X-ray Scattering Studies of Dynamics in Strongly Correlated Electron Systems

From Femto-seconds to Minutes

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Collaborators

Cuprate work:

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D. Casa (APS, USA)
G. Blumberg (Lucent Technologies, USA)

Manganite work

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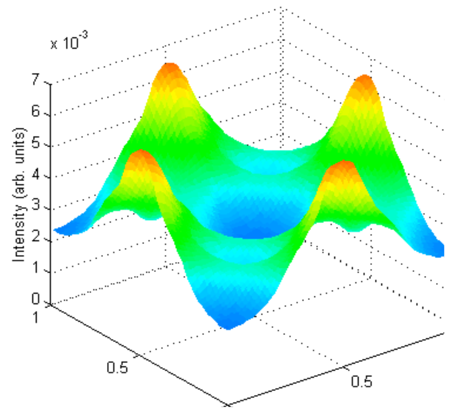
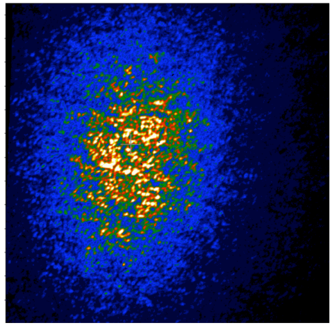
Y. Tokura (CERC, Japan)

Outline

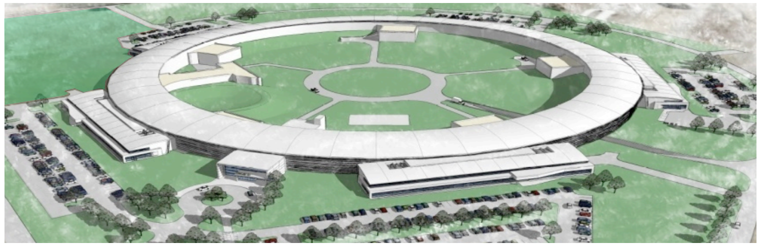
1. Dynamics in the Energy Domain
   - Resonant Inelastic X-ray Scattering
   - Recent results in the cuprates



2. Dynamics in the Time Domain
   - Coherent x-ray Scattering
   - Recent results in the manganites

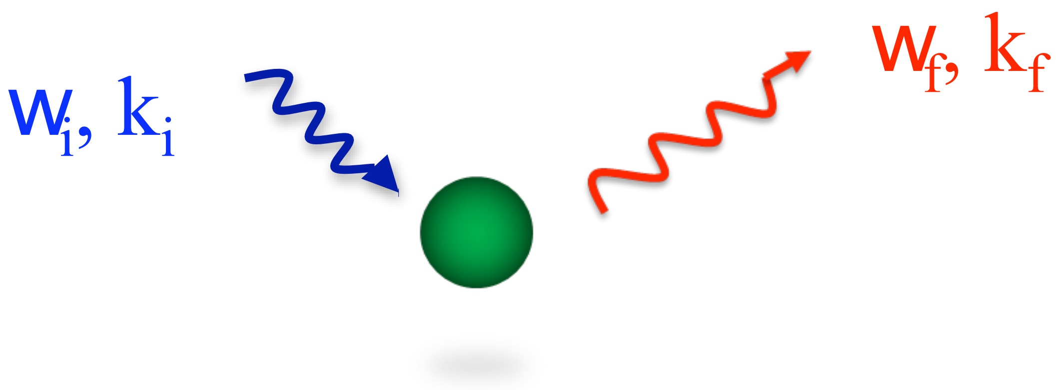


3. Future
   - NSLS-II
   - Instrumentation



1. Dynamics in the Energy Domain

Inelastic X-ray Scattering



$q = k_i - k_f$

$w = w_i - w_f$

Elastic scattering ($w = 0$) gives static properties.

Inelastic scattering ($\omega \neq 0$) gives dynamic properties.

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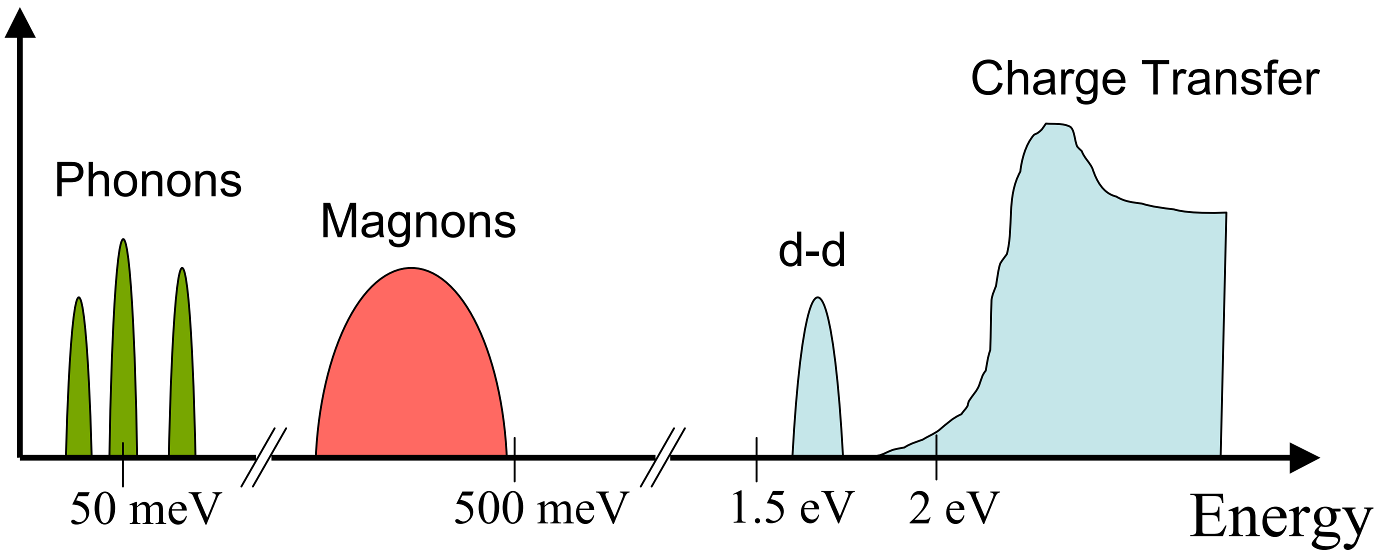
Electronic Excitations

1) Excitation spectrum determines the dynamic response of material.
2) Excitation spectra provide stringent test of theory.
3) “High-energy physics” of strongly correlated electron systems controls their behavior:

t ~ 1 eV, U ~ 8 eV, D ~ 2eV



Need a momentum and energy resolved probe → IXS

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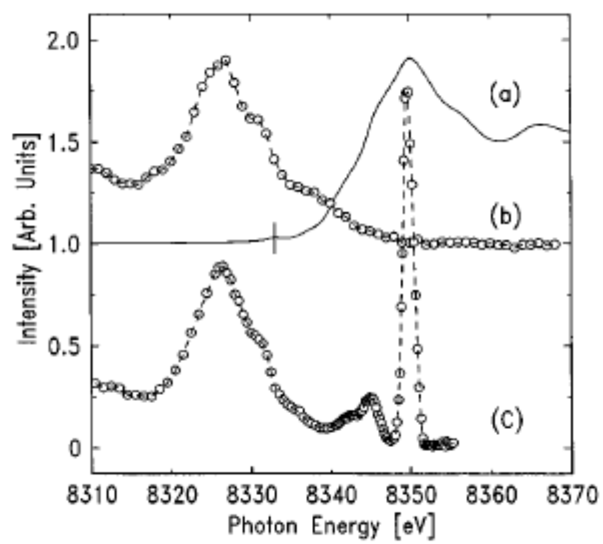
Resonant Inelastic X-ray Scattering

