Electron-hole pair excitations (doping asymmetries) in low dimensional cuprates

M. Zahid Hasan

Joseph Henry Laboratories, Department of Physics
&
Princeton Center for Complex Materials

Princeton University

Yinwan Li, D. Qian, MZH (Dept. of Physics, Princeton)

Y.D. Chuang, Z. Hussain (ALS)
APS/Argonne : M. Beno, T. Gog, D. Casa

Samples : M. Foo, R.J. Cava (Princeton)
T. Sasagawa, H. Eisaki, S. Uchida (Tokyo)

Discussions : P.W. Anderson, N.P. Ong, D. Haldane (Princeton),

Support : NSF-MRSEC, **DOE**

Fundamental Spectroscopies ?

Is there any significant lack of spectroscopic knowledge on condensed matter electron systems ?

Spectral function (single-particle) :

$\mathcal{H}$ → **A(k,ω)** ---> $A^{-}(k,\omega)$ + $A^{+}(k,\omega)$

ARPES Inv-ARPES ?

Correlation functions (Two-Particle) :

$\mathcal{H}$ → C(q,w) : Spin --> **S(q,ω)** Neutron (well-known)

Charge --> **N(q,ω)** q (small) -> 0

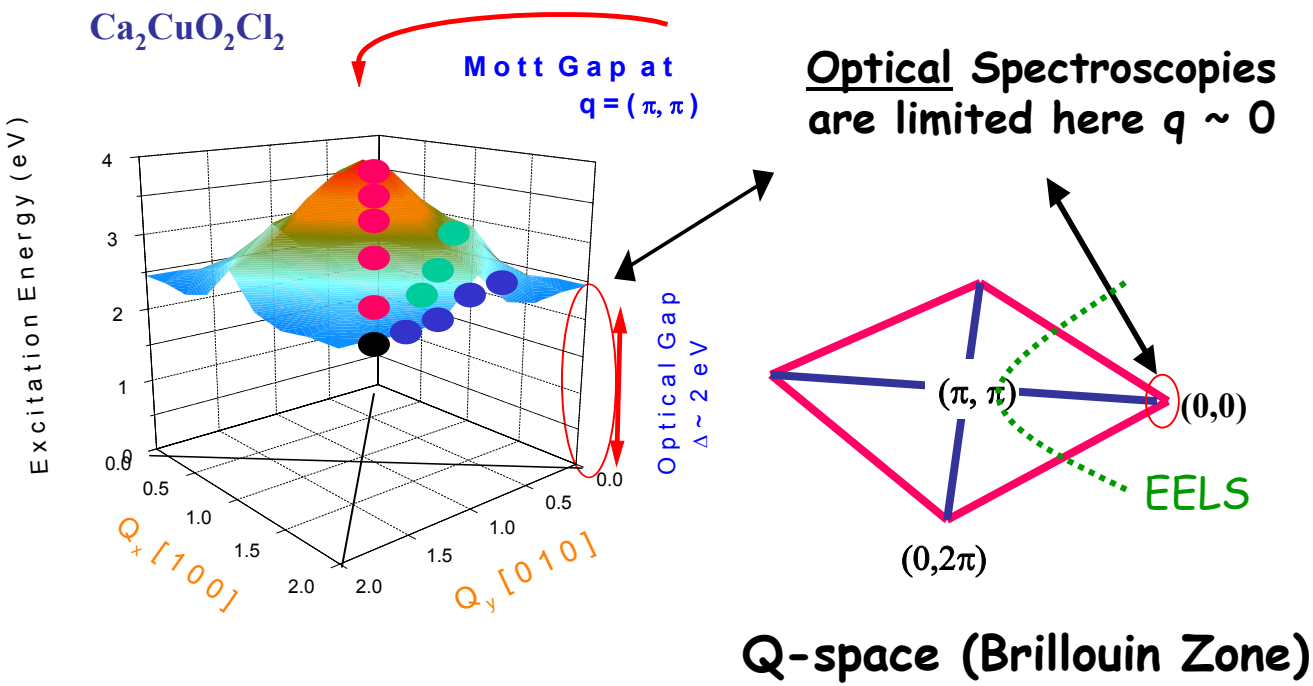
Optical Spectroscopies

EELS

Charge Dynamics: Finite-q Charge Fluctuations :

q-dependence (Zone Boundary etc.) is mostly unknown !

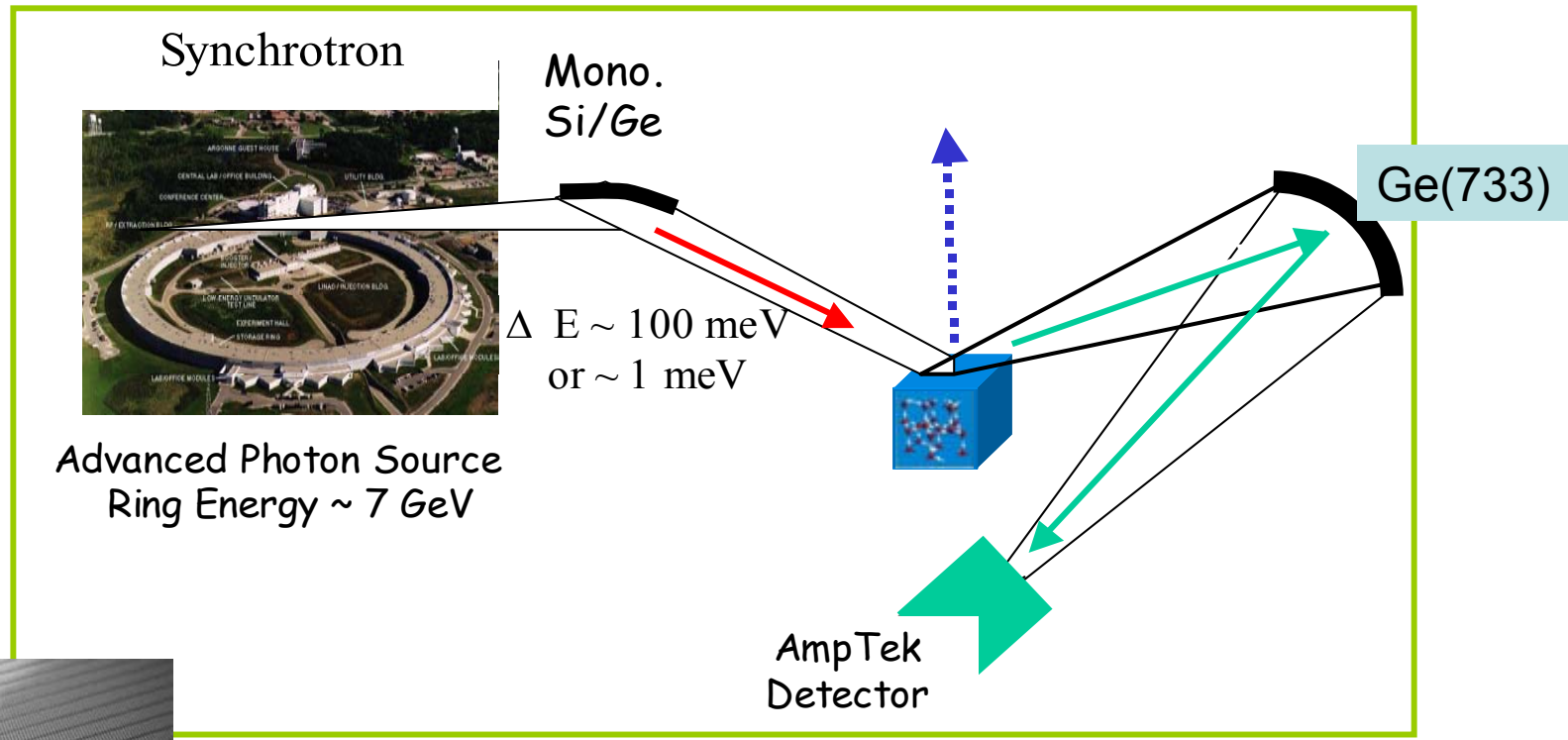
Spectroscopy over Complete Momentum Space

