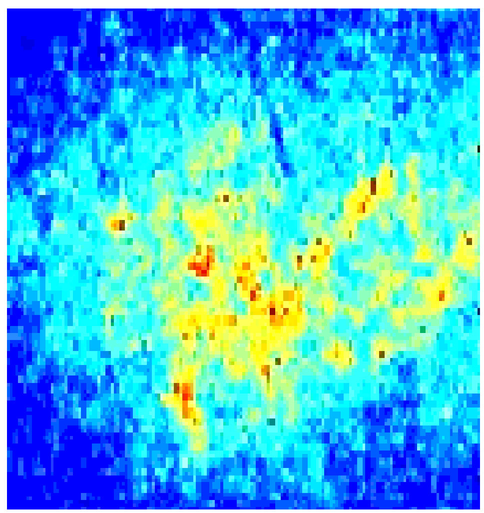
XPCS Studies of Antiferromagnetic Domain Wall Dynamics in Elemental Chromium

Oleg Shpyrko
Department of Physics,
University of California San Diego



"Crunchy" & "Squishy" Physics

Soft Condensed Matter
"Squishy"

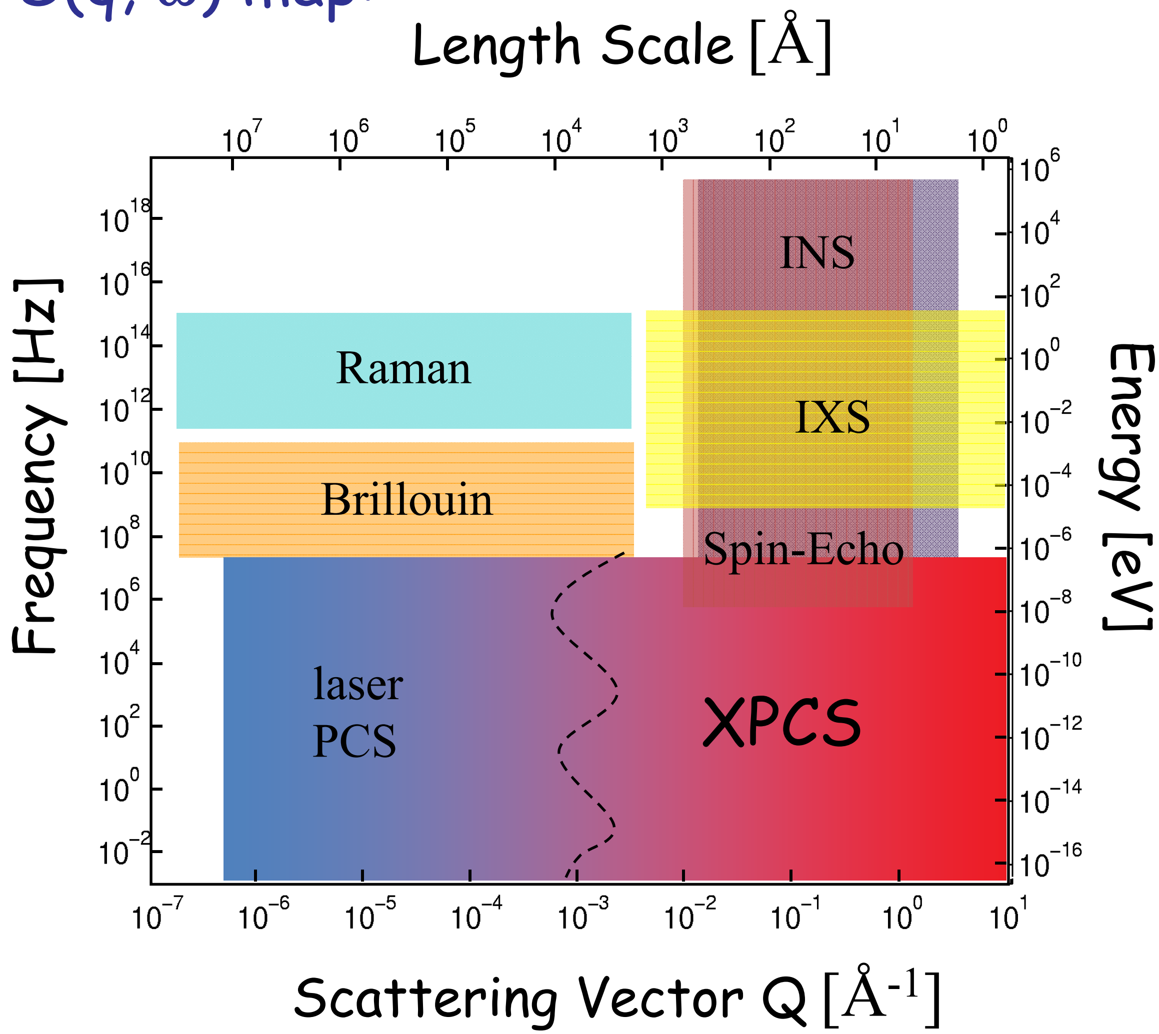
Gels, Colloids
Polymers, Fluids
Liquid Crystals
Membranes
Bio-materials

