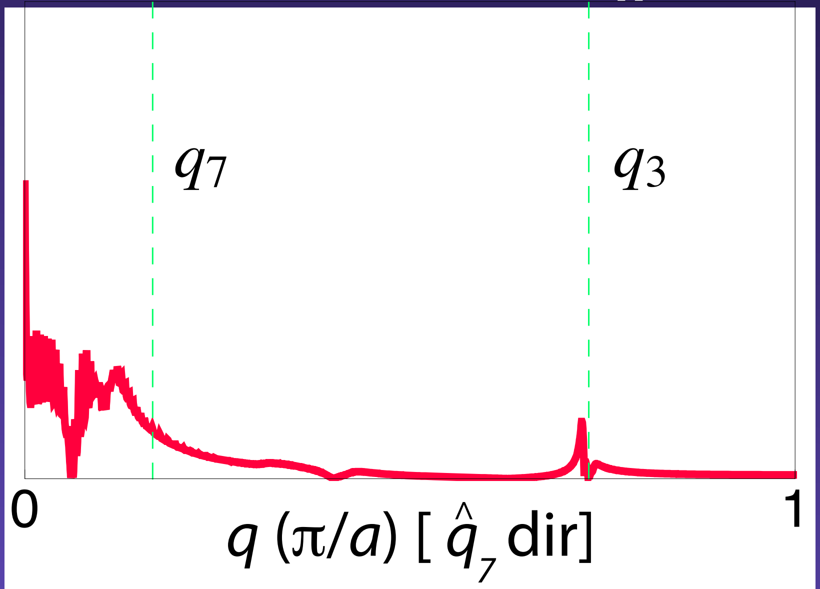
Free qp

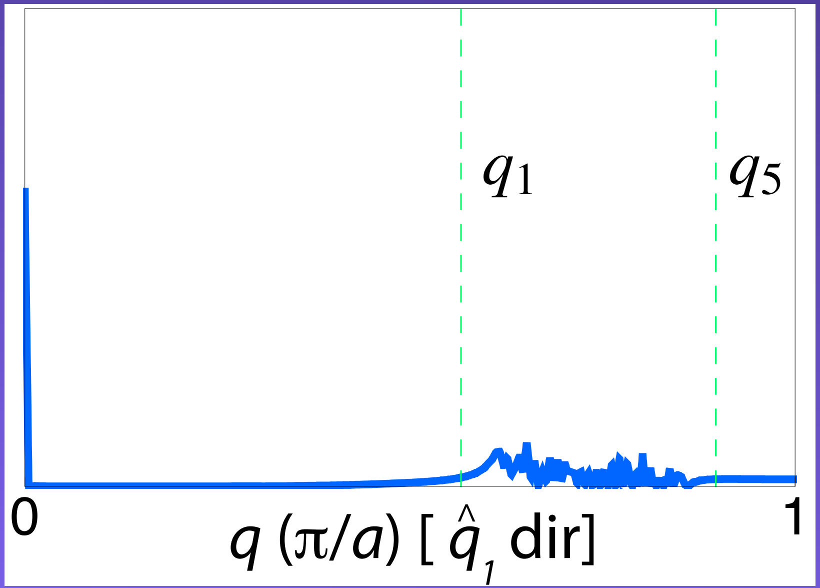


Nodal nematic qp

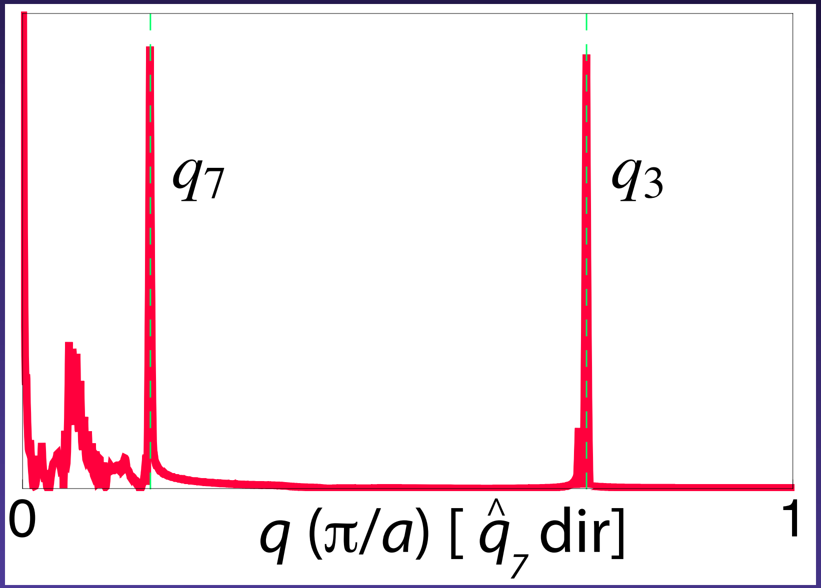
QPI linecuts (charge impurity)