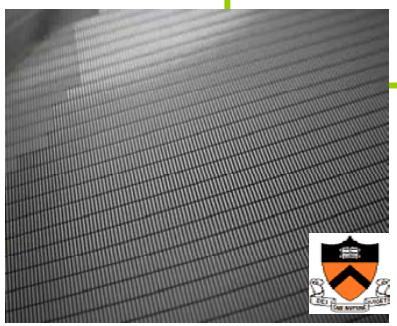


Momentum-Resolved Resonant Inelastic X-ray Scattering
Hasan, Isaacs et.al., Science 288, 1811 (2000)

NSLS x-21BL, Brookhaven National Lab (2000)

IXS Spectrometer





Diced Crystals Optics

(Hard) X-ray Energy ~ **9 KeV**
Energy Resolution ~ 350 meV

1D Mott Insulators (Spin-1/2)

E.H.Lieb & F.Y. Wu (1968)
P. W. Anderson (1988)
R. B. Laughlin (1990s)
& others

Physics in 1-D

No quasiparticle
(unlike in Fermi Liquids)

Two collective modes :
Spinons & Holons

Model 1-D spin-1/2 QH Compounds

$SrCuO_2$ & Sr_2CuO_3
(success in crystal growth
by Eisaki et.al.)

No long range AFM spin order
$T_{Neel} < 5K$

No Spin-Peierls transition

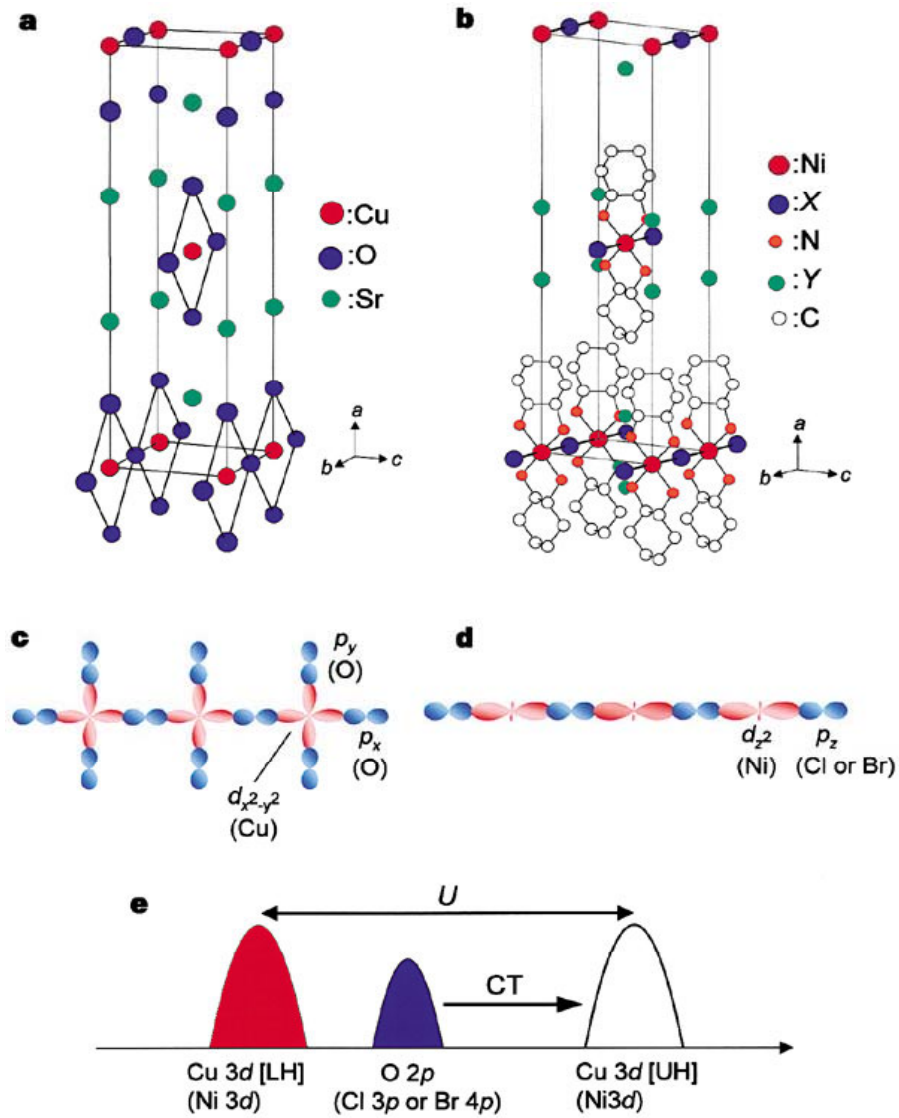
Motoyama et.al., PRL 76, 3212 (1996),

Eggert, Affleck et.al. PRL 73, 332 (1994)

q-resolved charge excitations using inelastic x-ray scattering ?

