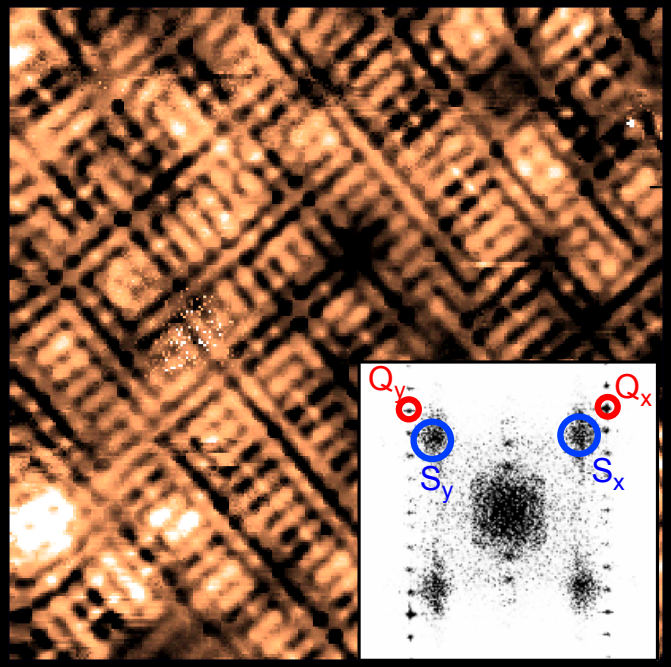
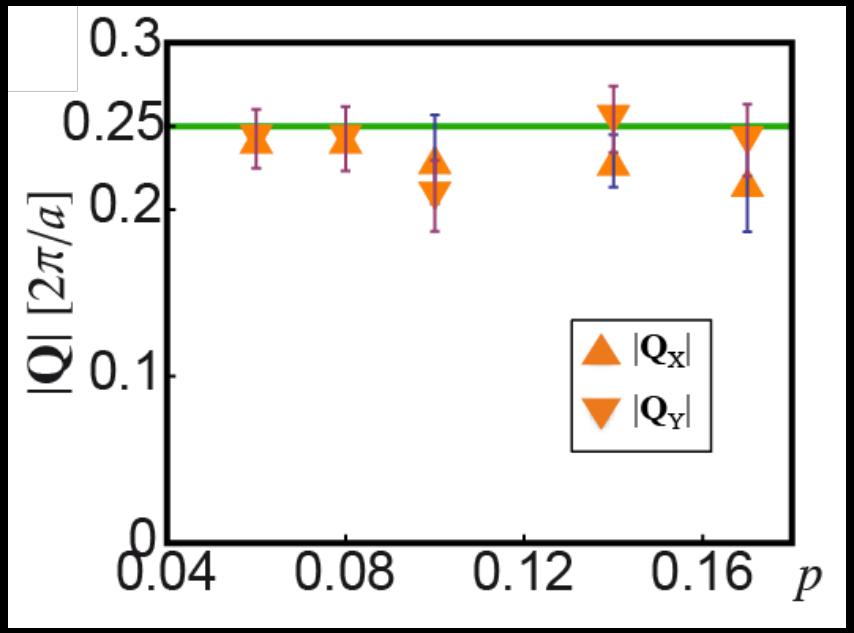
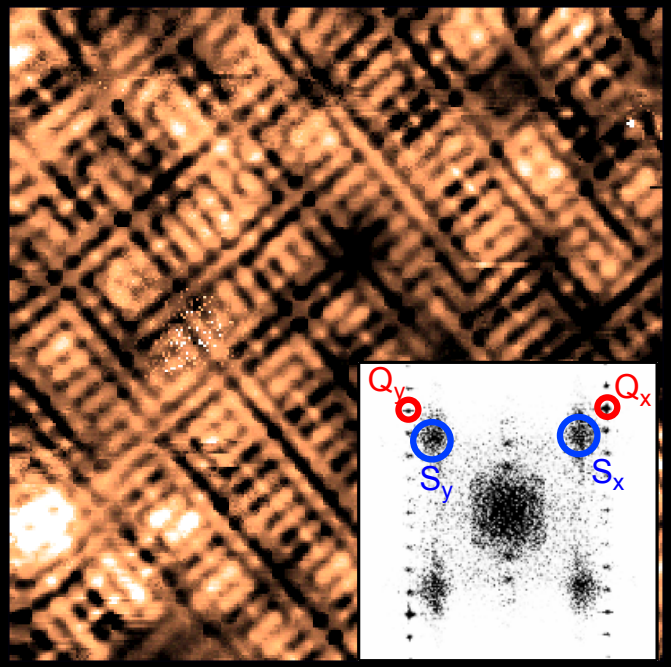
Origin and Implications of Glassy Charge Order in Underdoped Cuprates



Eun-Ah Kim
(Cornell)

Origin and Implications of Glassy Charge Order in Underdoped Cuprates





Eun-Ah Kim
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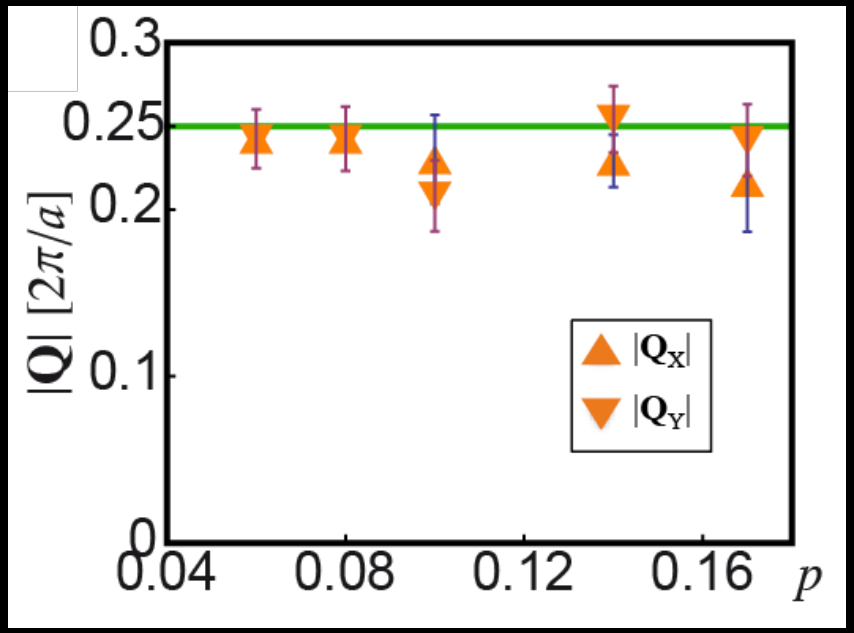

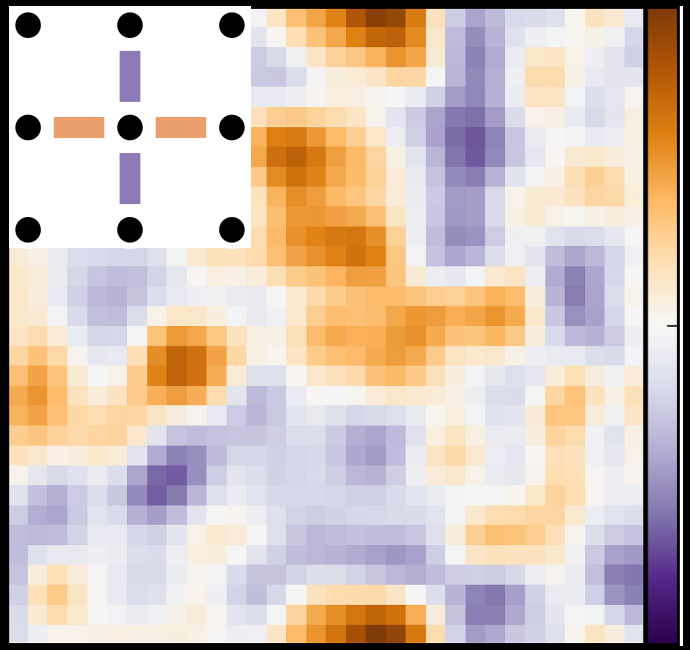

Eun-Ah Kim
(Cornell)

Density Wave and Nematic Order

Tranquada et al, Nature (1995)
Zimmermann et al, Europhys Lett (1998)
Howald et al, PRB (2003)
Abbamonte et al , Nature Phys (2005)
Ghiringhelli et al, Science (2012)
Blackburn et al PRL (2013)
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de Silva Neto et al, Science (2014)
Fujita et al, PNAS (2014)
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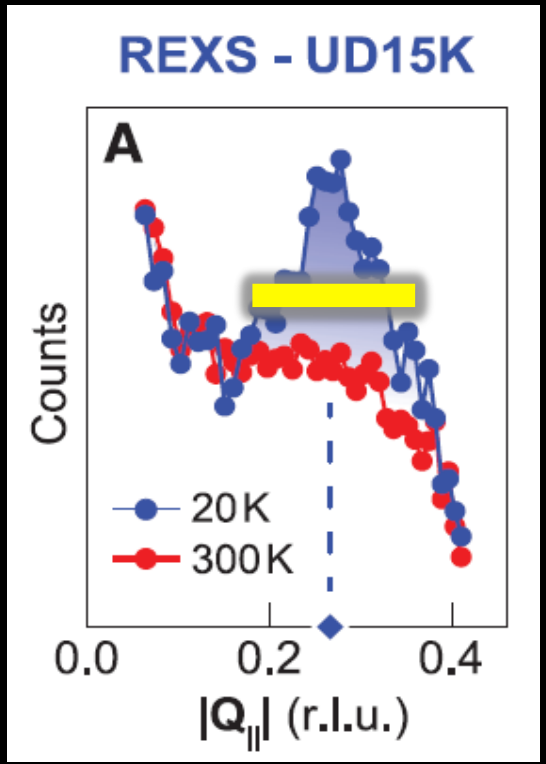

Comin *et al.* (2014)

Density Wave and Nematic

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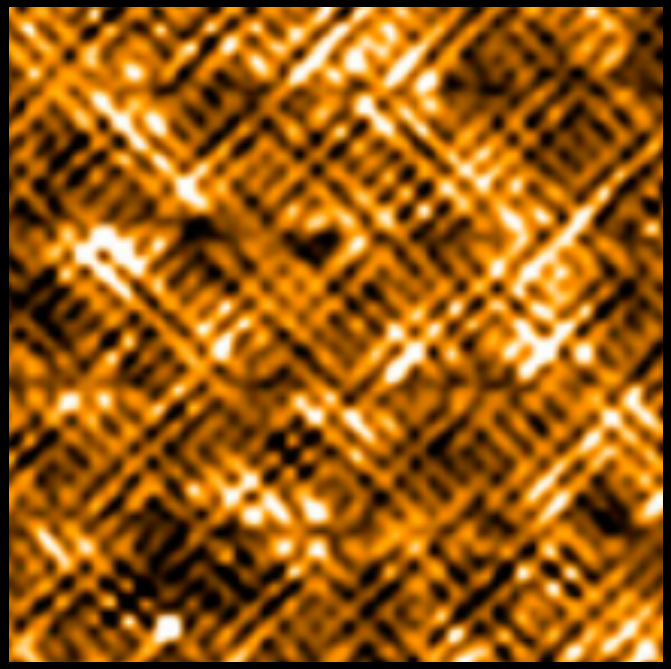
Local Information!



Fujita *et al.* (2014)

Origin and Implications of Glassy Charge Order in Underdoped Cuprates

Origin:
r-space or k-space?

Universality of Commensurate 4a period

Andrej Mesaros
Cornell

Kazuhiro Fujita
BNL

Stephen Edkins
St Andrews

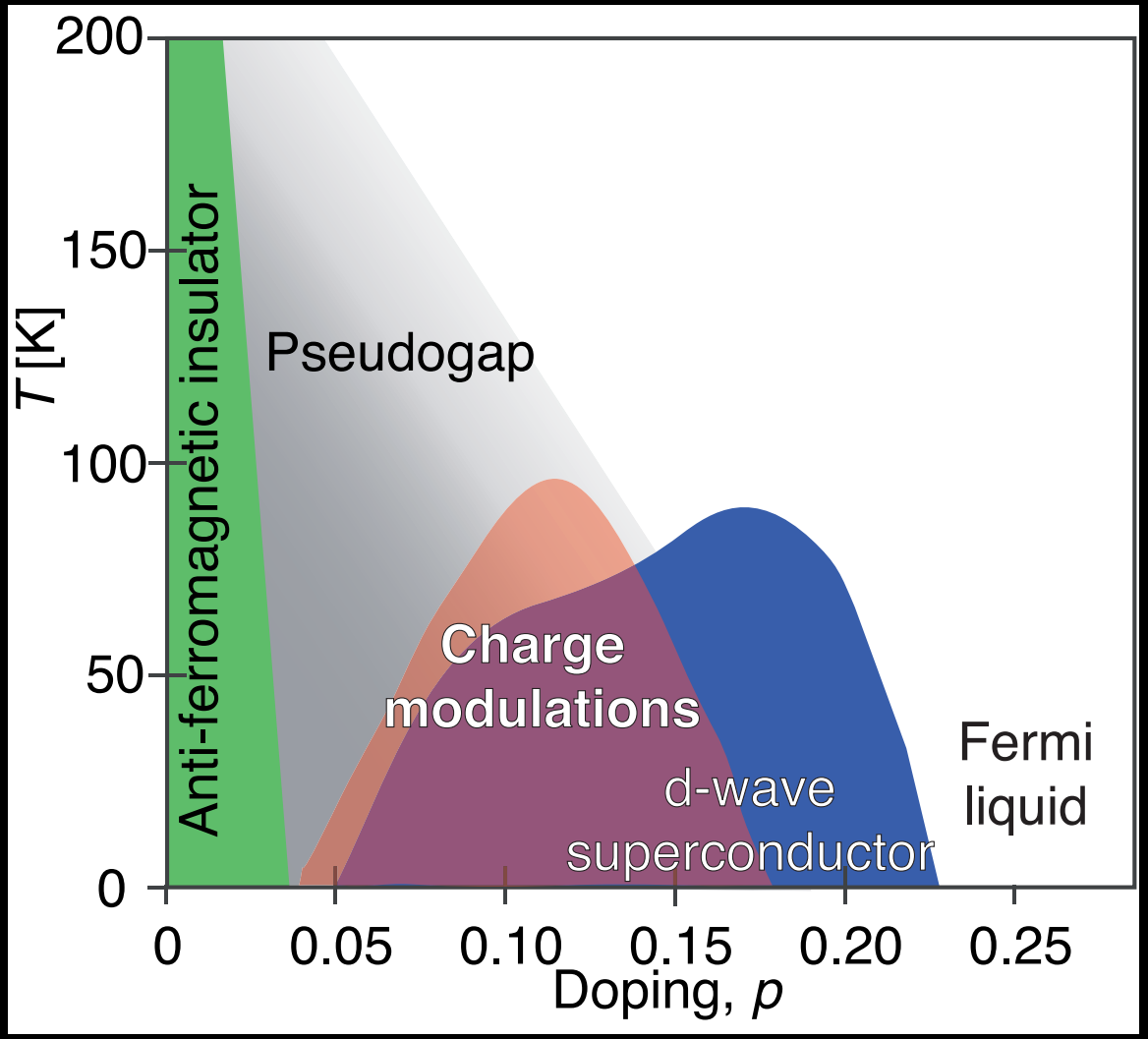
Mohammad Hamidian
Harvard

Michael Lawler
Cornell/Binghamton

J.C. Seamus Davis
Cornell/BNL

Mesaros et al, H8.00001 2:30pm Tuesday (304)

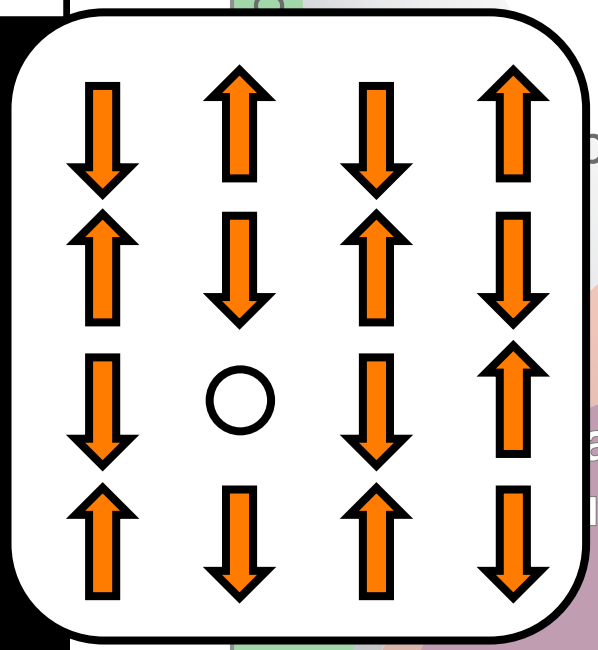
Underdoped Cuprates



Keimer *et al.*, Nature(2015); Comin *et al.*, arXiv(2015)

Underdoped Cuprates

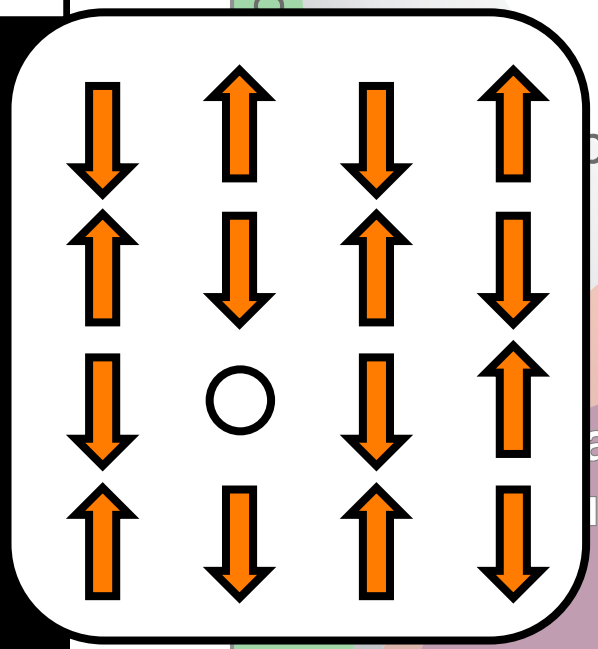
r-space



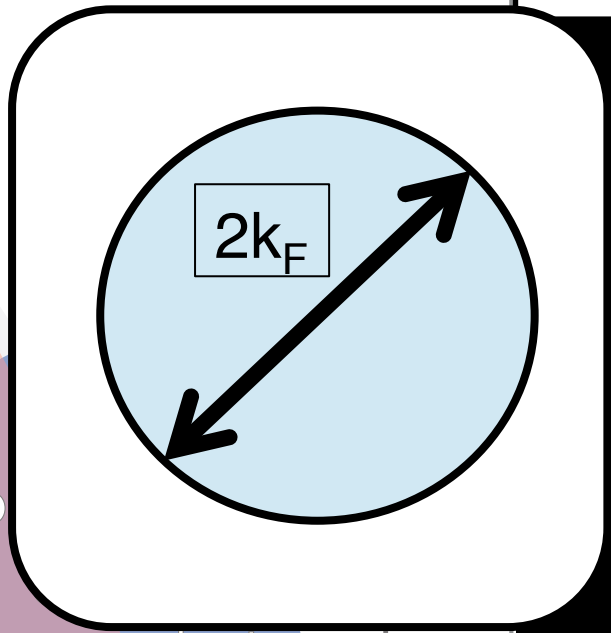
Keimer *et al.*, Nature(2015); Comin *et al.*, arXiv(2015)

