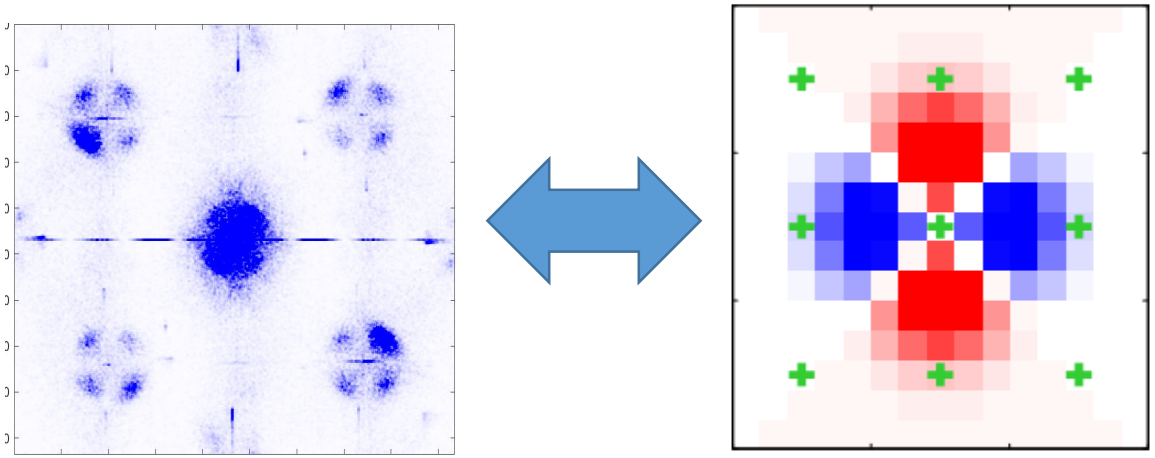
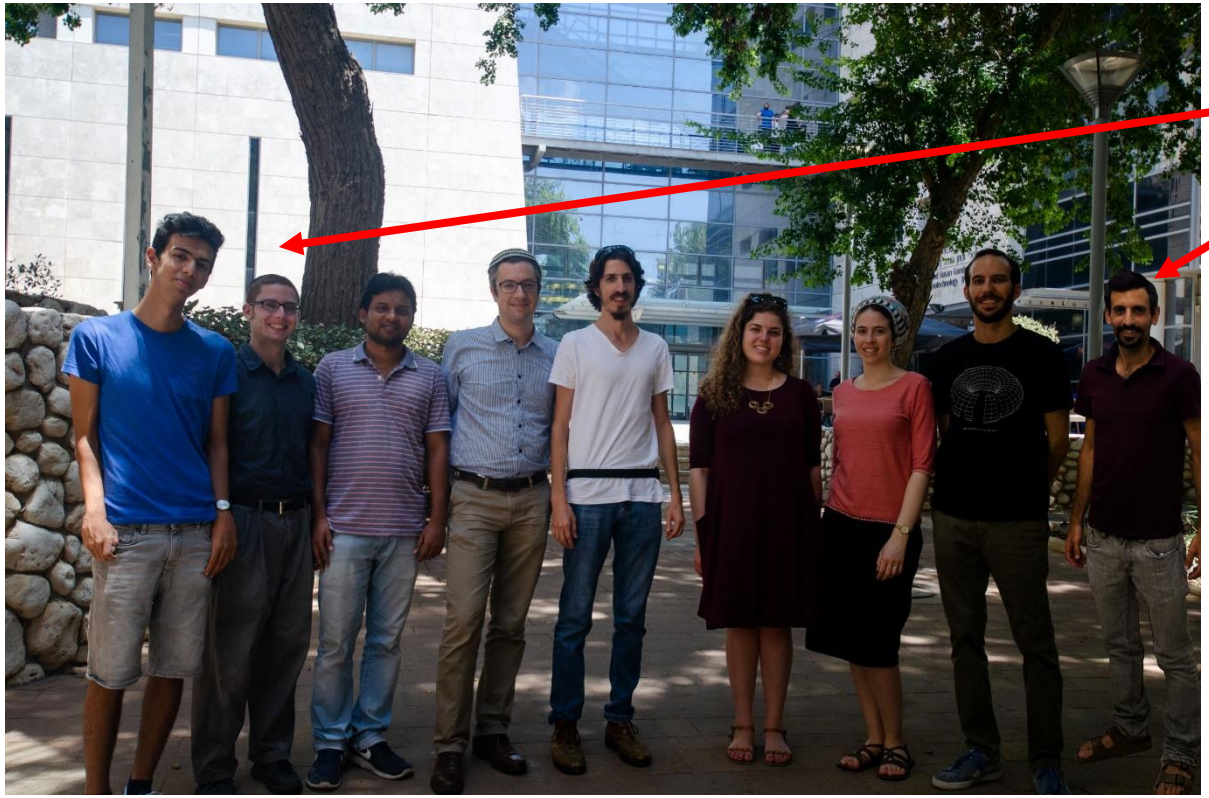
Phase sensitive STM

of disorder superconductors



Nonequilibrium Quantum Dynamics



On this project:

Joseph Rubin
(Undergraduate)
David Dentelski
(Ph.D. student)

