Momentum-Resolved Charge Dynamics in Mott Systems

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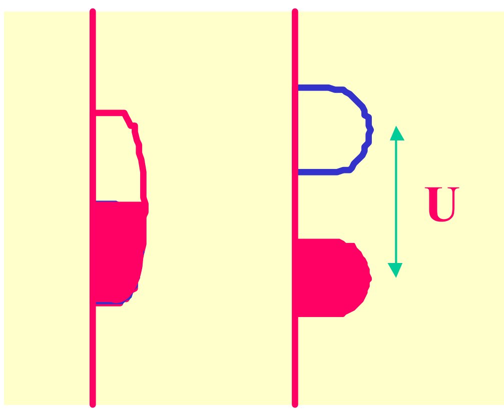
Strongly Correlated (Mott) Systems

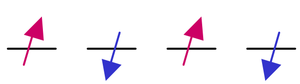
Strong Coupling Limits

$U/t >> 1$



One-electron
Band Theory

Mott Insulators



Antiferromagnetism

Doped Mott Insulators

High-T_c Superconductivity
Cuprates

Colossal Magnetoresistance
Manganites

Large Thermopower
Cobaltates

Novel Phases : Stripes & Orbital Order
(many Oxides)

Anomalous Transport & Magnetic
& Spectroscopic properties

Novel (Exotic) Order &
Non-Fermi Liquid Behavior
Non-purterbative physics

.

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Why Inelastic with X-rays ?

- **Momentum of Light** :
  Laser : hk ~ 0.001 angs^{-1}
  X-ray : hk ~ 1-10 angs^{-1} ~ Brillouin Zones

  Finite-q spectroscopy of charge fluct.'n
- **Bulk** Sensitive Probe of Elect. Structure: $1\mu m$ to 1mm
- Study **any direction** in 3-D in a crystal (unlike ARPES).
- Good **intensities at high-q** (unlike EELS).
- **No multiple scattering** complications. Weak-coupling probe.
- Couples to **charge density** directly (unlike Neutrons).
- Can be applied in the presence of **external fields** (unlike ARPES)
- **Symmetry selectivity** at Resonance (unlike EELS).
- **Small samples (~ 1 mm)** (unlike neutron).

An Emerging Novel Tool to Measure Charge Dynamics

Photon is a weak-coupling probe

Probe	Fundamental Coupling Strength	
Electron	$(2Z/r_B Q^2)^2$	$\sim 10^{-15}$
Neutron	b^2	$\sim 10^{-24}$
Photon	$(Zr_C)^2$	$\sim 10^{-25}$

		Energy Resolution / Momentum Range	
1970s	Neutron/INS	0.1 meV / 10 meV	10^{-2}
1990s	Electron/ARPES	1 meV / 30 eV	10^{-4}
2000s	Photon/IXS	1 meV / 10 KeV	10^{-7}

Inelastic X-ray Scattering experiments are
several orders of magnitude more (technically) challenging
...

- *High Brightness Synchrotrons*
- *Excellent, Ultra-High Precision X-ray Optics*

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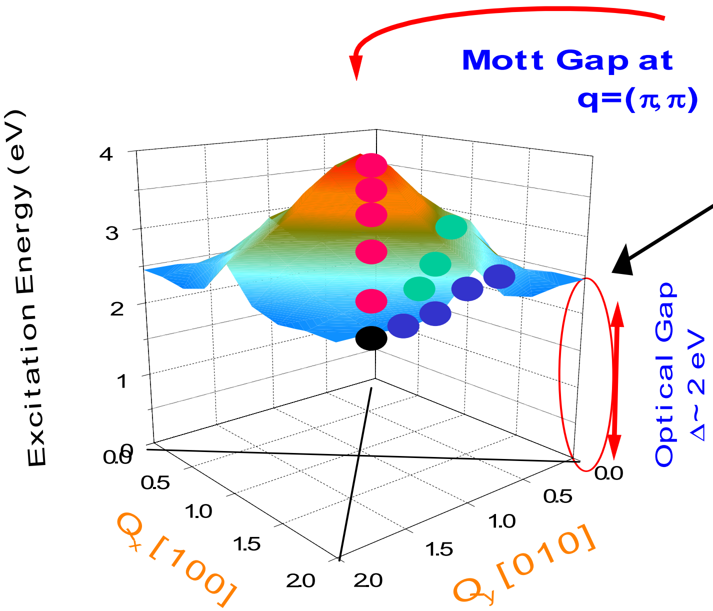
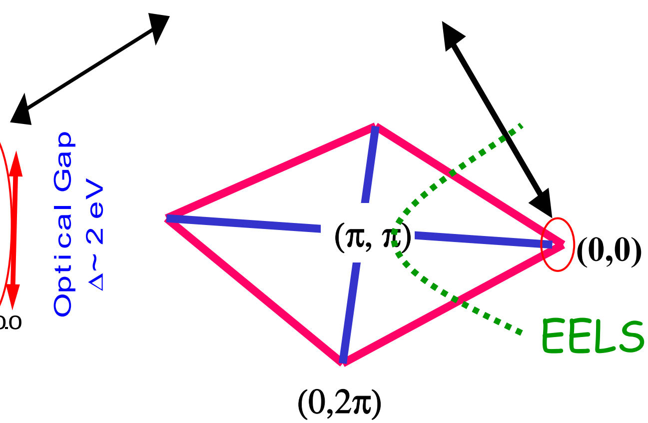
Charge Excitations & Mott Gap

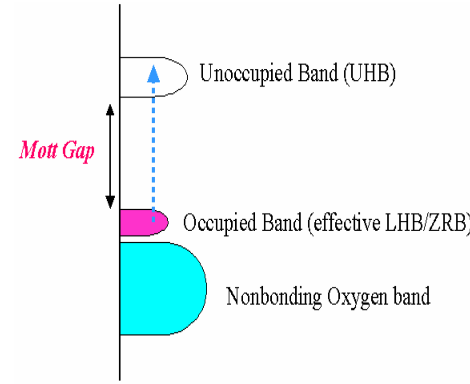
Example-1



<u>Optical</u> Spectroscopies are here q ~ 0



Q-space (Brillouin Zone)



Information about Unoccupied states (electrons) ?