1-D (chain) cuprates

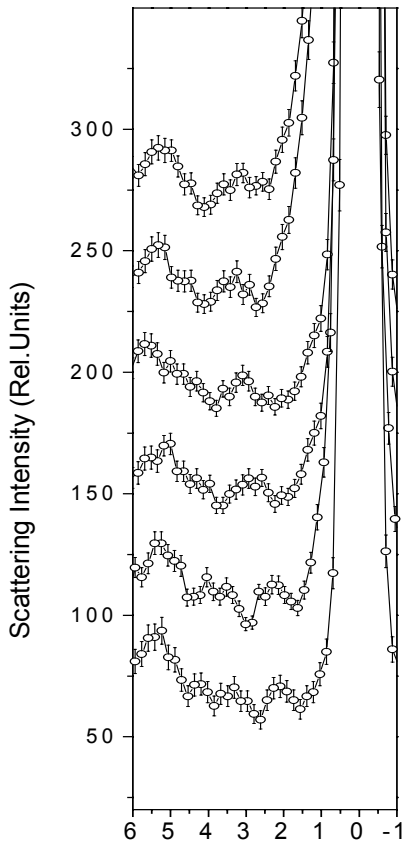
SrCuO2



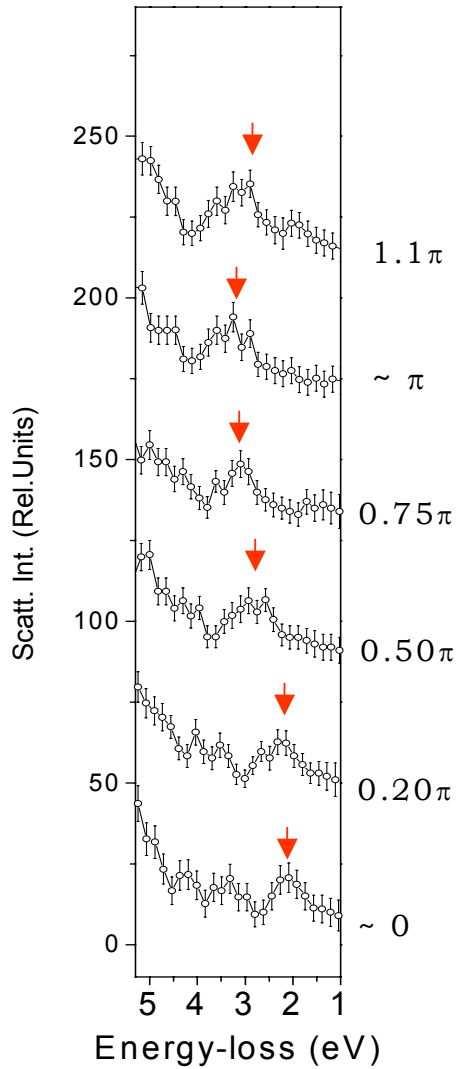
Dispersion in 1-D

$SrCuO_2$, q||chain

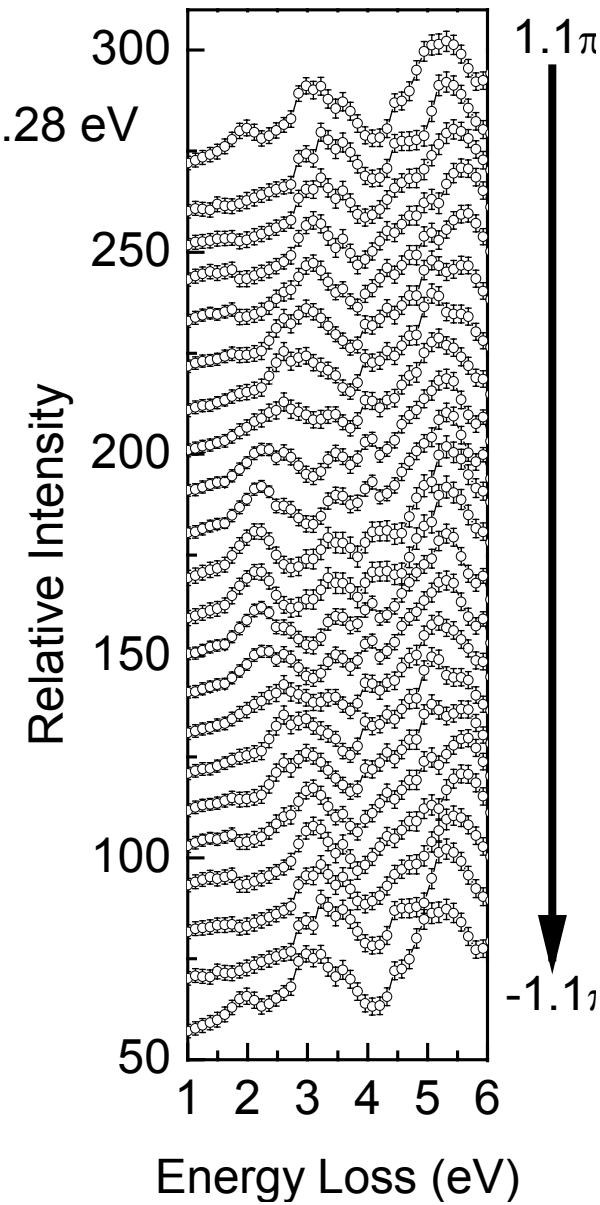
A highly q-dependent feature is seen in at $SrCuO_2$ the edge of the Mott gap similar behavior is seen in Sr_2CuO_3



dE ~ 0.5 eV



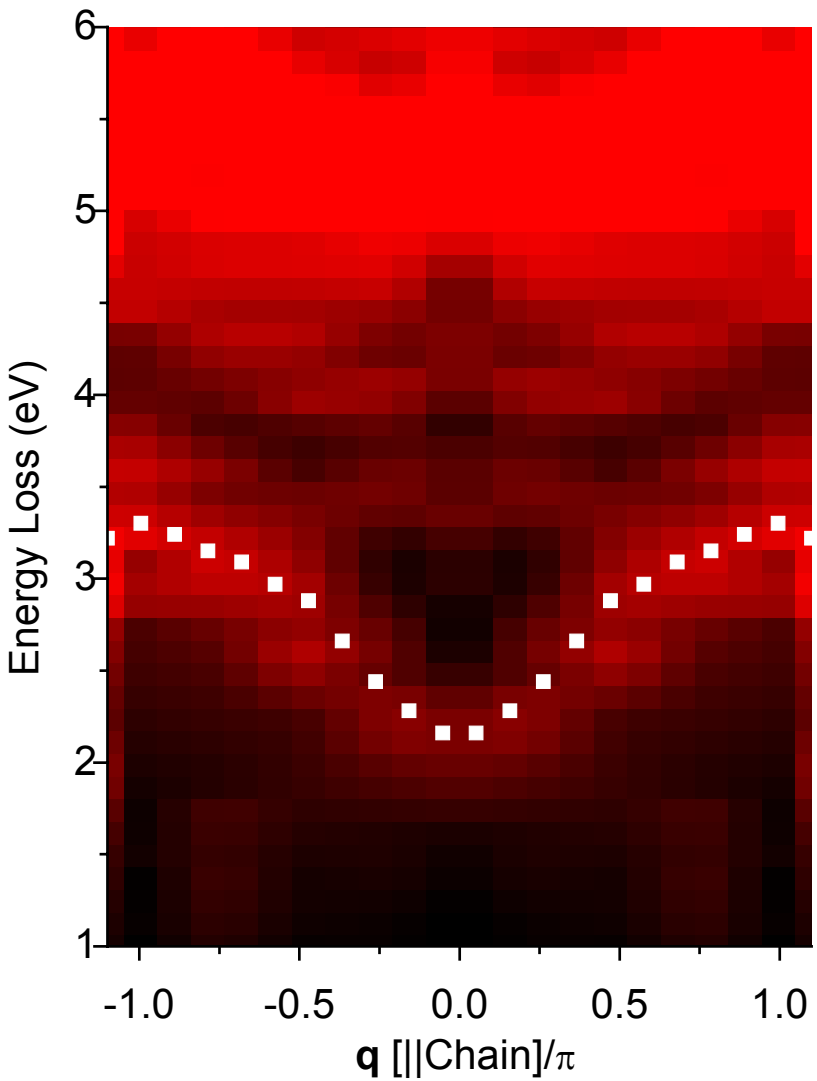
dE ~ 0.28 eV

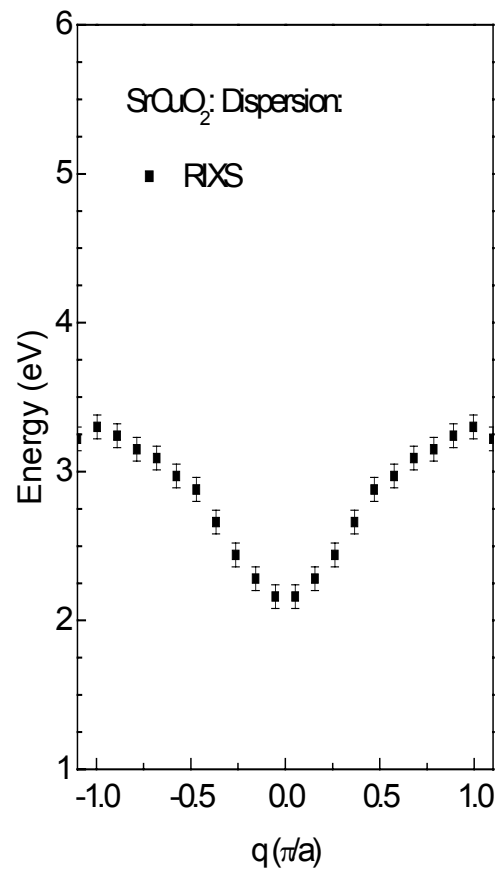


Hasan, Montano et.al., B'SRC/APS (2003)