But….IXS from electronic excitations is weak (unlike the case for phonons)

$$\frac{d^2\sigma}{d\Omega d\omega} \propto \left| \langle f \,|\, H_{\rm int} \,|\, i \rangle + \sum_{|n\rangle} \frac{\langle f \,|\, H_{\rm int} \,|\, n \rangle \langle n \,|\, H_{\rm int} \,|\, i \rangle}{E_i - E_n + i\Gamma} \right|^2$$

Non-resonant scattering (weak)



Kao et al, PRB 1996, NiO

Resonant IXS is > 100 x Non-Resonant IXS

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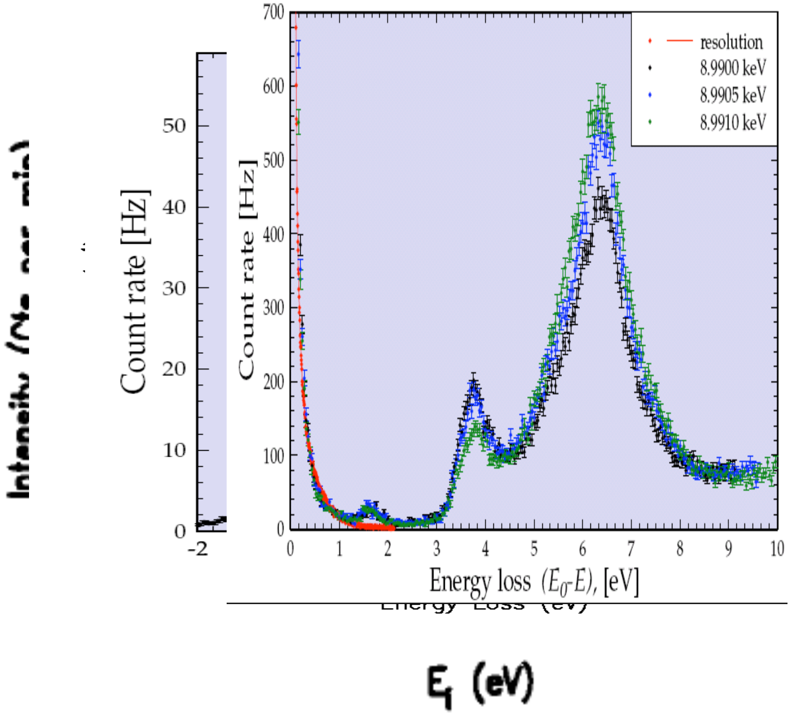
10 years of RIXS Progress: $CuGeO_3$



1999	1 cps	1500 meV	X21, NSLS
2002	6 cps	300 meV	9IDB, APS
2006	50 cps	115 meV	30IDB, APS
2007	600 cps	90 meV	30IDB, APS

Figure of merit = count rate/resolution, increased by 10^4!

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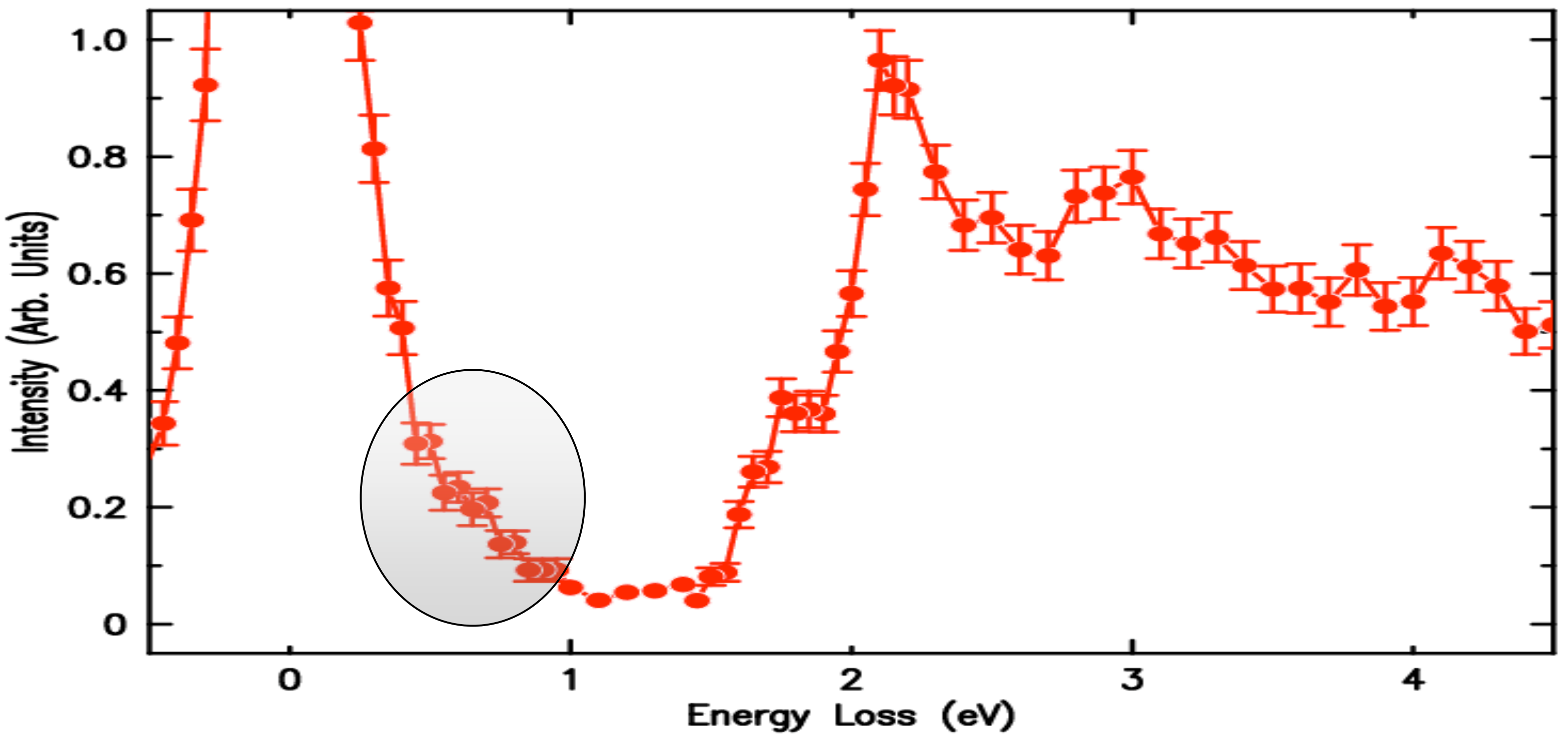
La_2CuO_4