Underdoped Cuprates

r-space



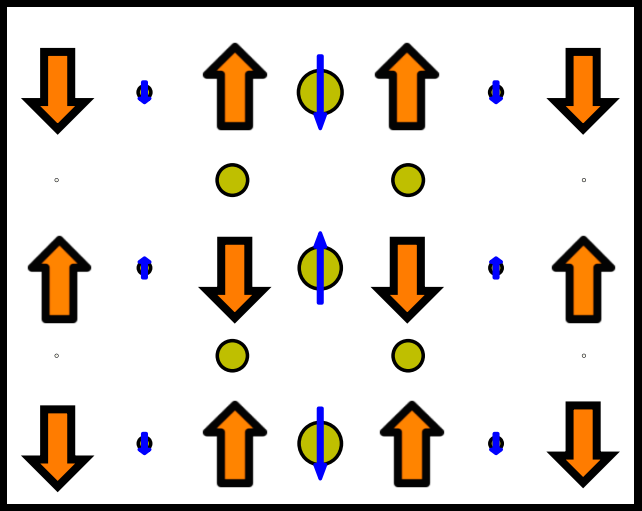
k-space



Keimer *et al.*, Nature(2015); Comin *et al.*, arXiv(2015)

Strong Coupling Mechanism

- Frustration of AFM order upon doping



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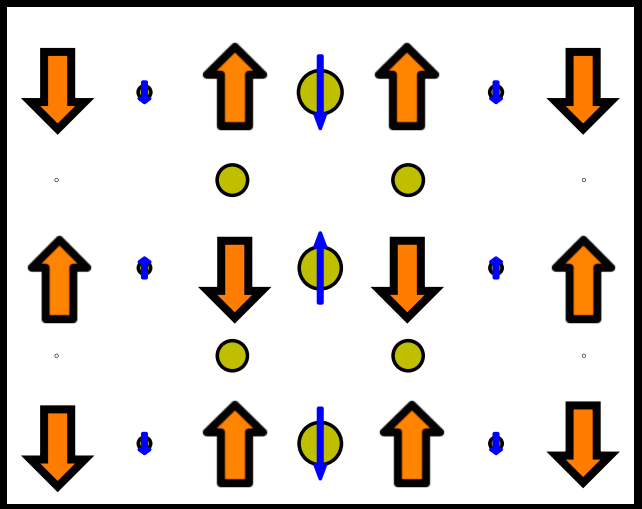
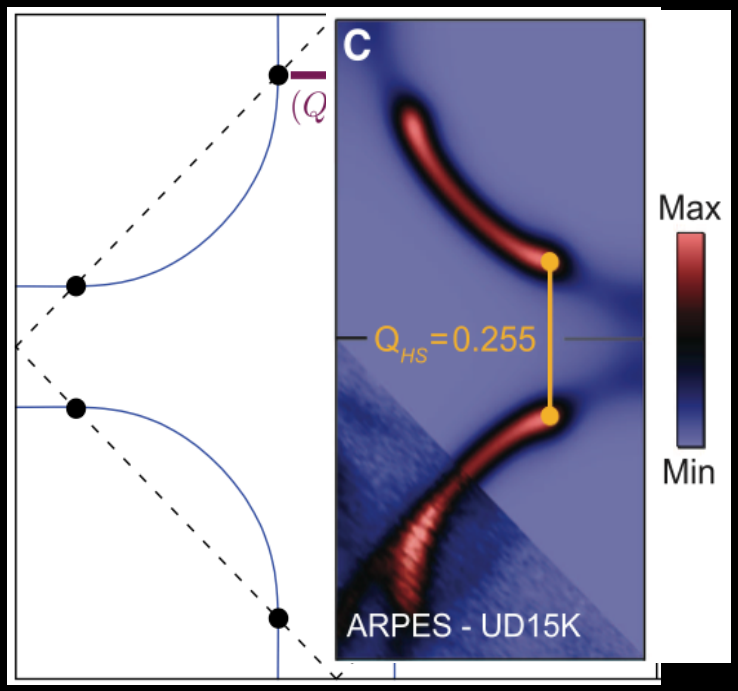


Zaanen, Gunnarson, PRB (1989)
Low, Emery, Fabricious, Kivelson (1994)
Vojta, Sachdev(1999)
White, Scalapino,PRL(1998)
Capponi, Poilblanc (2002)
Corboz, Rice, Troyer, PRL (2014)
Fischer, EAK *et al.*, NJP (2014)

Commensurate Charge Modulation, period 4a at p=1/8

Weak Coupling Mechnism

- Nesting driven Fermi surface instability

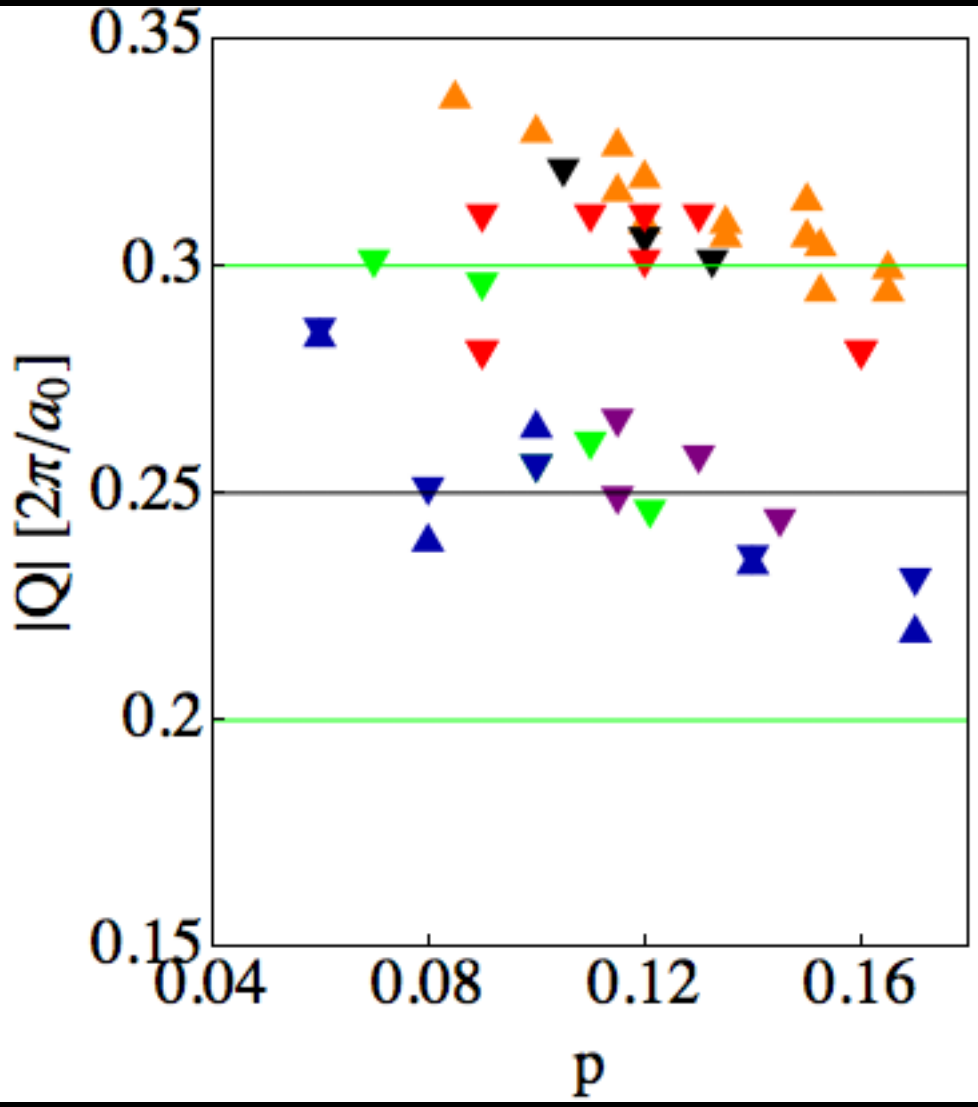


Comin *et al.*, Science(2014)

Efitov et al, Nature Physics (2013)
Pepin et al, PRB (2014)
Wang, Chubukov, PRB (2014)
Loder et al, PRL (2011)

Incommensurate,
Q decrease with *p*

(Conventional) Wavevector *Q*/Hole-density *p*



YBCO XRS, XRD, NMR
Blanco-Canosa *et al.*, PRB(2014)
Blackburn *et al.*, PRL(2013)
Chang *et al.*, NatPhys(2012)
Ghiringhelli *et al.*, Science(2012)
Le Tacon *et al.*, NatPhys(2014)
Wu *et al.*, NatComm(2015)

Hg-1201 RIXS,RXD
Tabis *et al.*, NatComm(2014)

Bi-2212 REXS, RIXS, STS
Da Silva Neto *et al.*, Science(2014)
Hashimoto *et al.*, PRB(2014)
Hamidian *et al.*, NatPhys(2015)

Bi-2201 STS+REXS
Comin *et al.*, Science(2014)

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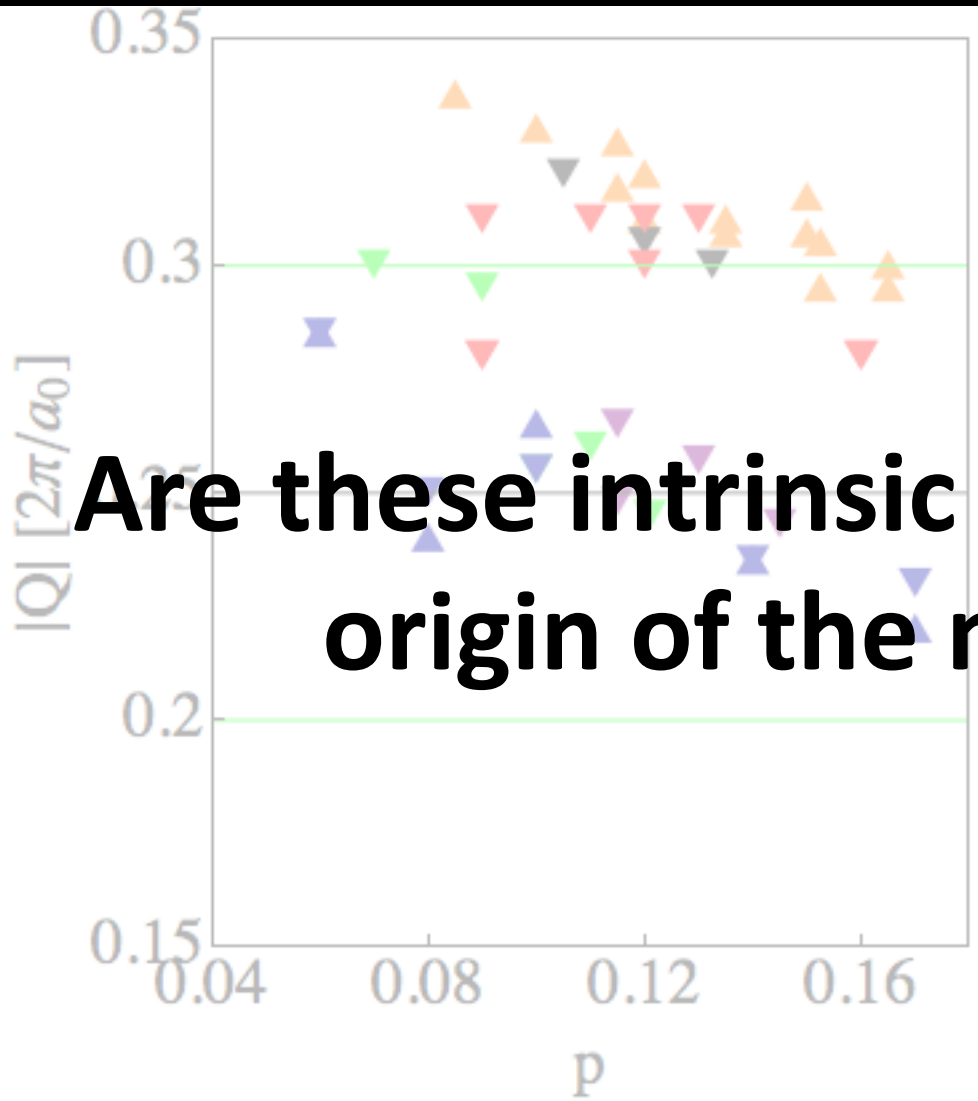

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Bi-2201 STS+REXS
Comin *et al.*, Science(2014)

Are these intrinsic Q's reflecting the origin of the modulation?

Conventional Amplitude Based approach

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- Diffraction probe
  - Phase info lost
  - Fit a line cut of intensity (amplitude)
  - "Average Q"

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- Diffraction probe
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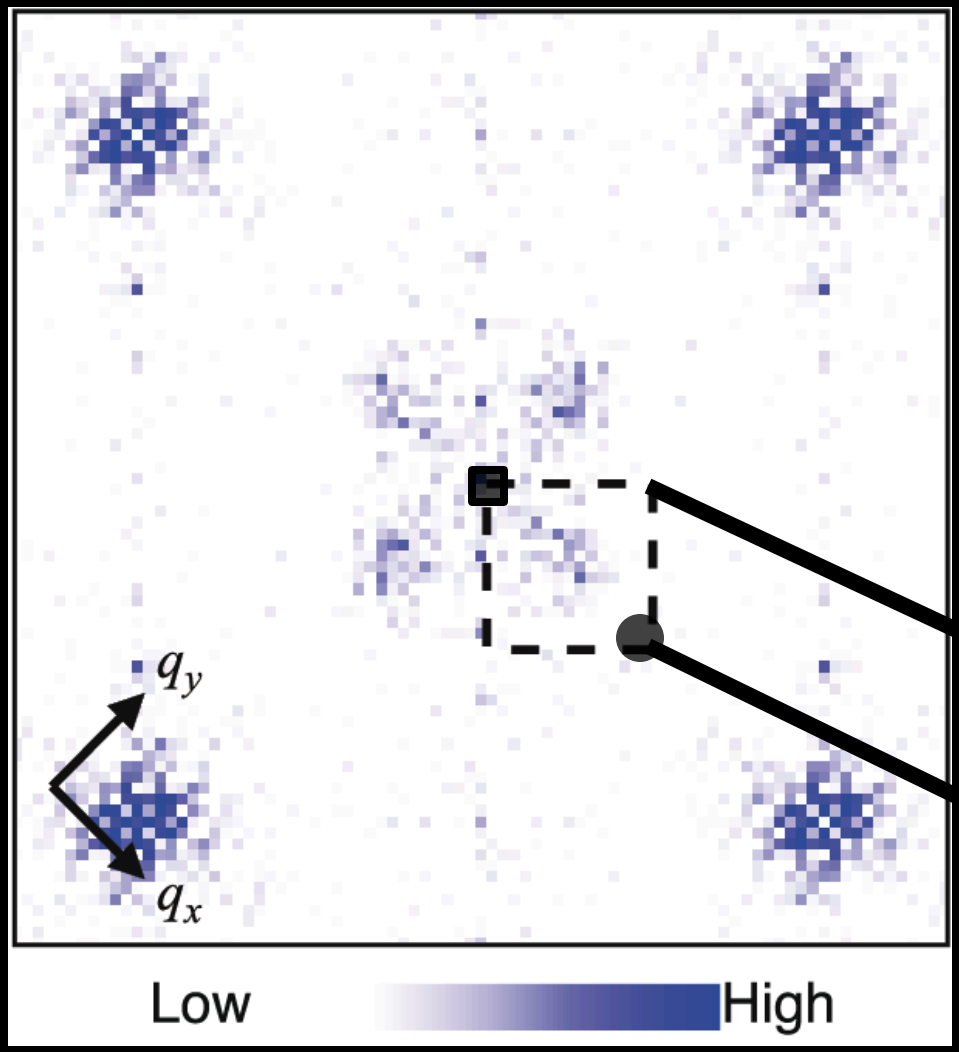
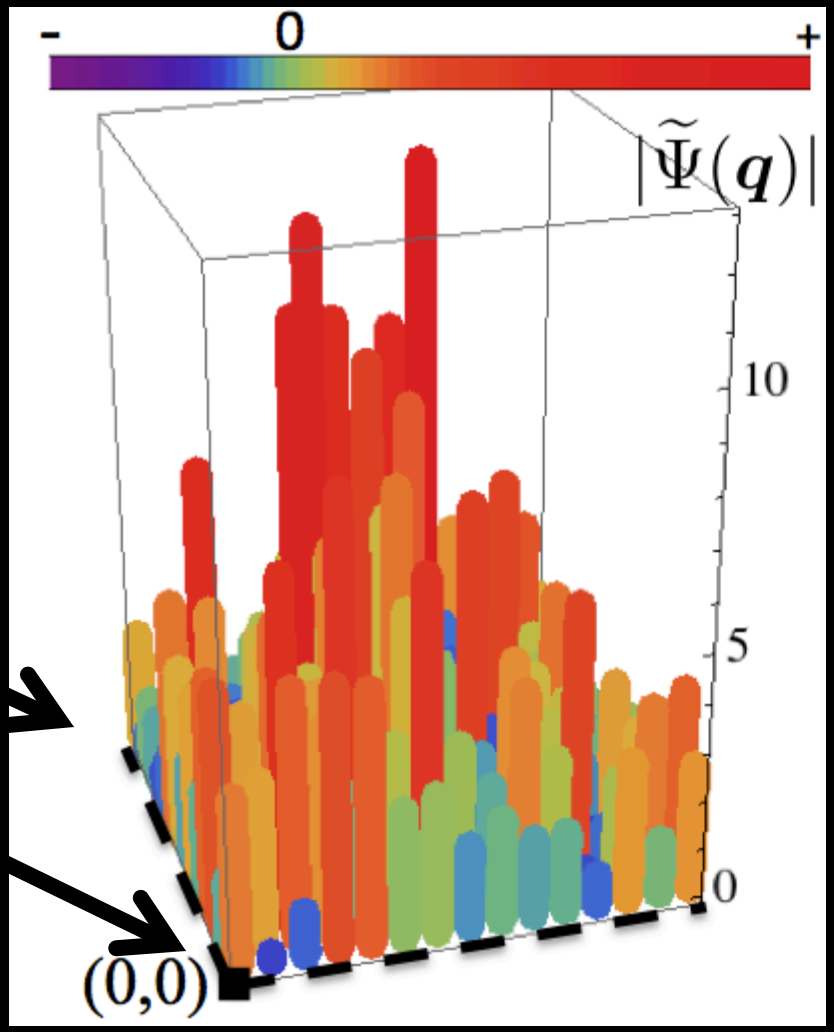
- STM
  - Phase sensitive
  - Fit a line cut of intensity (amplitude)
  - "Average Q"