Dispersive Excitations in 1-D

$SrCuO_2$, q||chain, Vertical Geometry

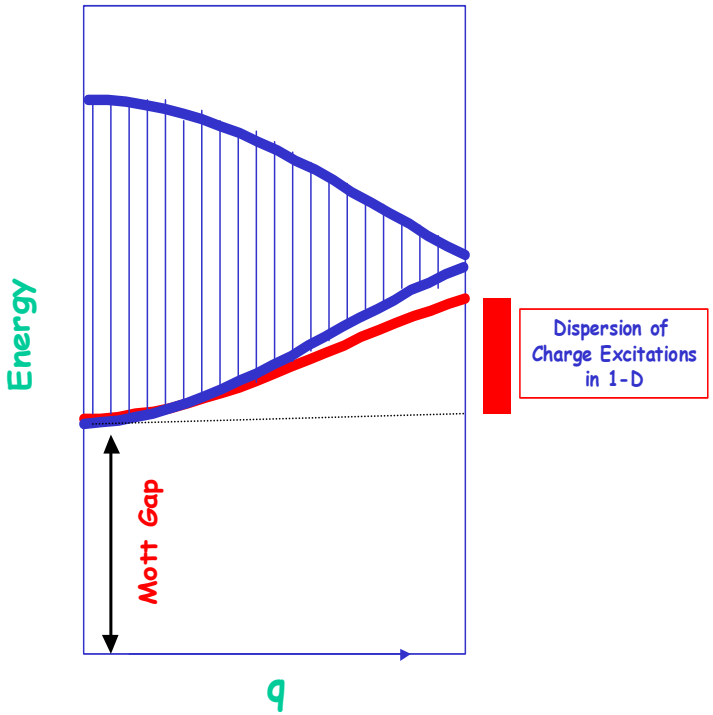




Dispersion & 1-D Hubbard Model

q-dependence of charge excitations in 1-D

$SrCuO_2$ and Sr_2CuO_3

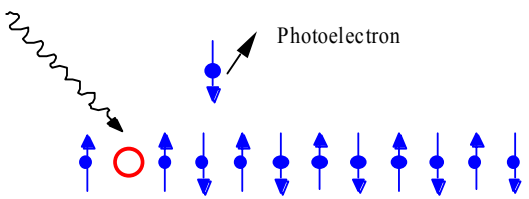


Neudert et.al., Phys. Rev. Lett. (1998).
Tsutsui et.al., Phys. Rev. B (1999).

Spinless charge excitations ?

Topological Excitations unique to 1-D

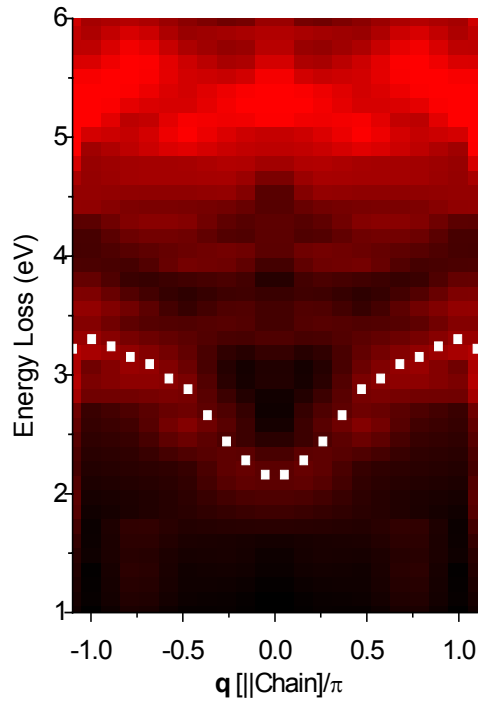
Excitations in 1-D : spin-charge separation

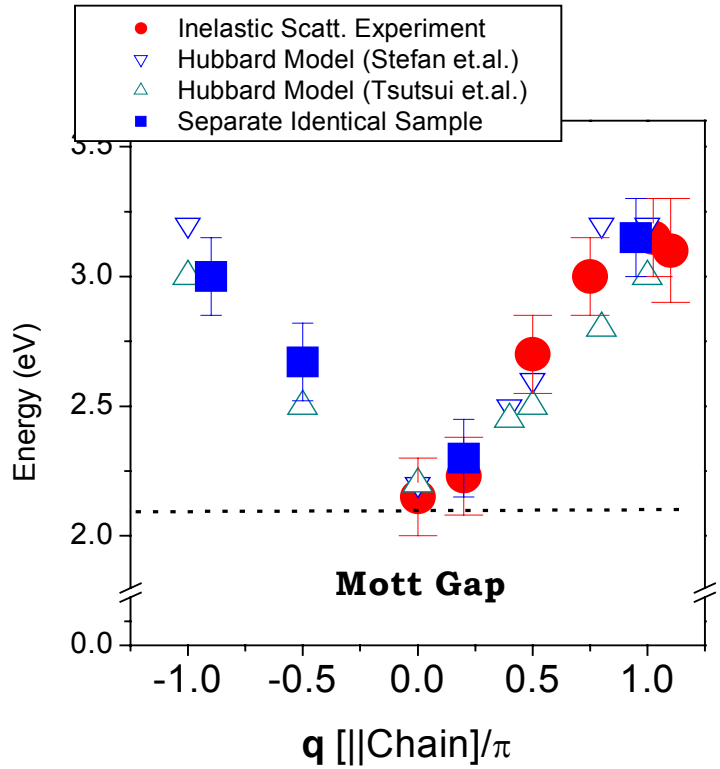


Two topological defects

Spinon: speed controlled by J

holon: speed controlled by t

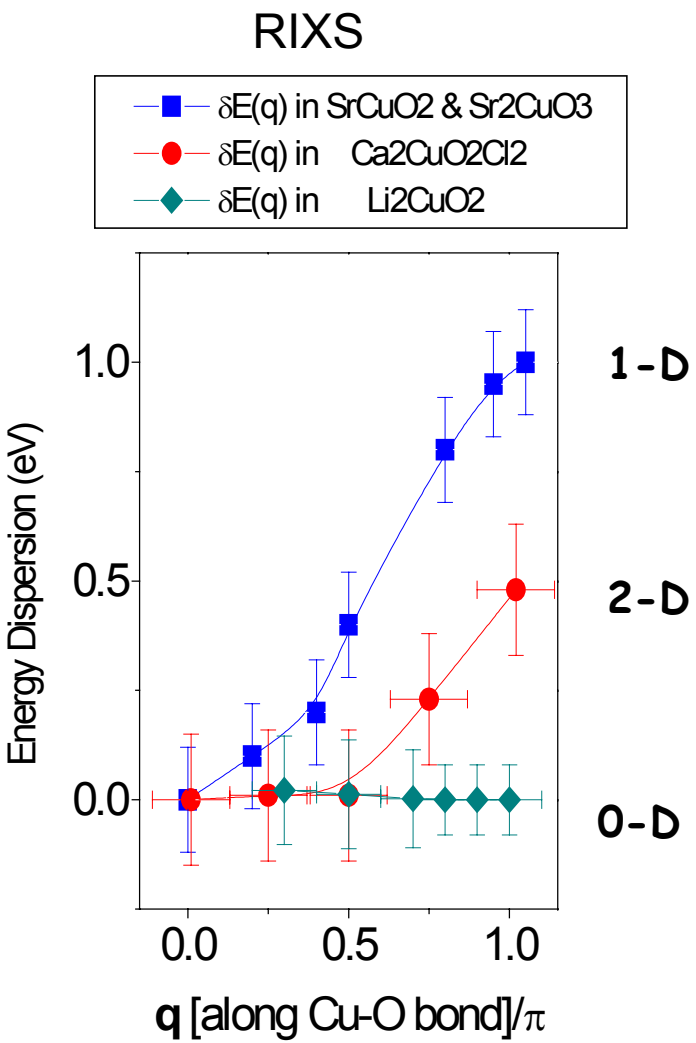




Adv Photon Src, CMC(Princeton BL)/Argonne Lab

Phys. Rev. Lett. 88, 177403 (2002)

Bandwidth & Dimensionality



1-D results are consistent with dispersions of "Holons" (spin-less charge excitations)