DE=120 meV



9IDB, APS

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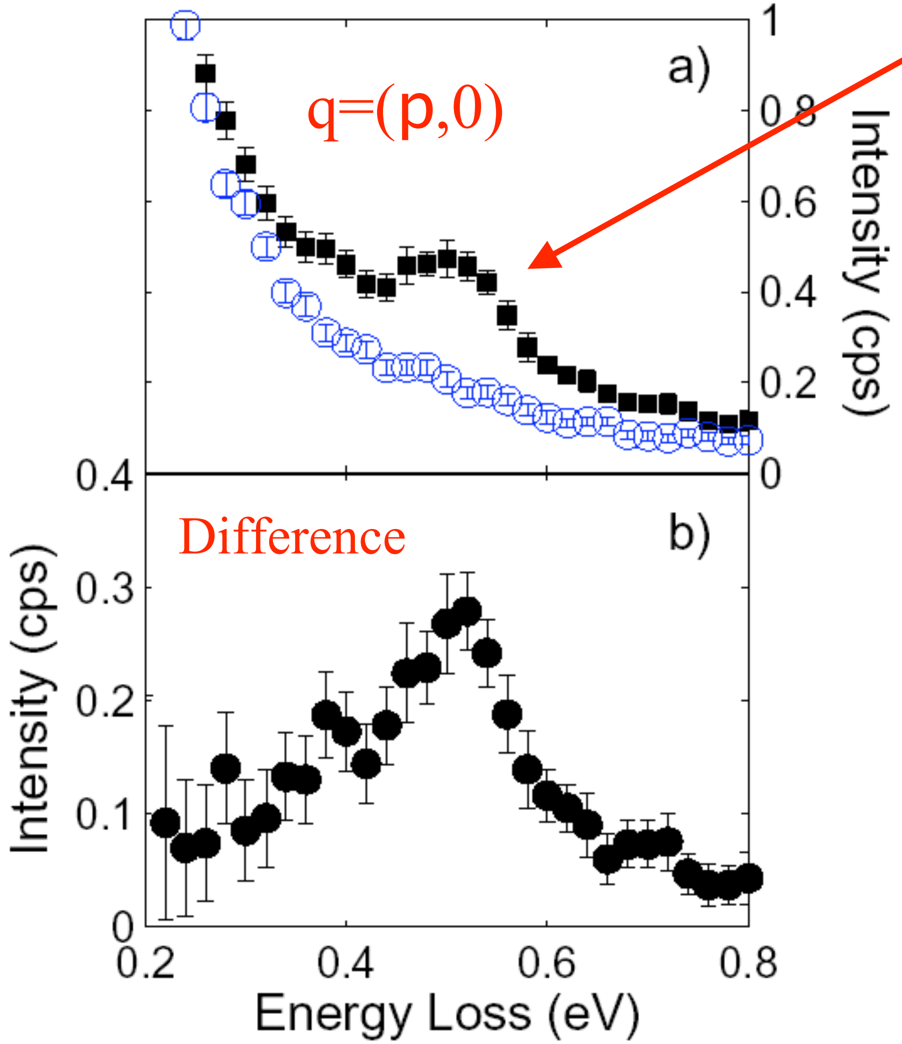
Something New at 500 meV…

La_2CuO_4



Characteristics of 500 meV mode:

- Strongly peaked around (p,0)
- Strongly doping dependent
- Present only for e parallel to c
- Rotates polarization of photon.

JPH, G. Blumberg, Y-J. Kim, D. Ellis *et al.*, Phys. Rev. Lett (2008)

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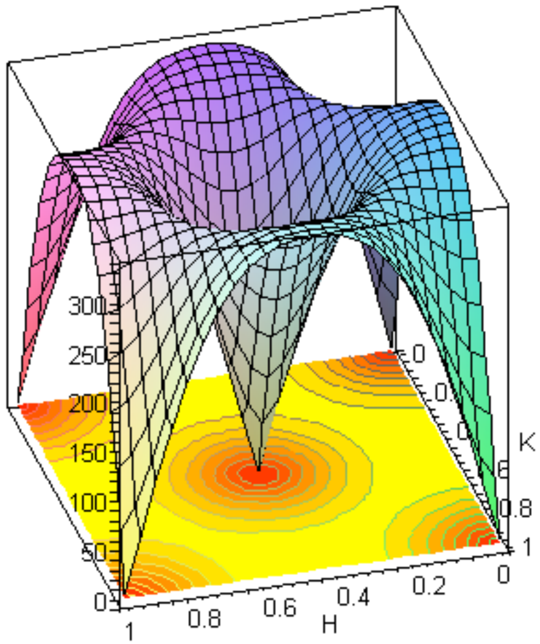
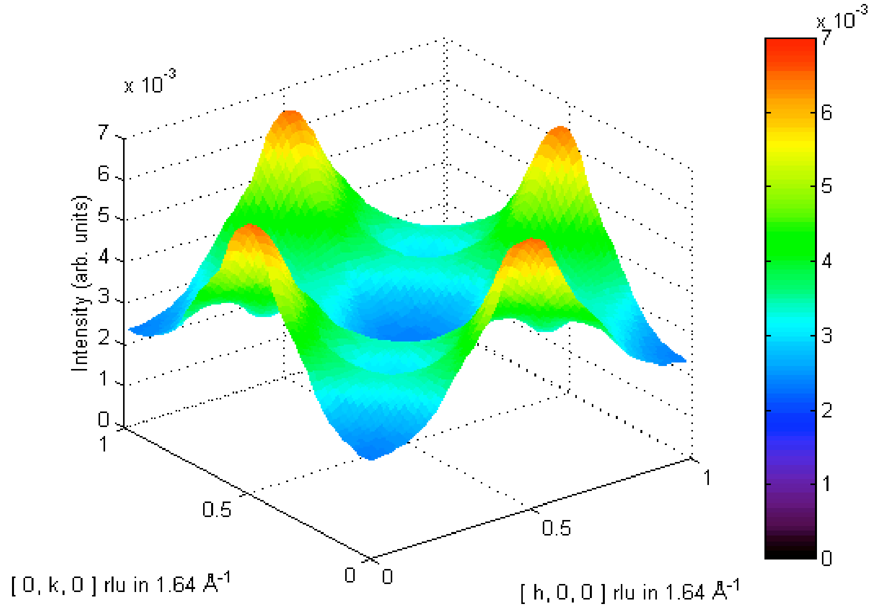
2-Magnon Scattering?

Single Magnon Dispersion Surface



R. Coldea (PRL, 2001)

Calculated 2-magnon DOS



2-magnon DOS has strong peaks at (p,0) at ~500 meV

Calculated energy and momentum behavior, and doping dependence all resemble two-magnon scattering

N.B. Predicted by Tsutsui, Tohyama and Maekawa (1999)