Hard Condensed Matter
"Crunchy"

Metals, Alloys
Oxides (Insulators)
Semiconductors
Ferroelectrics
Magnets

XPCS and other spatio-temporal probes

S(q, ω) map:



XPCS is the extension of dynamic light scattering probe (laser PCS)

Pros:

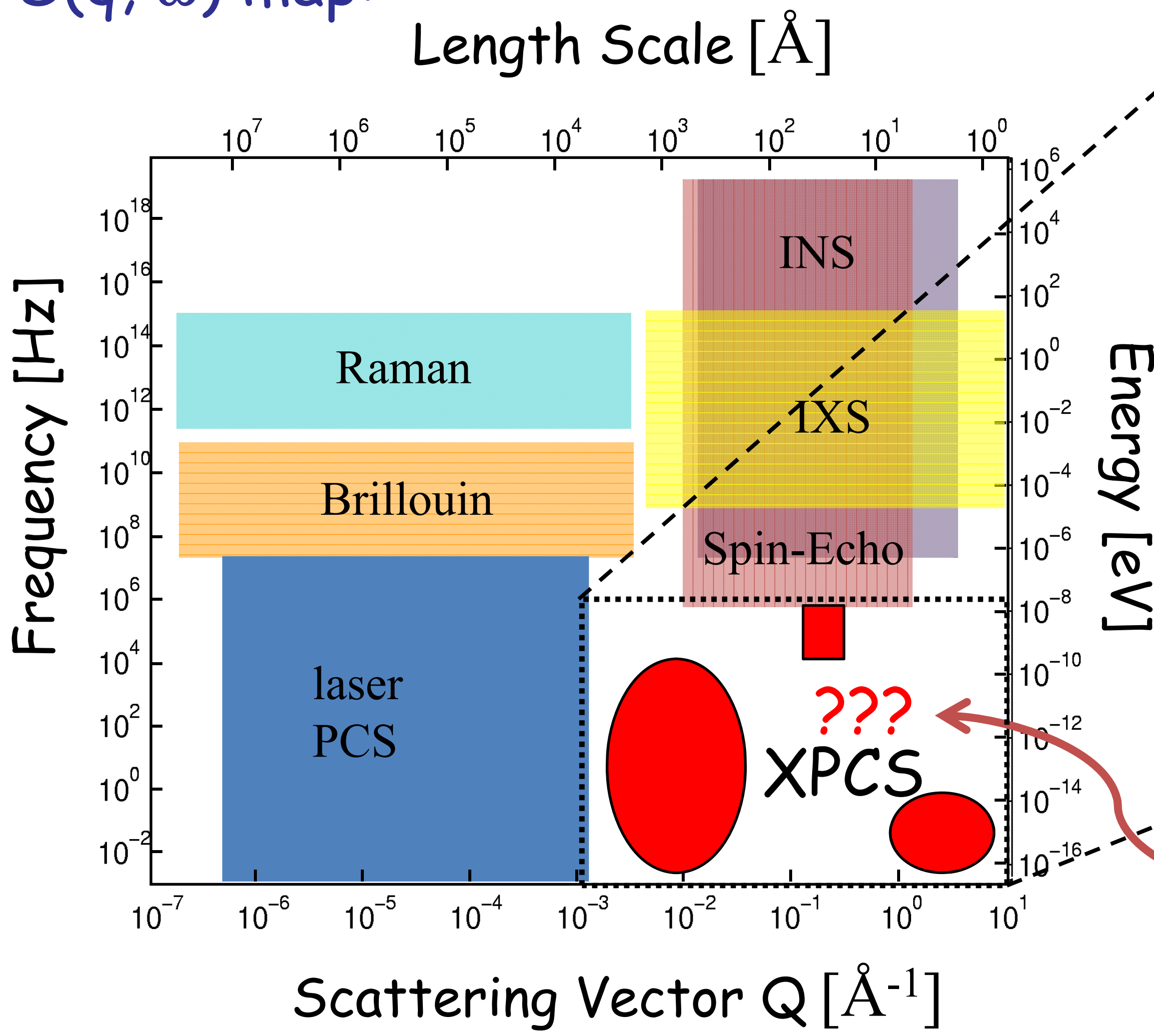
- Smaller lengthscales
- Non-transparent materials
- Charge, Spin, Chemical and atomic structure sensitivity