QP Bandwidth : 1-D vs. 2-D

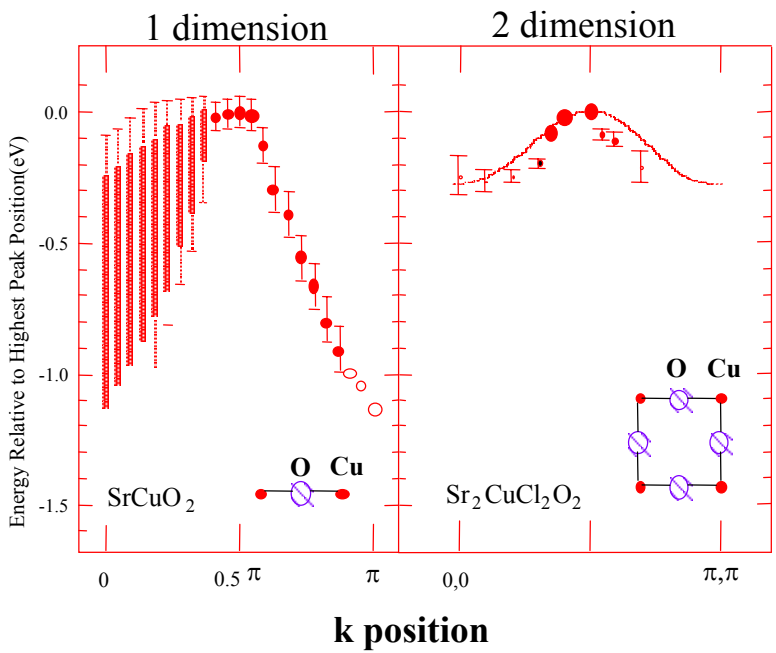
How about single-particle bandwidth ?