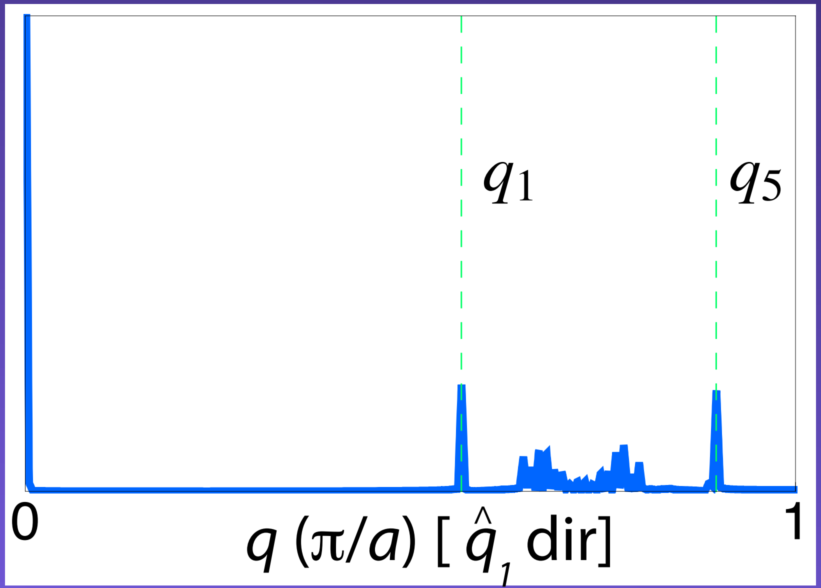
Free BdG qp





Nematic critical qp





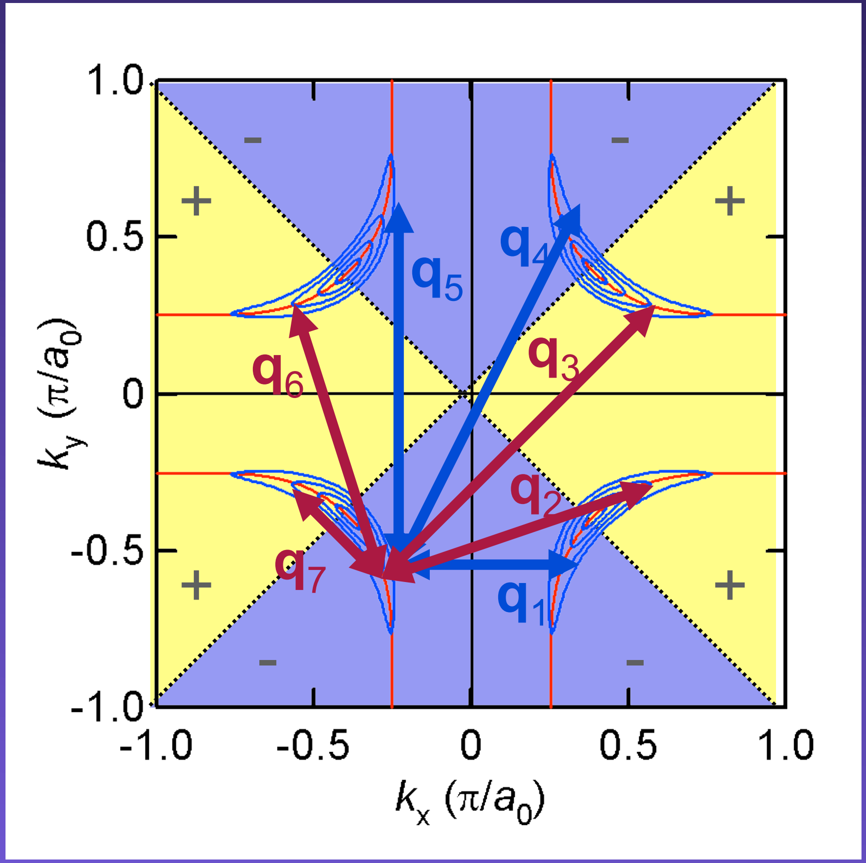
T. Hanaguri group's field dependence study

Courtesy of T. Hanaguri (RIKEN)

T. Hanaguri et al (unpublished)

Na-CCOC V_{sample} = -0.1 V, I_t = 0.1 nA

FT map 4.4 meV



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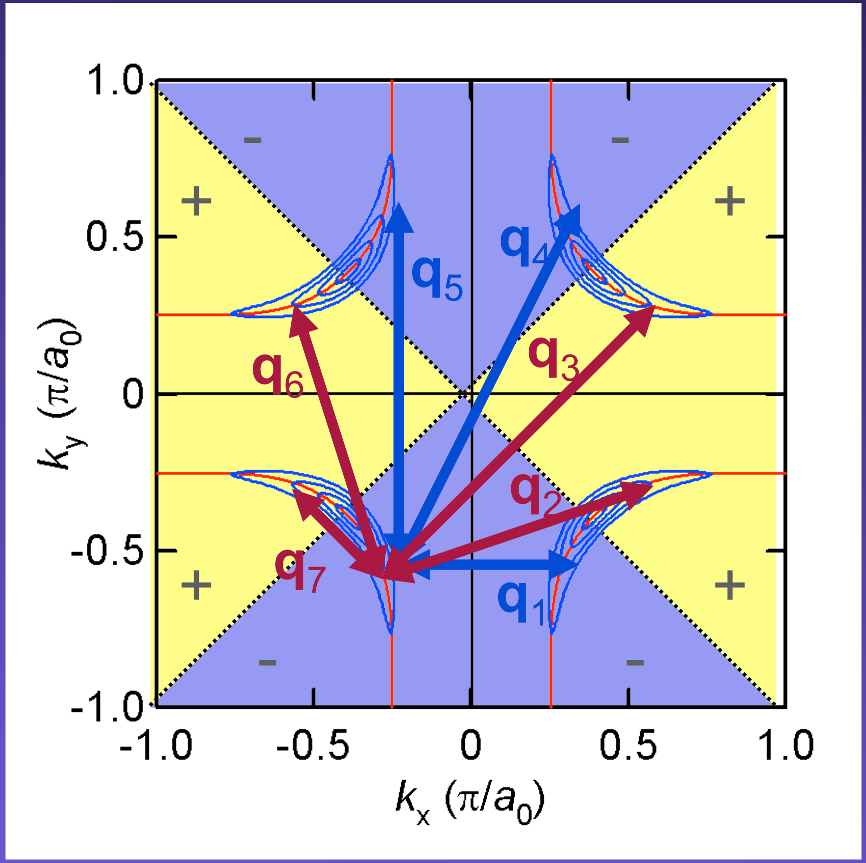