Fourier Amplitude of dFF CDW



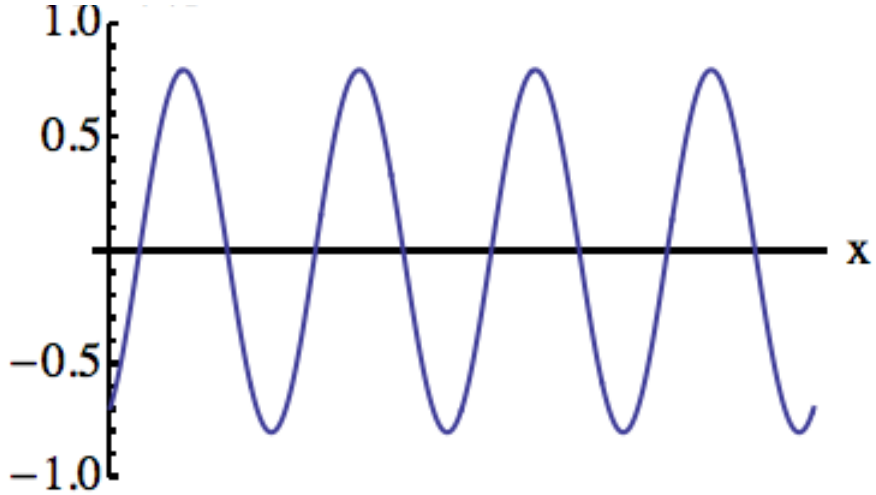


Use the Phase of the Density Wave

Phase of Long Range 1D CDW

$$W(x) = A\exp[iS(x)]$$

$Re[W(x)]$



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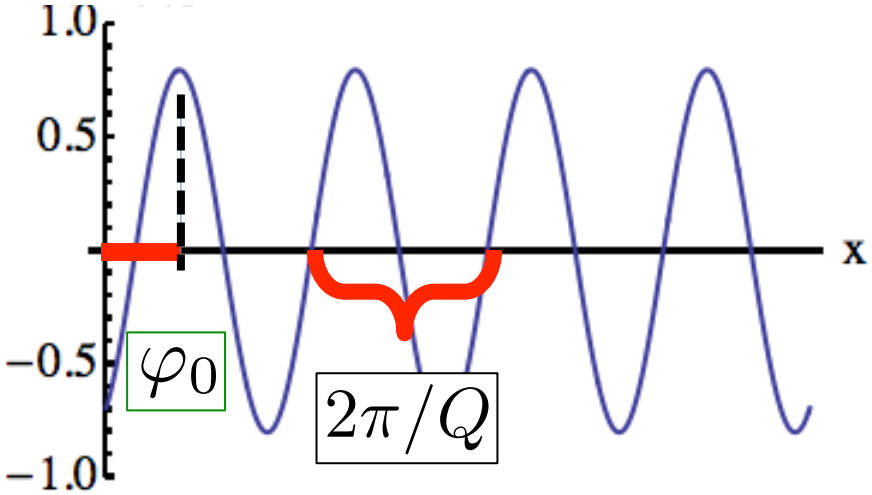
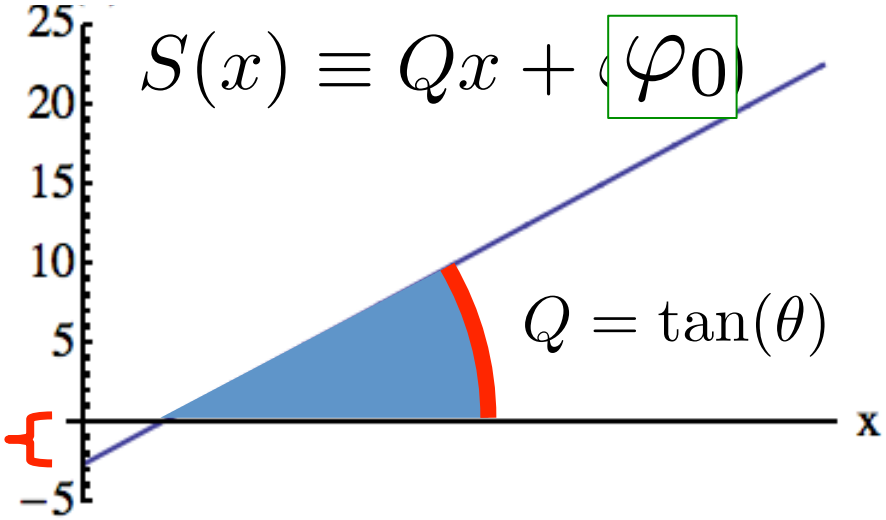
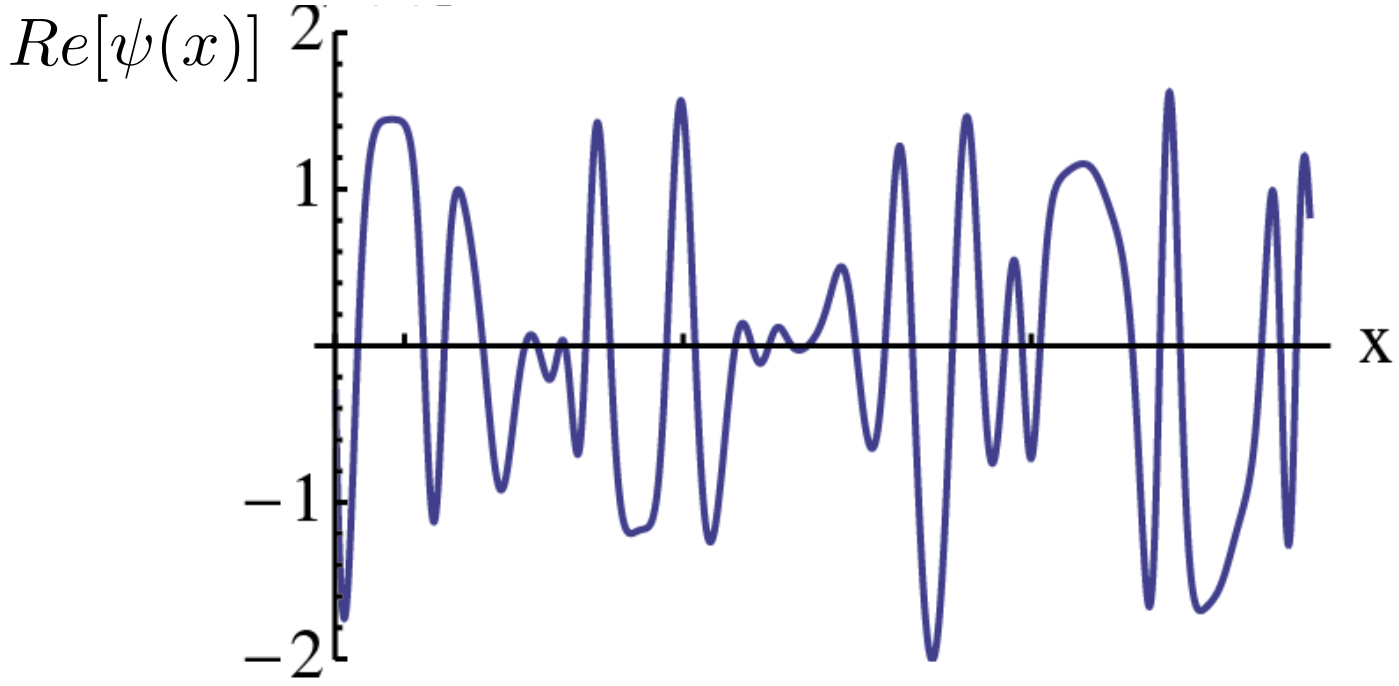


$S(x)$



Phase of Glassy 1D CDW

$$S(x) \equiv Qx + \varphi(x) \qquad \psi(x) \equiv A(x)\exp[iS(x)]$$



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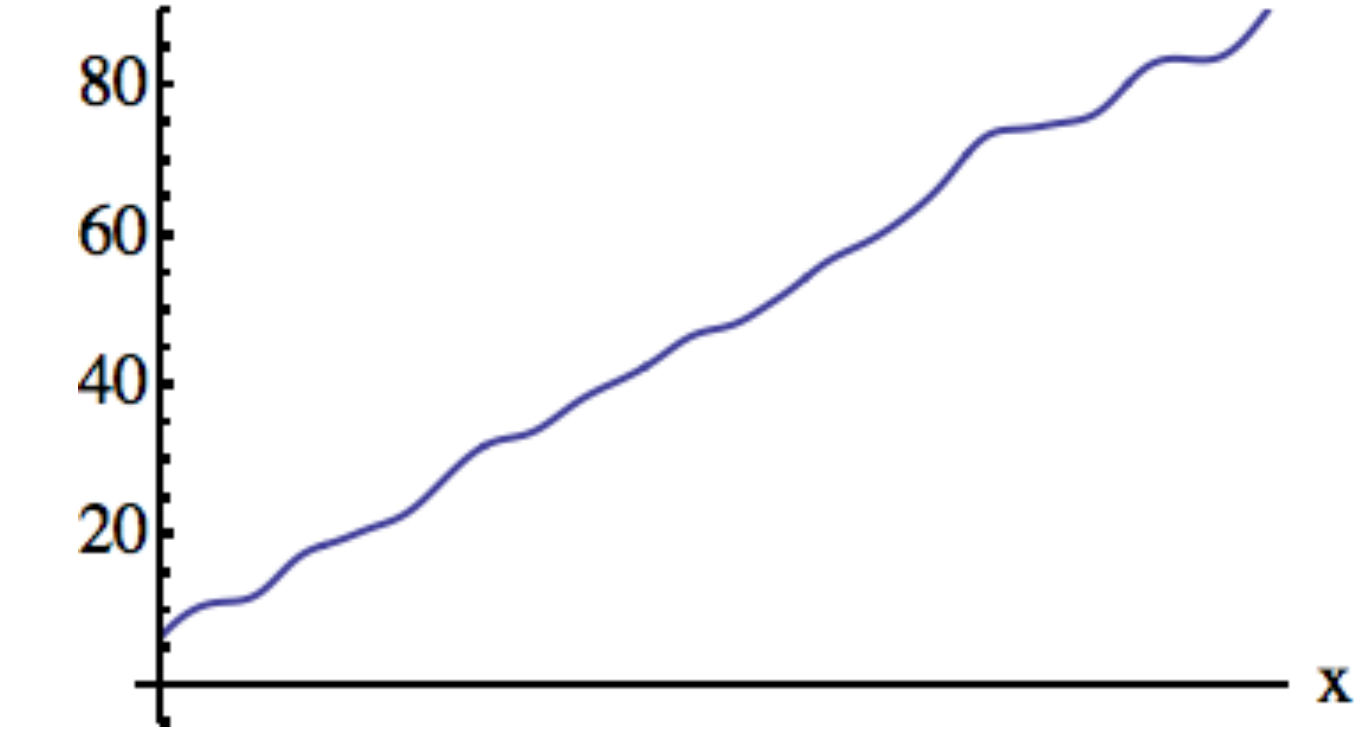

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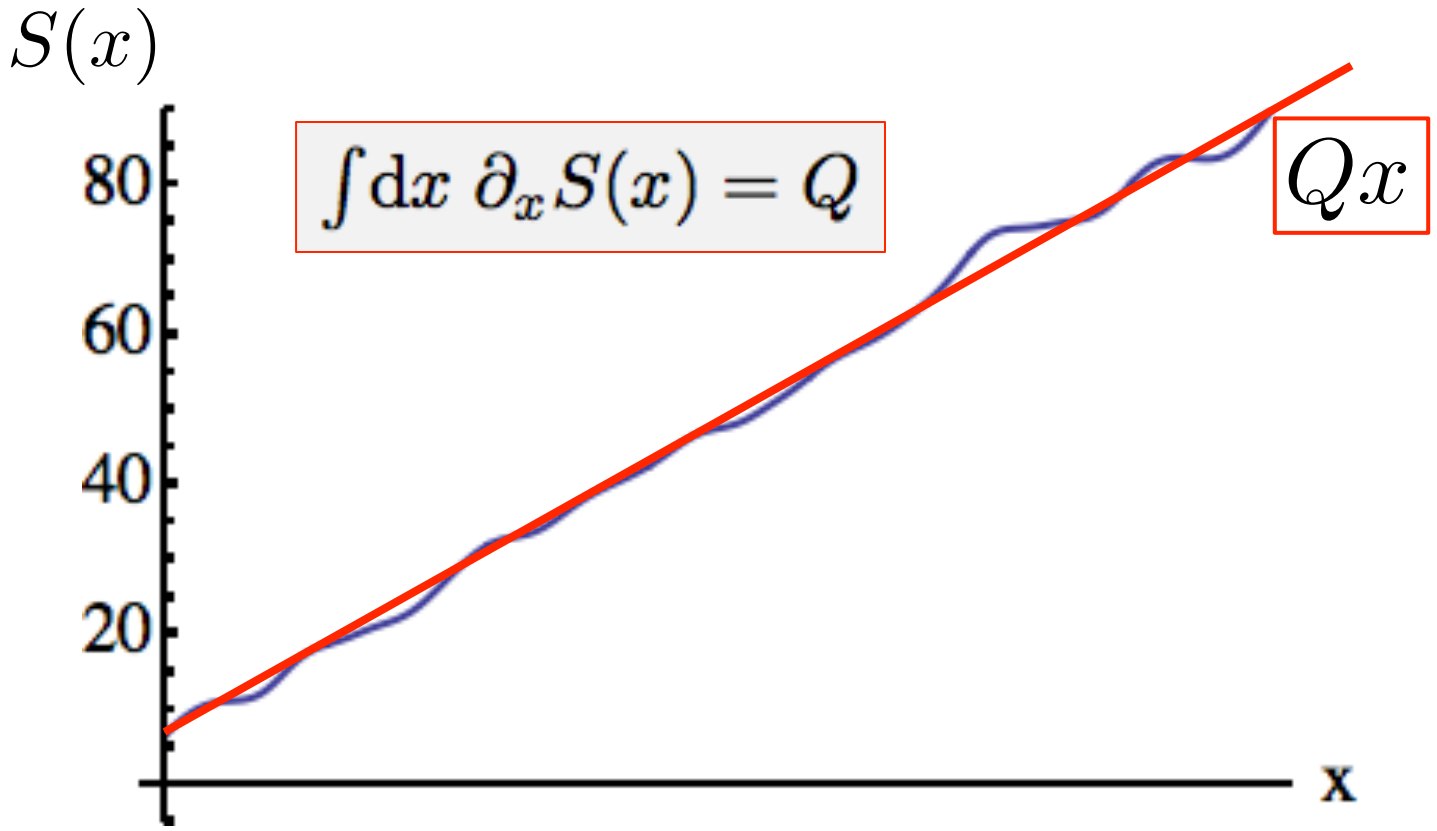

Intrinsic *Q* Search Algorithm

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- Notice

$$\int dx\ \psi^*(i\partial_x)\psi = \int dx\ |A(x)|^2\ \partial_x S(x) \sim Q$$

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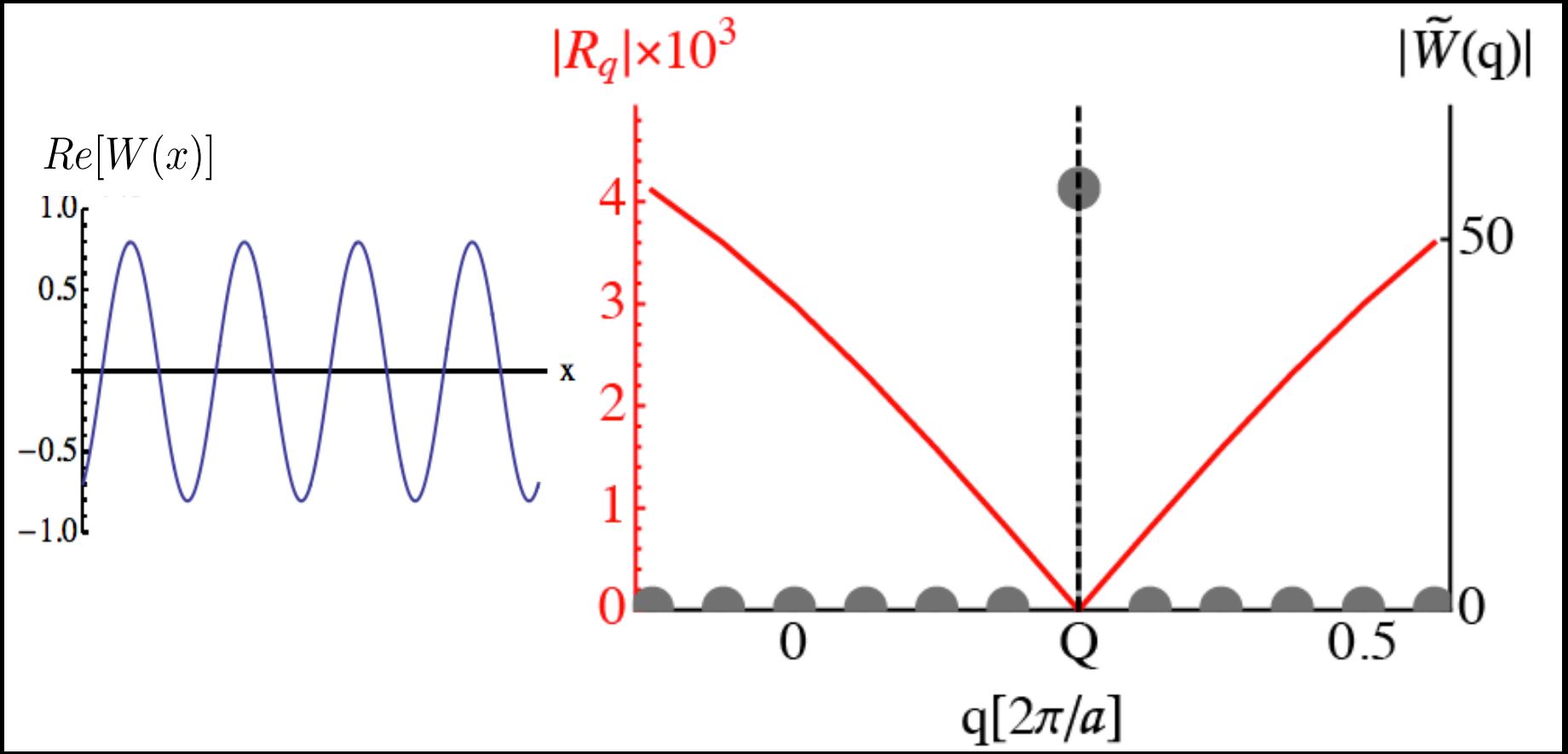
  3. Vanishing residue selects intrinsic *Q*