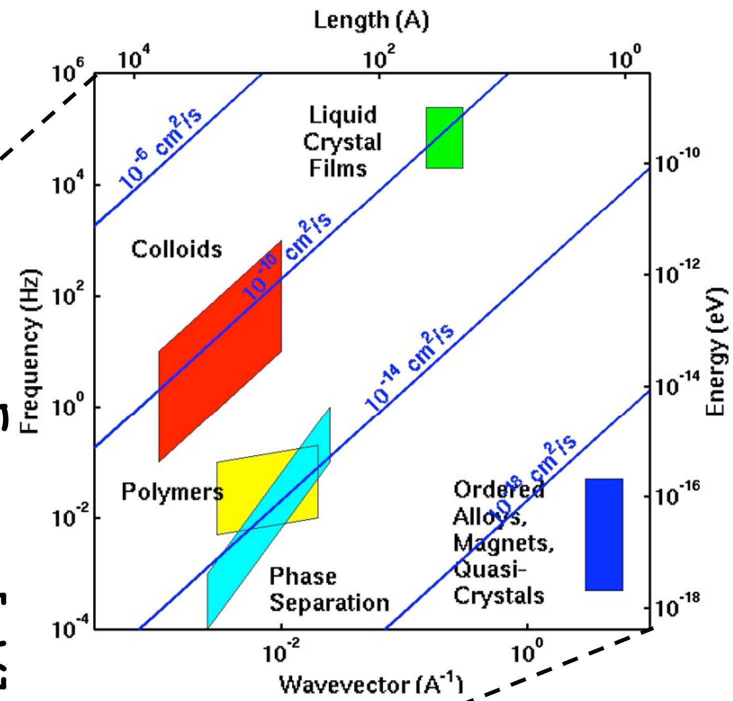
Cons:

- Need fully coherent x-ray sources!

XPCS and other spatio-temporal probes

S(q, ω) map:





Courtesy G. B. Stephenson

New X-ray Sources (NSLS-II, LCLS) +Faster detectors!

Mesoscale “Texture” in Strongly Interacting Fermi Systems

Coexistence of multiple phases:

superconducting and AF domains (stripes or checkerboards) in underdoped high-Tc cuprates

AF and FM domains in CMR manganites

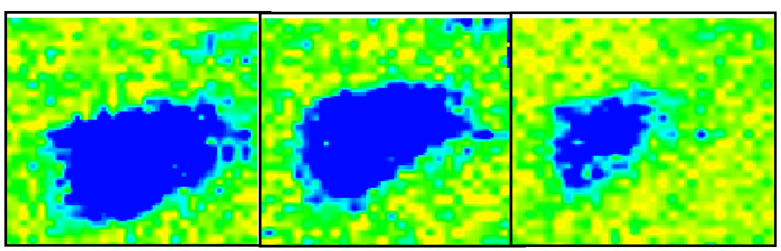
AFM domains with orthogonal orientation of spin- and charge- density waves in Cr

What underlies such mesoscopic “texture”?