Expectation based on
Tight-Binding Model

Bandwidth 1-D vs. 2-D

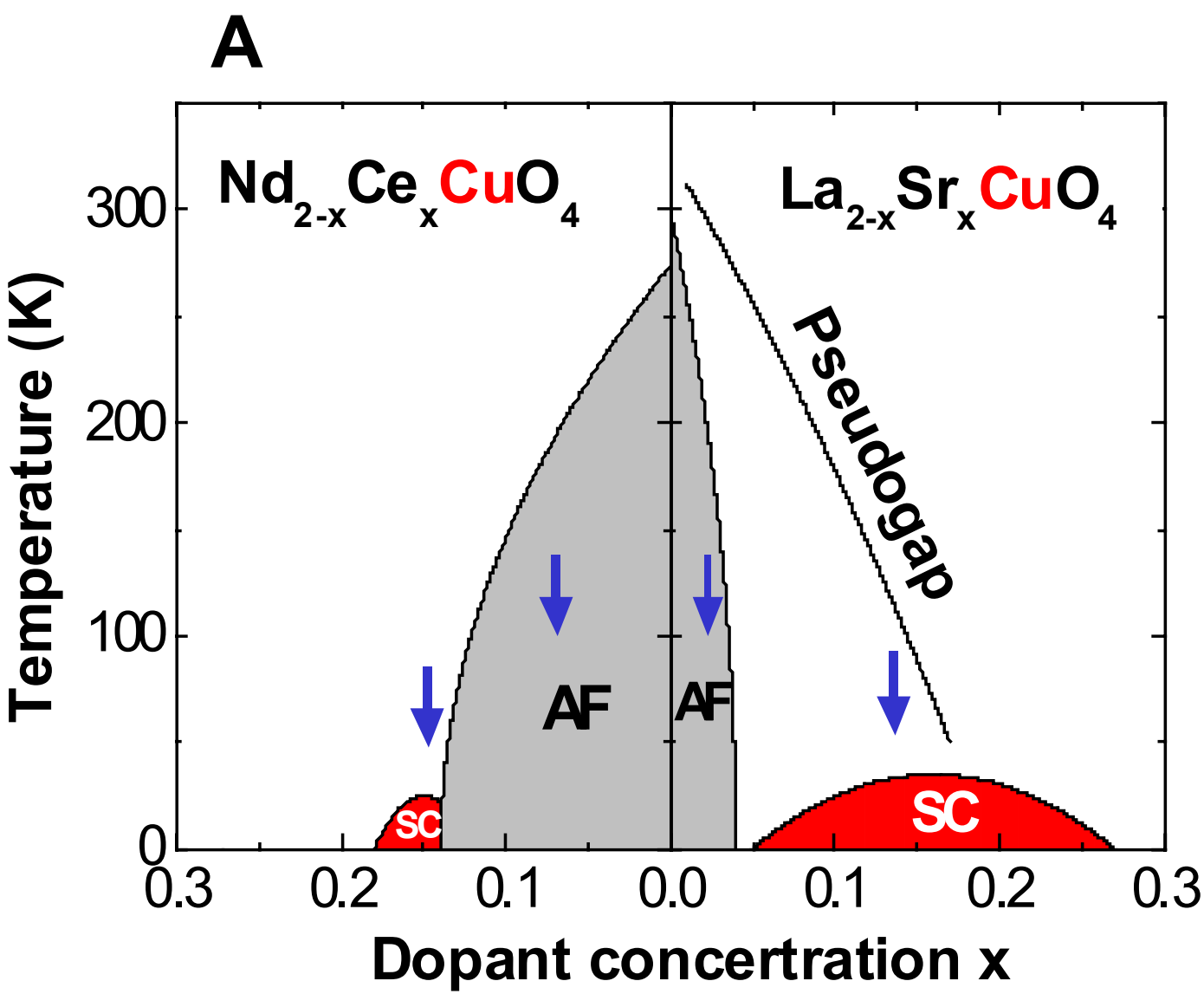
1-D --> 4t
2-D --> 8t

ARPES (Photoemission) Data
on 1-D cuprates

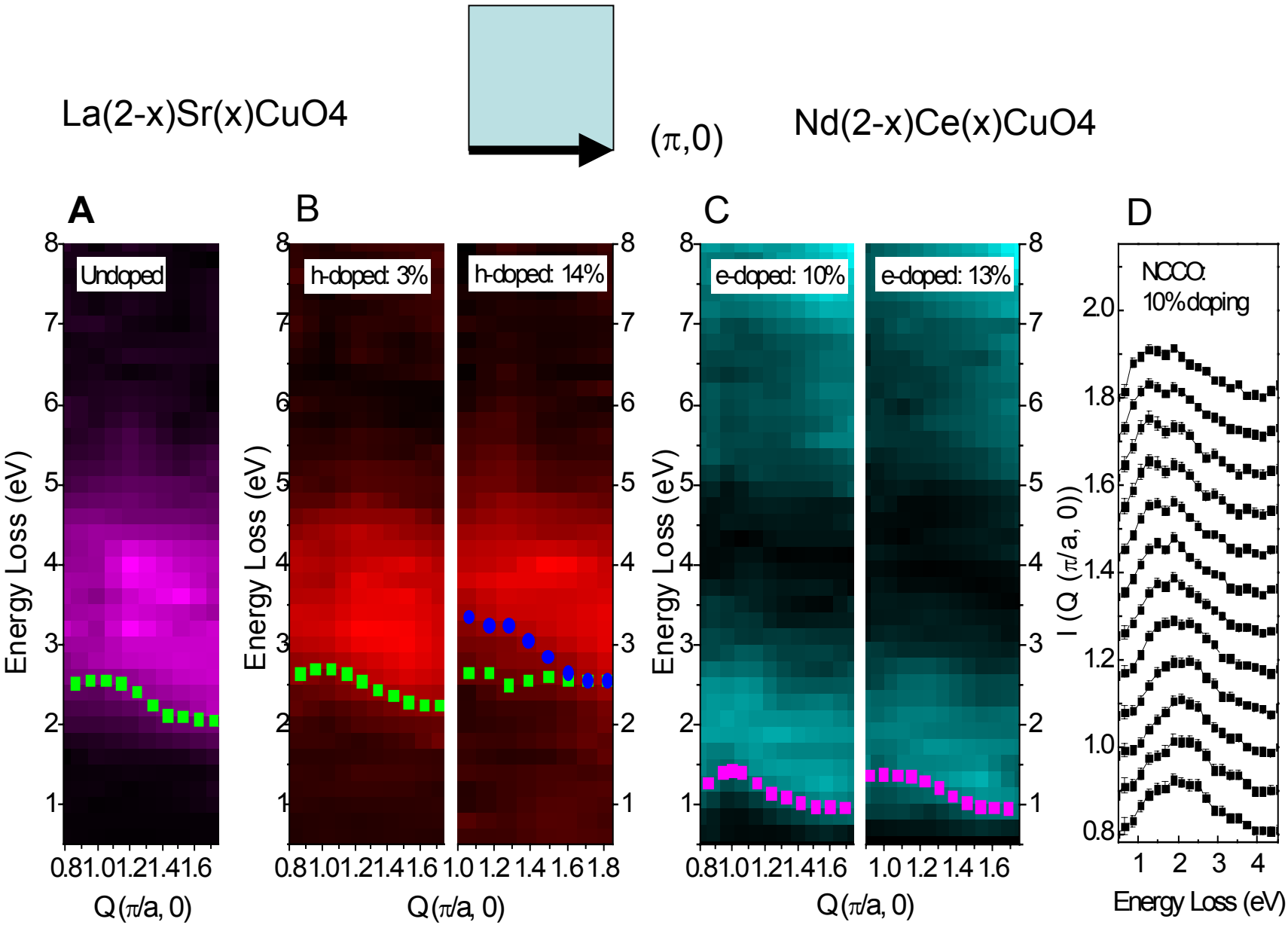


C. Kim et al., PRL (1996)

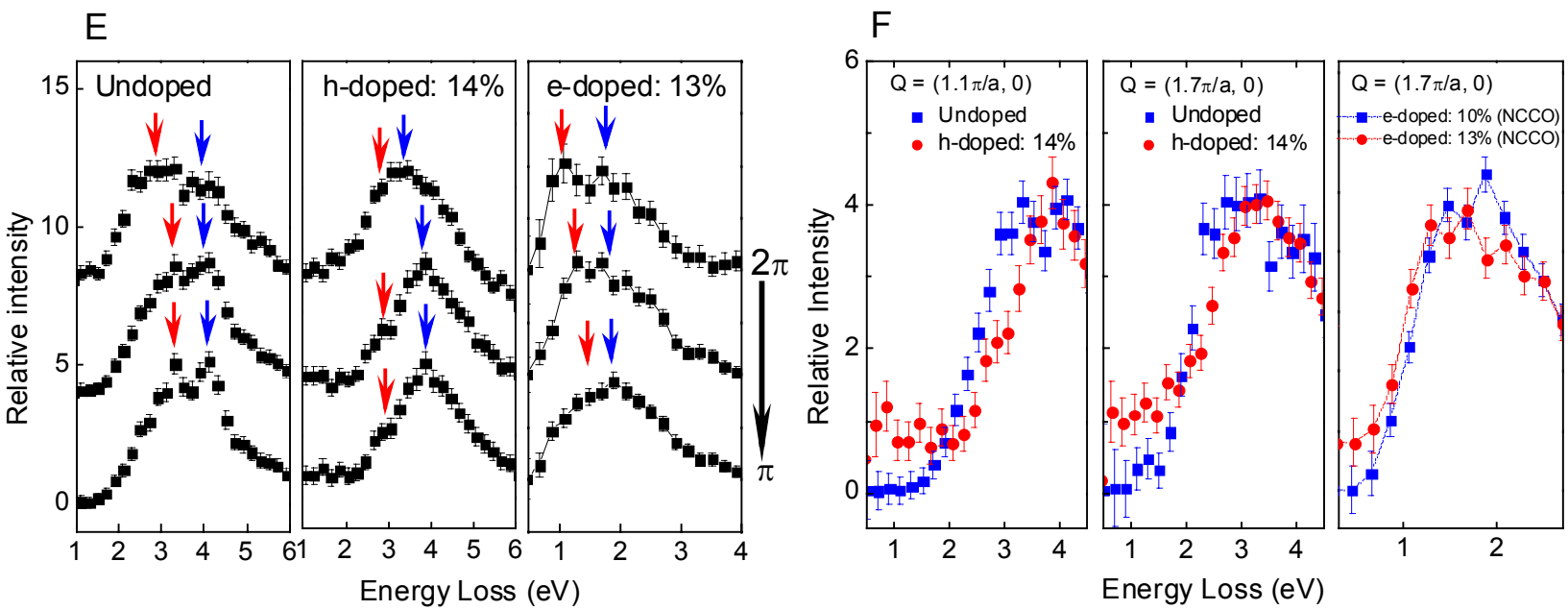