Collaborations:
Theory
Eugene Demler
David Benjamin

Experiments
Yang He
Jennifer Hoffman

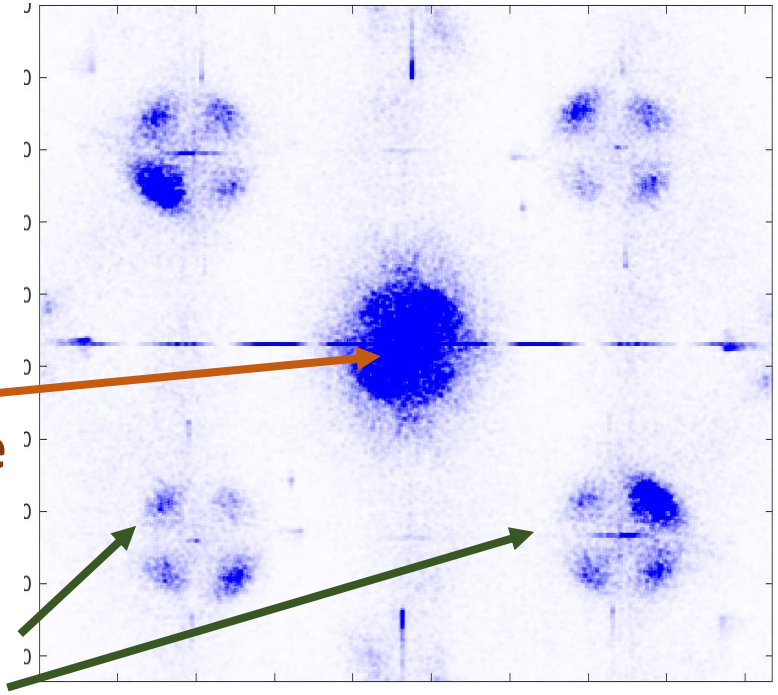
Like

http://www.facebook.com/nonequilibrium

QPI : no introduction needed

Puzzle 1 : Cuprates at high voltage

$$V \approx 1.5\,\Delta$$

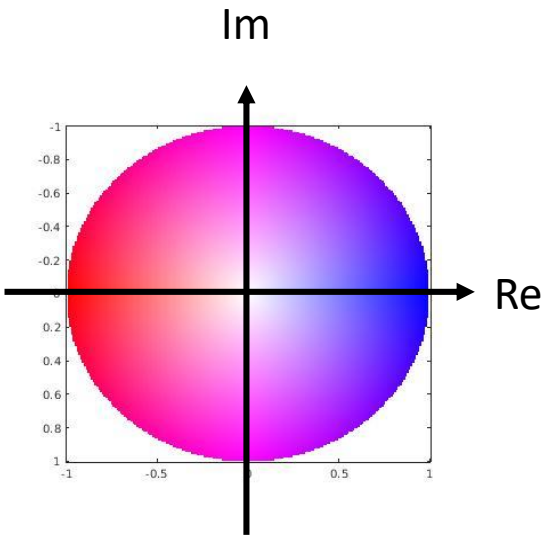


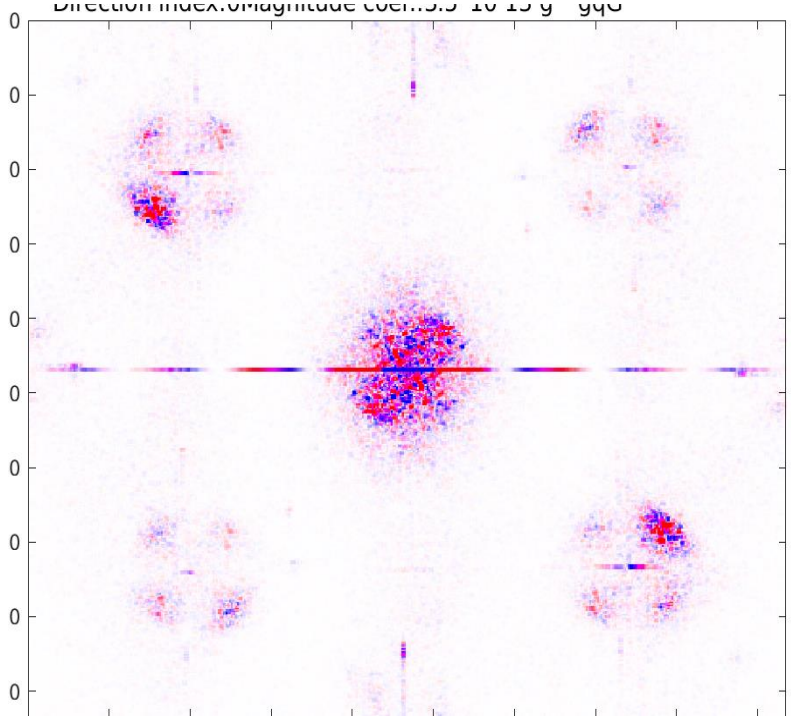
No peaks in the central Brillouin Zone

Satellite peaks in the first Brillouin Zone

Data from Wise etal (Nature Physics 2008)

Puzzle 2 : complex phase

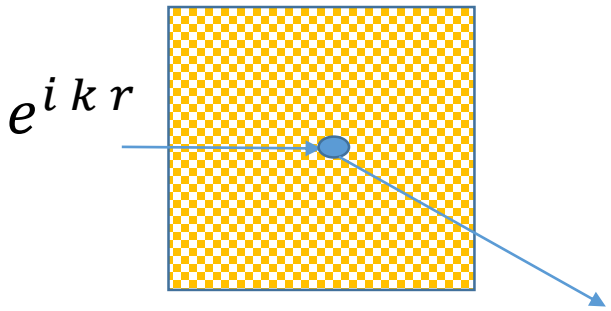




Random Phase

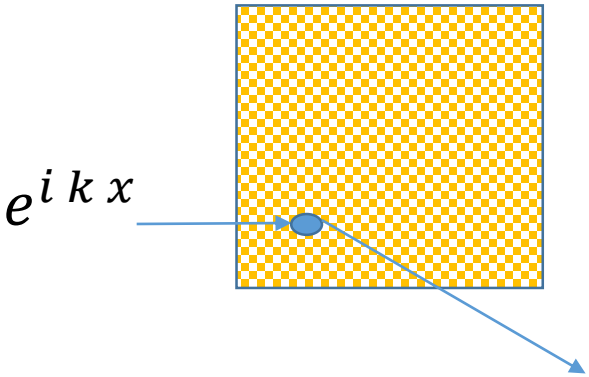
Random position of impurities

$x_{\text{imp}} = 0$



$e^{i\,(k+q)r}\,A_{q,\omega}e^{i\phi_{q,\omega}}$

$x_{\text{imp}} \neq 0$



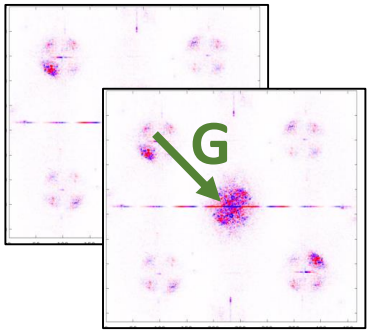
$e^{i\,(k+q)x}\,A_{q,\omega}e^{i\phi_{q,\omega}}\mathbf{e}^{\mathbf{i\,q\cdot}x_{\mathbf{imp}}}$

$$g(\vec{q},\omega) = A_{q,\omega}e^{i\phi_{q,\omega}} \sum_{\text{i=impurities}} e^{i\vec{q}\cdot\vec{x}_i}$$

See also the talk by Huan Yang

New idea: Holographic Maps

$$h_G(q,\omega) = g(q,\omega)\, g^*(q+G,\omega)$$



G: inverse Bravais vector

Properties:

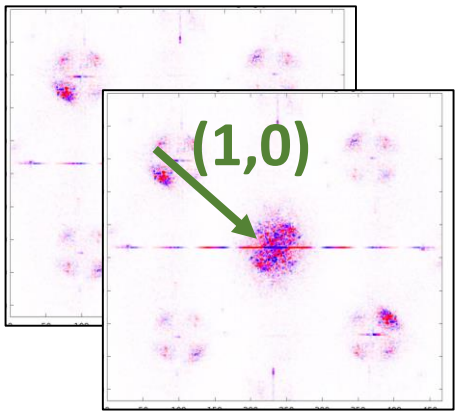
1. Independent on the position of impurities:

$$h_G(q,\omega) \sim e^{i\,q\,x_i}\;\; e^{-i\,(q+G)x_i} = e^{i\,G\,x_i} = 1$$

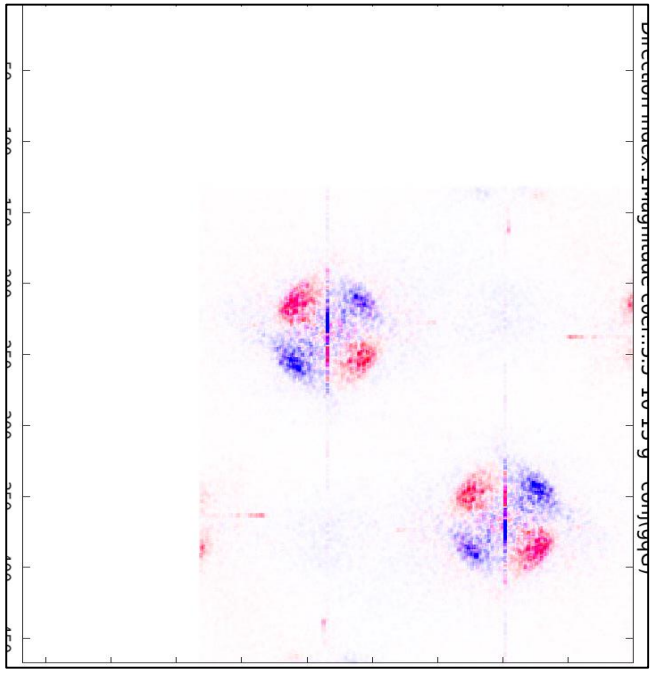
2. For $G = 0$ → holographic maps = intensity map