NSLS X-21(1997-99)

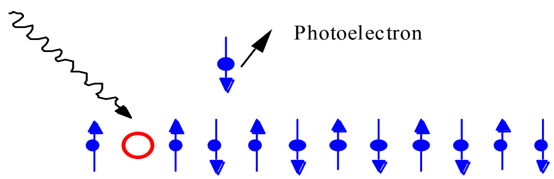
M.Z. Hasan, E. Isaacs et.al., Science 288, 1811 (2000)

Holon Dynamics

Example-2

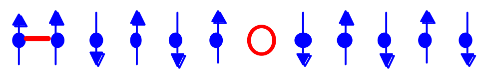
$SrCuO_2$ and Sr_2CuO_3

Excitations in 1-D : spin-charge separation



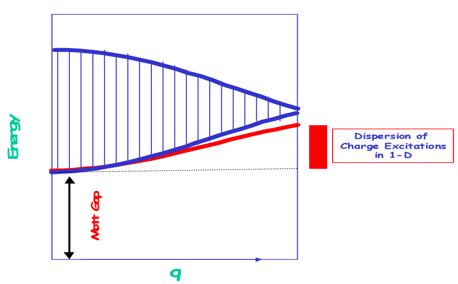
Charge physics in 1-D

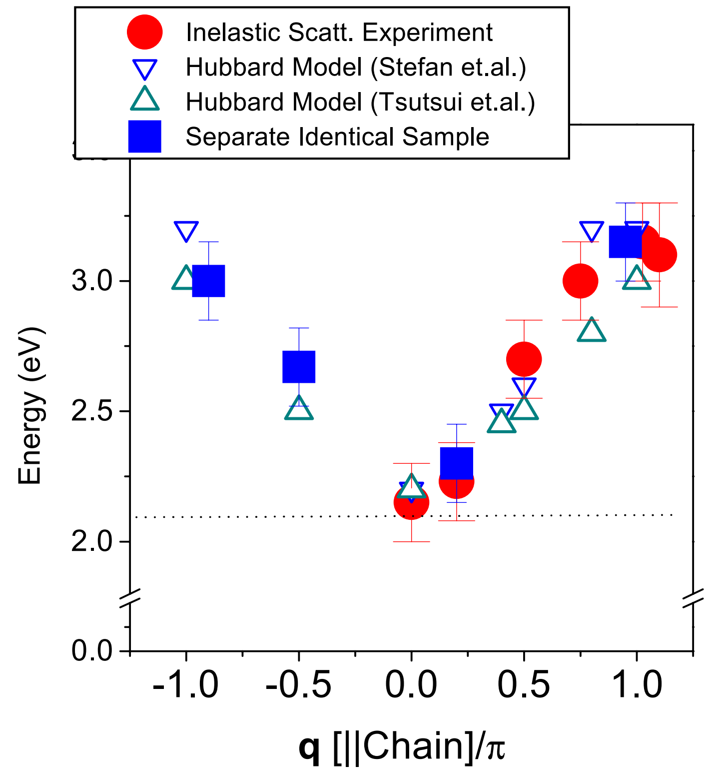
Two topological defects



Spinon: speed controlled by J

holon: speed controlled by t





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

BESSRC-CAT (2000-01)
M.Z. Hasan, P. Montano et.al., Phys. Rev. Lett. (2002)

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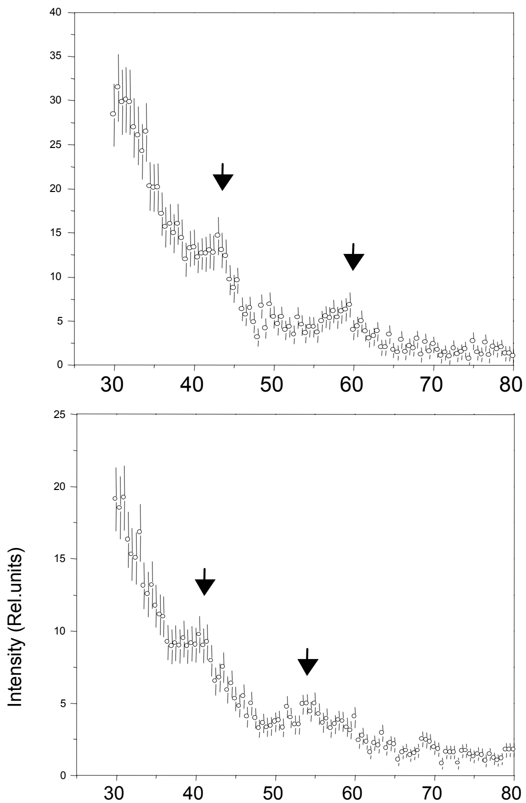
Stripes & Phonons