Min Residue v.s. Max Amplitude

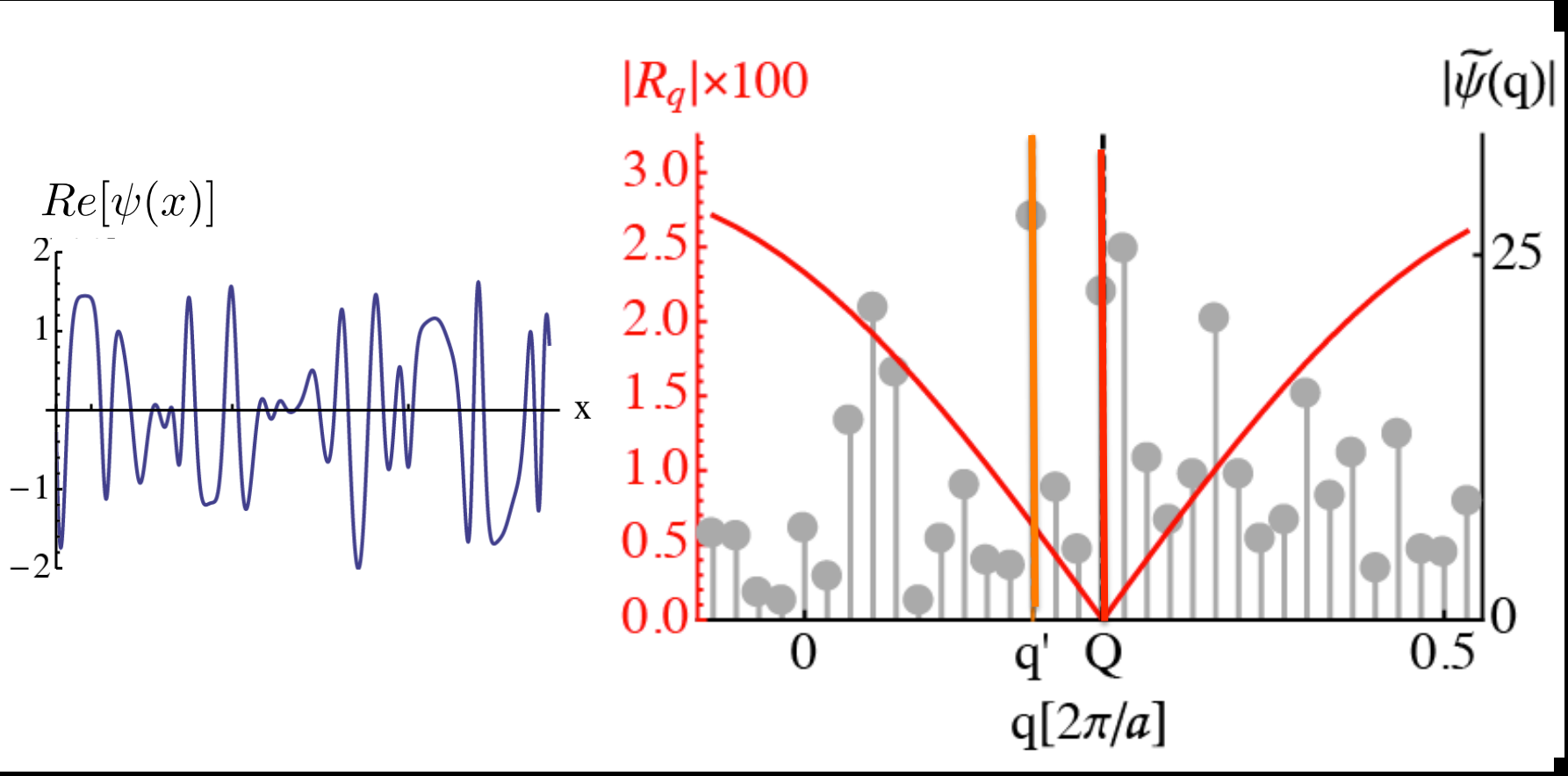
Min Residue v.s. Max Amplitude

Long range ordered CDM



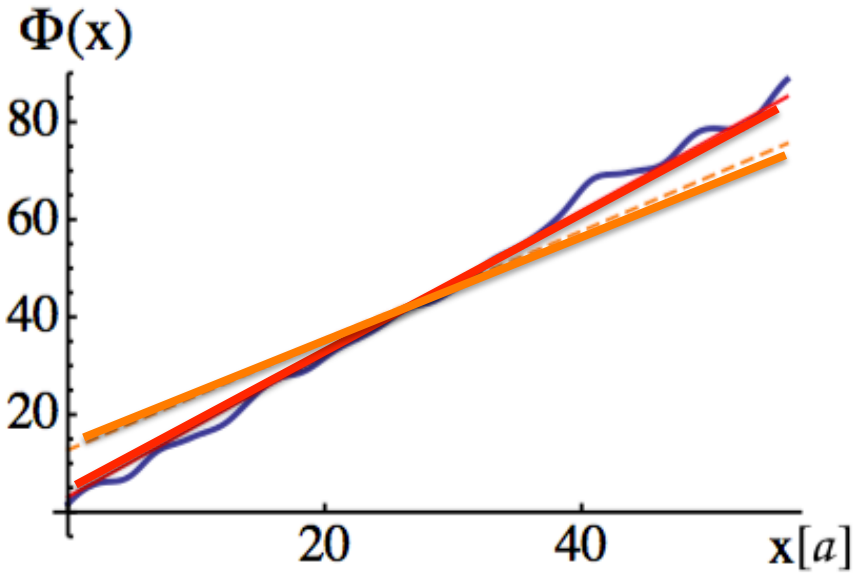
Min Residue v.s. Max Amplitude

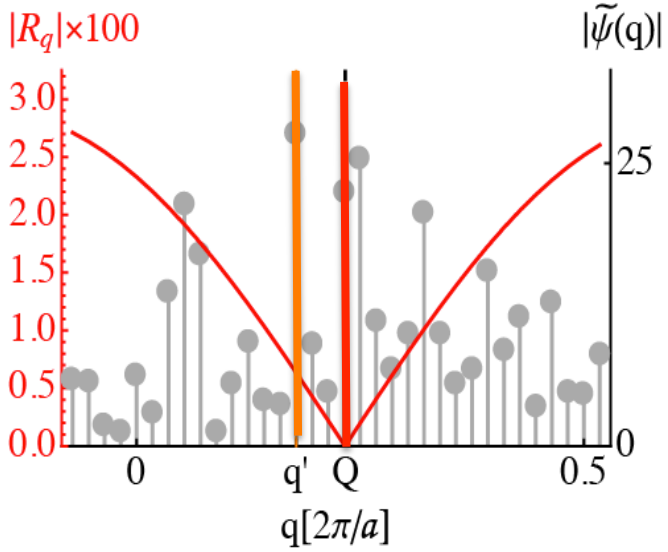
Glassy CDM



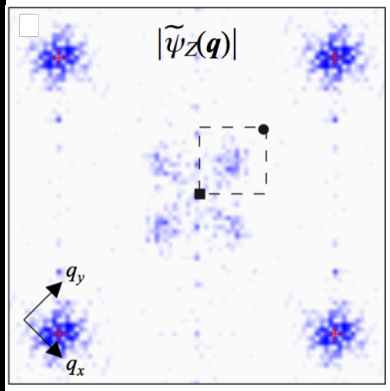
Min Residue v.s. Max Amplitude

Glassy CDM



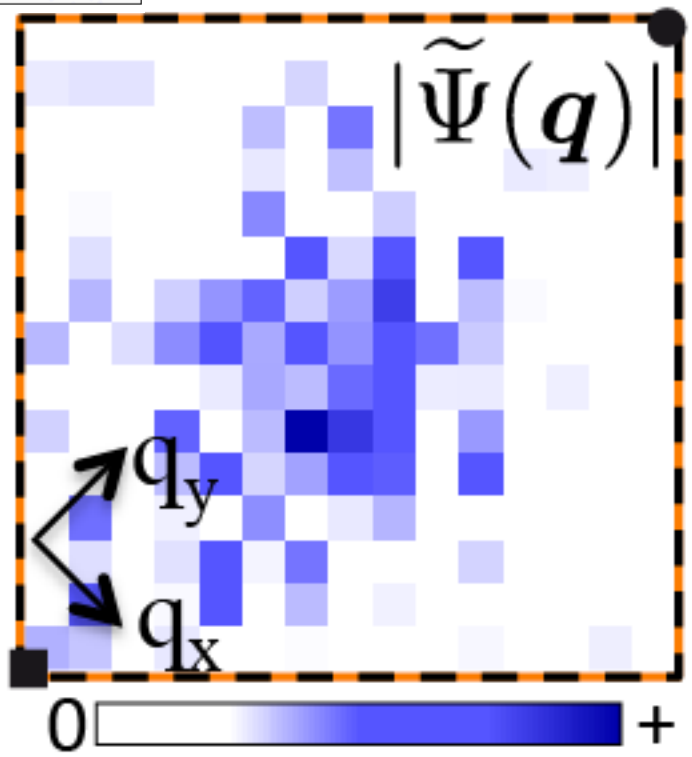


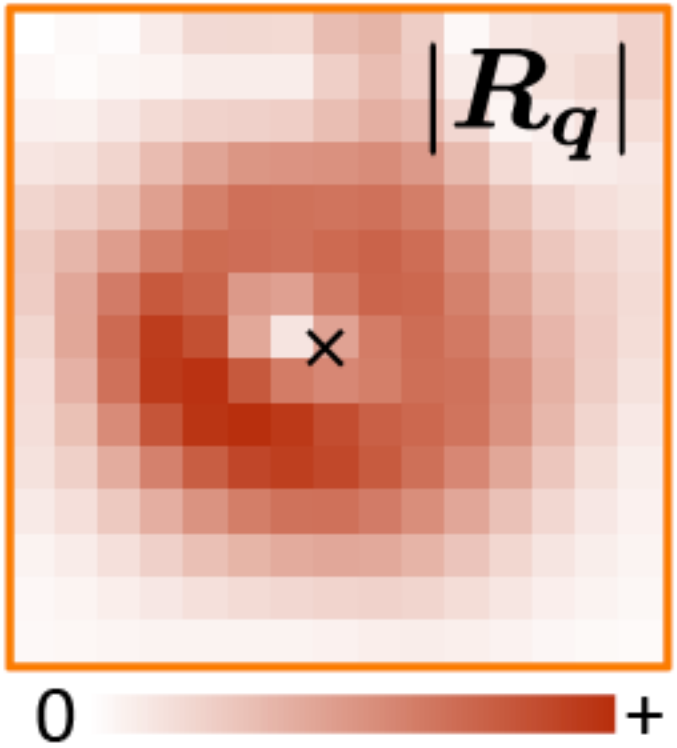
Doping Dependence of Cuprate CDW *Q* from R_q



$$|\boldsymbol{R_q}| \equiv \left| \int d^2\vec{r}\ \vec{R}_{\boldsymbol{q}}(\vec{r}) \right|$$

p=0.06, Q_y



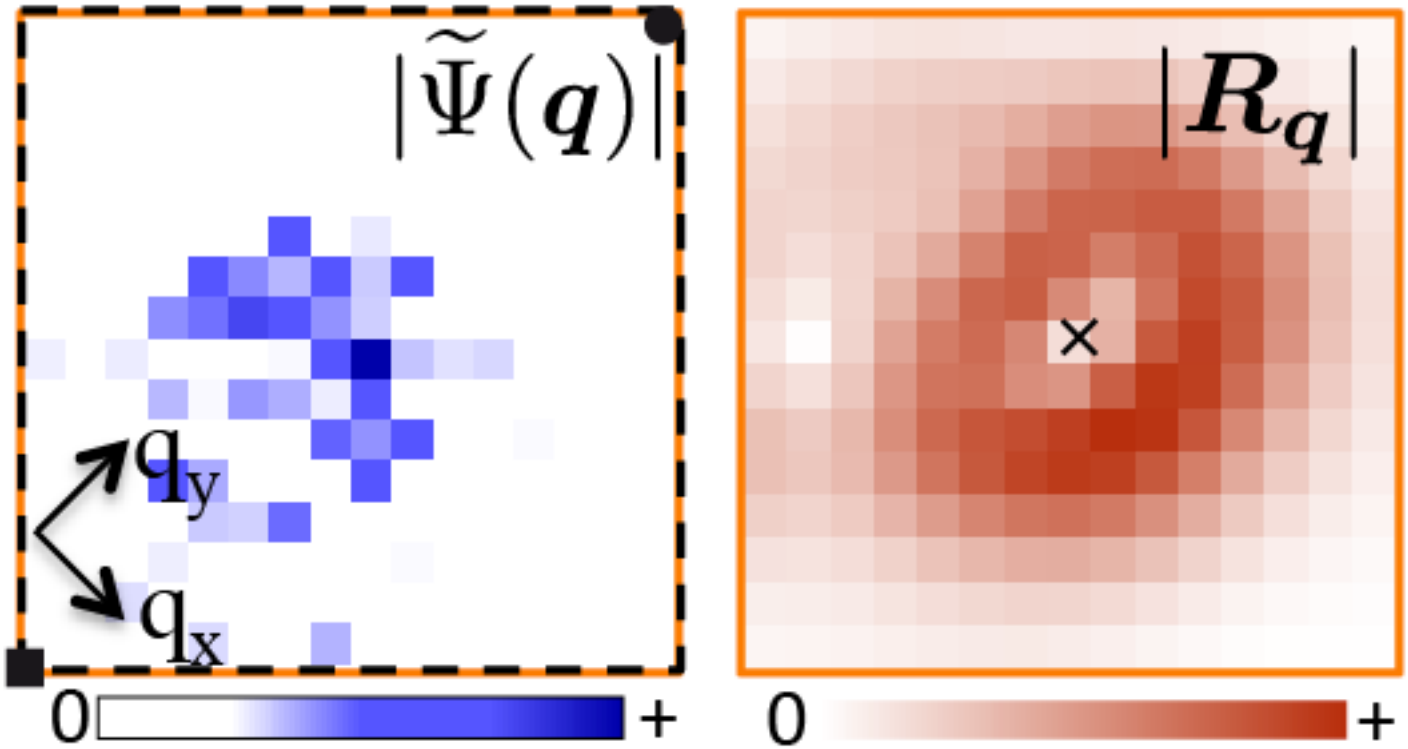


A. Mesaros & EAK et al (2016)

Doping Dependence of Cuprate CDW Q from R_q

$$|\boldsymbol{R_q}| \equiv \left| \int d^2\vec{r}\ \vec{R}_{\boldsymbol{q}}(\vec{r}) \right|$$

p=0.08, Q_y

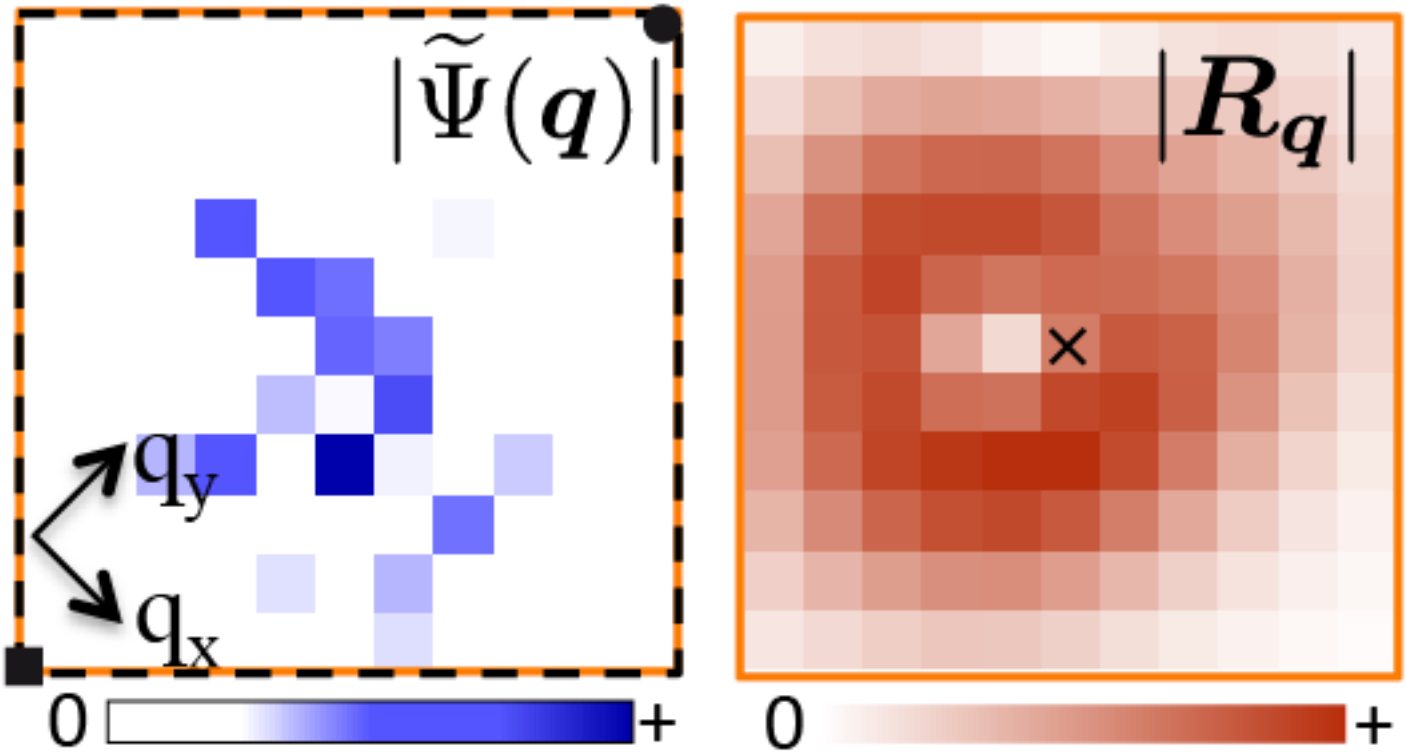


A. Mesaros & EAK et al (2016)

Doping Dependence of Cuprate CDW Q from R_q

$$|\boldsymbol{R_q}| \equiv \left| \int d^2\vec{r}\, \vec{R}_{\boldsymbol{q}}(\vec{r}) \right|$$