Holographic map : $G = (1,0)$

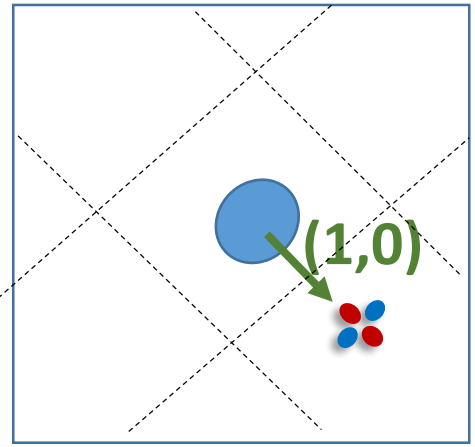
g-map



h-map



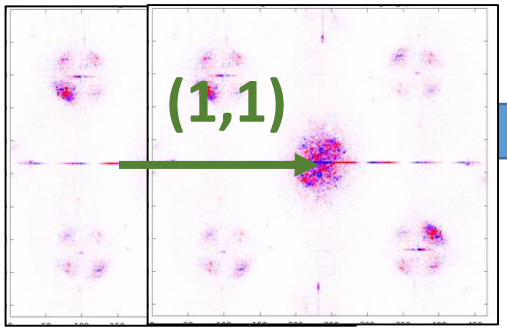
Phase sensitive g-map



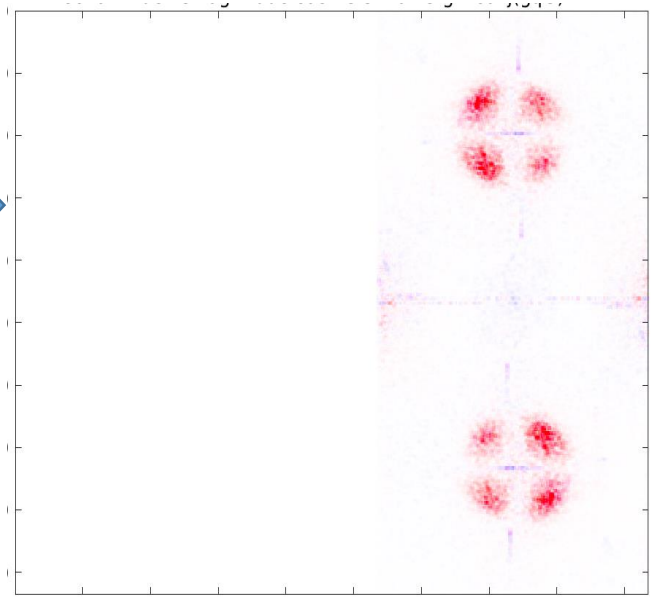
$$h(q,\omega) = g(q,\omega)\, g^*(q+(1,0),\omega)$$

Holographic map : $G = (1,1)$

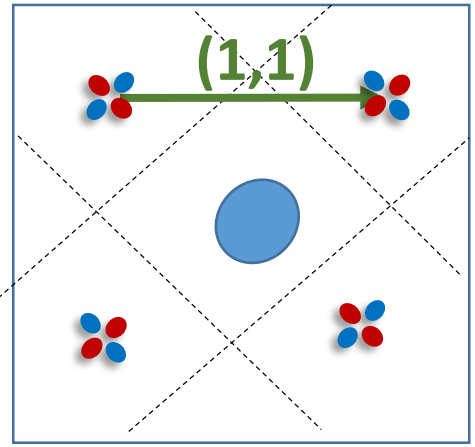
g-map



h-map



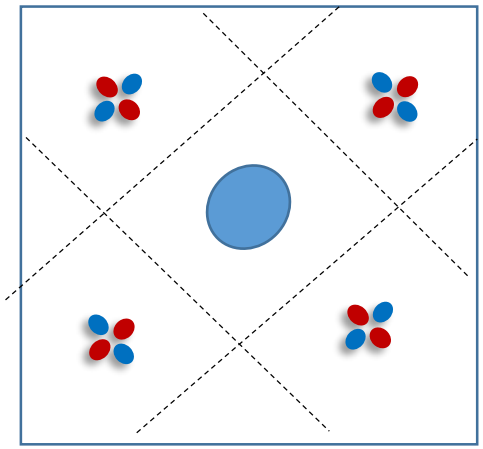
Phase sensitive g-map



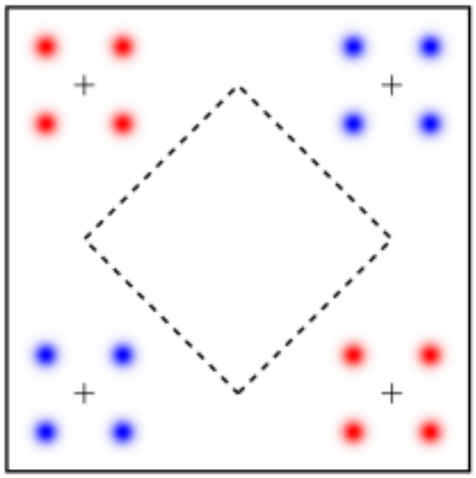
$$h(q,\omega) = g(q,\omega)\, g^*(q+(1,1),\omega)$$

Phase sensitive STM

Our g-map



"d-form factor CDW"

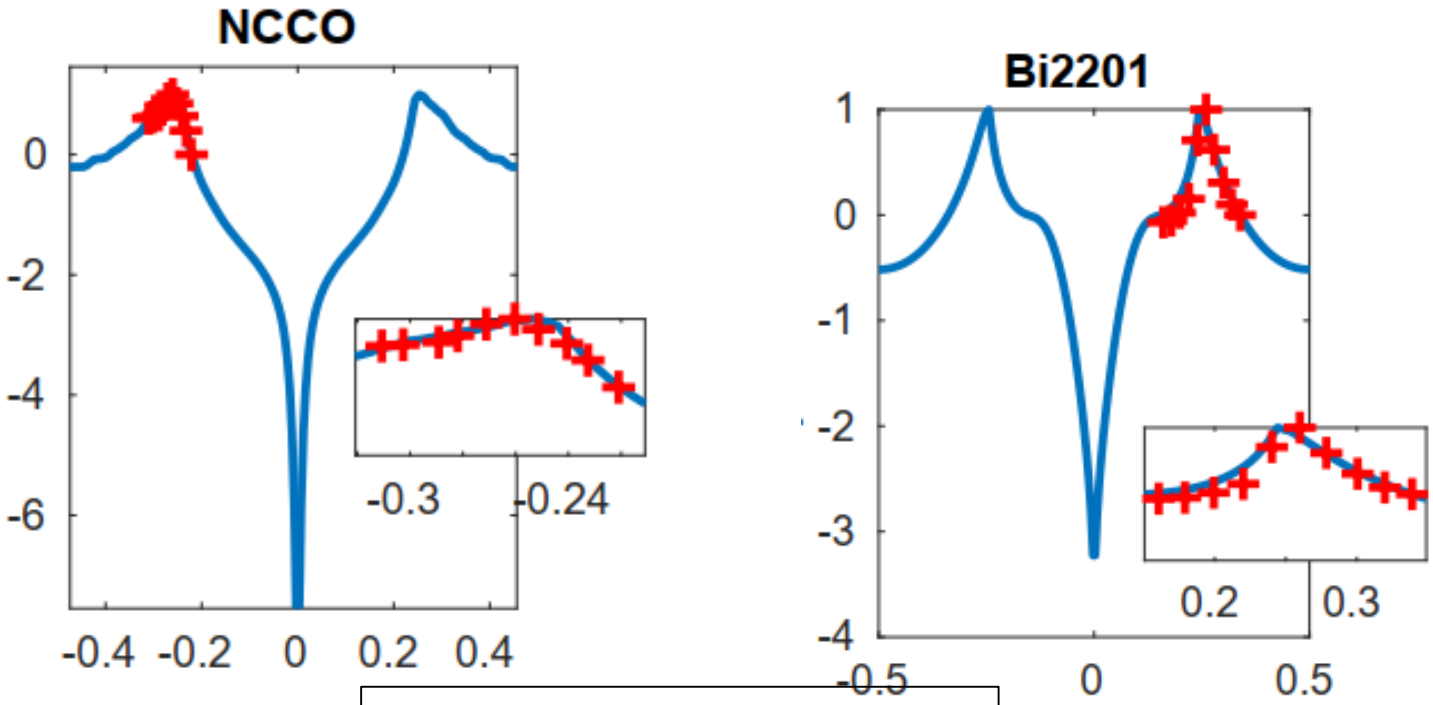


Hamidian,…, S. Davis, S. Sachdev, etal
(Nat. Phys. October 2015)