Is the texture (domain structure) frozen?

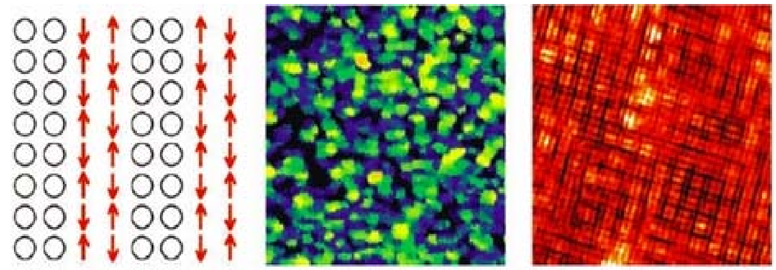
What are the effects of thermal and quantum fluctuations?

AFM chromium



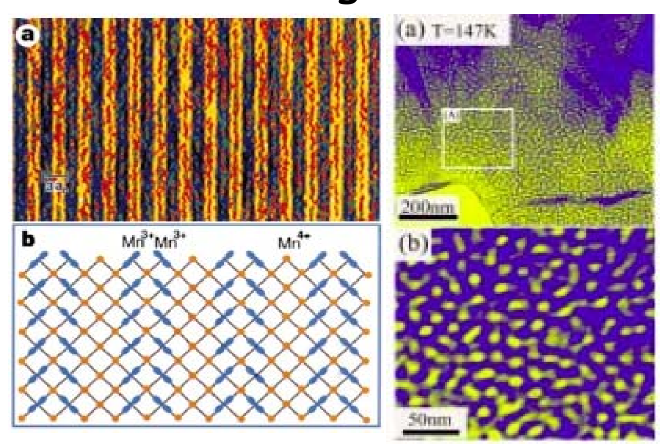
P. G. Evans et al., *Science* (2002)

High-Tc cuprates



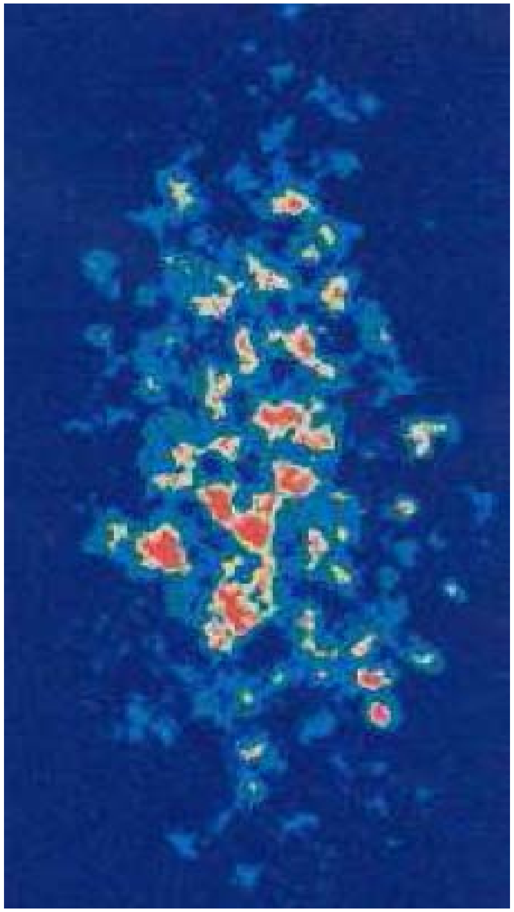
E. Dagotto, T. M. Rice, *Science* **271**, 618 (1996).
T. Hanaguri et al., *Nature* **430**, 1001 (2004).