Example-3

Electron-Phonon Interaction in manganites

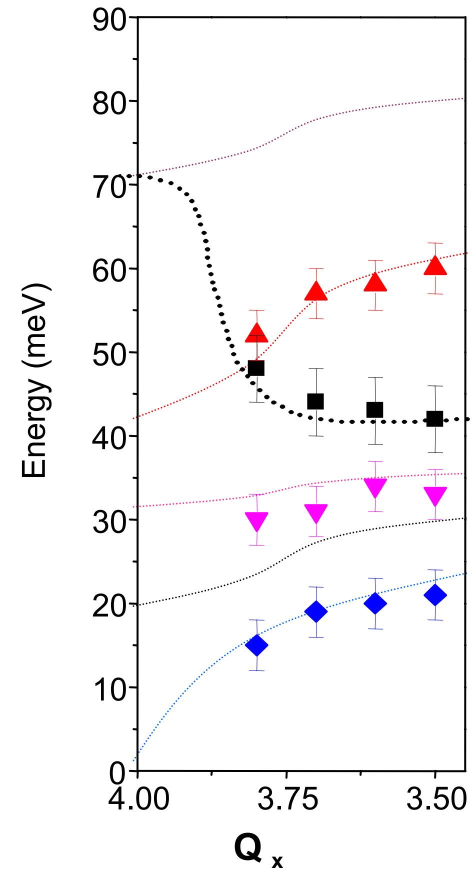
IXS can look at <u>single domain samples</u>

$\delta\omega \sim 5$ meV, Si(888) optics



meV

Phonon Dispersions :



M.Z. Hasan, d'Astuto, et.al. ESRF (2002)

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Why Soft ?

dd excitations enhanced- orbital degrees of freedom

$Q = (\pi,0)$

Weak quasielastic scattering makes low-energy accessible

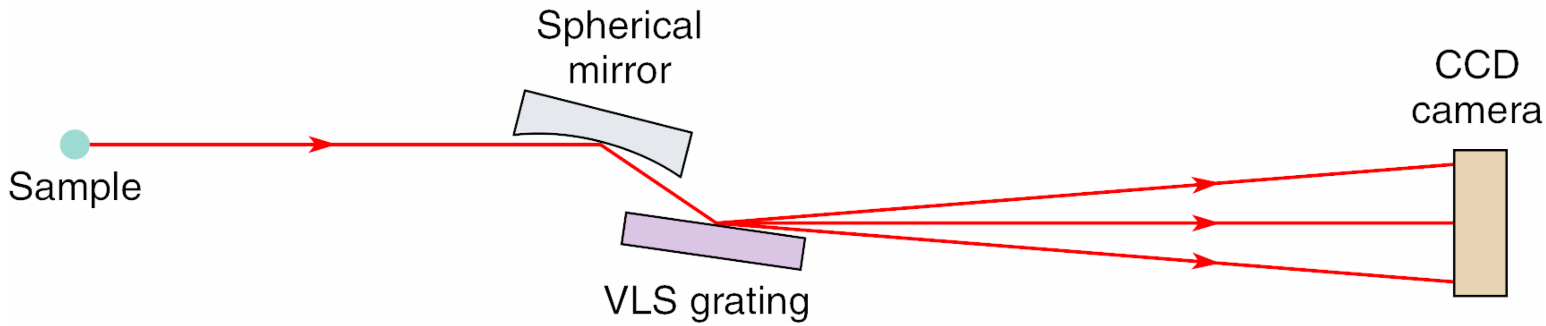
Spin-orbit split edges (L_2, L_3) + CP-light -> Magnetism

Better energy resolution (~ 10-50 meV) and several edges (L,M etc.)

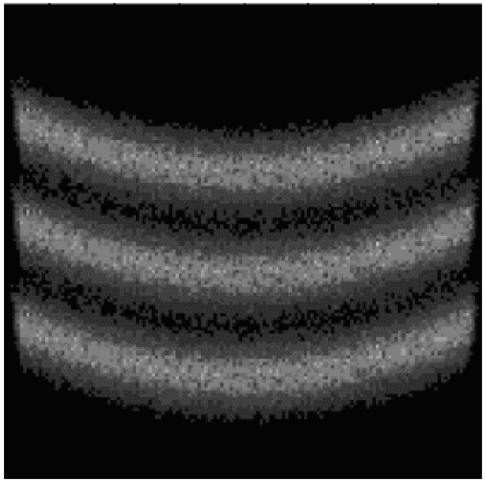
Spectrograph mode (Full w-spectra in a single shot)