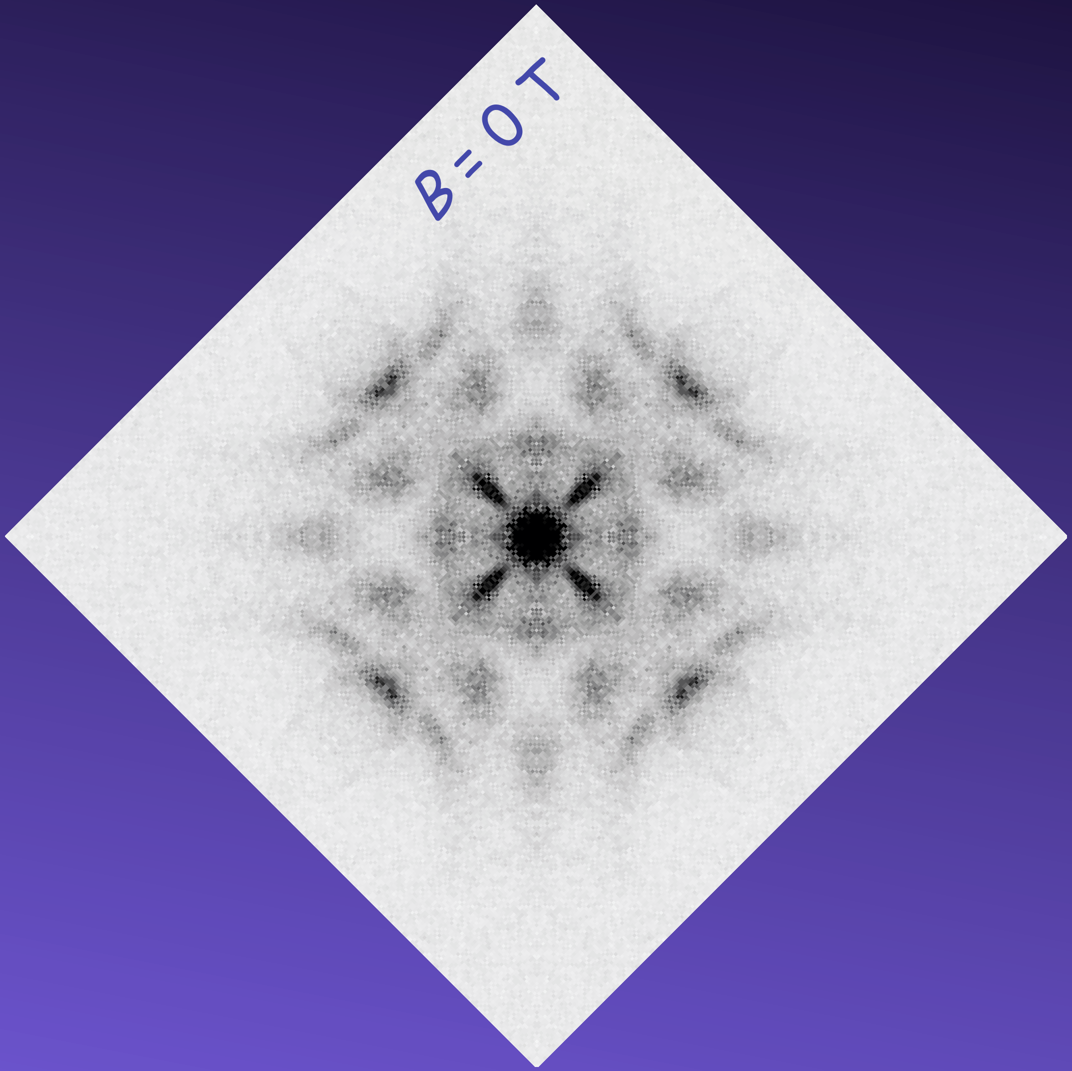

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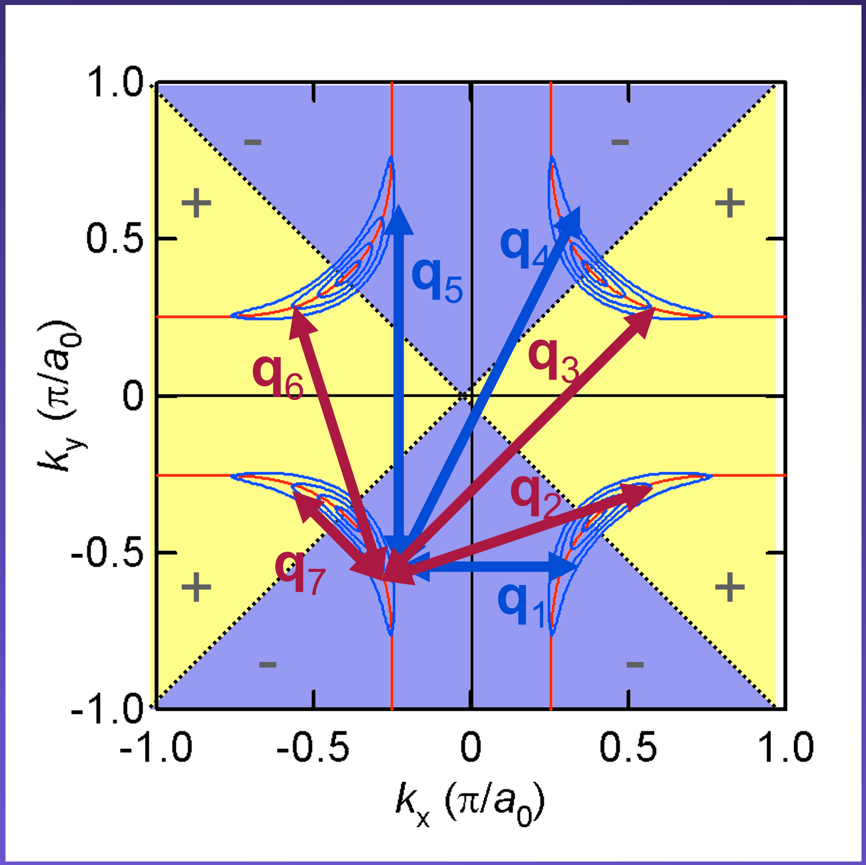