"There is no CDW, only Friedel oscillations"

$$\chi(q,w) = v_q \sum_k \frac{f_{k-q} - f_k}{\hbar(w + i\delta) + E_{k-q} - E_k}$$

$$\epsilon_k = -2t\cos(k_X) + \cos(k_Y) - 4t'\cos(k_x)\cos(k_y)$$



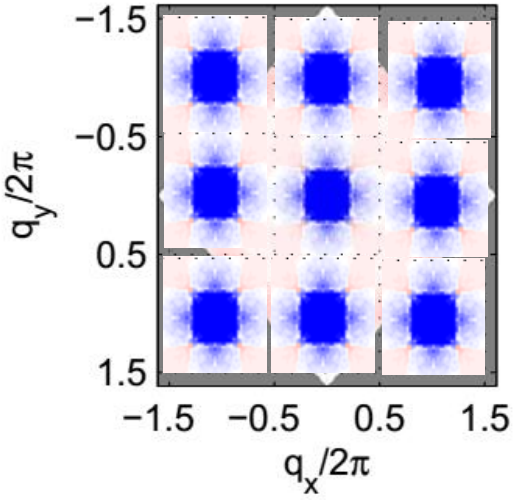
D. Dentelski et al, unpublished

Why differences between Brillouin zones?

$$G_{k,k+q} = G_0(k,\omega)\ T(k)\ G_0(k+q,\omega)$$

q-independent

Periodic (Bloch theorem)



Wannier functions = subatomic details

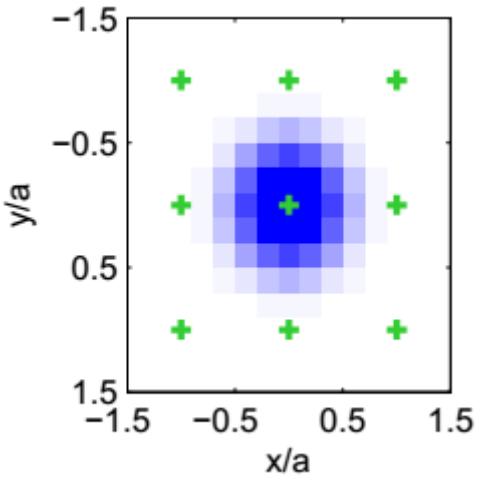
$$g(q,\omega) = \sum_k W(k)\ G_{k,k+q}\ W(k+q)$$

Not periodic

Podolski etal (PRB, 2003). See also talk by Andreas Kreisel

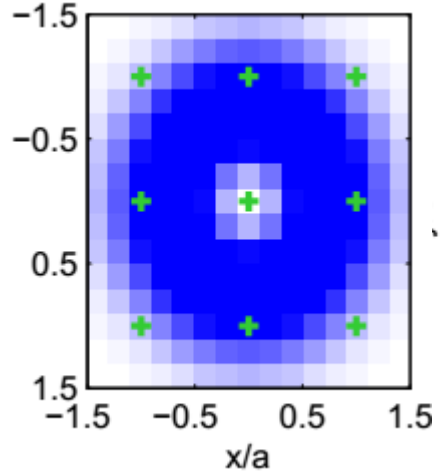
From Wannier functions to g map

(1)



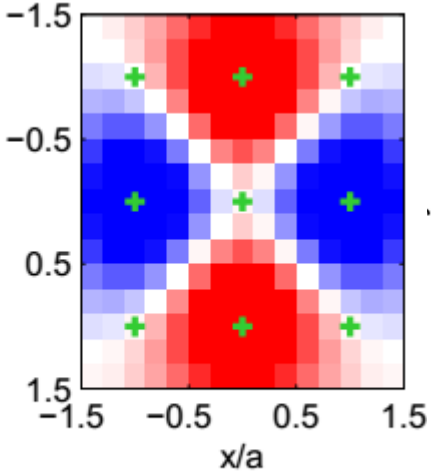
$$e^{-\frac{x^2+y^2}{2\sigma^2}}$$

(2)



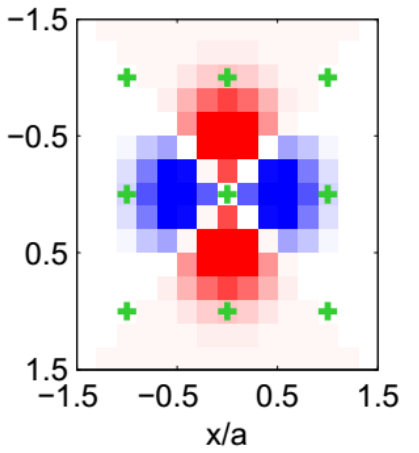
$$(x^2+y^2)e^{-\frac{x^2+y^2}{2\sigma^2}}$$

(3)

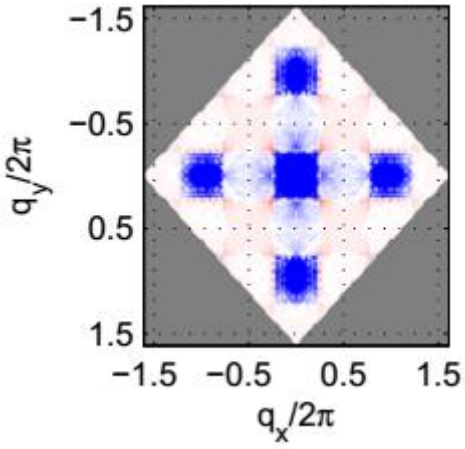


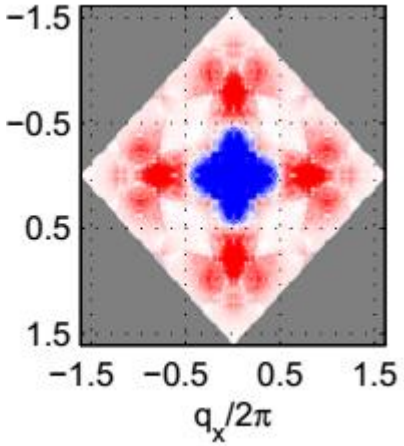
$$(x^2-y^2)e^{-\frac{x^2+y^2}{8\sigma^2}}$$

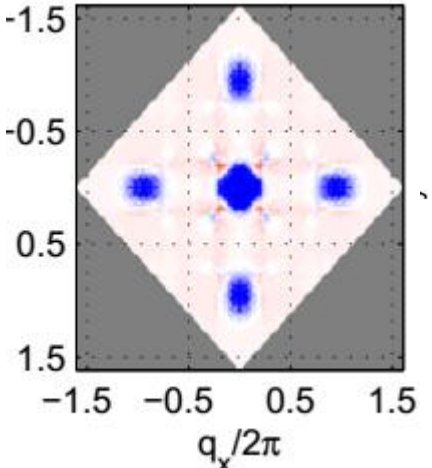
(4)