p=0.10, Q_y

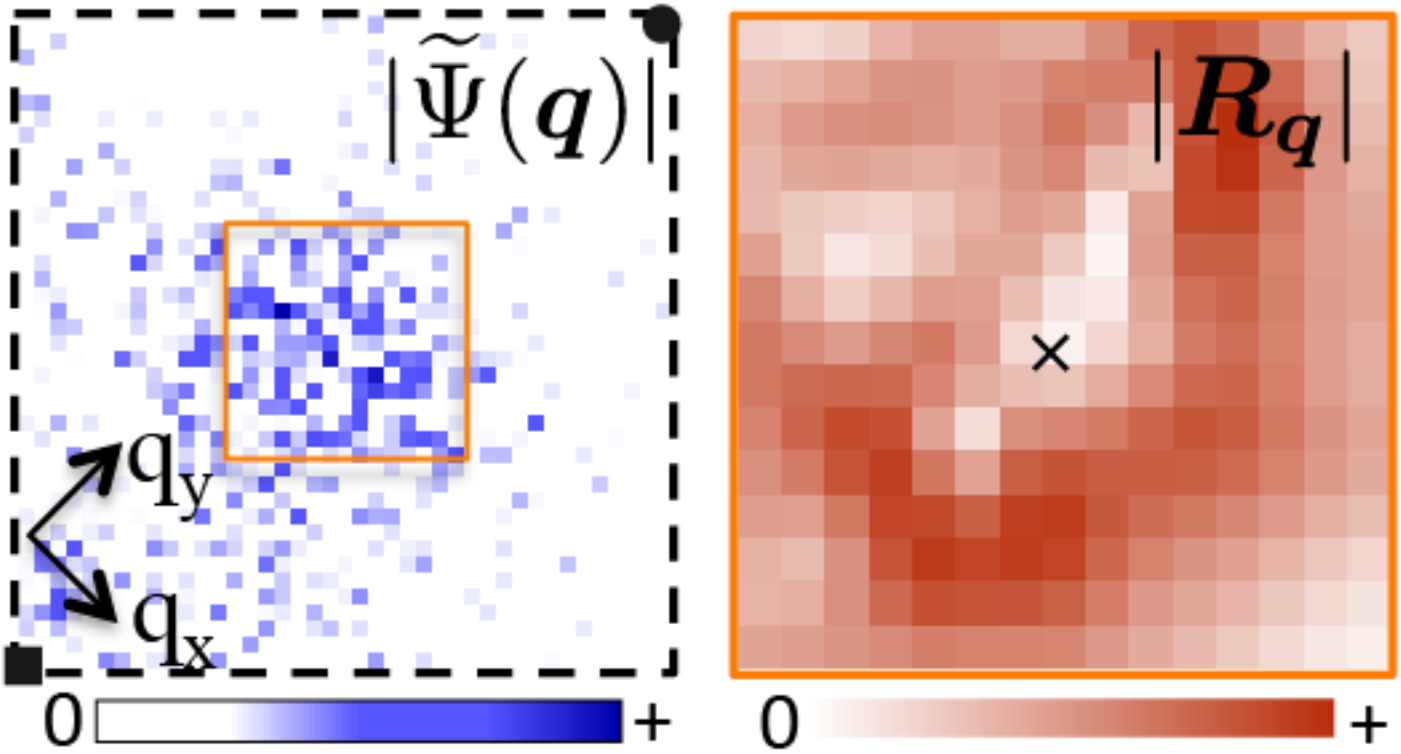


A. Mesaros & EAK et al (2016)

Doping Dependence of Cuprate CDW *Q* from R_q

$$|\boldsymbol{R_q}| \equiv \left| \int d^2\vec{r}\; \vec{R}_{\boldsymbol{q}}(\vec{r}) \right|$$

p=0.14, Q_y

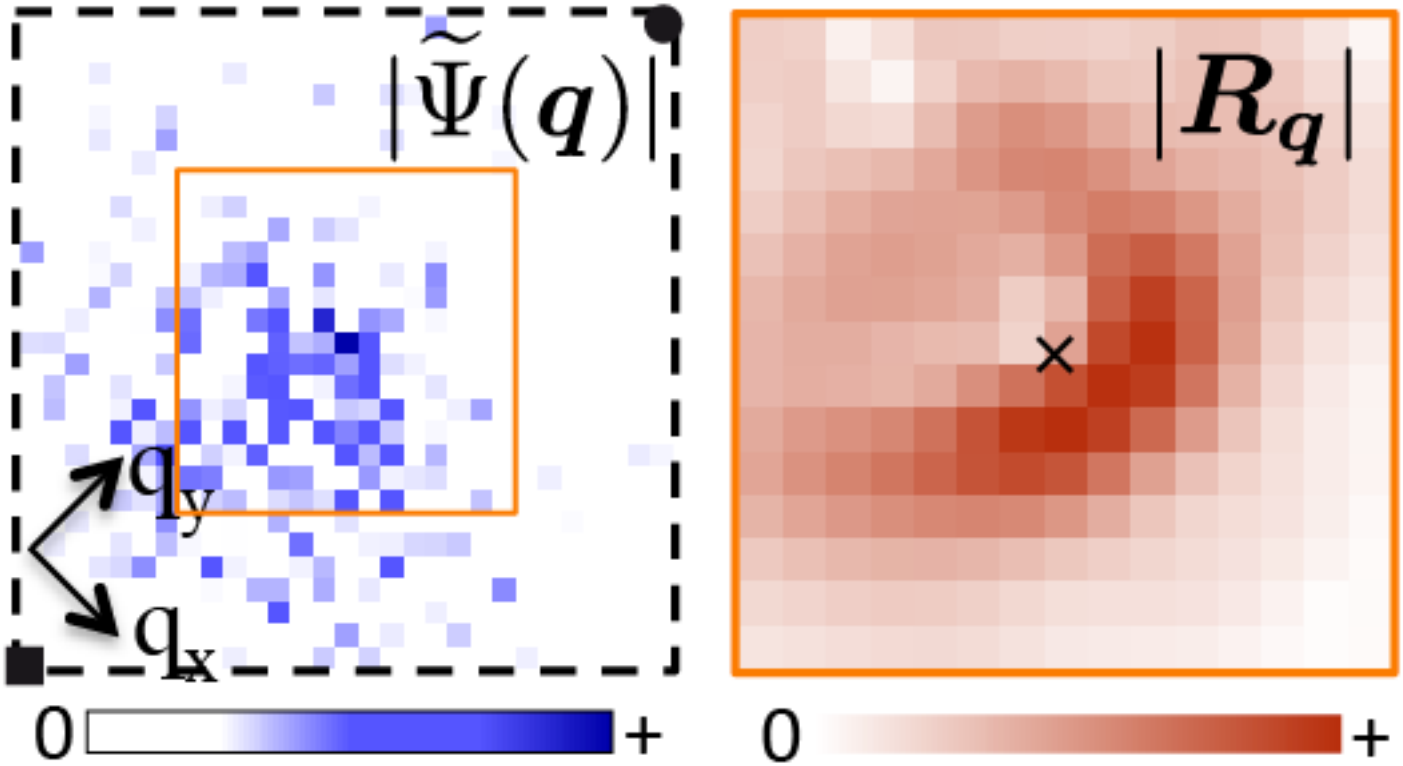


A. Mesaros & EAK et al (2016)

Doping Dependence of Cuprate CDW Q from R_q

$$|\boldsymbol{R_q}| \equiv \left| \int d^2\vec{r}\ \vec{R}_{\boldsymbol{q}}(\vec{r}) \right|$$

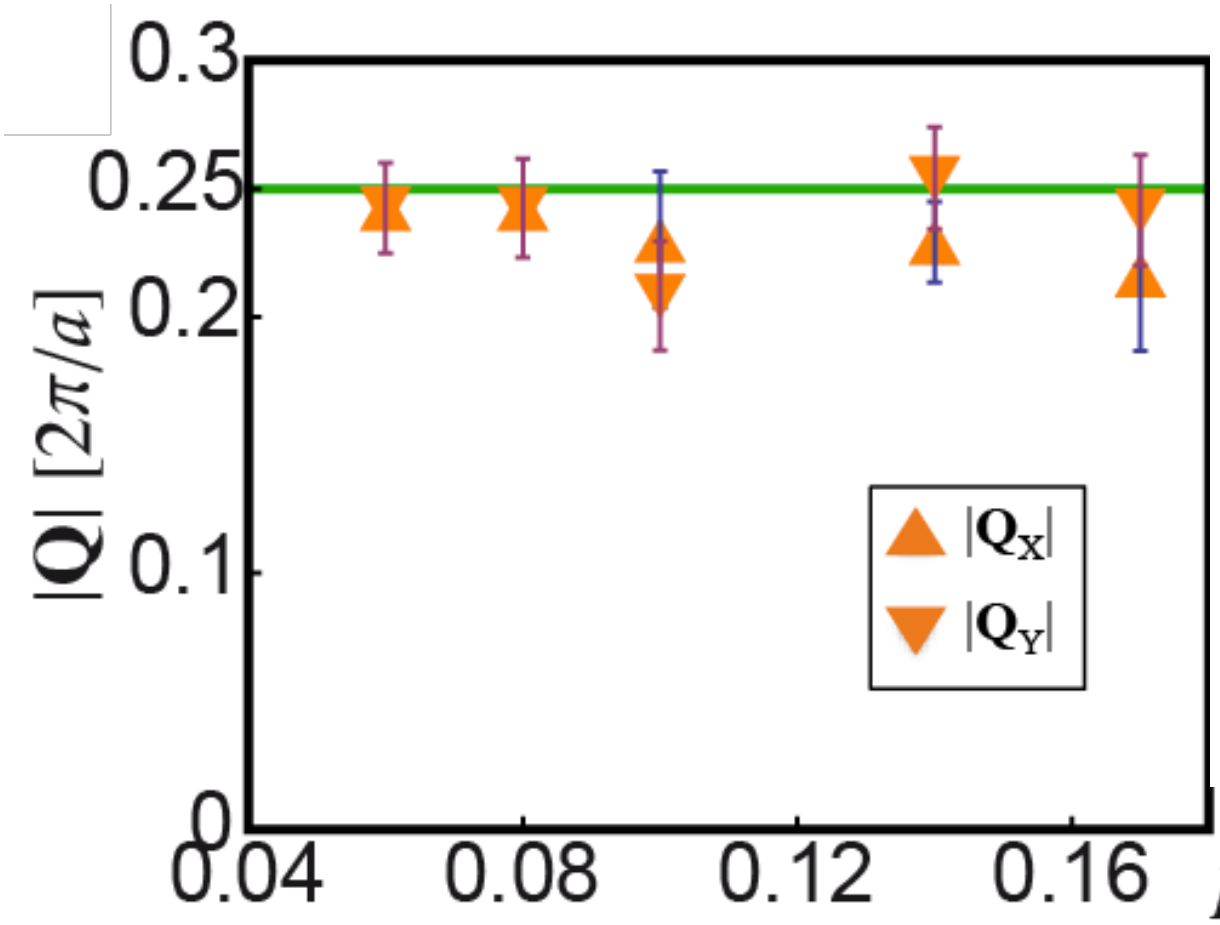
p=0.17, Q_y

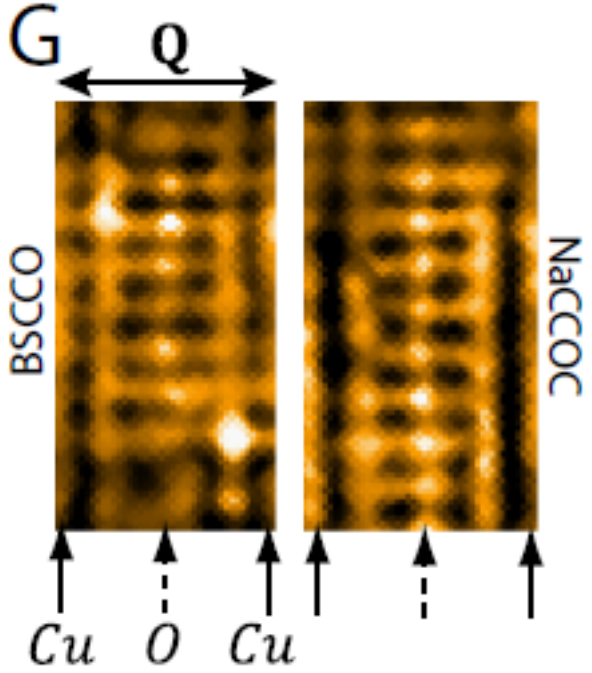


A. Mesaros & EAK et al (2016)

Doping Dependence of Cuprate CDW Q from R_q

Universality of Commensurate $4a_0$ CDW in BSCCO-2212





Origin and Implications of Glassy Charge Order in Underdoped Cuprates

Implications:
"Anomalous" spectral features?

Cold-spots and glassy nematicity in underdoped cuprates

Kyungmin Lee
Cornell

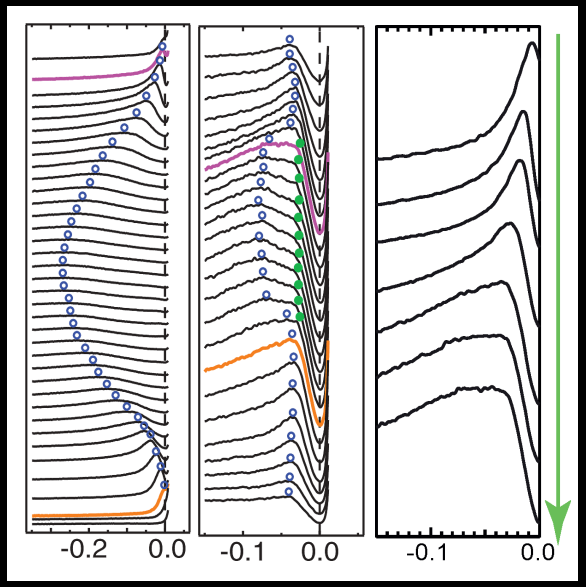
Steve Kivelson
Stanford

arXiv: 1603.03104

X25.00002 8:12am (Friday)

“Anomalous” spectra in underdoped SC

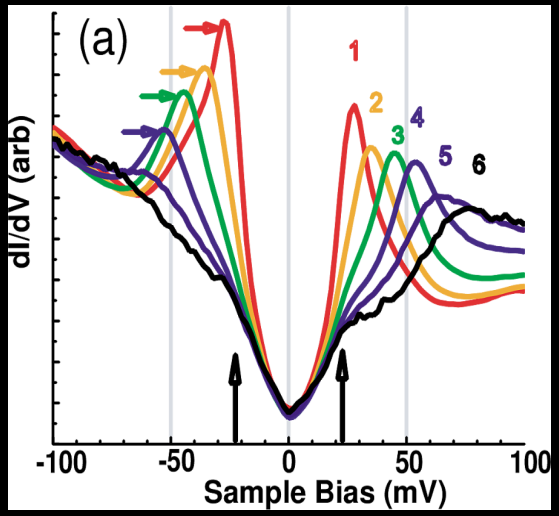
ARPES



He *et al.* (2011)

Nodal – antinodal dichotomy

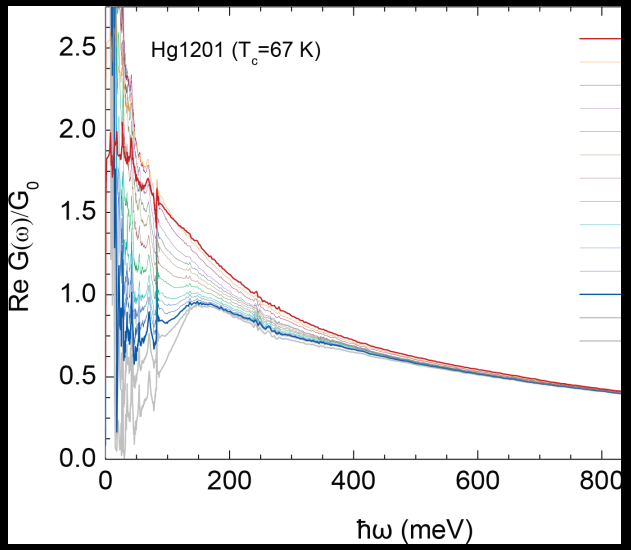
STM



McElroy *et al.* (2005)

Energy-dependent heterogeneity

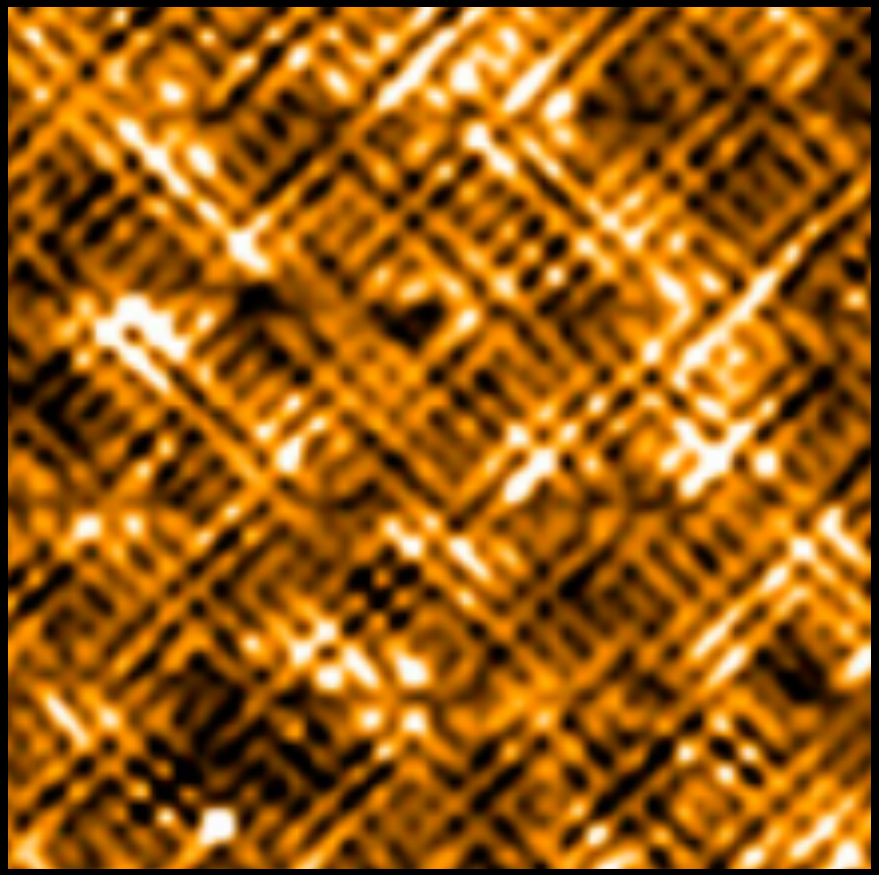
σ(ω)



Mirzaei *et al.* (2013)