CMR manganites



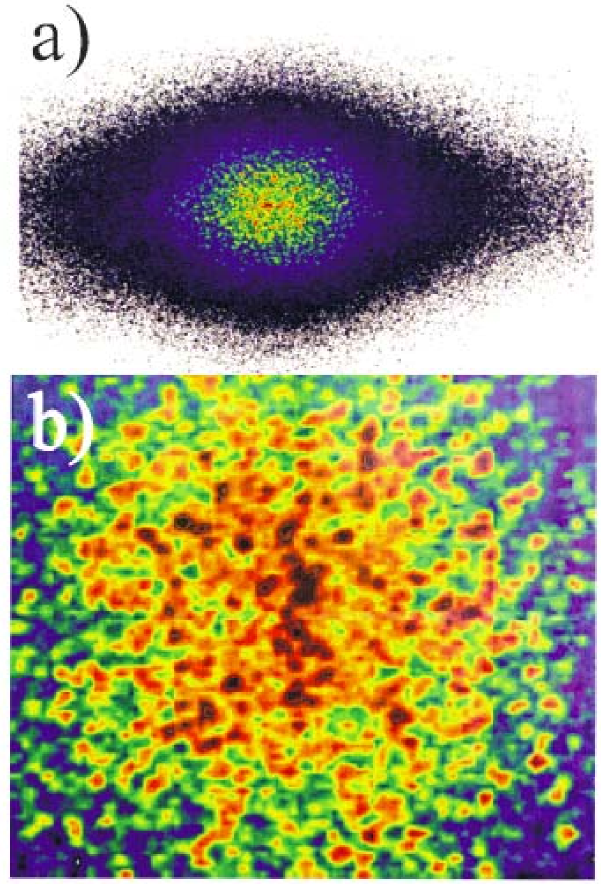
S. Mori et al., *Nature* **392**, 473 (1998)
M. Uehara et al., *Nature* **399**, 560 (1999)

Brief Review - X-ray Speckle, the early years:



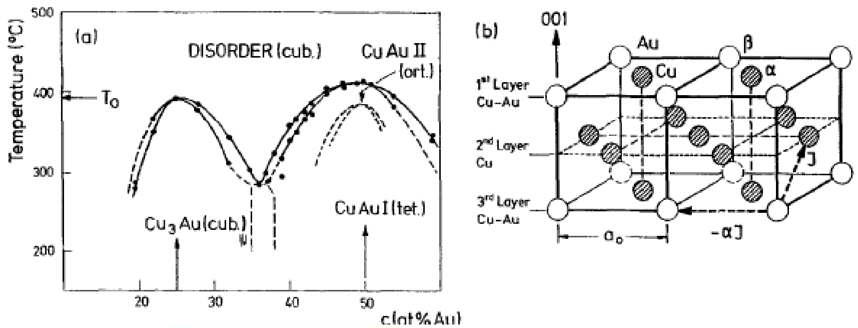
Speckle of (001) Cu_3Au peak

M. Sutton et al., "The Observation of Speckle by Diffraction with Coherent X-rays" *Nature* **352**, 608-610 (1991).



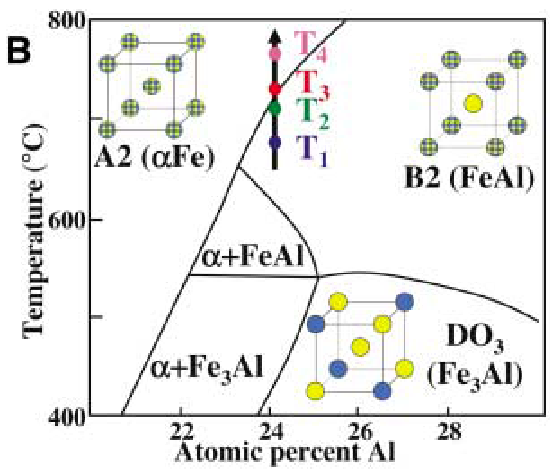
Speckle of the Fe_3Al (1/2,1/2,1/2) super-lattice reflection showing frozen-in disorder. b) Zoom of the central region in a) where the speckle structure is obvious.
Grubel et al., ESRF News (1995)

Binary Alloys:



Cu_3Au

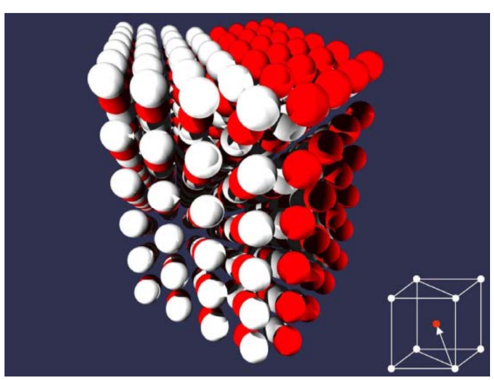
Sutton et al., Nature 1991, PRL 2005



Fe_3Al

Brauer et al., PRL 1995

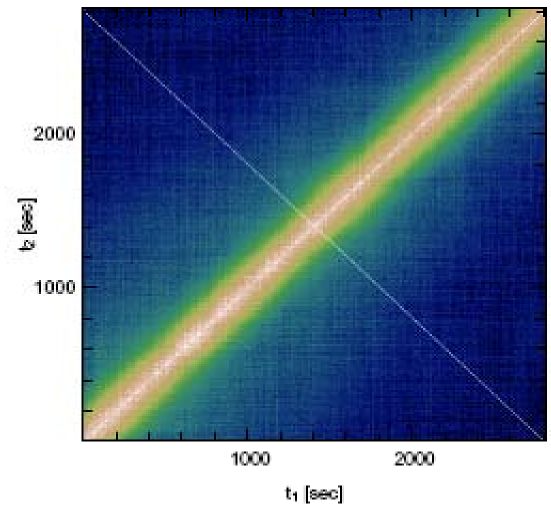
Mocuta et al., Science 2002