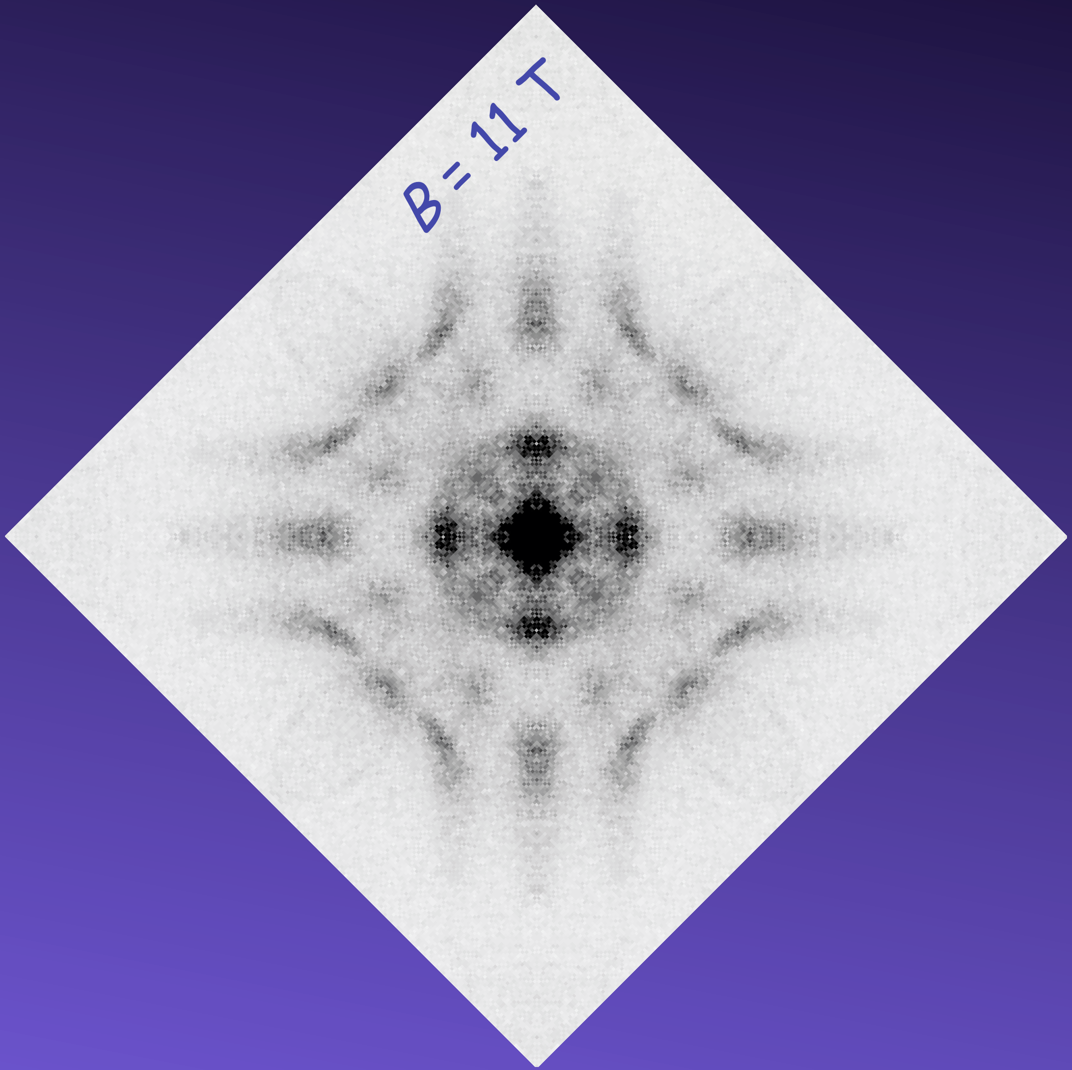

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