meV Resolution VLS Spectrograph

Optical Design



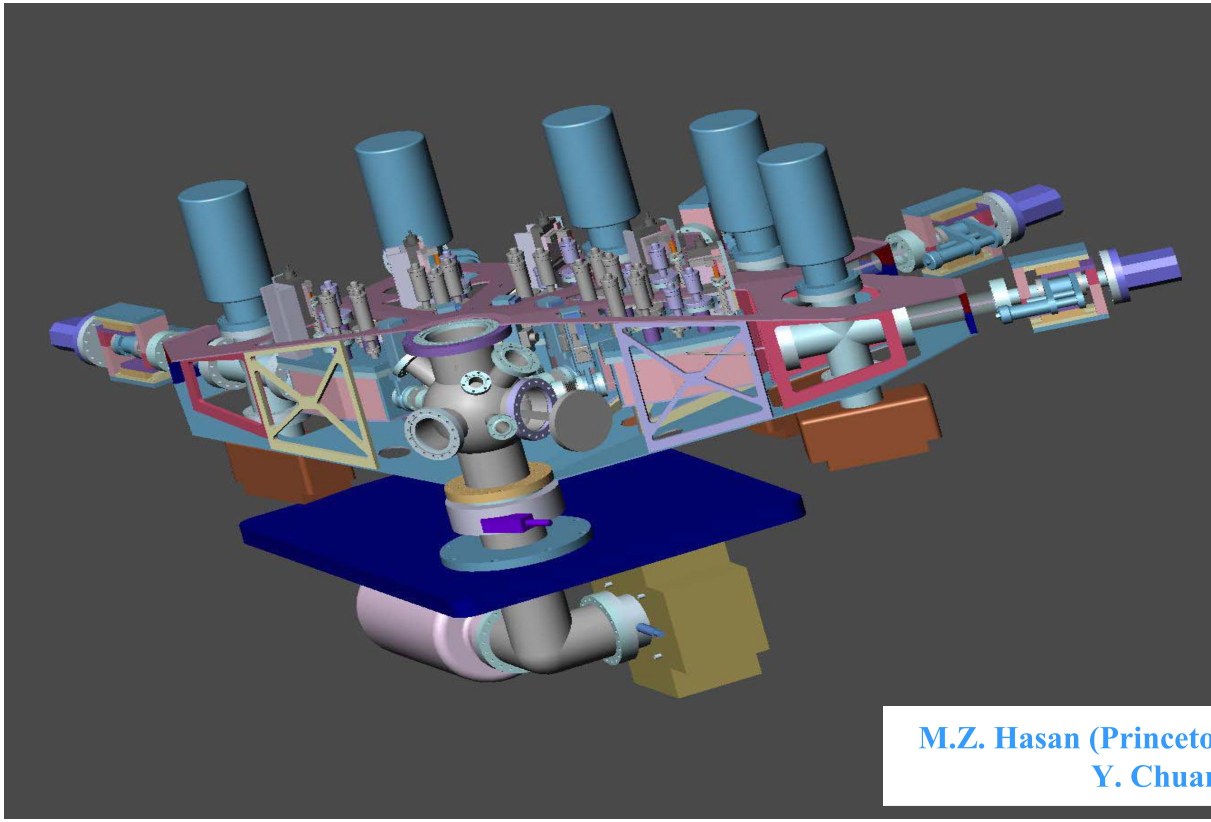
Ray Traces (Shadows)



- **Resolution approaching 1 meV**.
- Overall length = 2 meters.
- Designed for Mn 3p (47 eV)
- Source size = 4 microns.

hν = 47 eV ± 2 meV

Ultra-high Resolution Spectrometer



Soft X-rays < **1 KeV**
Energy Resolution ~ 10-100 meV
Integration of Magnetic Field

M.Z. Hasan (Princeton), J. Underwood, E. Gullikson (CXRO)
Y. Chuang, Z. Hussain (ALS/LBNL)

New Physics …

Correlated Elect. Physics

- **q-resolved charge & lattice dynamics in Doped Mott & other complex Systs.**
- **Organic (Molecular Crystals) Systems, C-60, ET-salts etc.**

Biophysics **Optical Proteins & Biomacromolecules**

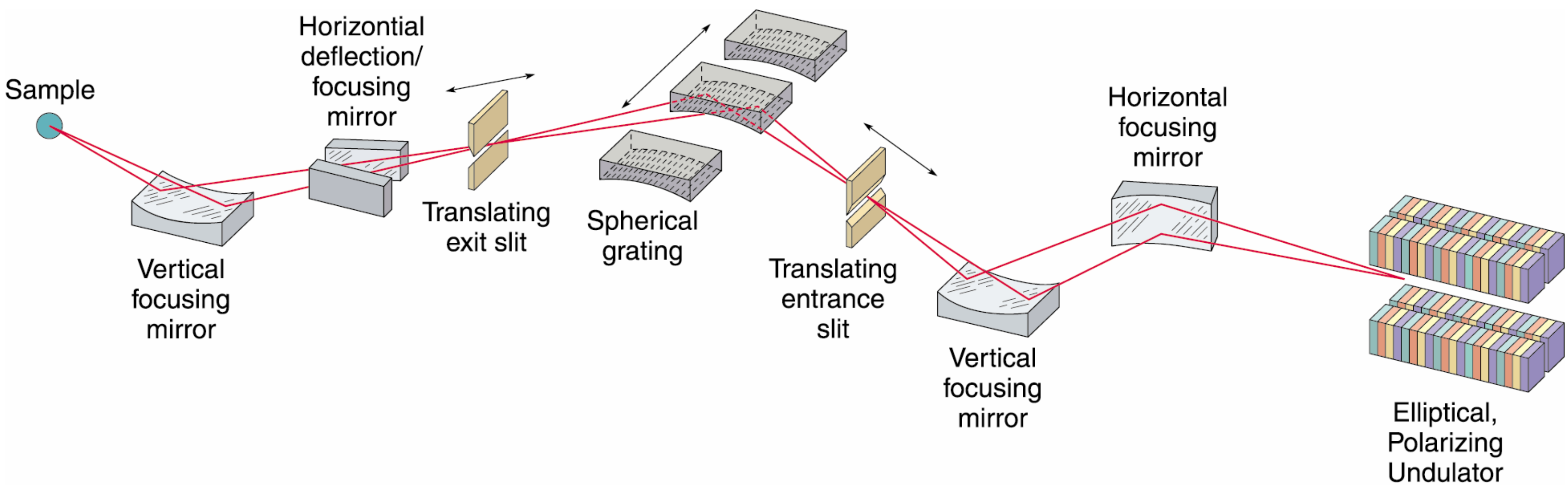
Nanophysics **Nanocrystals, nanoscale physics etc. (need better optics)**

meV Resolution Spectroscopy Beamline at ALS

Specifications:

- **Resolving power:** E/ΔE=100,000 with 5μm slits
  i.e. better than 1 meV when photon energy is below 100eV
- **Photon energy range:** 15eV to 140eV, fully optimized
  maximum achievable photon energy ~140eV
- **Elliptically Polarized Undulador (EPU):** full polarization selection (linear and/or circular)
- **Photon Flux:** ~1.5 $\times 10^{11}$ photons/s/meV

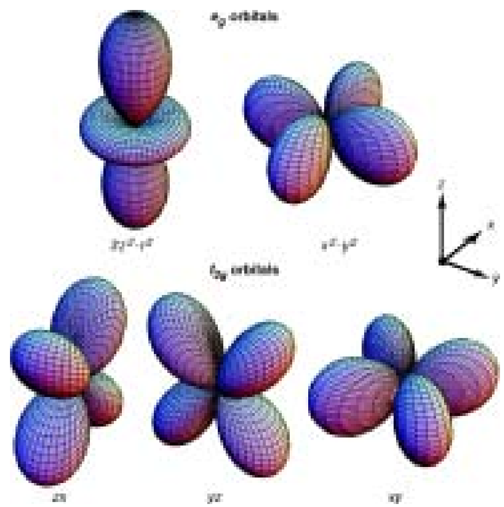
Optical Layout (SGM)



meV-EPU PRT : Z. Hussain et.al.,

Zahid Hasan (Princeton University)

Manganites



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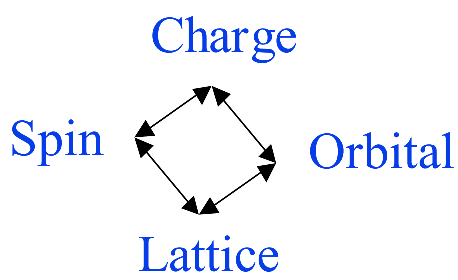
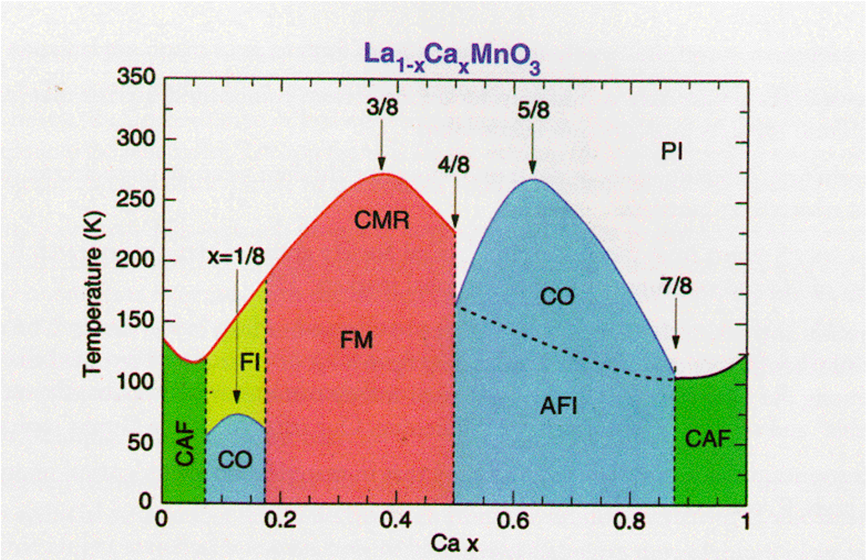
Interacting Degrees of Freedom

Interacting Degrees of Freedom (Complex Electron Systems)



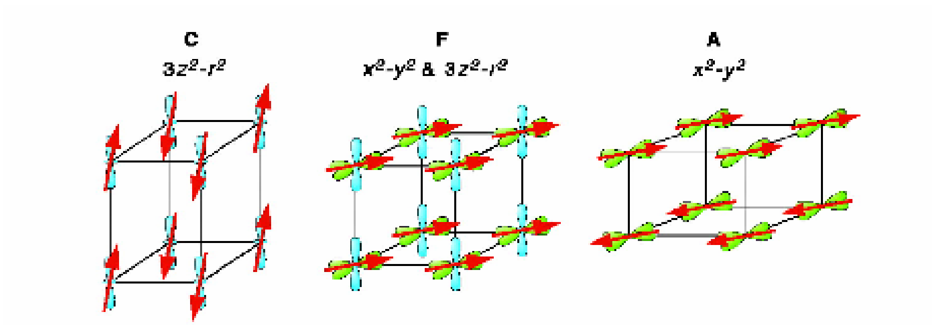


Example :

Manganese Oxides (CMR systems)