Doped Cuprates



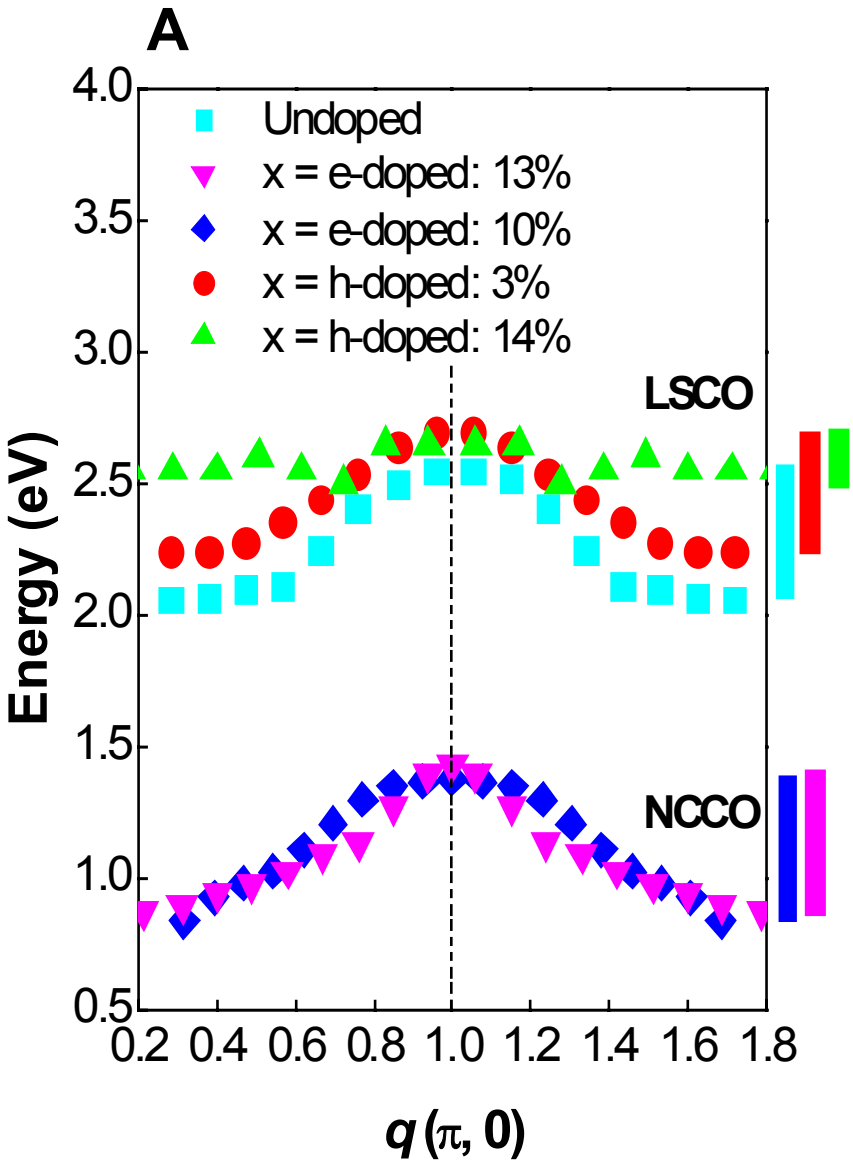
Doping Dependence



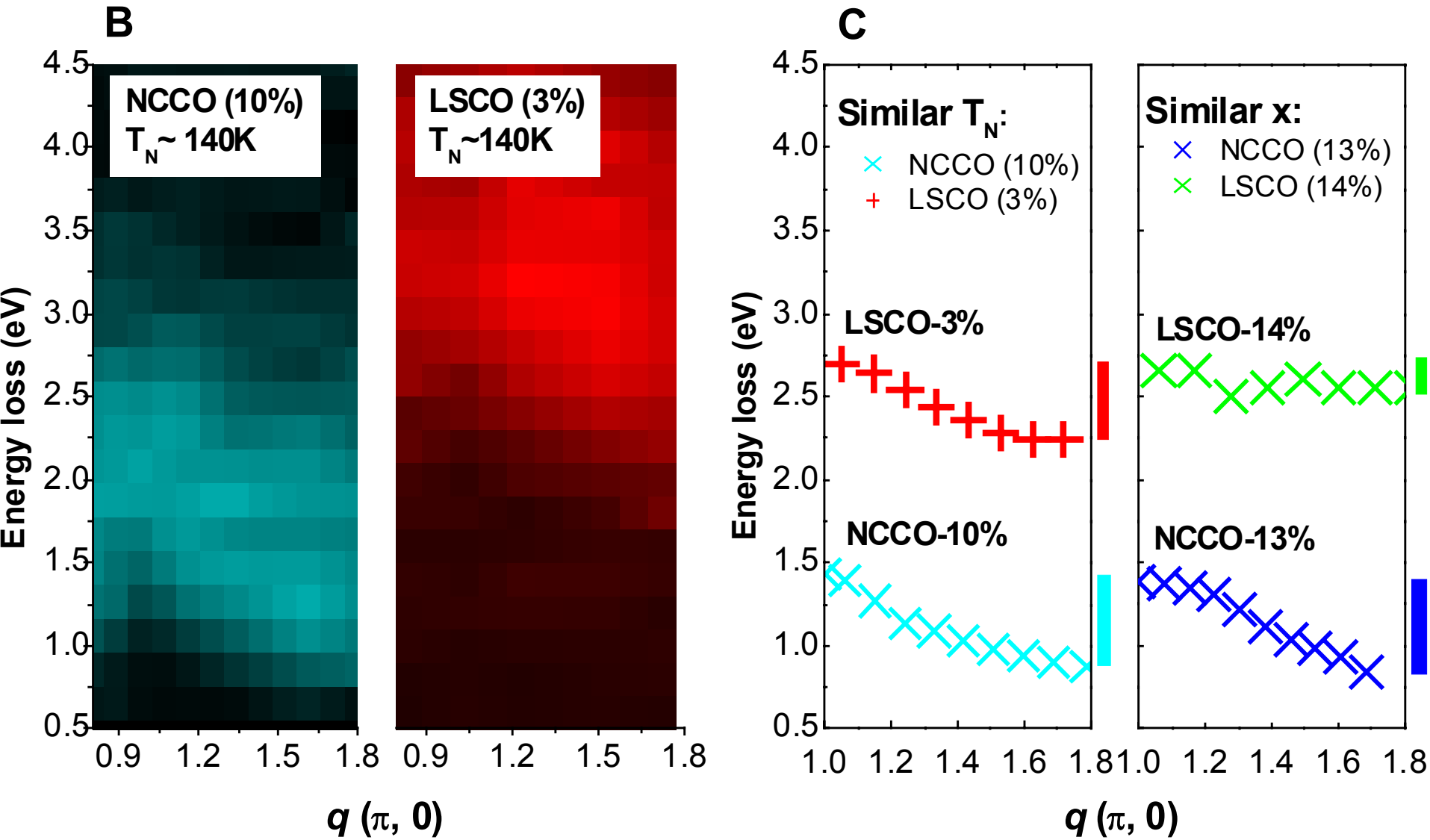
Doping Dependence



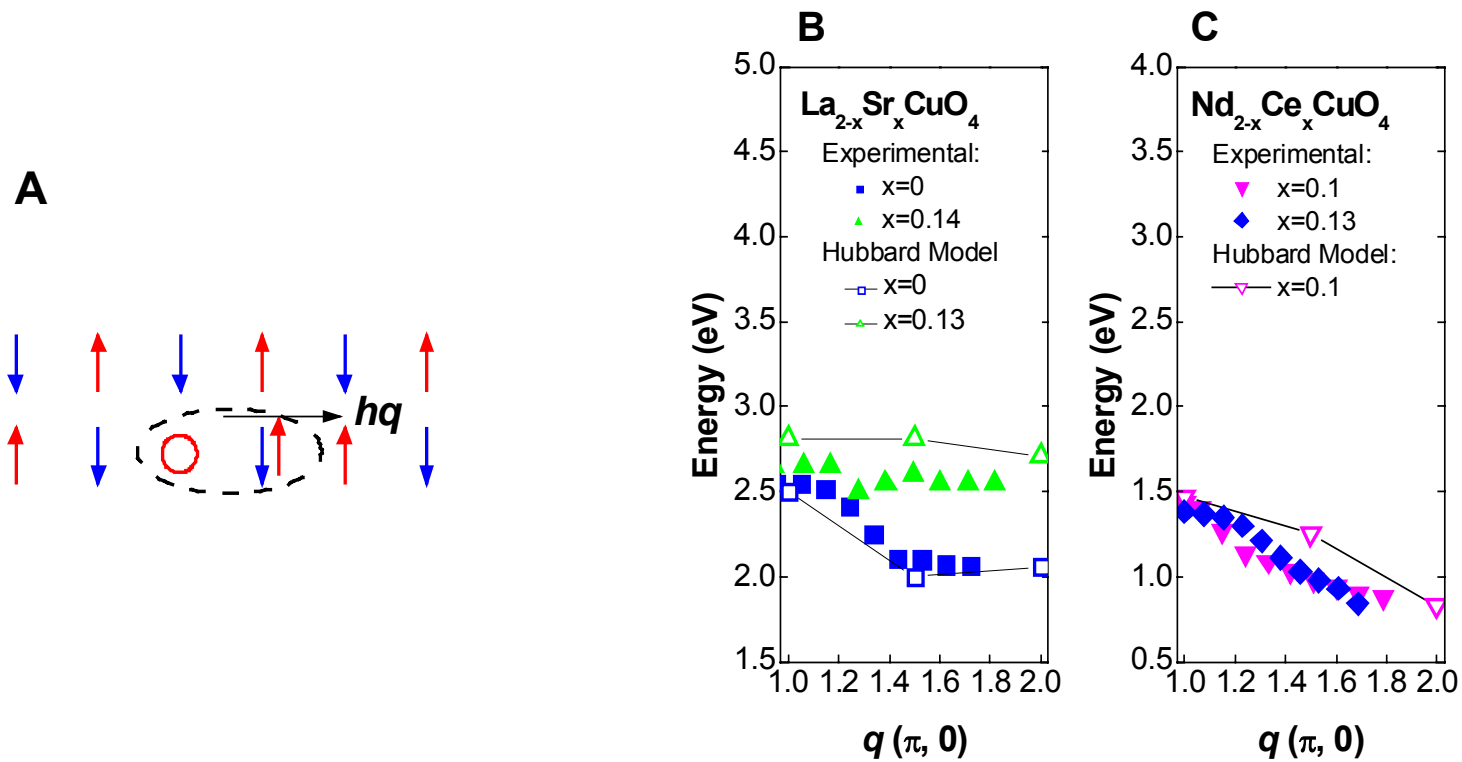
Doping Dependence of Electron-hole Pair Dispersion At the Mott Gap edge