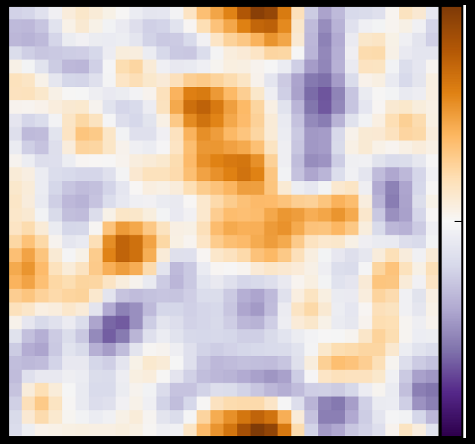
two-peak

Model Nematic Glass Superconductor

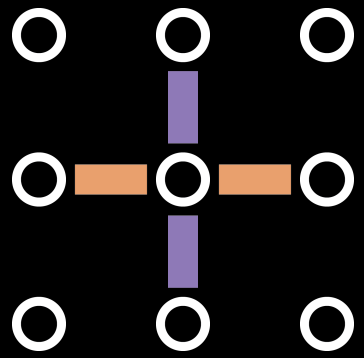


Self-consistent Bogoliubov-de Gennes

Model Nematic Glass Superconductor



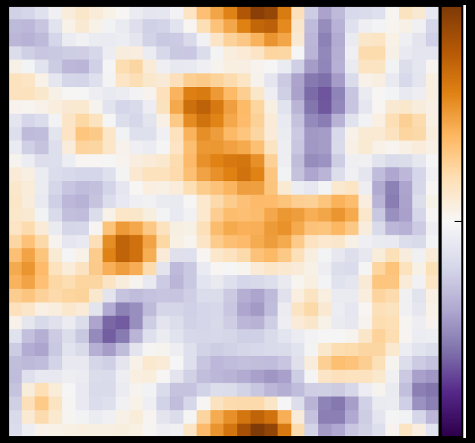
Glassy



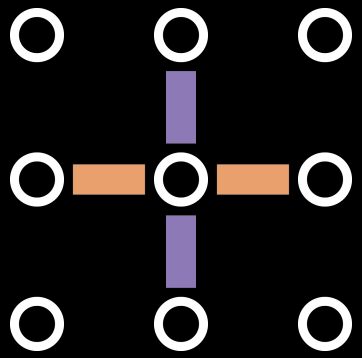
Nematicity: d-form factor

Self-consistent Bogoliubov-de Gennes

Model Nematic Glass Superconductor



Glassy



Nematicity: d-form factor

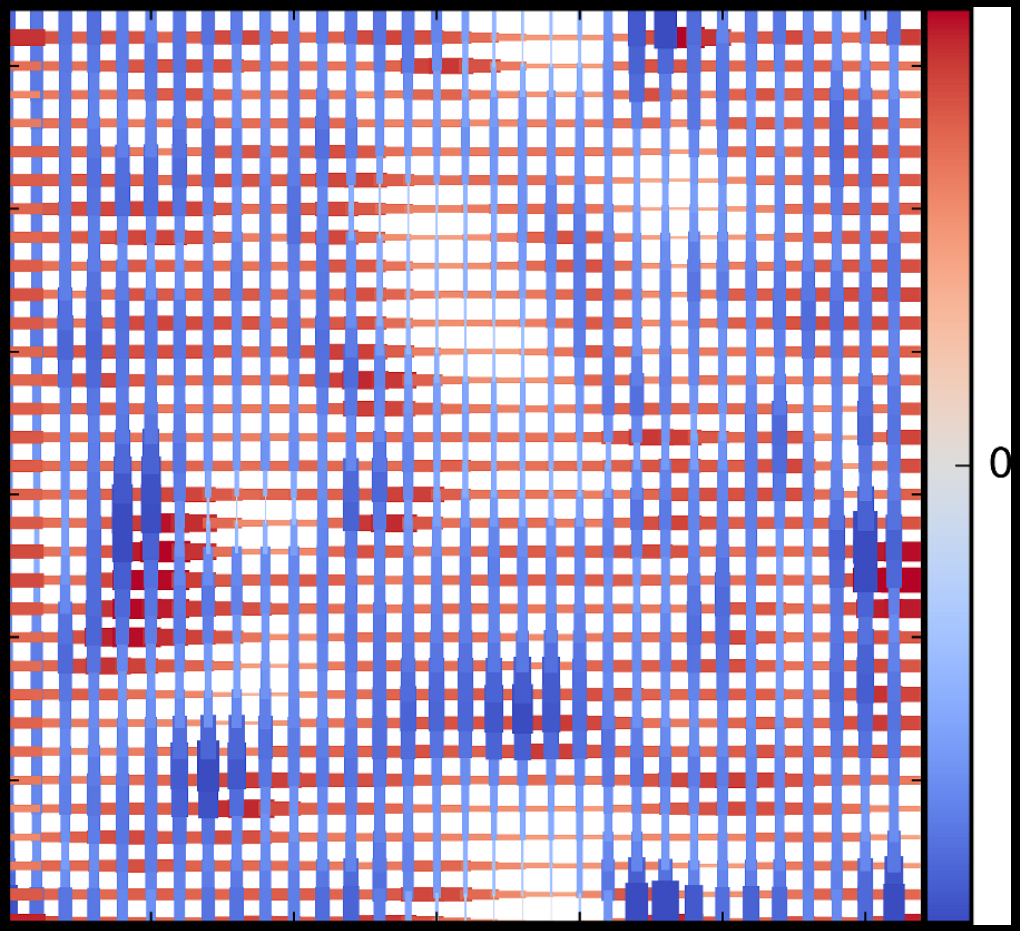
$$\mathcal{H}_{\mathbf{xy}} = \begin{pmatrix} t_{\mathbf{xy}} & \Delta_{\mathbf{xy}} \\ \Delta^*_{\mathbf{yx}} & -t_{\mathbf{yx}} \end{pmatrix} \qquad t_{\mathbf{xy}} = t^{(0)}_{\mathbf{xy}} + V(\mathbf{x},\mathbf{y})$$

$$V(\mathbf{x},\mathbf{y}) = \frac{1}{2} f(\mathbf{x}-\mathbf{y}) \left[\varphi(\mathbf{x}) + \varphi(\mathbf{y})\right]$$

Self-consistent Bogoliubov-de Gennes

Model Nematic Glass Superconductor

Self-consistently determined d-wave Gap

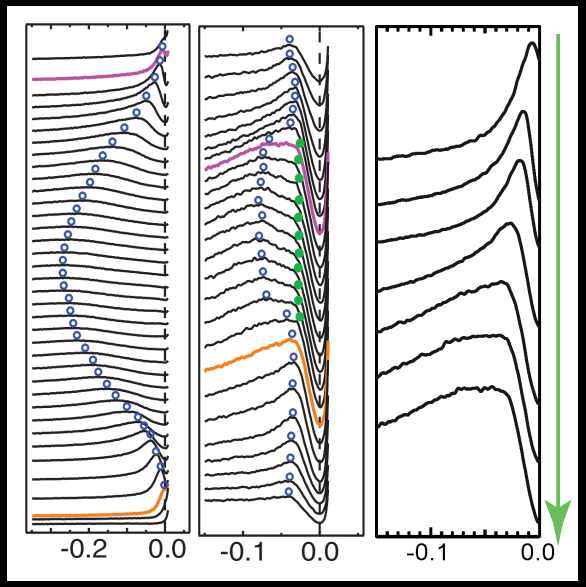


Self-consistent Bogoliubov-de Gennes

Spectroscopic "Measurements"

“Anomalous” spectra in underdoped SC

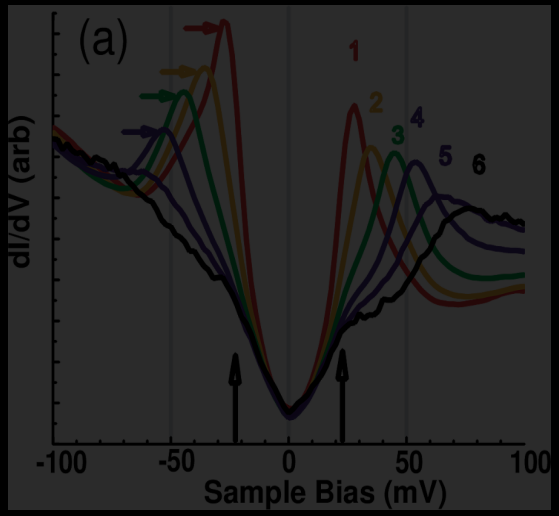
ARPES



He *et al.* (2011)

Nodal – antinodal dichotomy

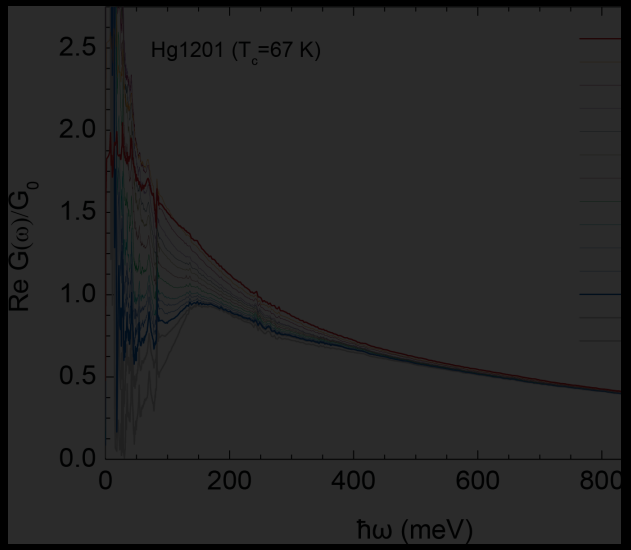
STM



McElroy *et al.* (2005)

Energy-dependent heterogeneity

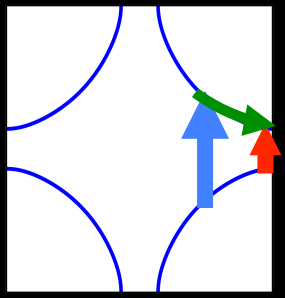
σ(ω)

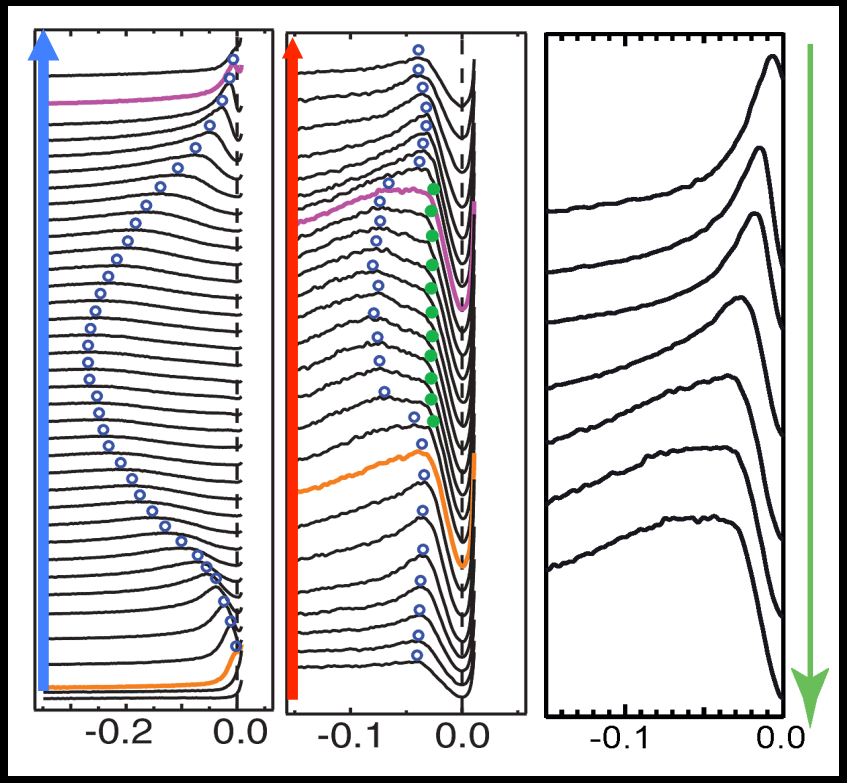


Mirzaei *et al.* (2013)

two-peak

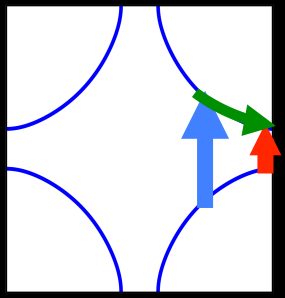
ARPES: Nodal-antinodal dichotomy

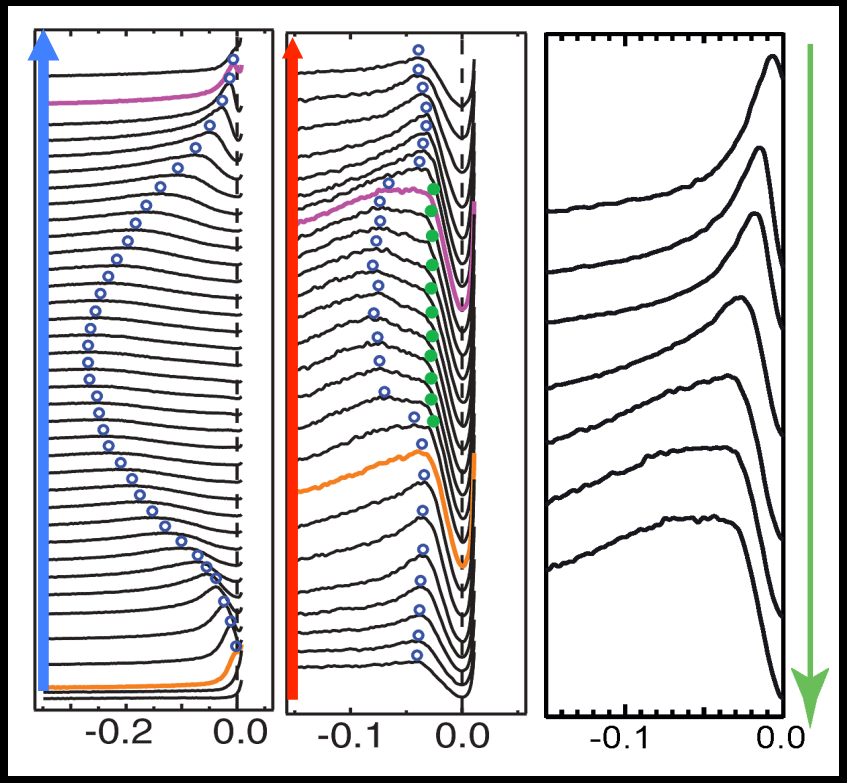


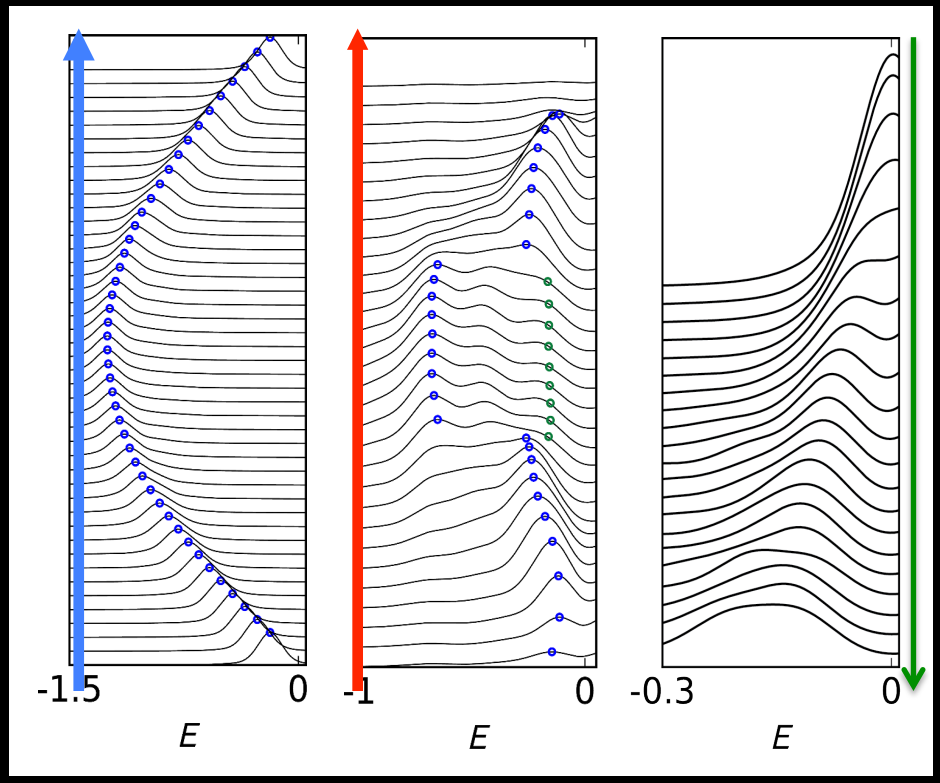


He *et al.* (2011)

ARPES: Nodal-antinodal dichotomy





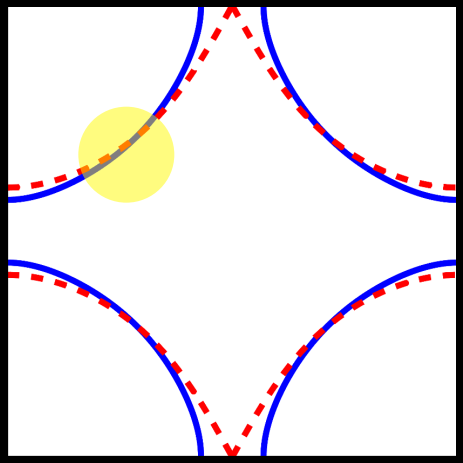


He *et al.* (2011)

Kyungmin Lee, S. Kivelson, EAK
arXiv: 1603.03104

Glassy Nematic and Cold Spots

Uniform
Nematic



Glassy Nematic and Cold Spots

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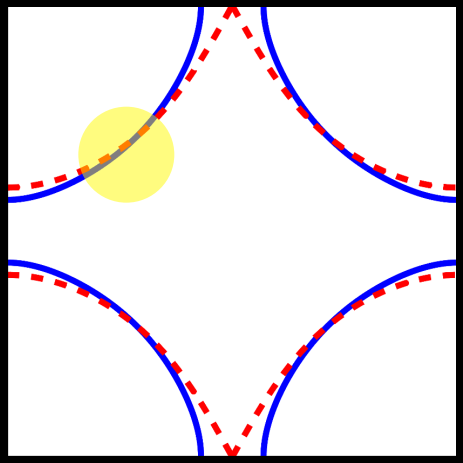
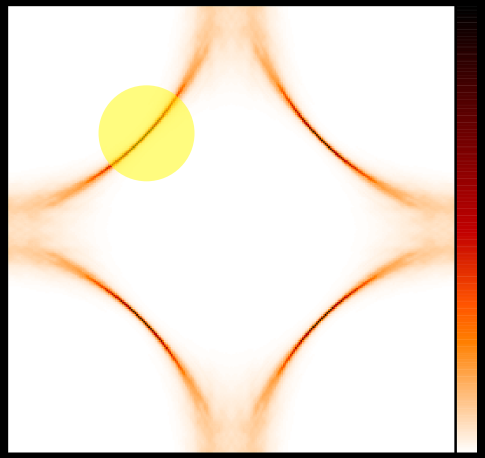