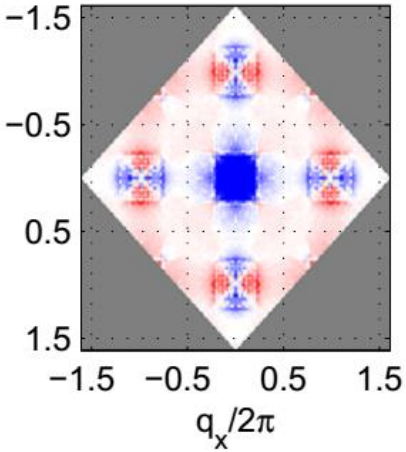


$$(x^2-y^2)e^{-\frac{x^2+y^2}{2\sigma^2}}$$

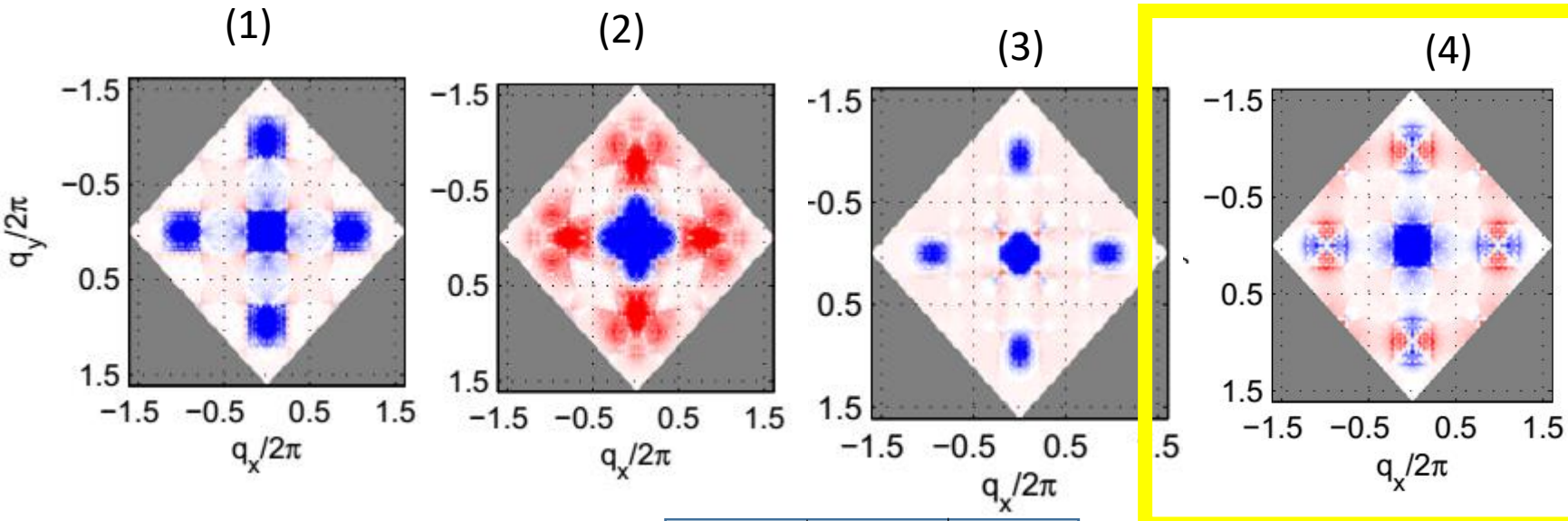




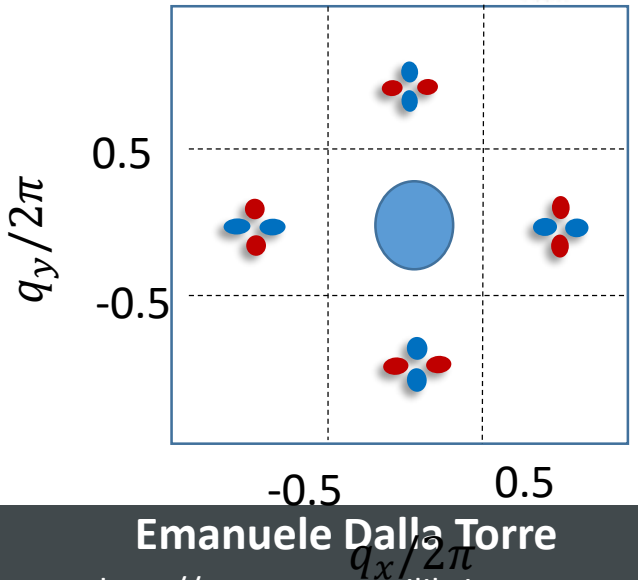




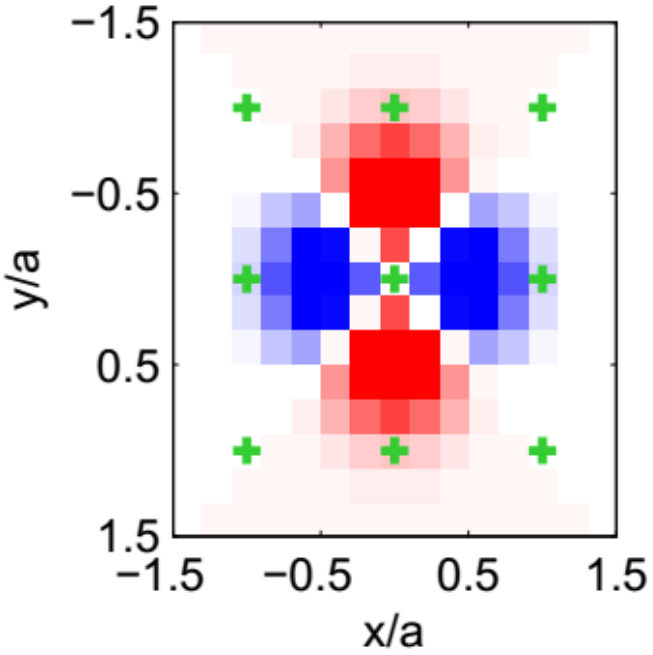
Resulting g-map



Experiment:



Main result: Wannier function



Agrees with

Zhang and Rice

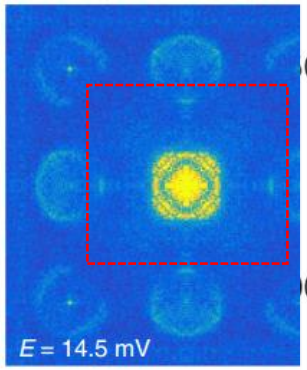
(PRB 1988)

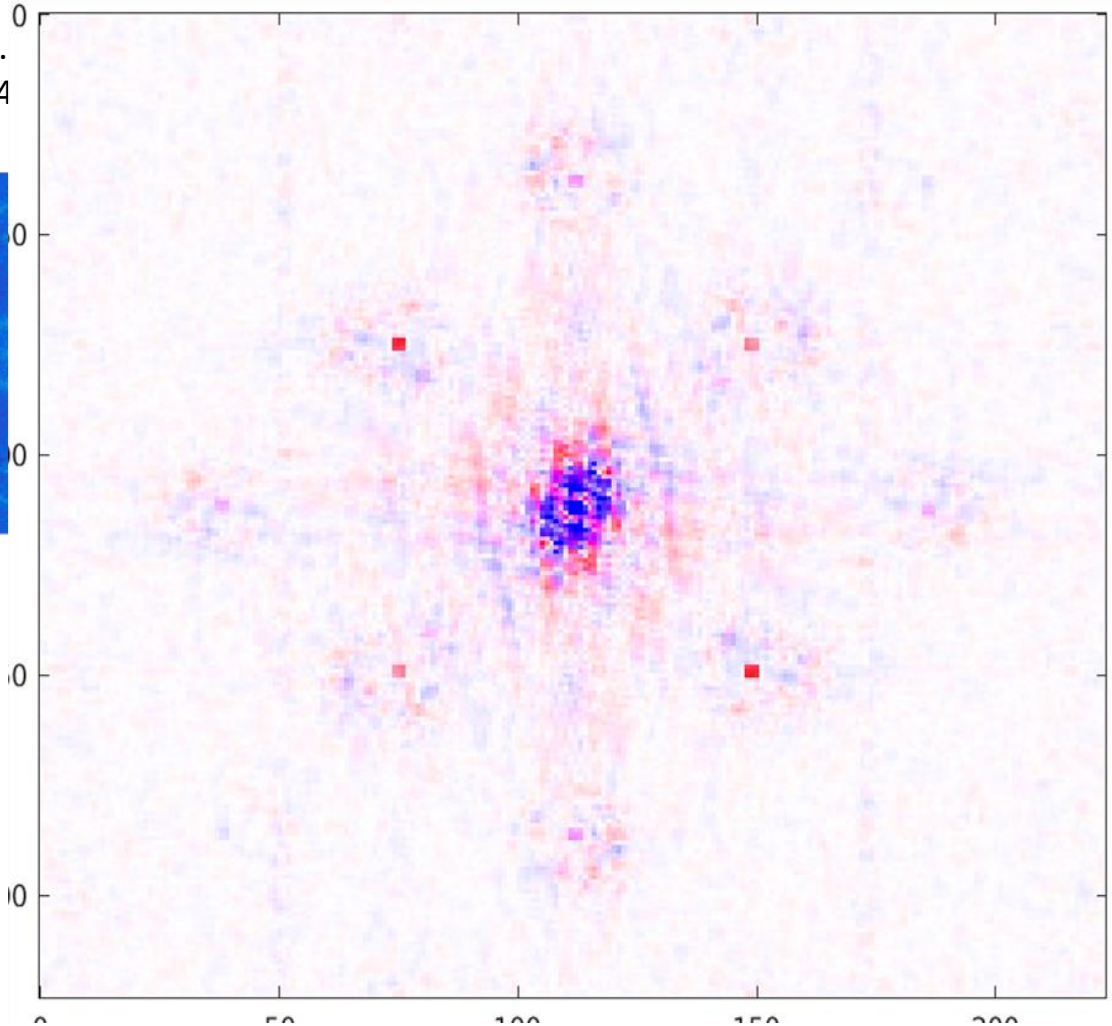
Similar conclusion by:

Kreisel etal (PRL 2015), Choubey etal (PRB 2017)

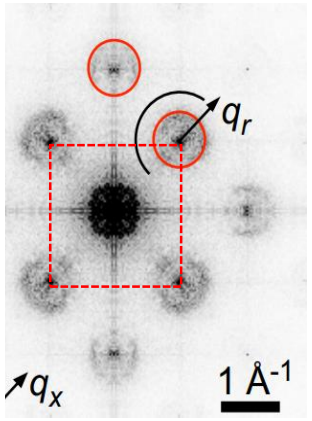
Iron Based Superconductors

Du etal, Nat.Comm.
(LiFe)OHFeSe @ 14

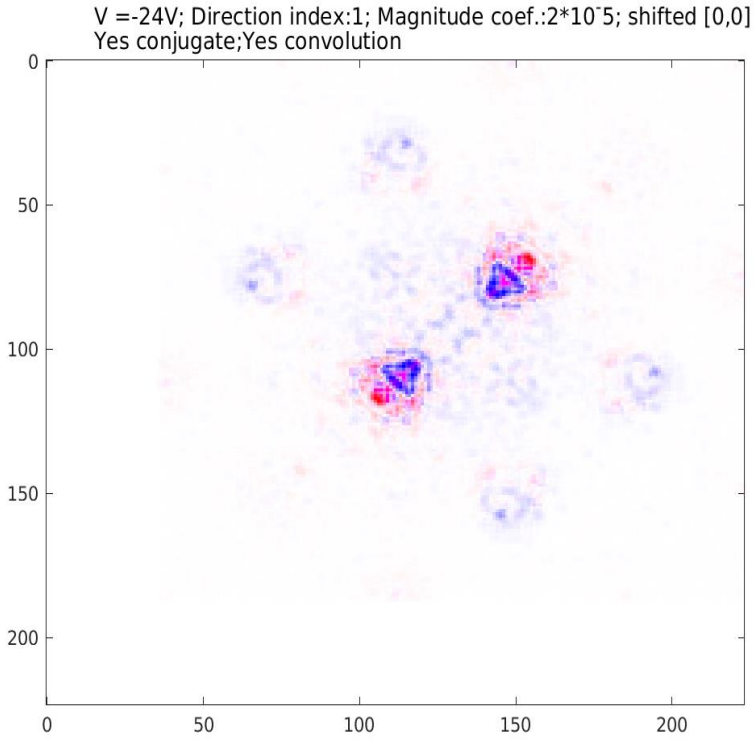


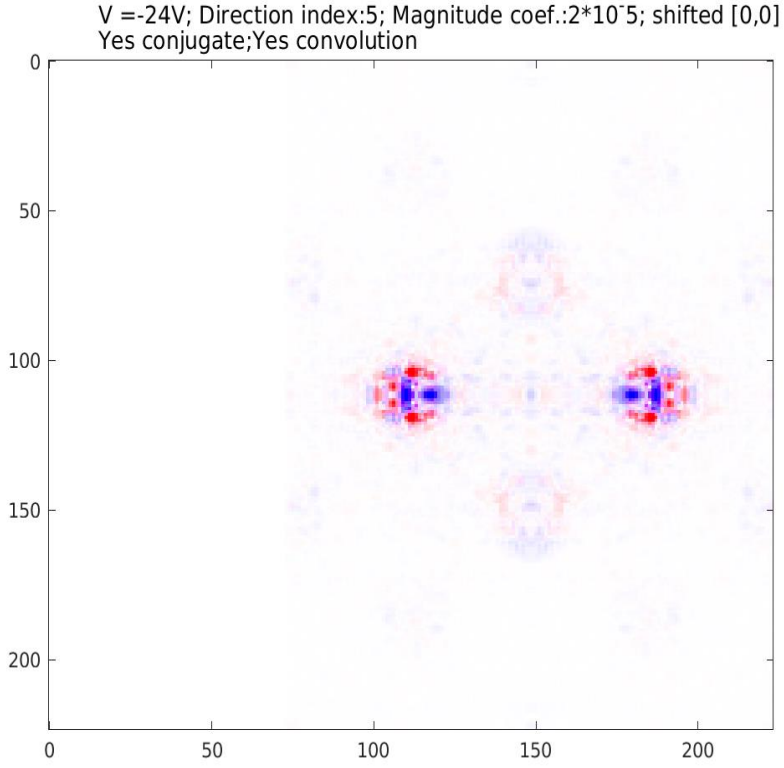


ıg etal, PRL (2015)
/SrTiO3 @ 10meV

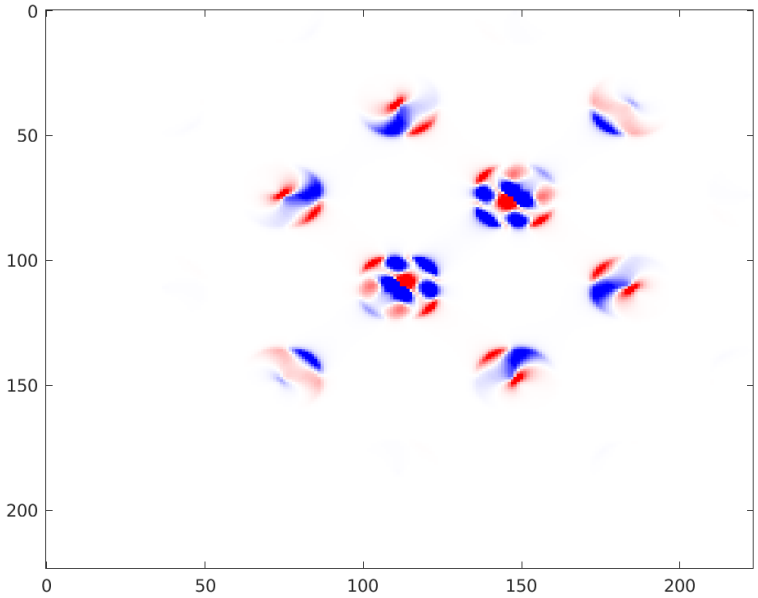


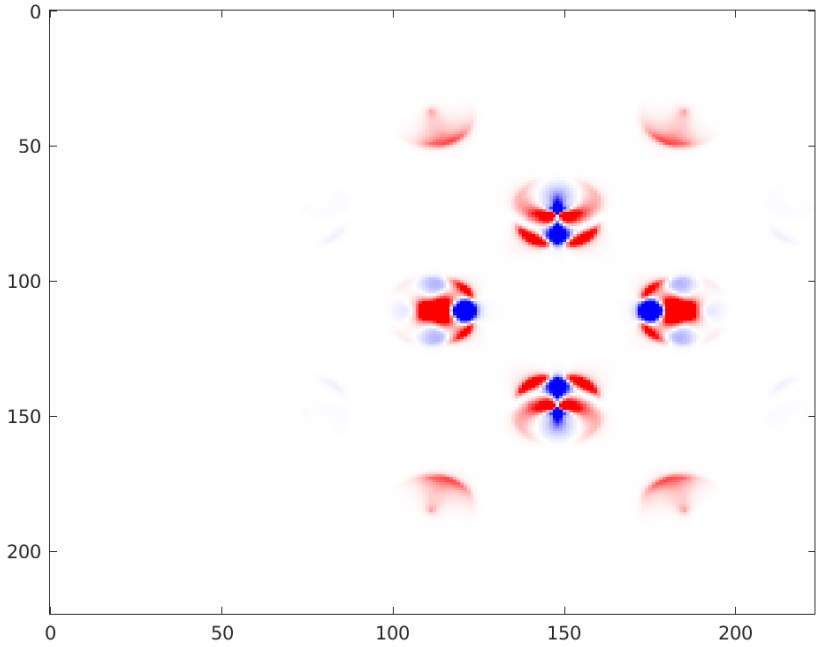
Holographic map - experiment





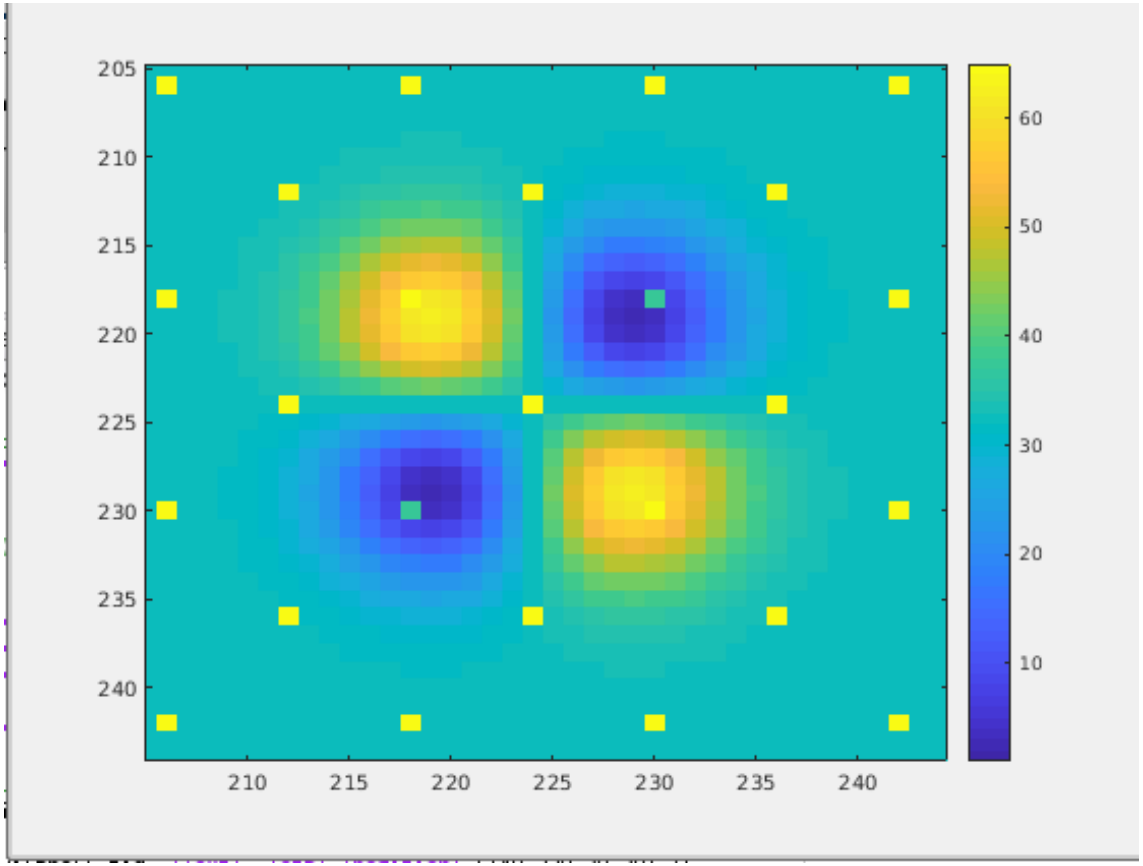
Holographic maps - theory





Joseph Rubin et al, unpublished

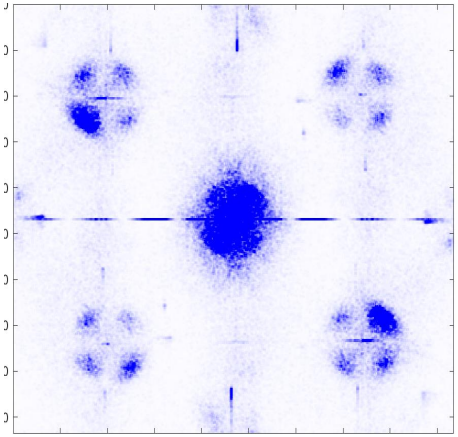
Main result: Wannier function