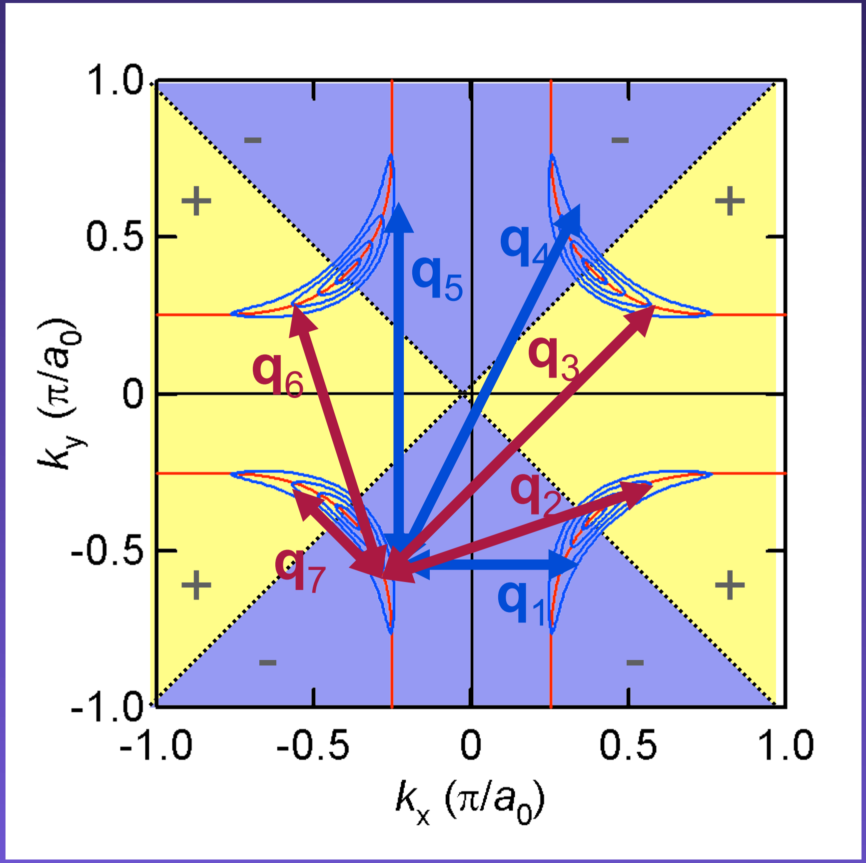
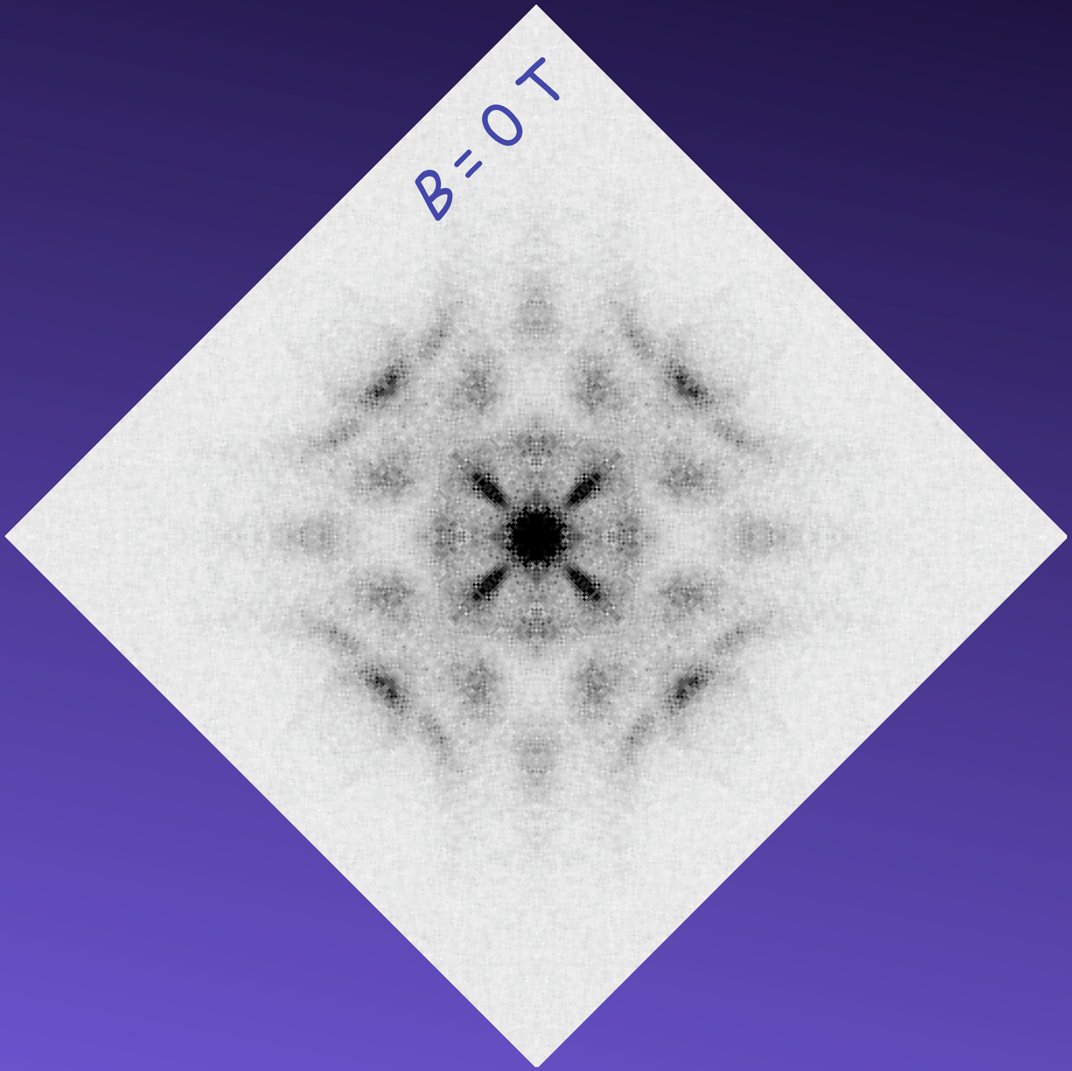
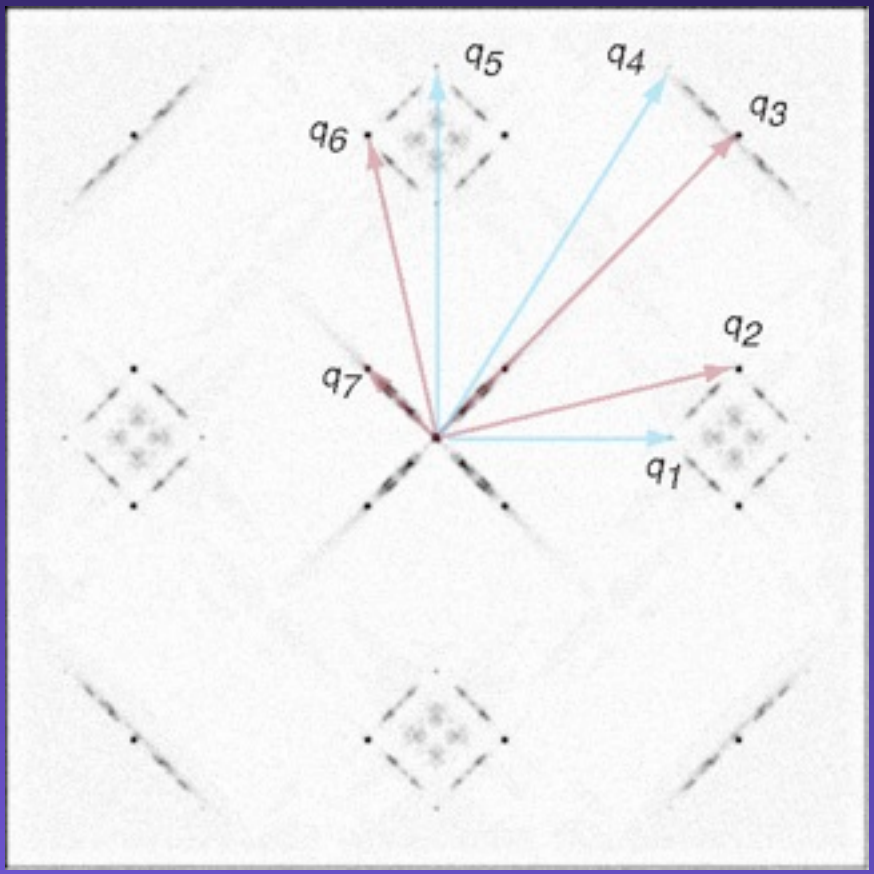