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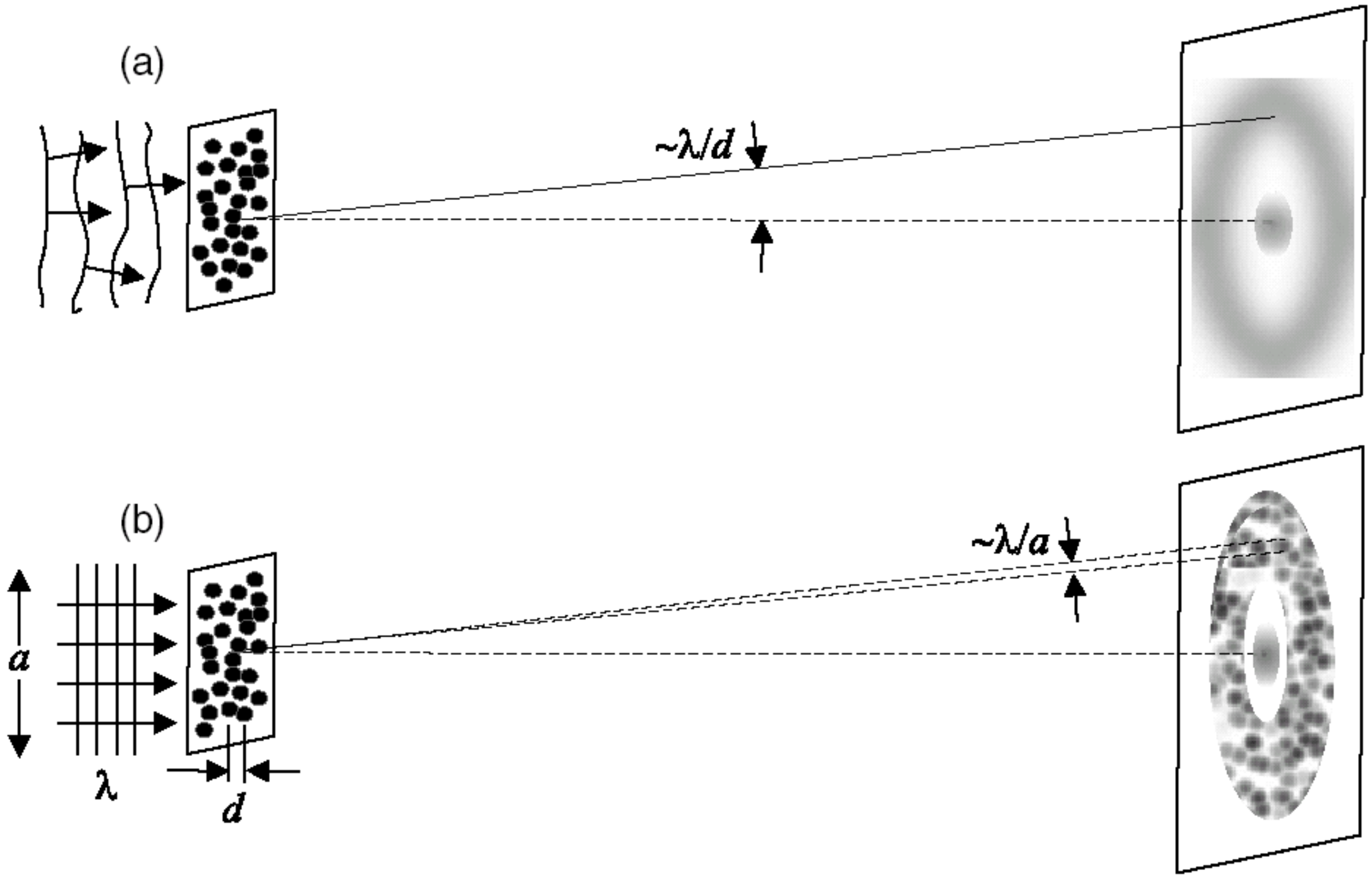
Summary: Cuprates

Used resonant inelastic x-ray scattering to look at excitations in mid-IR region of the cuprates

- Observed a new peak at 500 meV
- Peak occurs at (p,0). Softens, and broadens, away from there. Strongly doping dependent. Rotates the photon polarization
- Consistent with it being due to 2-magnon scattering.
- Future experiments will study the temperature dependence and detailed q-dependence to make the assignment unambiguous.

2. Dynamics in the Time Domain

Coherent X-ray Scattering



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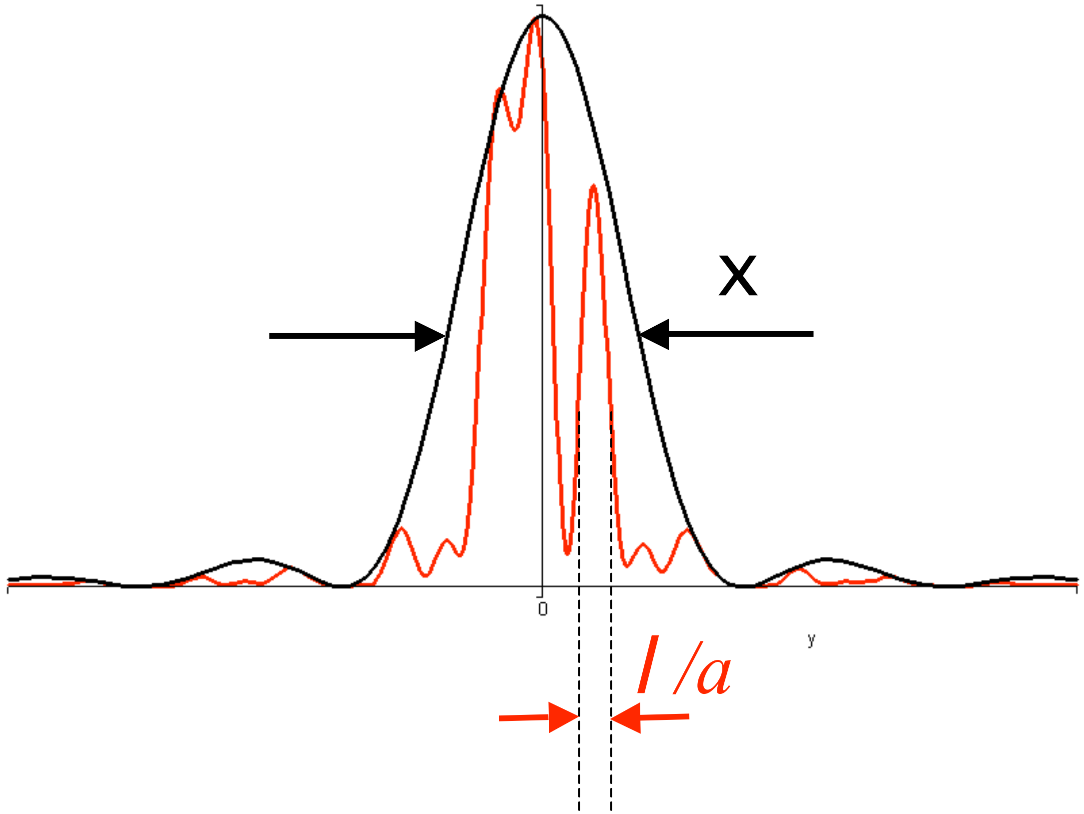
Coherent Scattering: Dynamic Speckle

Speckle pattern characteristic of domain structure:



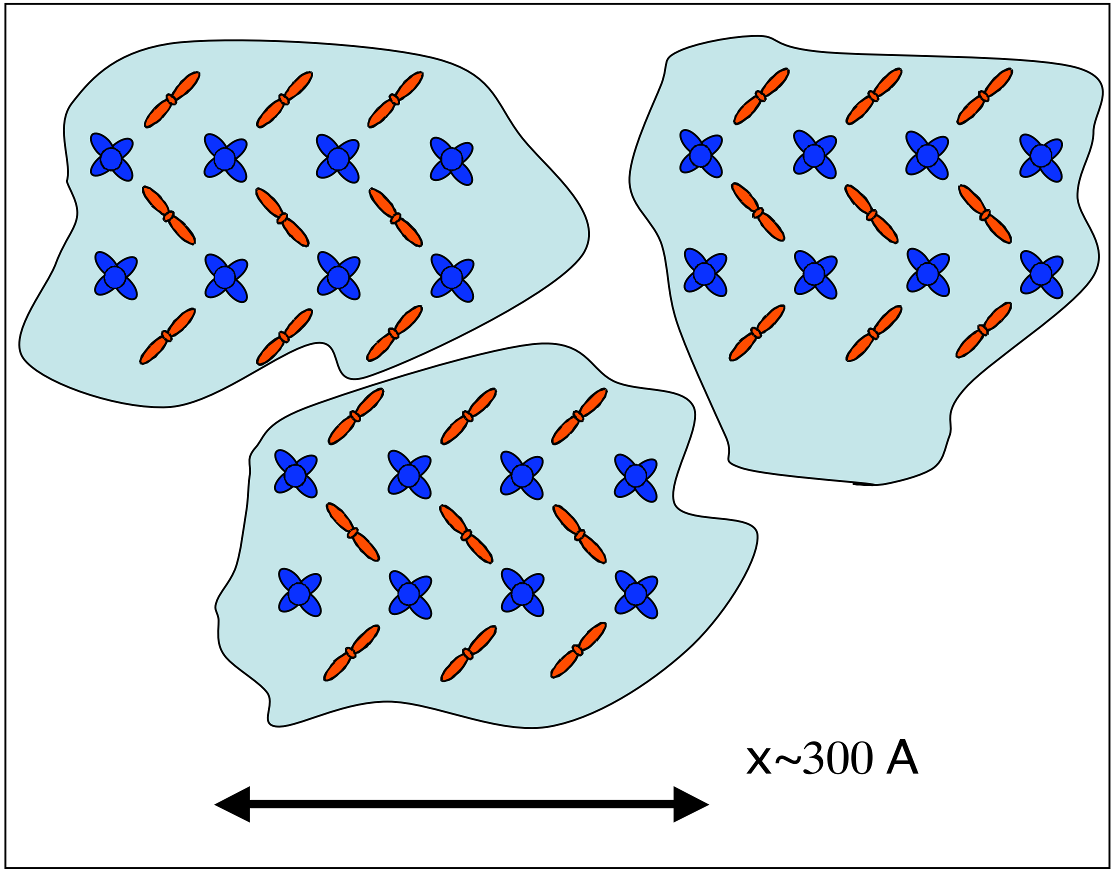
Transverse coherence length $\xi_t \sim \frac{\lambda R}{(2\pi\sigma_h)}$