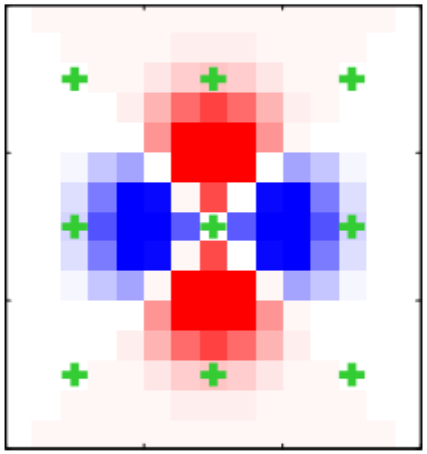
PRELIMINARY

Summary

High resolution STM



Wannier function



EG Dalla Torre, Y He, D Benjamin, E Demler, *New Journal of Physics 17*, 022001 (2015)
EG Dalla Torre, Y He, E Demler, *Nature Physics* 12, 1052–1056 (2016)
EG Dalla Torre, D Benjamin, Y He, D Dentelski, E Demler, *Physical Review B* 93, 205117 (2016)

Exchange program in Physics for undergraduate students from China

物理学专业大三学生本科学习项目

巴伊兰大学是目前以色列第二大的学术机构，也是目前以色列发展最快的高等教育机构。巴伊兰大学校区位于特拉维夫地区，环境怡人并正在不断扩大。

该校物理学系在固体物理和统计物理领域无论是教学还是研究都享有盛誉，并且，积聚了多位在该领域非常活跃、成绩斐然的科学家。近十年来，物理学系重点扶持了最前沿的研究方向之一——纳米技术。