Glassy Nematic



Kyungmin Lee, S. Kivelson, EAK arXiv: 1603.03104

Glassy Nematic and Cold Spots

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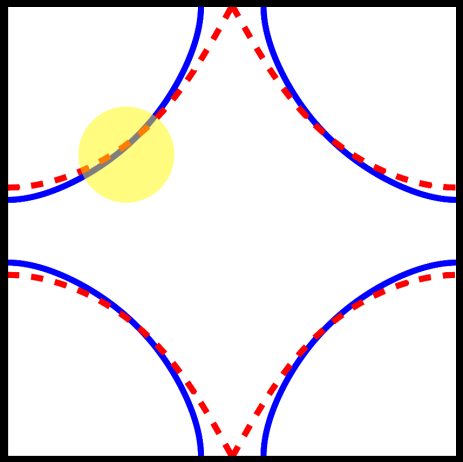
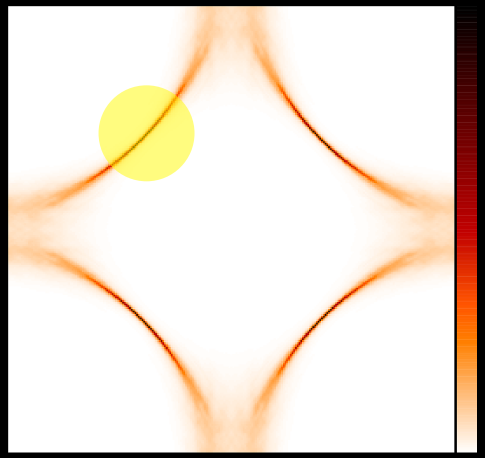
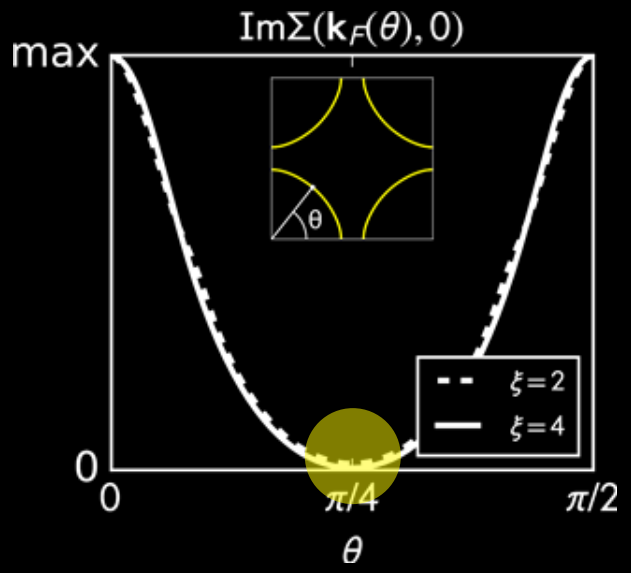


Glassy Nematic



Scattering Rate



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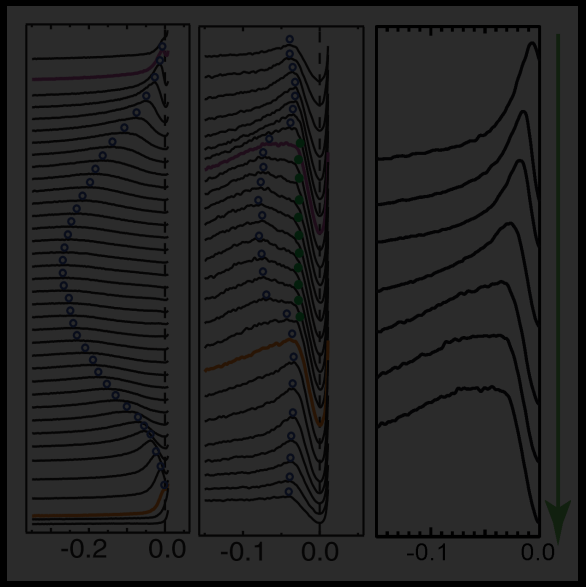
d-form factor <-> Cold spot at the zone diagonal

“Anomalous” spectra in underdoped SC

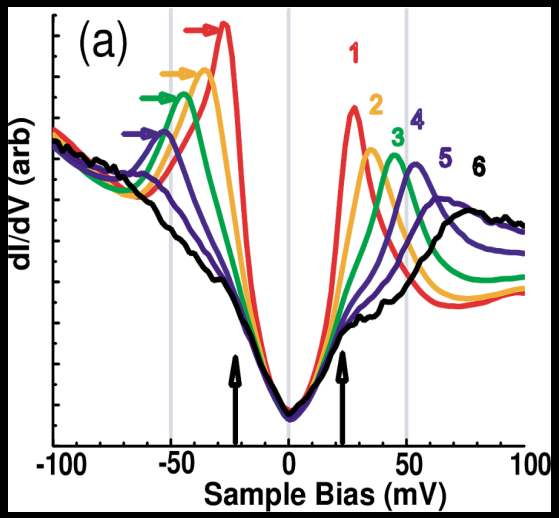
ARPES



He *et al.* (2011)

Nodal – antinodal dichotomy

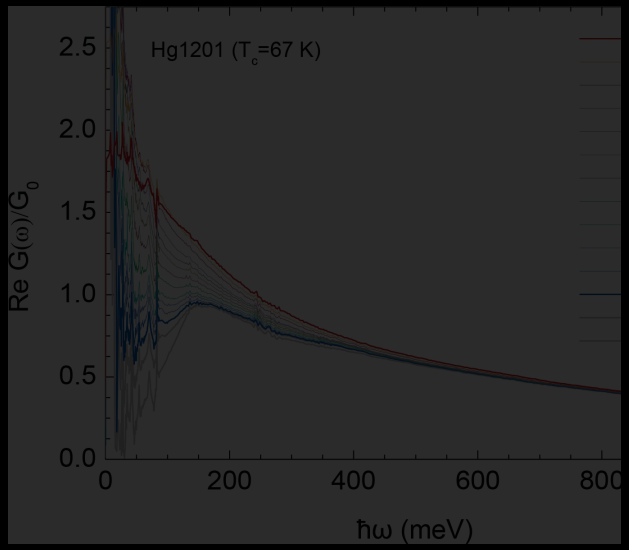
STM



McElroy *et al.* (2005)

Energy-dependent heterogeneity

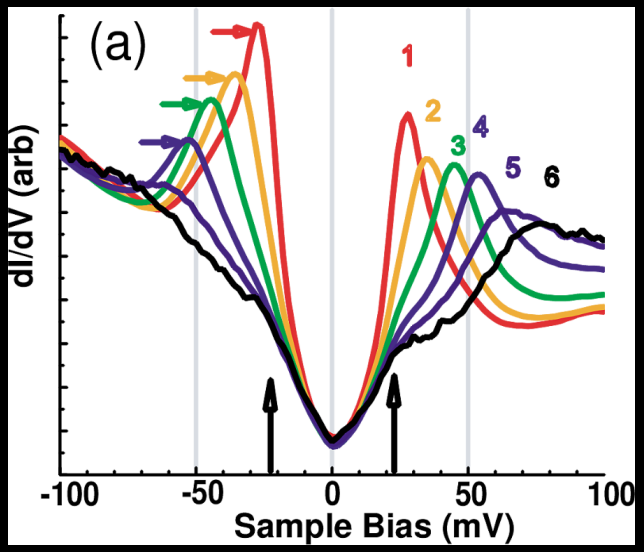
σ(ω)



Mirzaei *et al.* (2013)

two-peak

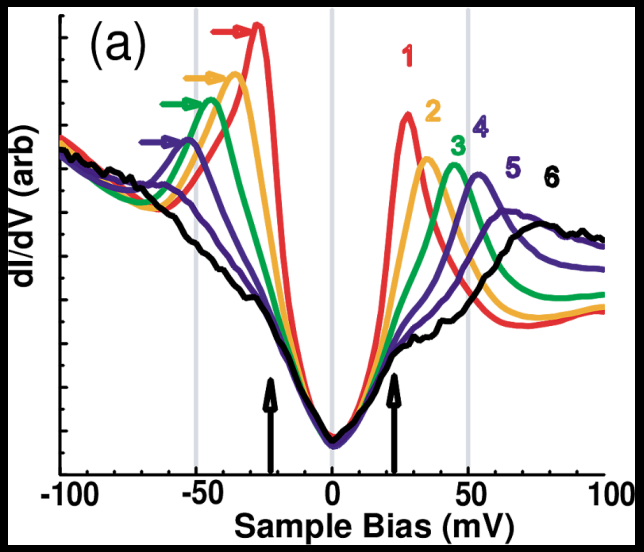
STM: Homogeneous at low ω



McElroy *et al.* (2005)

- Energy dependent heterogeneity
  - Low energy : homogeneous
  - High energy : heterogeneous

STM: Homogeneous at low ω



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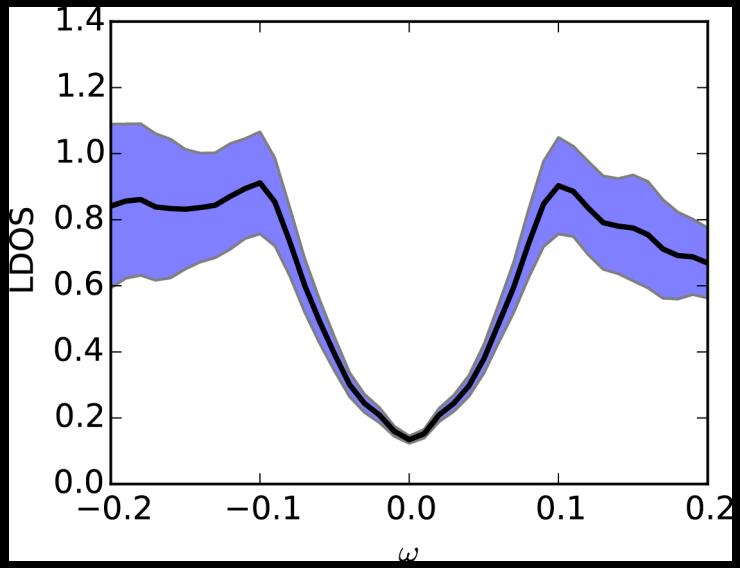

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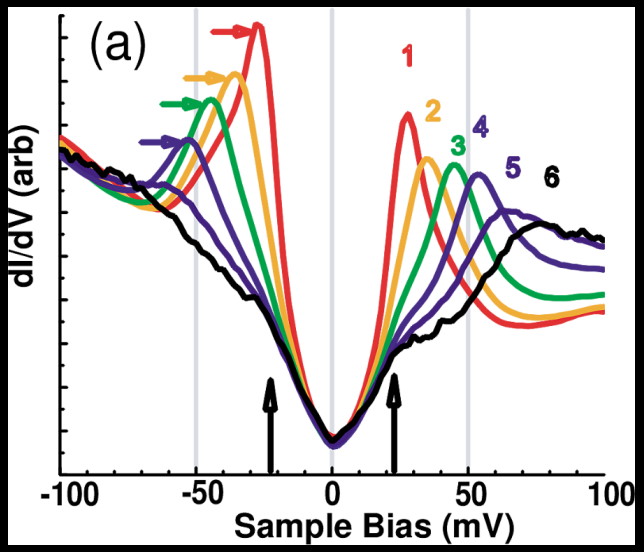

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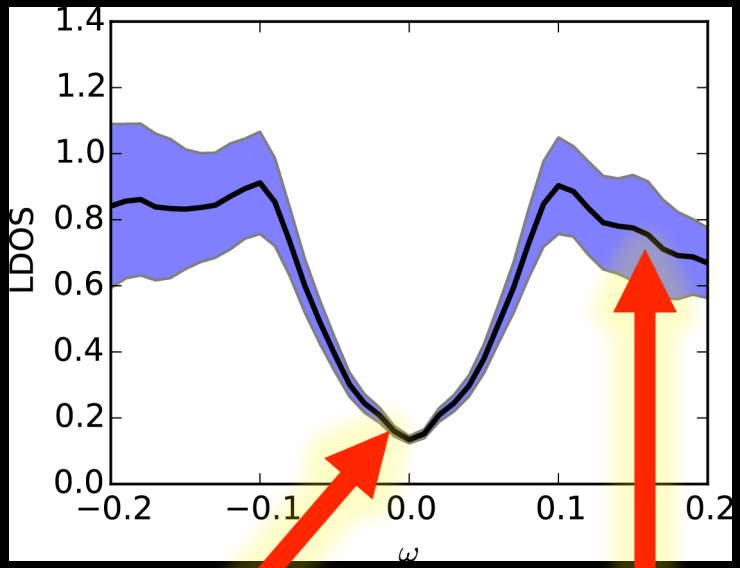

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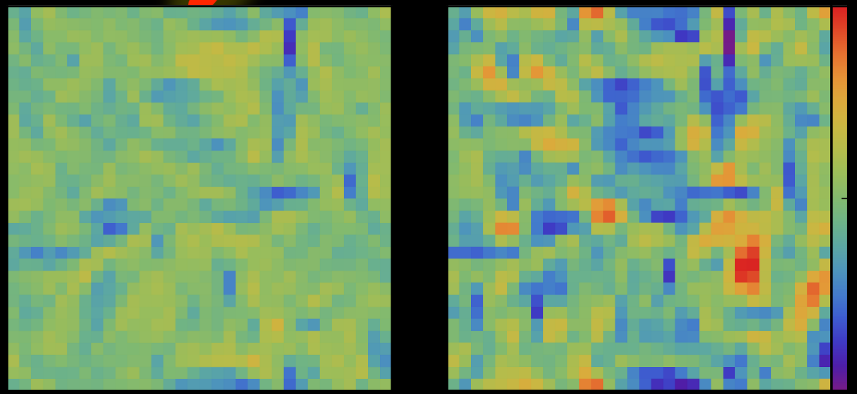
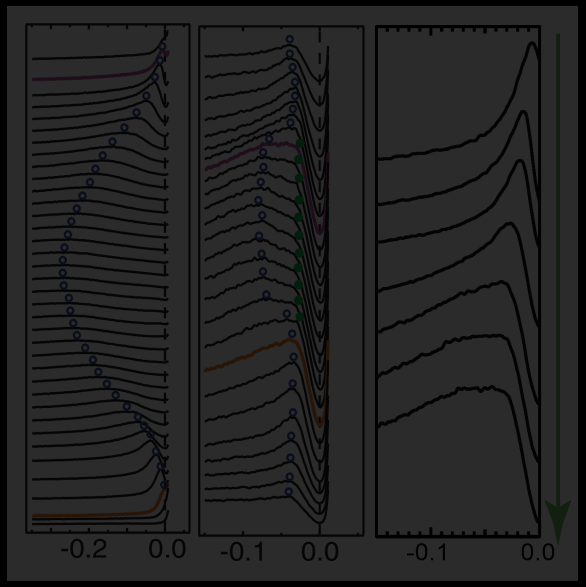


“Anomalous” spectra in underdoped SC

ARPES



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Nodal – antinodal dichotomy

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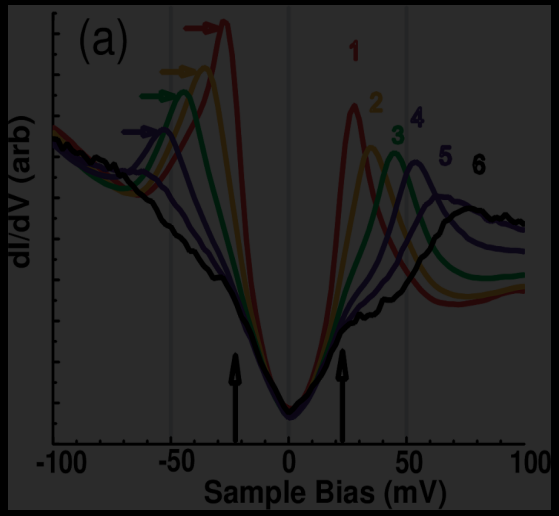

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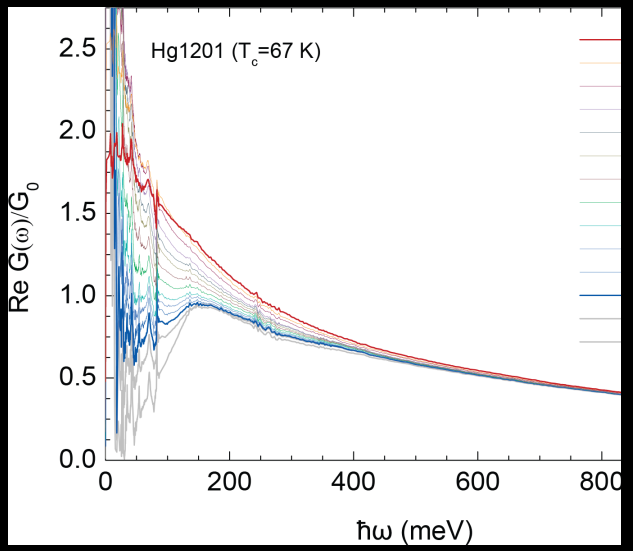
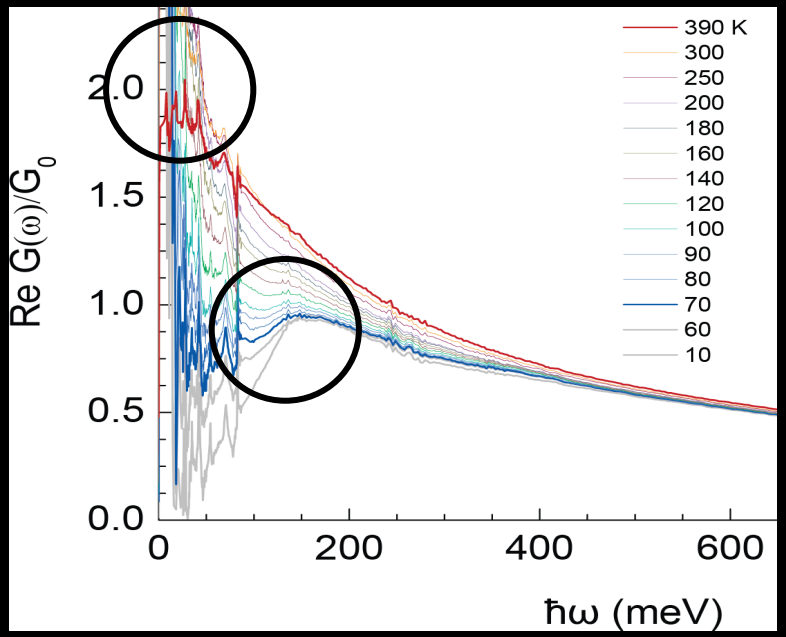