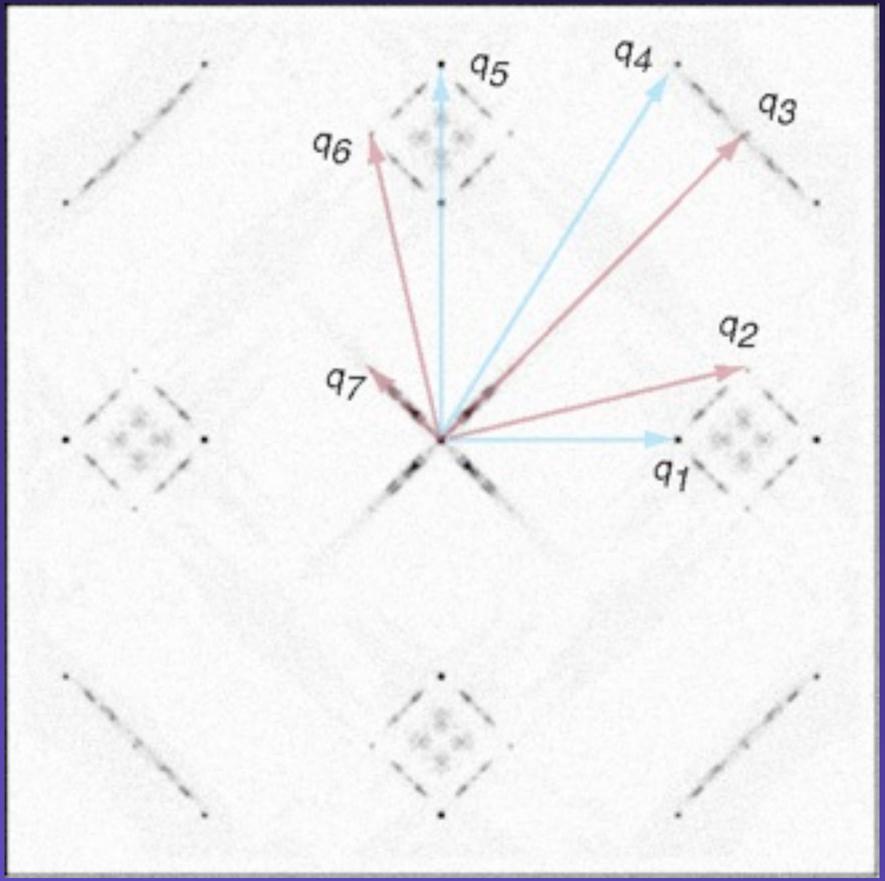


Nematic critical QPI linecuts



Charge impurity

Sign reversing



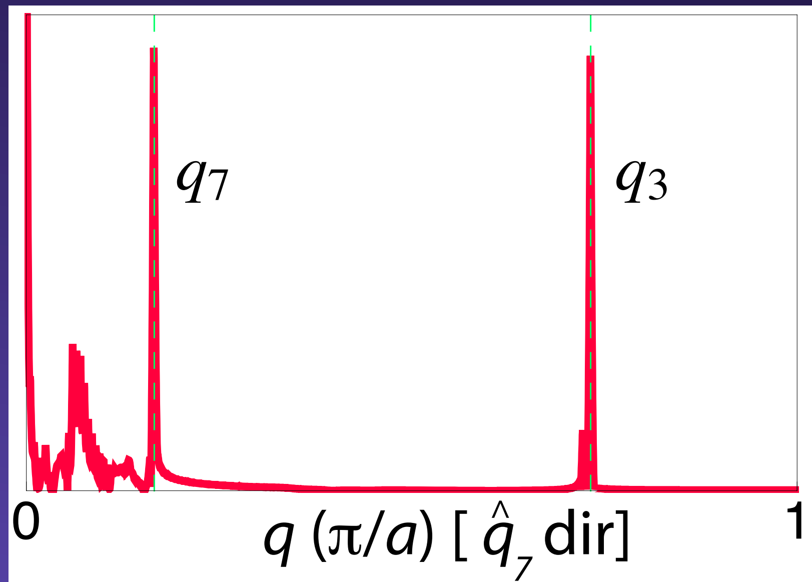
Magnetic impurity

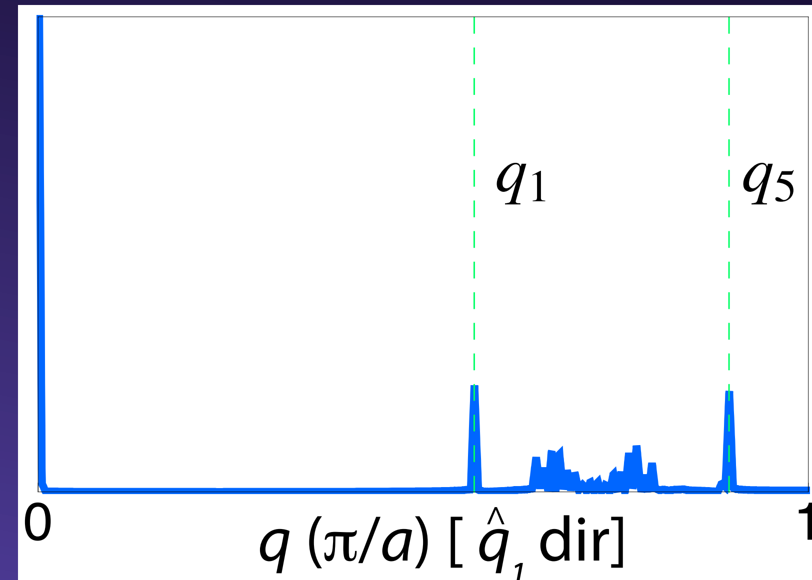