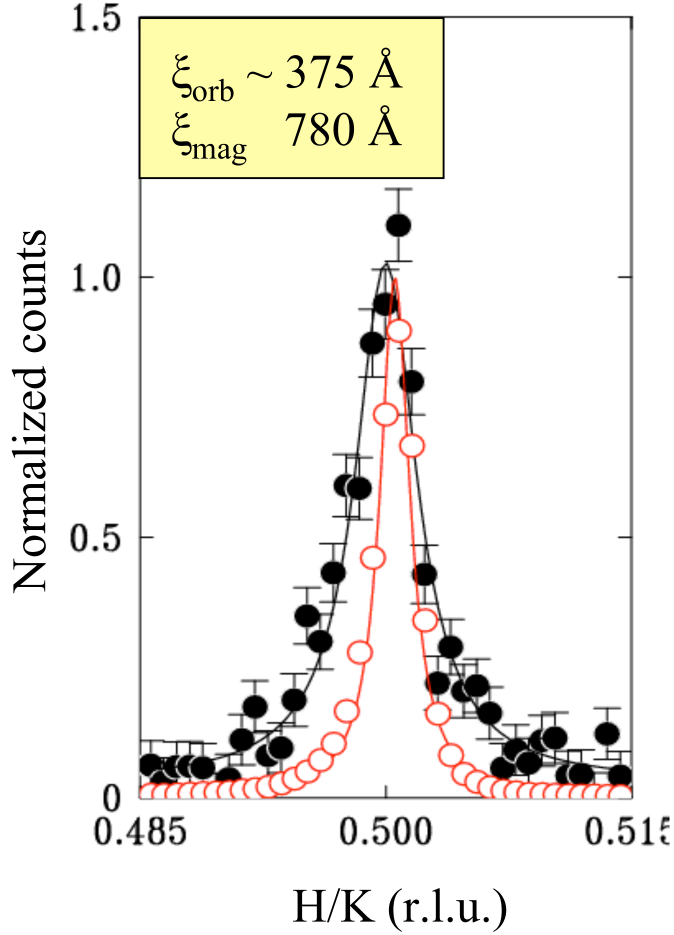
Longitudinal coherence length $\xi_l \sim \frac{\lambda^2}{(2\Delta\lambda)}$

Coherent flux $F \sim B\lambda\,\Delta\lambda$

An Orbital Glass?

$Pr_{0.5}Ca_{0.5}MnO_3$





S. Grenier, JPH, *et al*. PRB **69** 134419 (2004)
K.J. Thomas, JPH, *et al.* PRL **92** 237204 (2004)

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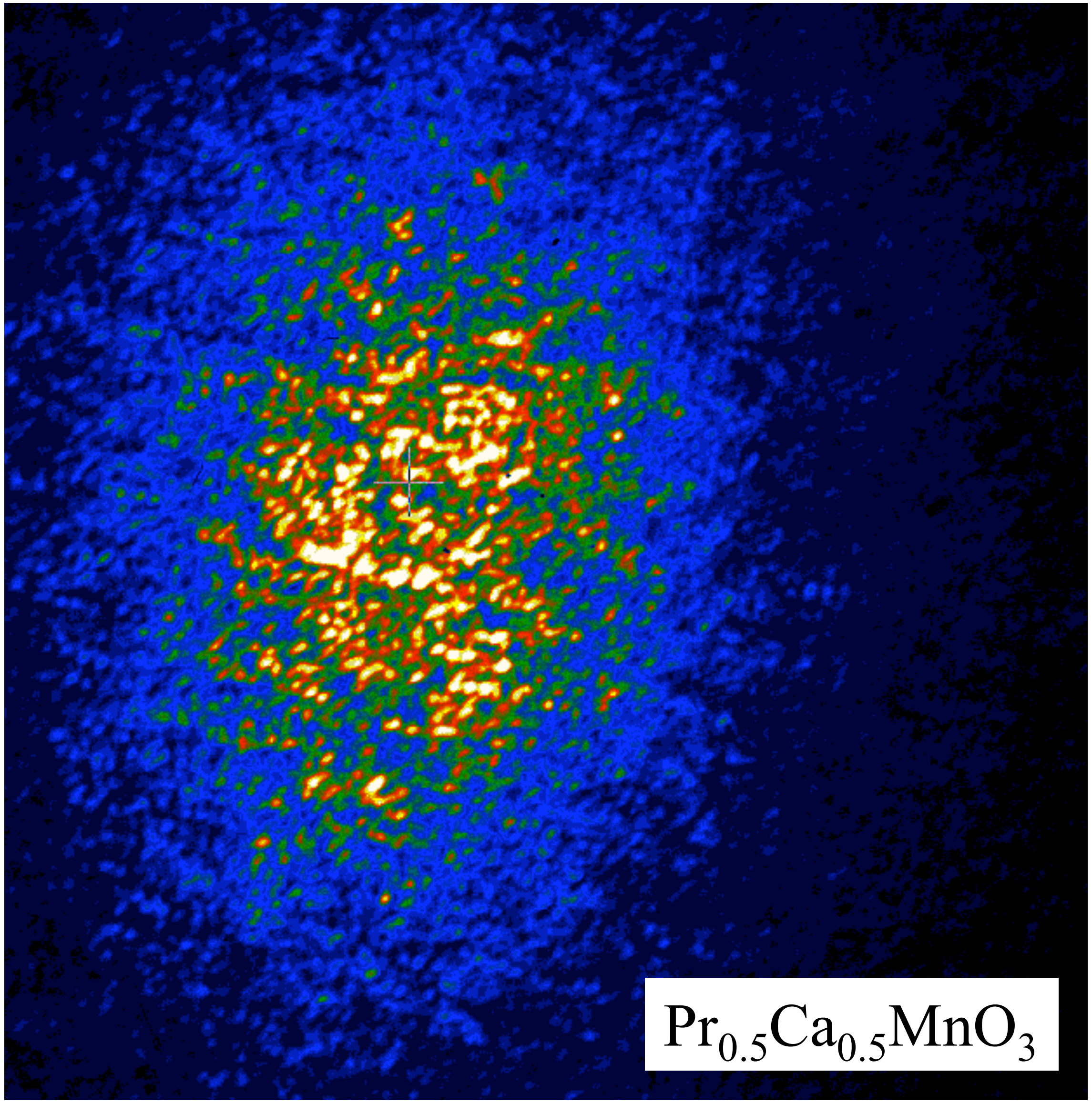
Orbital Speckle Observed