Electron Localization

Charge, Orbital & Spin Order



Competition among many Energy and Length scales

→ Complex Phase Diagram

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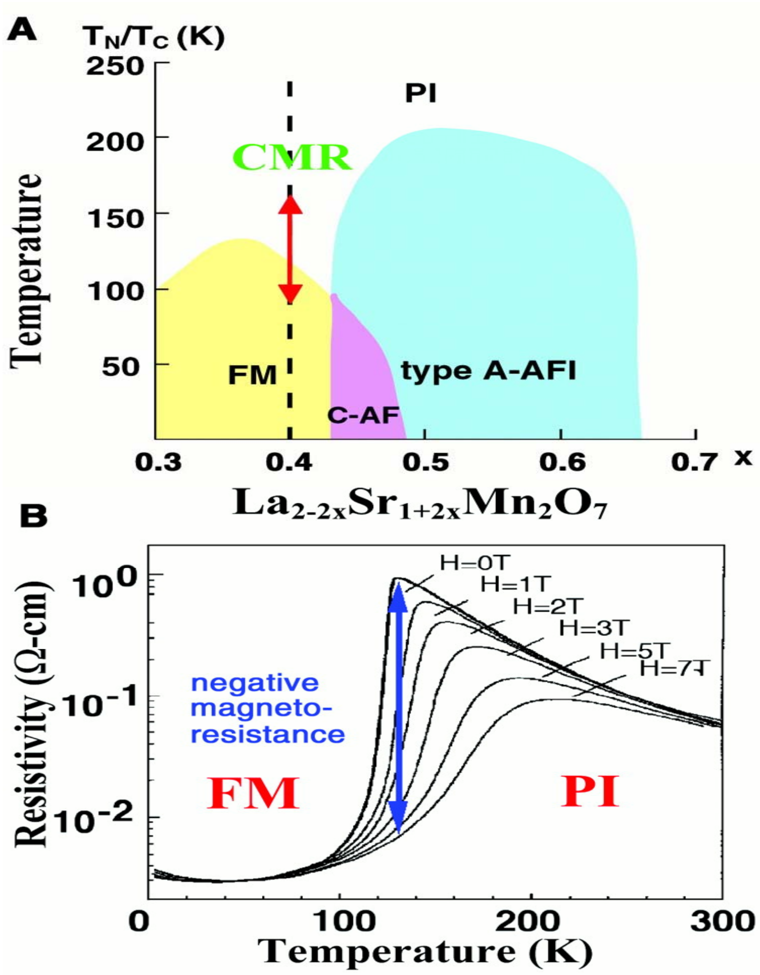
CMR effect



Colossal magnetoresistance

- Para → Ferromagnetism
- Large drop of resistivity upon relatively small magnetic fields
- Most dramatic on the insulating phase (short range orbital order)

FM Semicond.

High $T_{cr.}$

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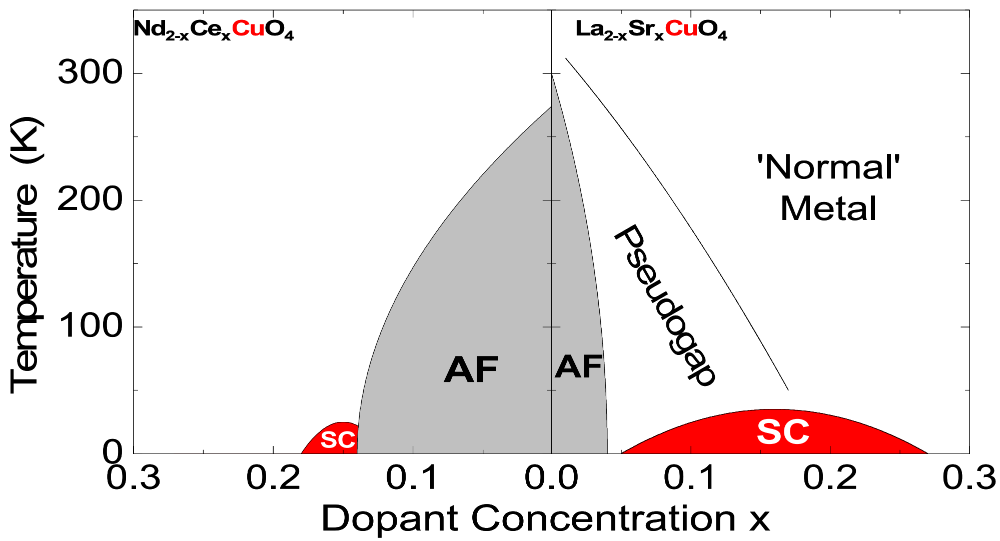
Cuprates



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10-20 meV charge physics in cuprates

Pseudogap & Doping dependence

Superconducting gap ~ 2Δ

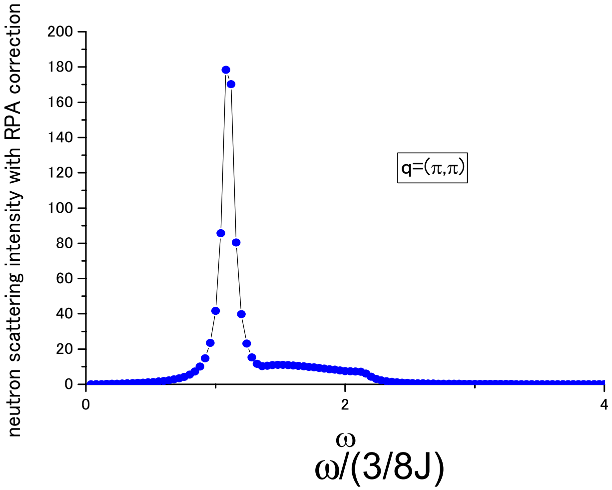
Field dependence

Charge collective modes (Plasmons, New modes)

Electron-phonon interaction etc.