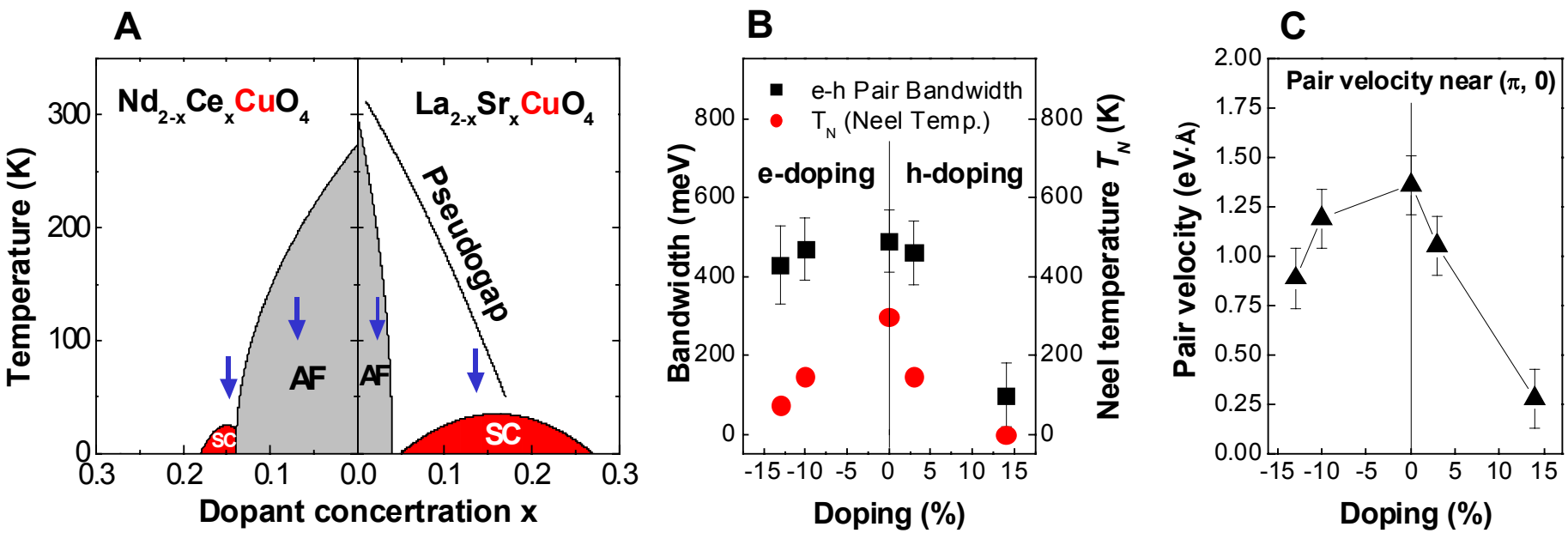
Dispersion and magnetism



Pair Dispersions and Hubbard Model



Electron-hole pair bandwidth and Magnetism



Conclusion : Pair Excitations in Cuprates

- **Mott Gap Excitations in quasi-2-D cuprates are highly anisotropic and Momentum-dependent. Agreement with Hubbard Model (Numerics) is seen in undoped case but not in doped cases.**

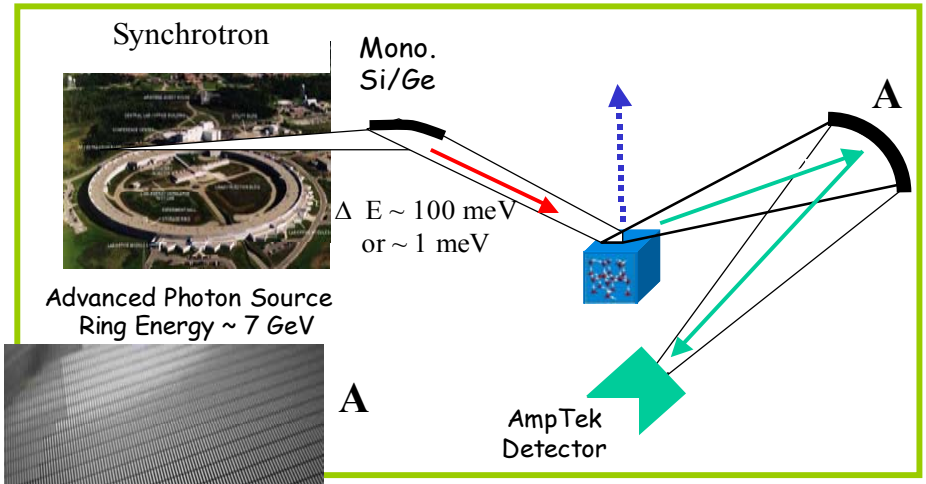
- **Doping melts the Mott Gap in quasi-2-D cuprates : changes involve a large energy scale ! Momentum-dependence is different for electron-doped and hole-doped systems : strong asymmetry is observed**

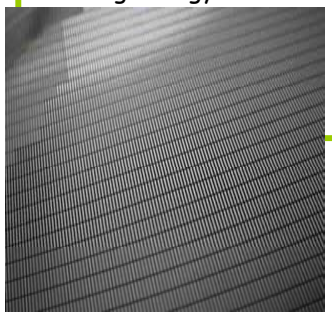
- **Charge fluctuations in quasi-1-D are more dispersive than in 2-D which is likely to be due to spin-charge separation : consistent with a view of spinless charge motion in 1-D.**

Many interesting (nontrivial) physics even at the gap energy scales!!

New Instruments : Ultra-high Resolution

To be used @ Advanced Photon Source, ANL

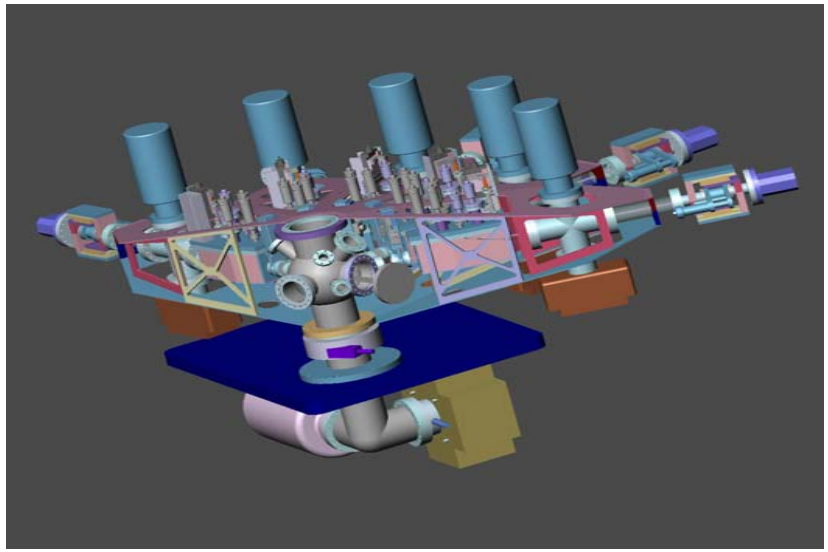




Diced Crystals Optics

(Hard) X-ray Energy ~ **10 KeV**
Energy Resolution ~ 100 meV
Integration of Magnetic Field

To be used @ Advanced Light Source, LBL



(Soft) X-ray Energy ~ **1 KeV**
Energy Resolution ~ 50-200 meV
Integration of Magnetic Field

MRLIN beamline : ARPES + soft-IXS (~20 meV)

<u>New Regimes for Spectroscopic Studies of CMS</u>

- **Mott Insulators (Low Dimensional)**
- **Charge, Orbital & Lattice Dynamics in TMOs**
- **Organic (Molecular Crystals) Insulators**
- **Optical Proteins & Biomacromolecules, Nanocrystals etc.**

Acknowledgement

Yinwan Li, D. Qian, MZH (Dept. of Physics, Princeton)

Y.D. Chuang, Z. Hussain (ALS)
APS/Argonne : M. Beno, T. Gog, D. Casa

Samples : M. Foo, R.J. Cava (Princeton)
T. Sasagawa, H. Eisaki, S. Uchida (Tokyo)

Discussions : P.W. Anderson, N.P. Ong, D. Haldane (Princeton),

Support : NSF-MRSEC, **DOE**