Mn LIII edge
10 μm pinhole

J.J. Turner et al., New Journal of Physics (2008)

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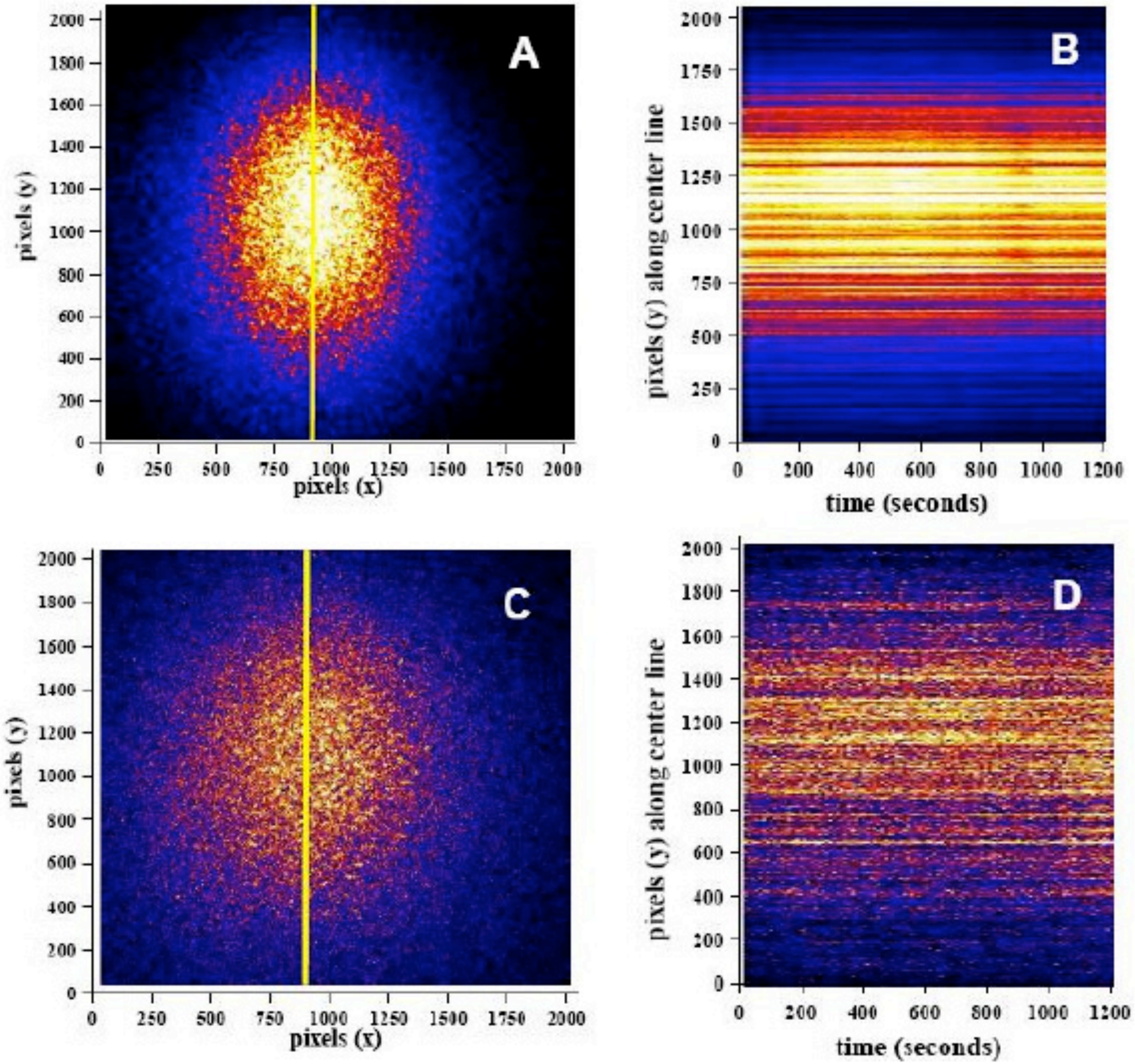
Speckle Patterns are Largely Static

Space

Time

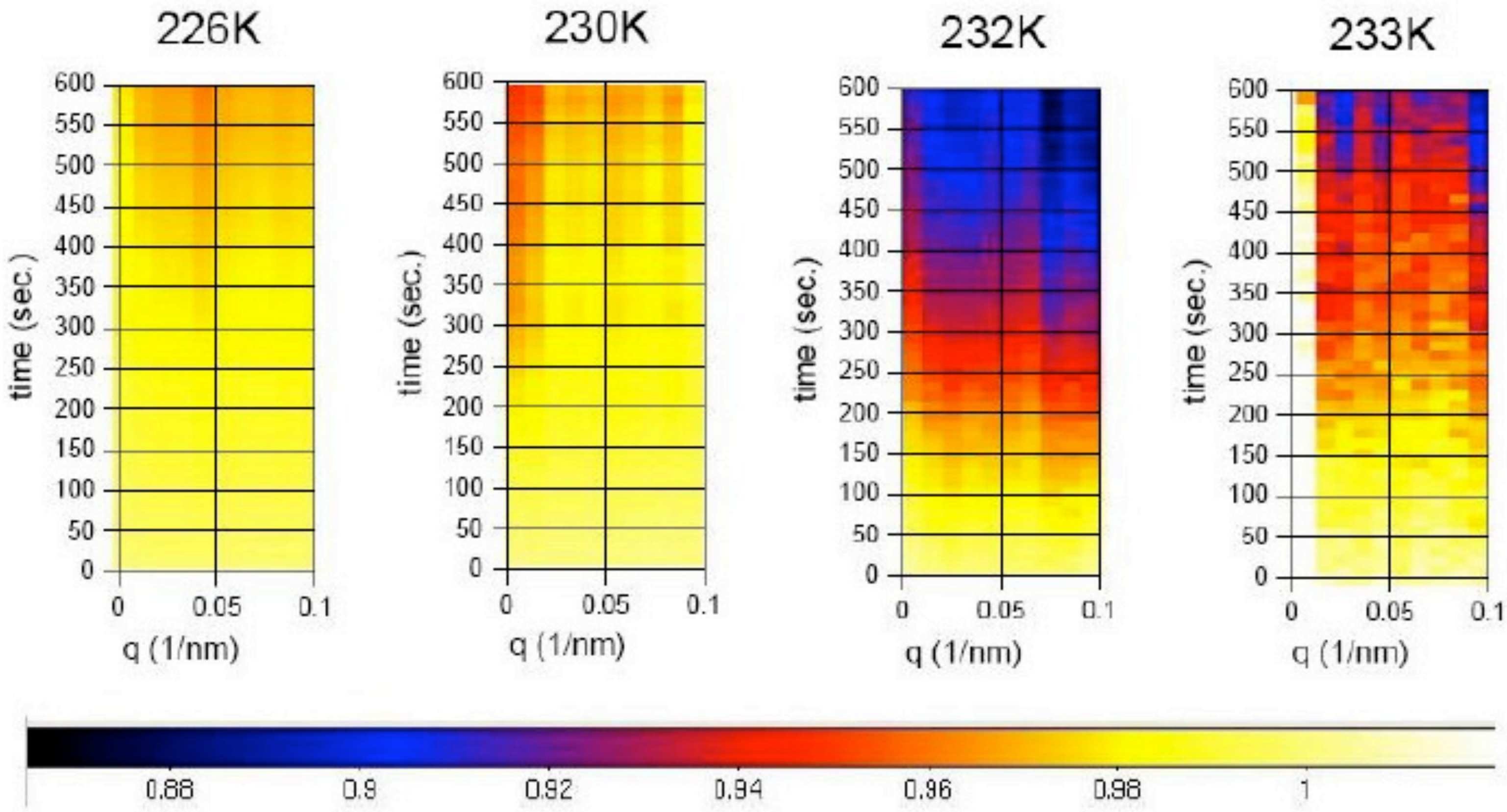
T = 205 K

T = 232 K



Some Dynamics Close to Transition

Correlations between images at fixed temperature drop off slightly near the orbital ordering transition temperature:



J.J. Turner et al., New Journal of Physics (2008)

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Summary: Manganites

Used soft x-ray coherent scattering (correlation spectroscopy) to look at orbital domains in a half-doped manganite.

• Observed "orbital speckle"
• The speckle was static at low temperatures – therefore the domains are static at low temperatures
• Even very close to the transition, (correlation length has halved to ~ 100A), the speckle was still largely static
• BUT, there is a small component close to the transition that is dynamic. Time constant is ~ 5 mins

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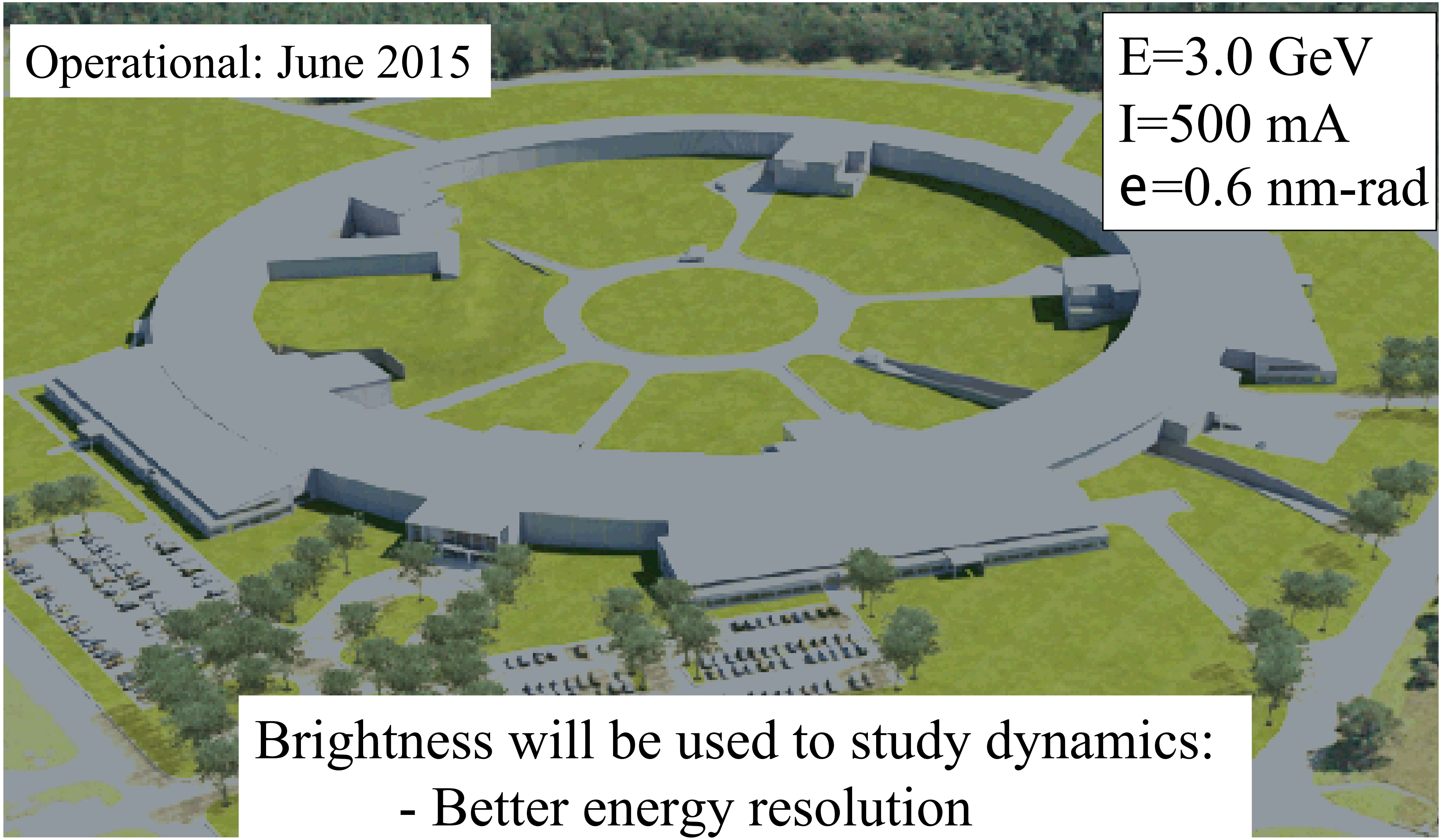
3. National Synchrotron Light Source-II