Sign preserving

Nematic critical QPI linecuts

Charge

Sign reversing





Magnetic

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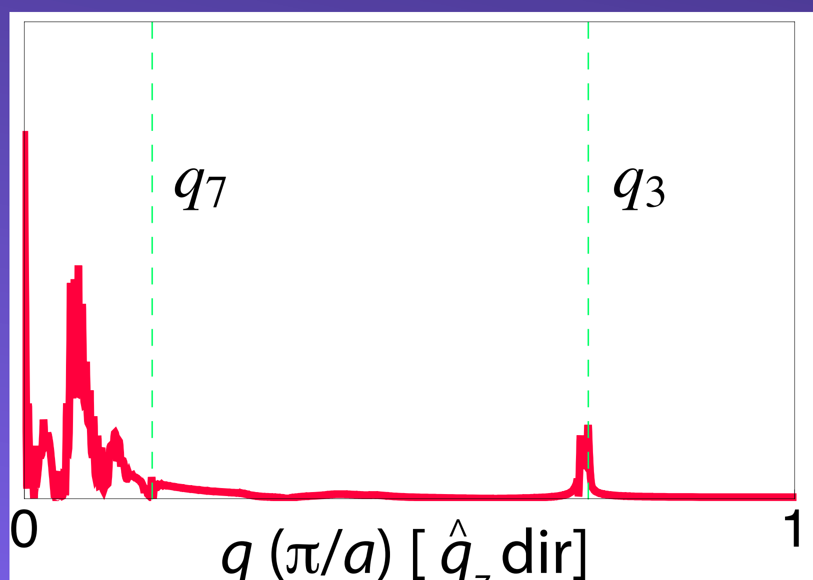
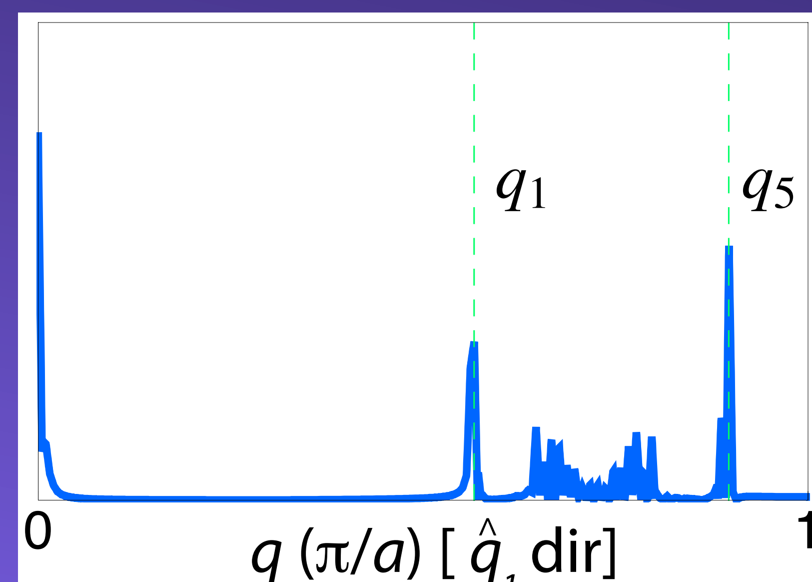