Mirzaei *et al.* (2013)

two-peak

σ(ω): Two-peak structure at "low" T



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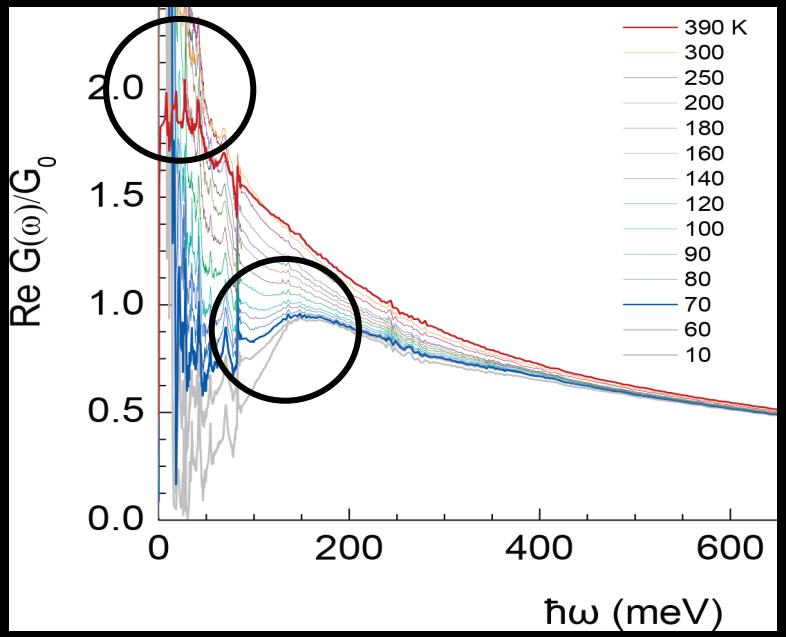

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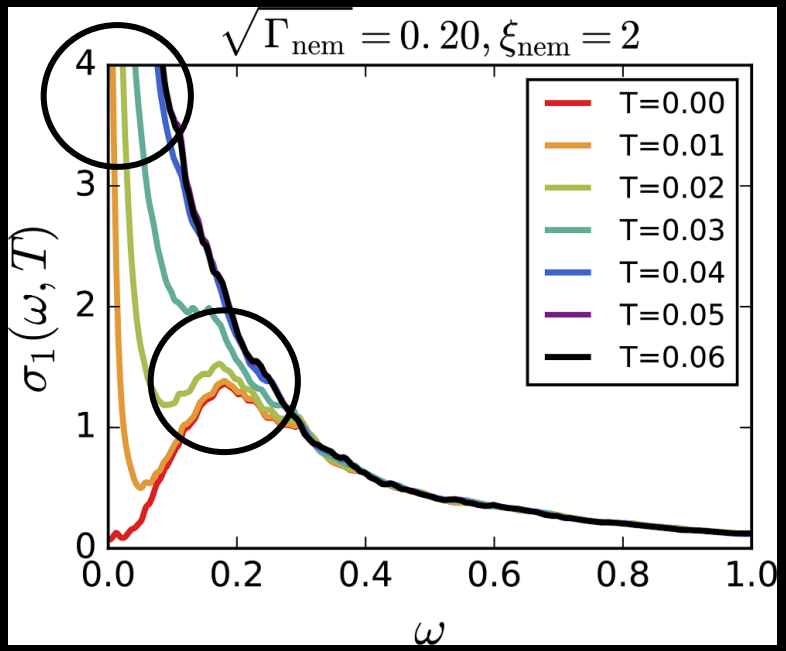

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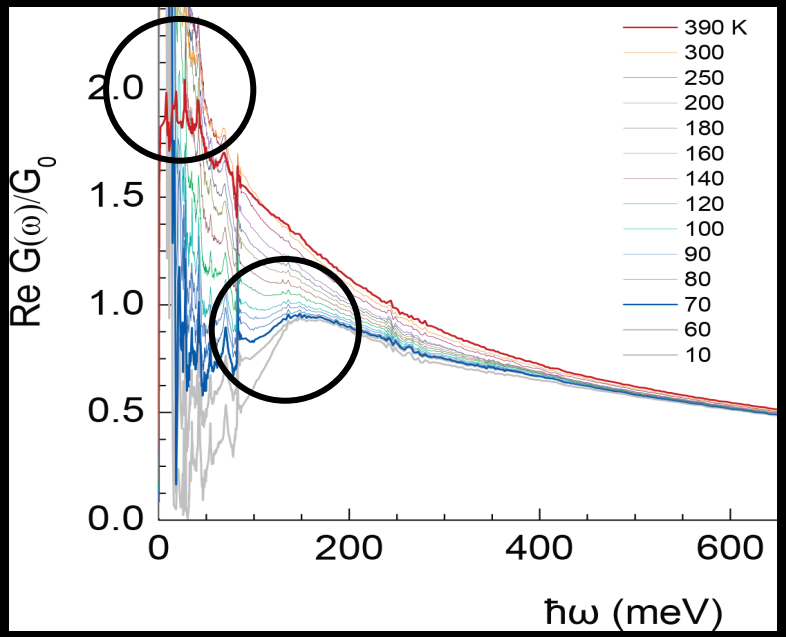

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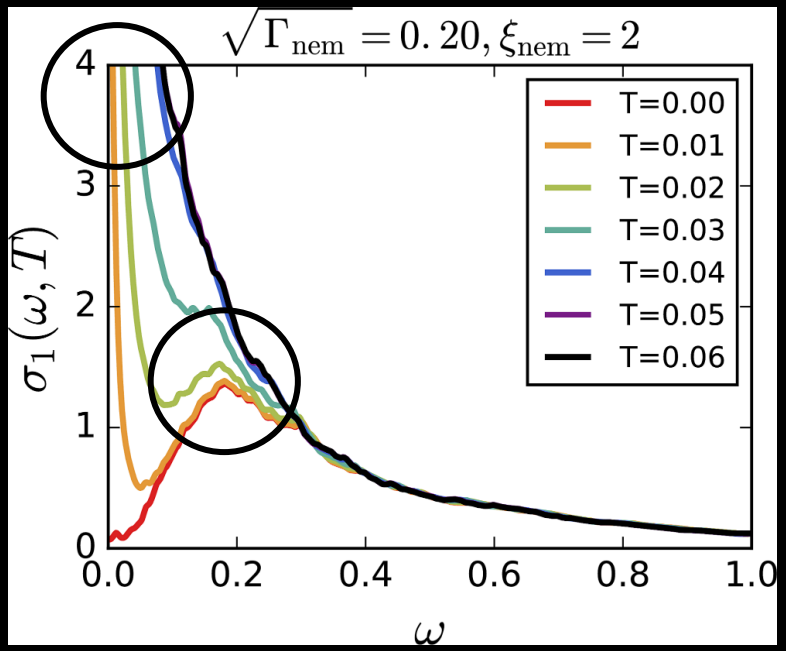

Kyungmin Lee, S. Kivelson, EAK
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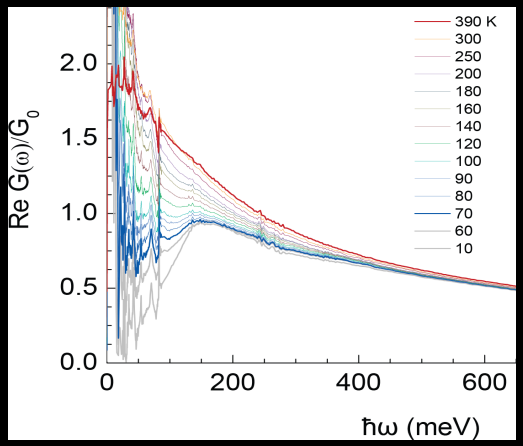
onset $T \sim T^*$

onset $T \sim T_c$

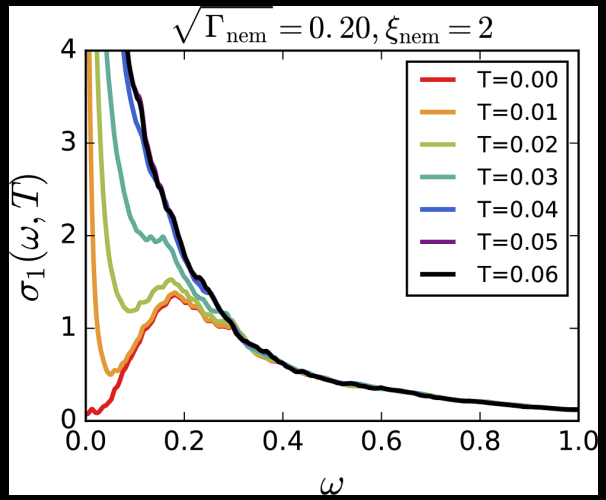
σ(ω): Two-peak structure at "low" T

Experiments

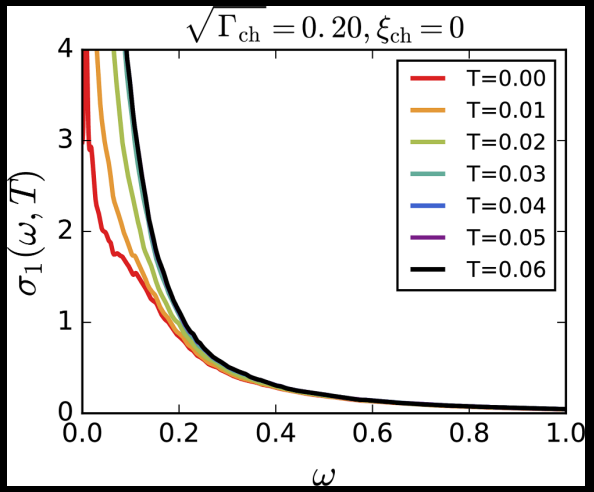


Mirzaei *et al.* (2013)

Nematic glass



Other scatters



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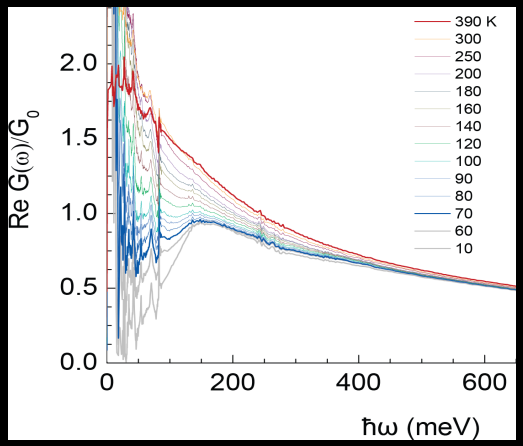

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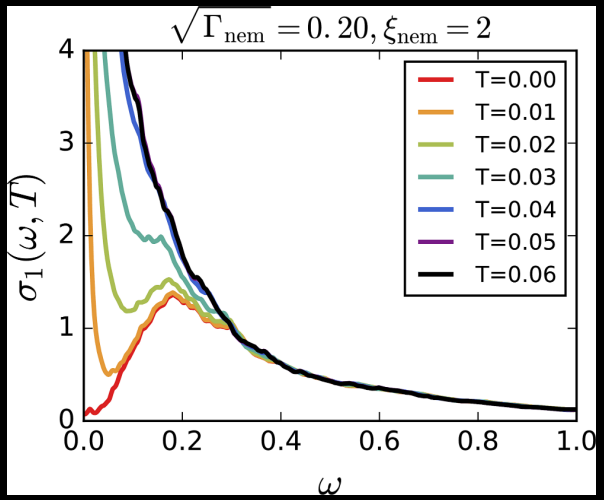

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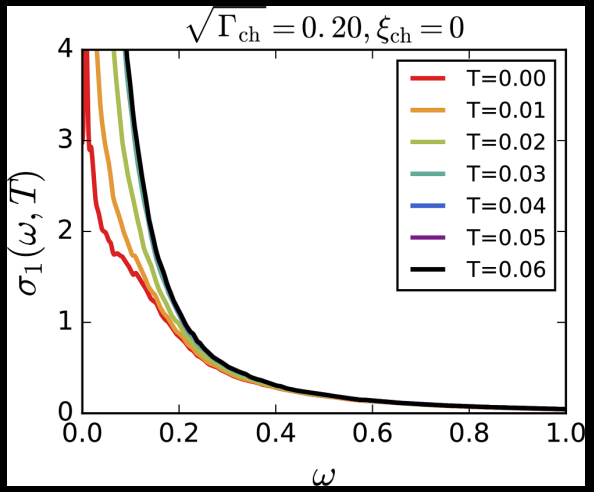
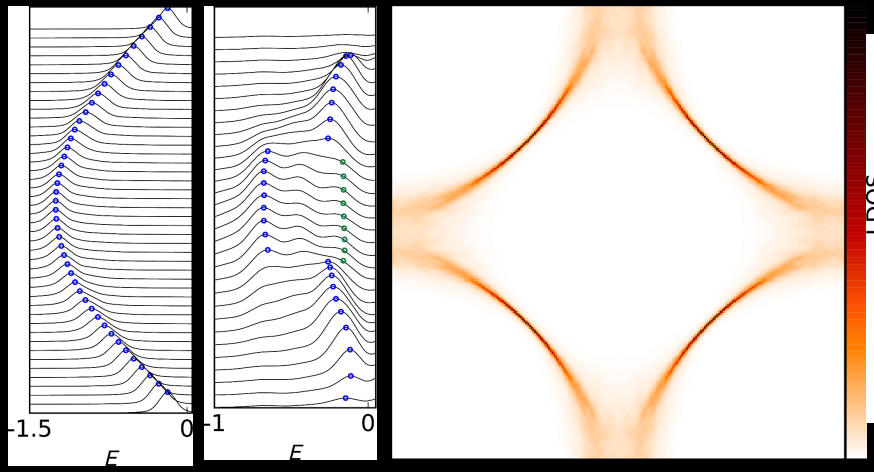
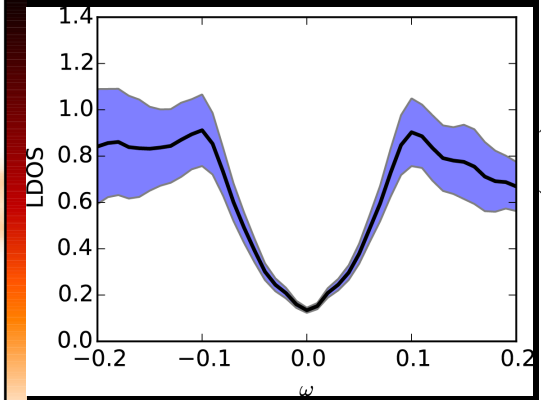


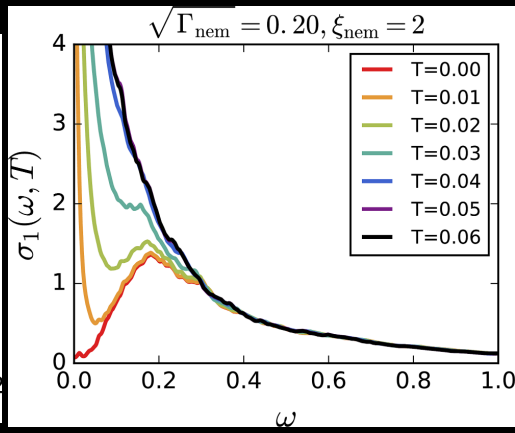
Requirements: Dirac nodes (vanishing DOS)

Gap the rest (d-SC) + Protect the node (dFF scatter)

"Anomalous Spectra": Another Face of Nematic Glass







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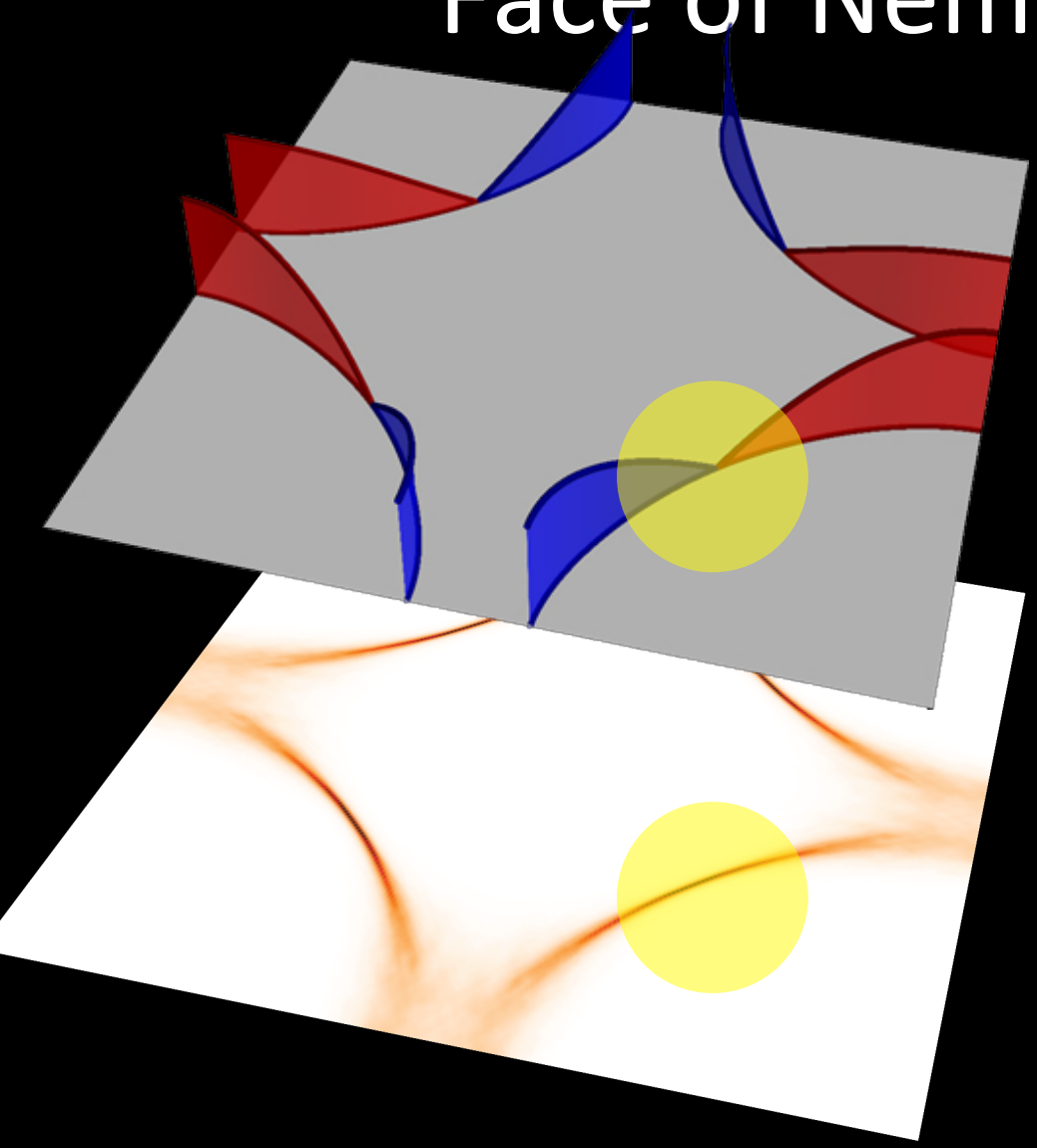
Consonance of
d-SC node & the nematic glass cold-spot

"Anomalous Spectra": Another Face of Nematic Glass



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Consonance of d-SC node & the nematic glass cold-spot