物理学系的教学与科研将使学生能够认识和了解在纳米技术领域中占主导地位的物理学定律，为学生在这个新领域从事尖端学术研究和工业研发提供强有力的保障。

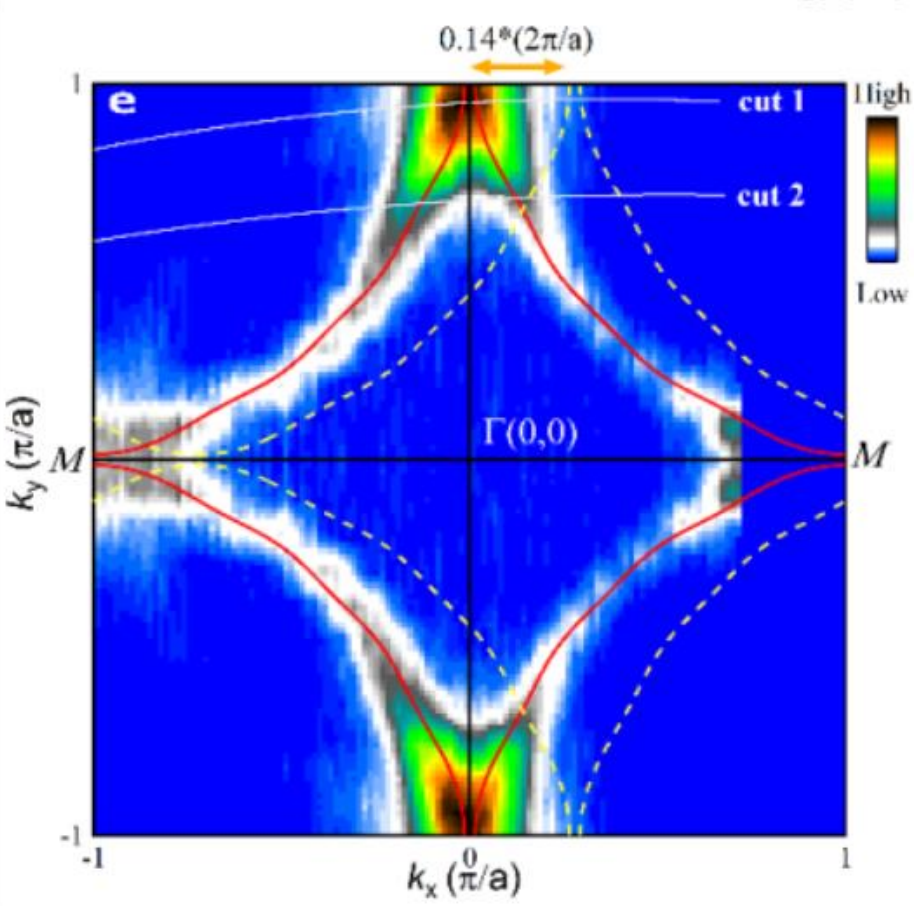
.物理学系目前已经启动面向海外高年级本科学生一学年物理基础学科在以学习交流项目，申请该学习项目的学生必须具有良好的英语听说能力。在该项目中，我们安排了与前沿研究紧密相关的课程，这些课程一般被安排在四年本科教育的第三年学习中，包括四门核心课程：（1）量子力学；（2）统计物理学；（3）电动力学以及（4）固体物理学。另外，巴伊兰大学物理系还提供若干选修课程，例如激光、高等固体物理实验、纳米技术和制备概论，等等。

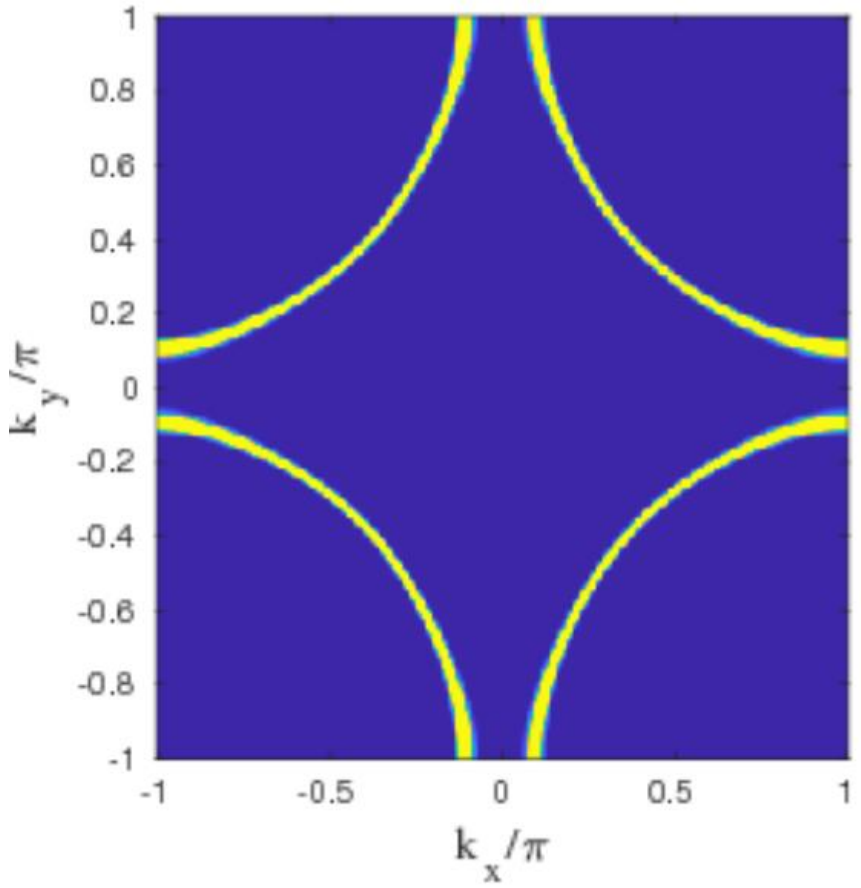
我们鼓励并支持交流学生在以期间参与科研项目训练，在来自物理学系和纳米技术中心的教授的指导下收获更多，度过愉快且充实的在以时光。

详细信息，请联系物理学系副主任优西·本·锡安博士 Yossi.Ben-zion@biu.ac.il。

EXTRA

Intermezzo : “there is no CDW, only Friedel”





$t' = -0.3t$

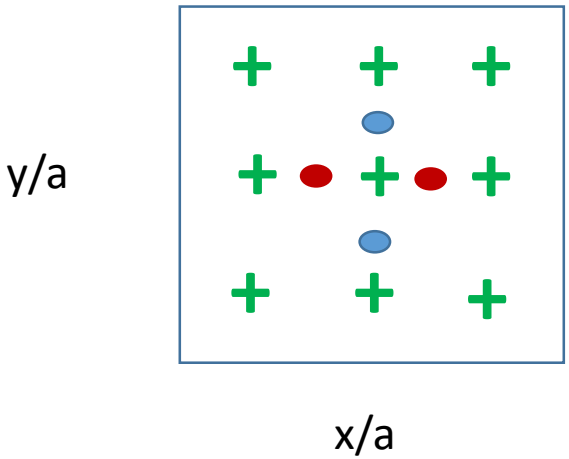
$x = 0.215$

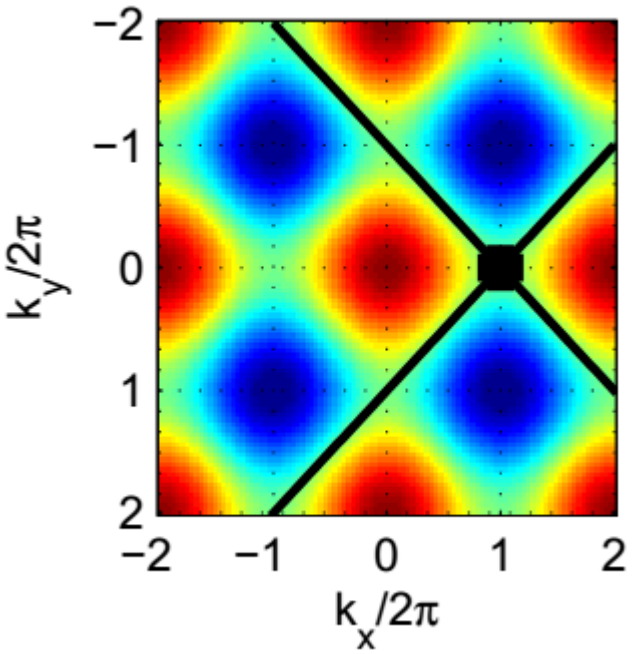
Intuitive interpretation

$$W(x,y) = \delta\left(x - \frac{a}{2}\right)\delta(y) + \delta\left(x + \frac{a}{2}\right)\delta(y)$$

$$-\delta(x)\delta\left(y - \frac{a}{2}\right) - \delta(x)\delta\left(y - \frac{a}{2}\right)$$

$$W(\vec{k}) = \cos\left(\frac{k_x}{2}\right) - \cos\left(\frac{k_y}{2}\right)$$





$$g(q,\omega) = \sum_k W(k)\, G_{k,k+q}\, W(k+q)$$

Periodicity of the Wannier function → **Periodicity** of the g-map