Collective Modes in RVB (P.Lee)

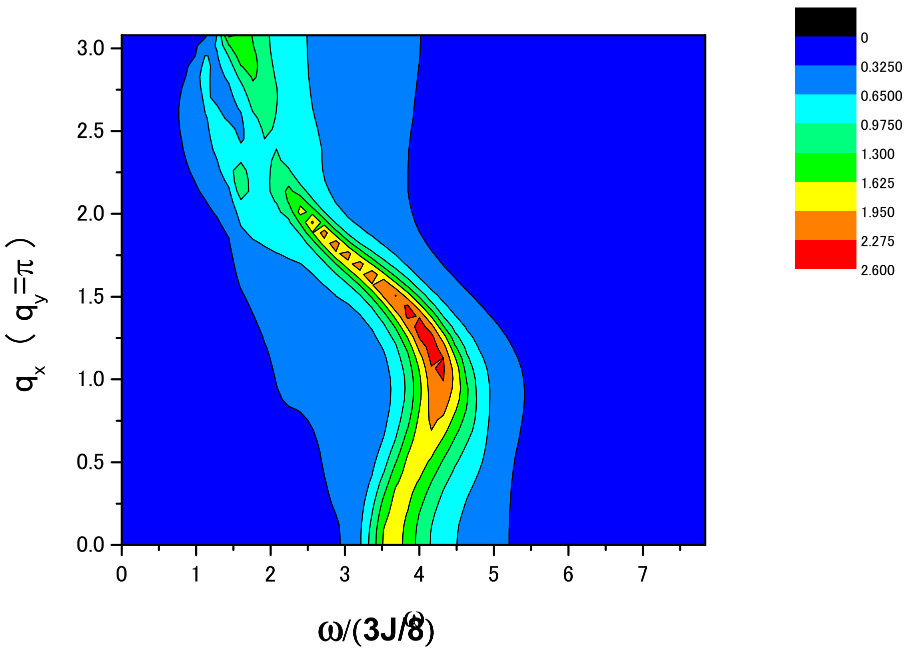
θ mode creates local moment: detectable by inelastic neutron scattering at (π,π).



Inelastic x-ray scattering couples strongly to fluctuations in bond-charge density

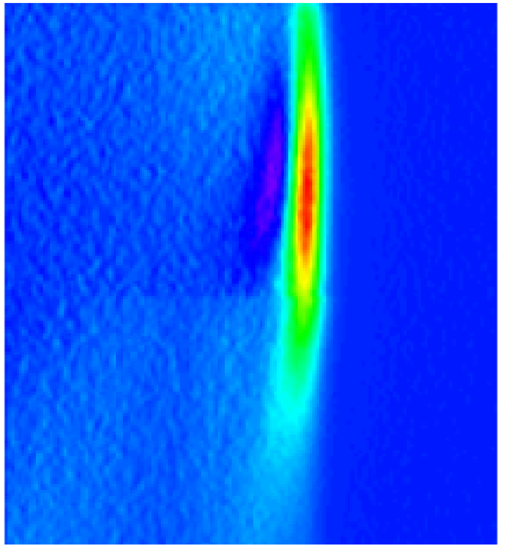
$\chi(q = (\pi,\pi))$:

q_x
$q_y=\pi$



Courtesy of P.A. Lee (2002)

Cobaltates



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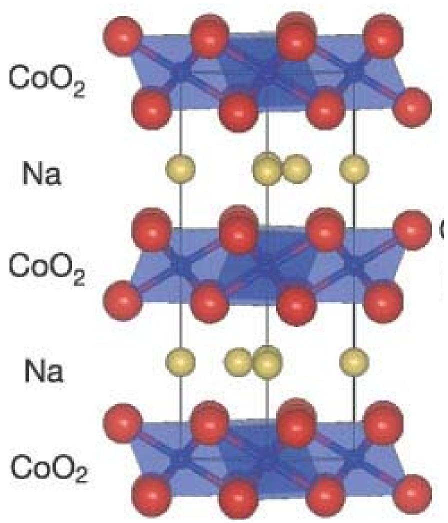
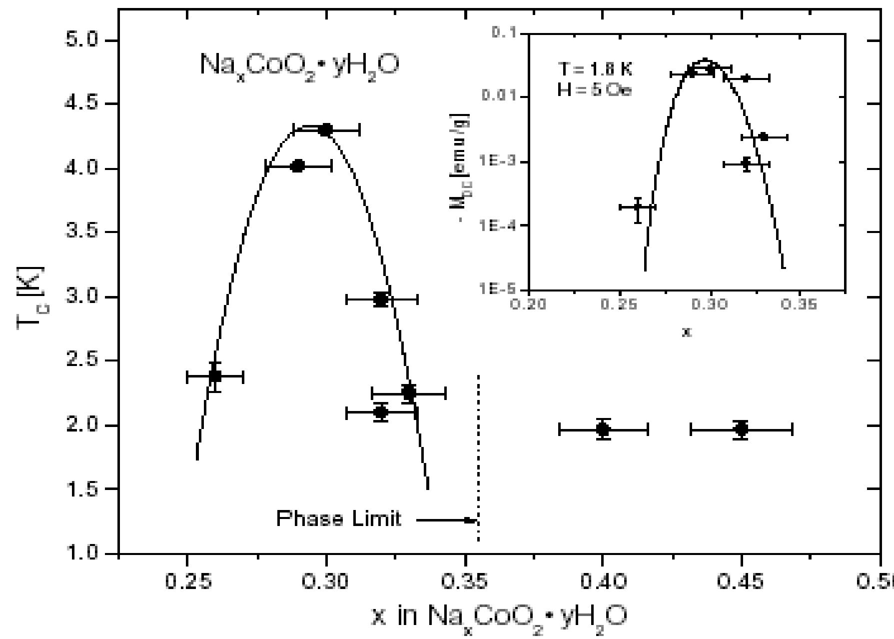
A New Class of Superconductors

A New Class of Superconductors
(analogous to the Cuprates)

K. Takada et.al., Nature 422, 53 (2003).
$Na_{0.35}CoO_2$, $T_c \sim 5$ K



Phase Diagram : Na_xCoO_2



R.J. Cava et.al., Nature (2003).