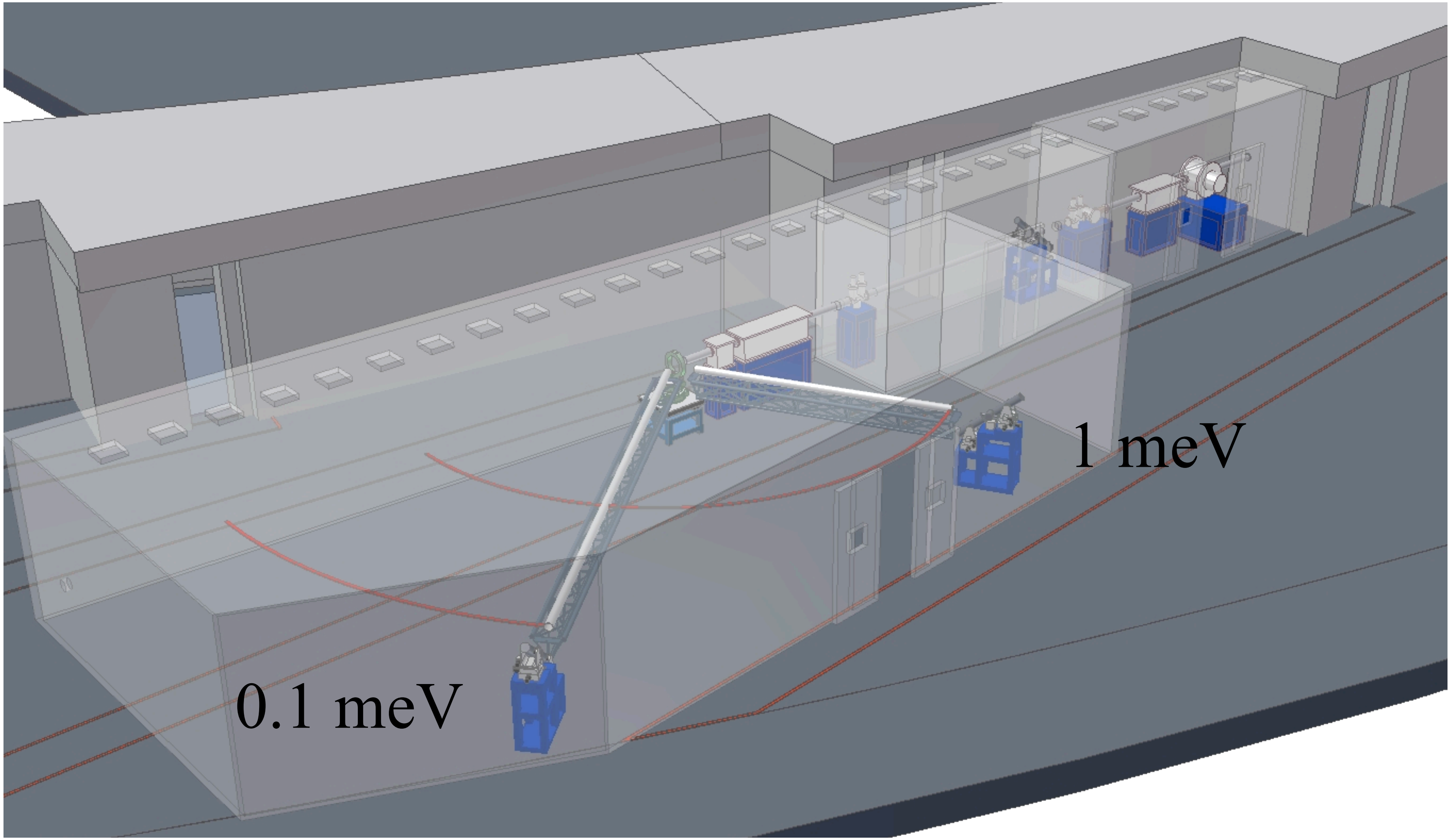
Operational: June 2015

E=3.0 GeV
I=500 mA
e=0.6 nm-rad

Brightness will be used to study dynamics:

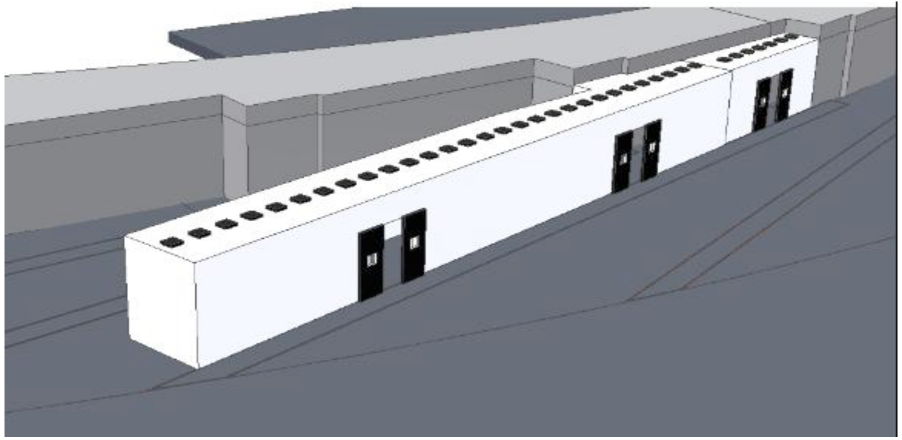
- Better energy resolution
- Faster time scales

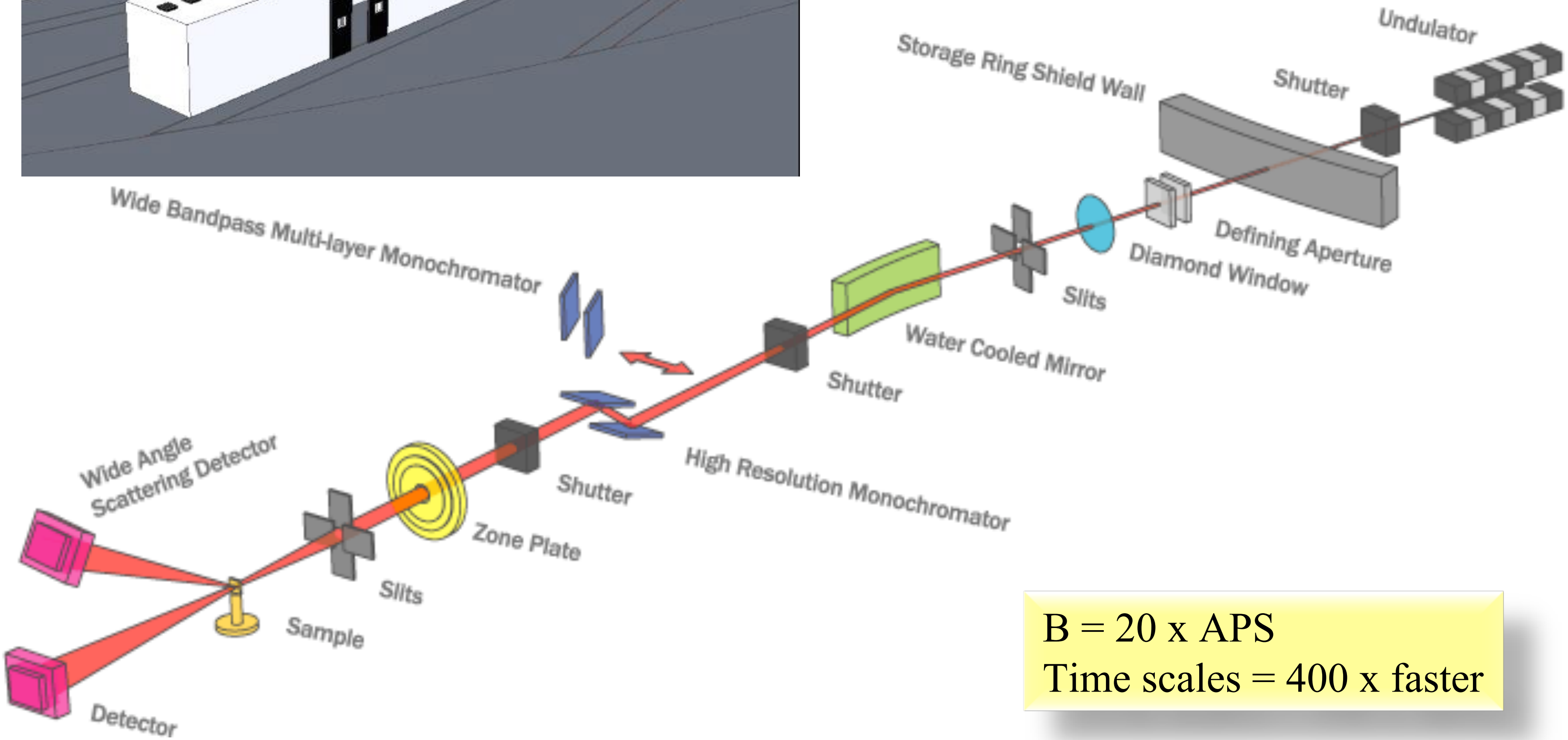
Inelastic X-ray Scattering Beamline



NSLS-II: Yong Cai

Hard X-ray Coherent Scattering





B = 20 x APS
Time scales = 400 x faster

NSLS-II: Andrei Fluerasu

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Conclusions

Strongly correlated electron systems exhibit dynamics over a wide range of time and space scales.

Inelastic x-ray scattering is a powerful probe of the very fast dynamics:

– Now ~2 meV – 10's eV

– NSLS-II 0.1 meV – 10's eV

Coherent x-ray scattering is a powerful probe of long length scale, slow dynamics

– Now ms to minutes

– NSLS-II μs to minutes