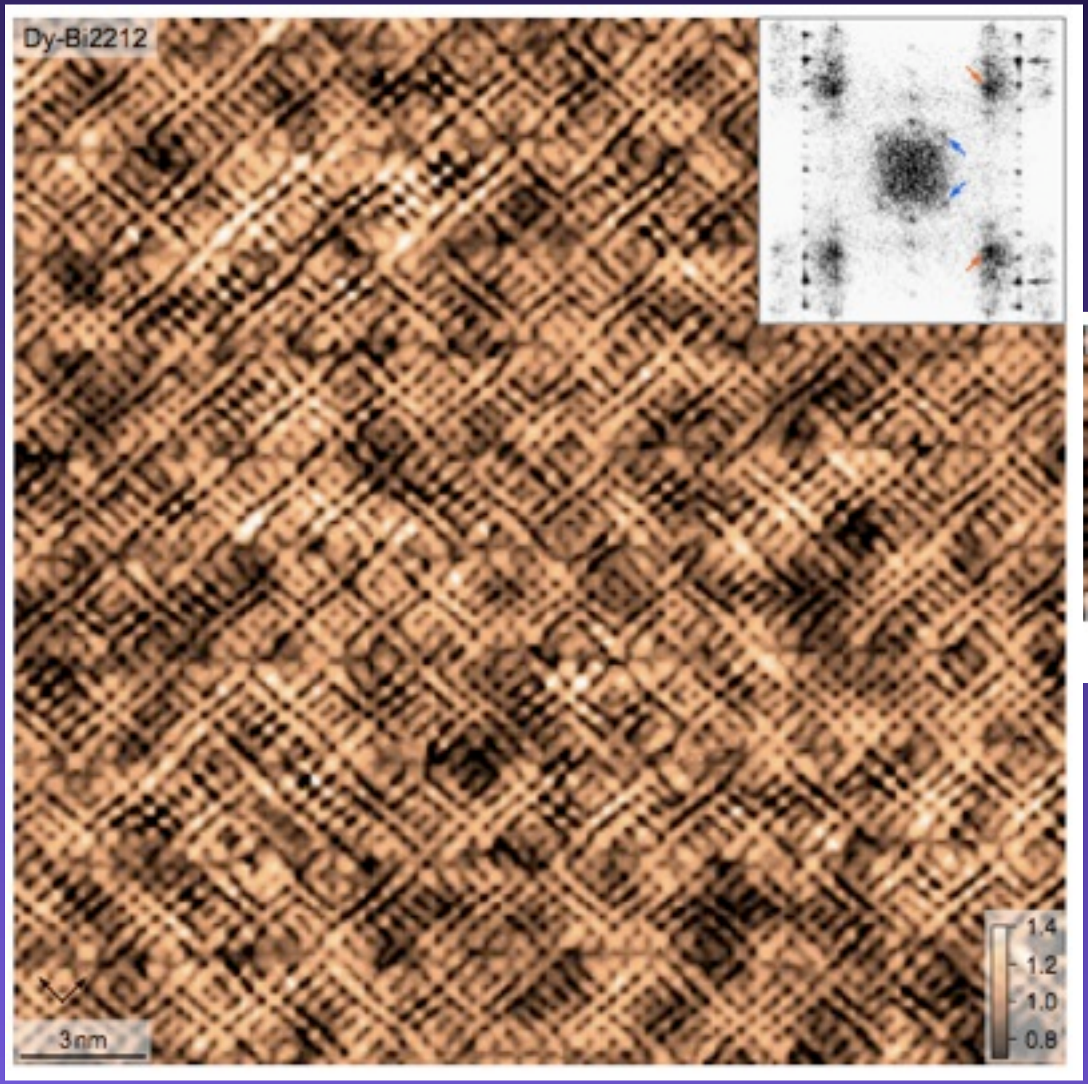
Summary and Outlook

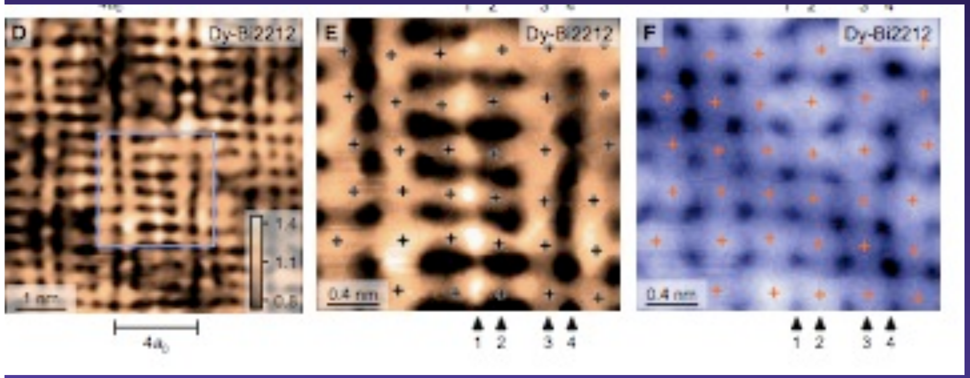
- Coexistence of ELC with SC can allow insight into ELC physics.

- Nodal nematic quantum criticality:
  - A new QCP
  - Nematic fluctuation effect enhances QPI
  - QPI field dependence agrees with experiment

- Growing number of cases for electronic liquid crystalline states in strongly correlated systems.

Glassiness revealed at high energy





Kohsaka et al, Science, 2007