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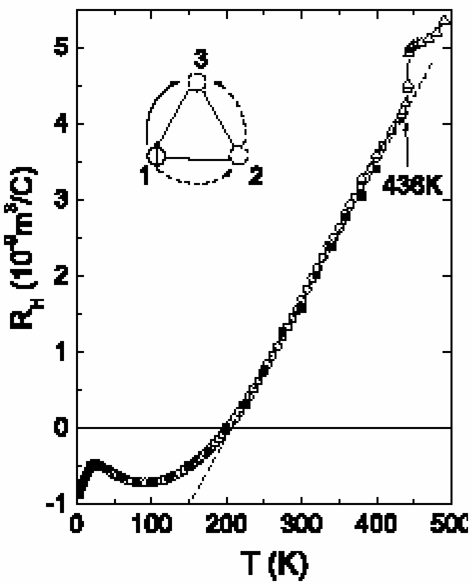
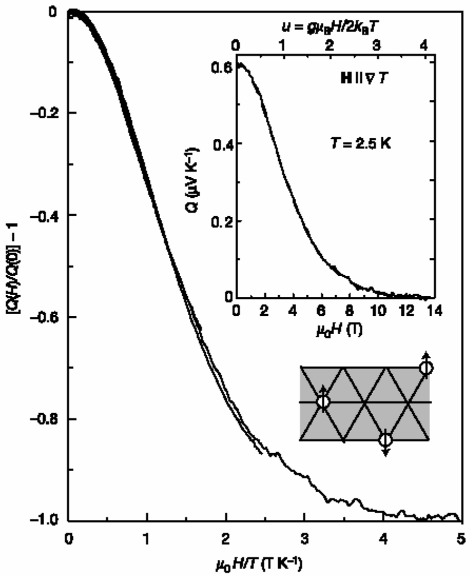
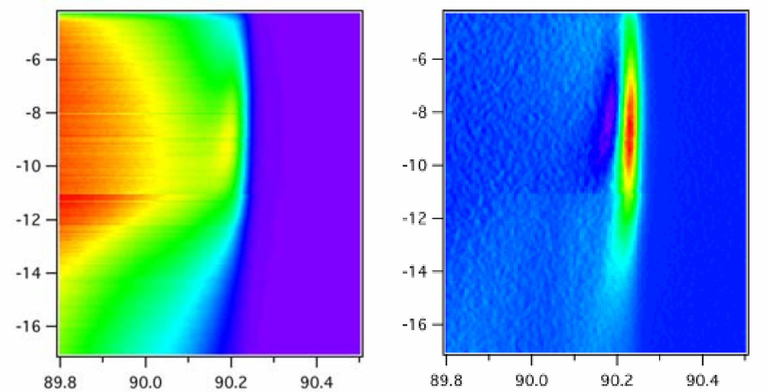
Quasiparticle Dynamics in $Na_{0.7}CoO_2$

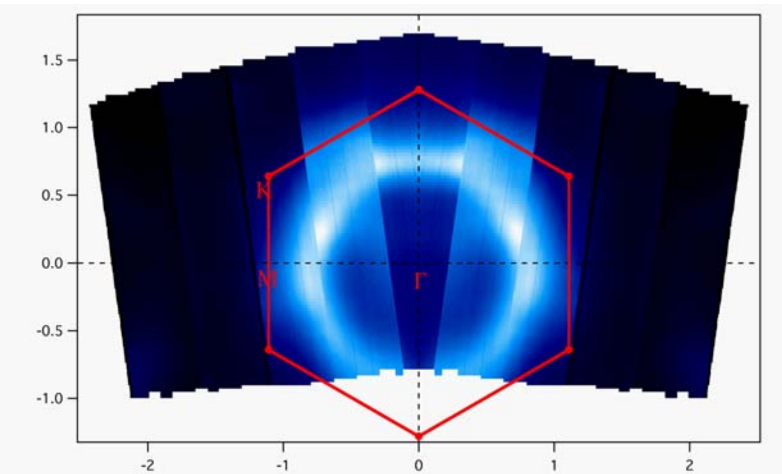
ARPES : M.Z. Hasan, Y.-D. Chuang et.al., cond-mat/0308438

A dip in the Hall signal









Y. Wang et.al., Nature (2003) & cond-mat/0305455

No saturation even at 500K

Q depends on H

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Acknowledgements

Princeton : D. Qian, Y. Li, Y.-D. Chuang, Y. Kong, MZH

Soft IXS + ARPES
Adv. Light Source : Z. Hussain, E. Gullikson, Y.-D. Chuang
(meV PRT)

Hard IXS + t-SAXS
Adv. Photon Source : E.E. Alp, H. Yavas, T. Gog
(CMC-CAT)

Samples : R.J. Cava (Princeton), S.W. Cheong (Rutgers), P. Canfield (Ames)
S. Uchida, Y. Tokura, T. Sasagawa, H. Takagi, H. Eisaki (Japan)