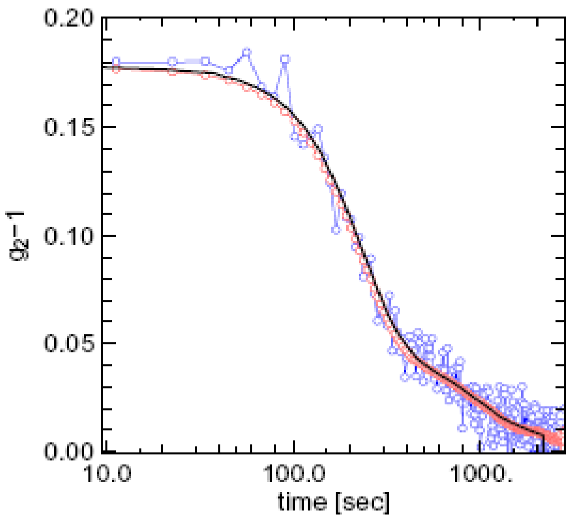


CoGa, AlLi, AlZn, AlAg

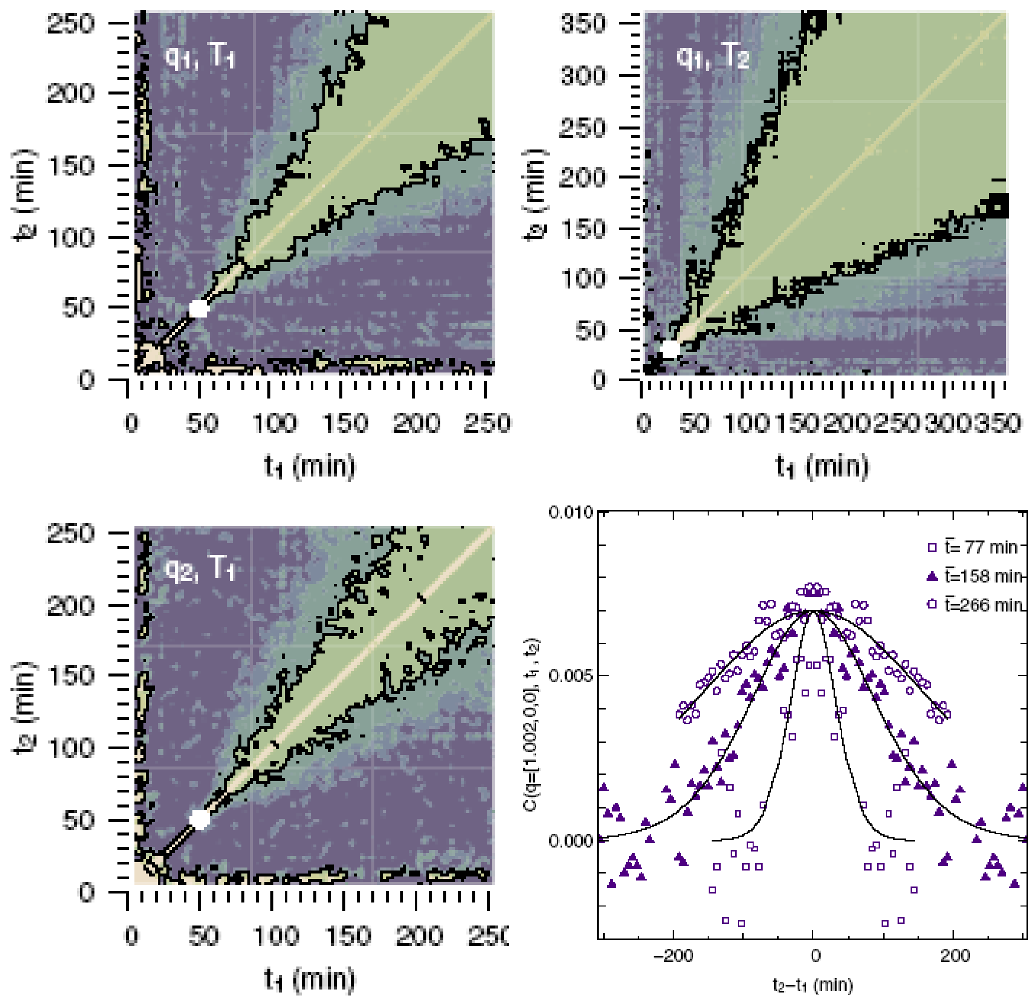
Stadler et al. 2004-7

Equilibrium:





Non-equilibrium:

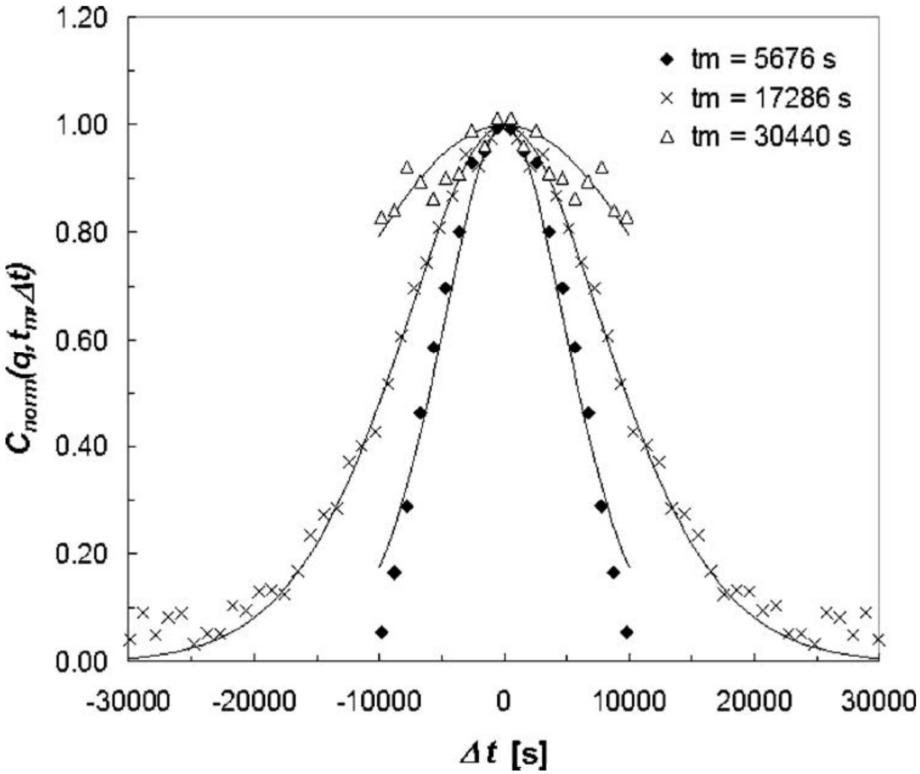


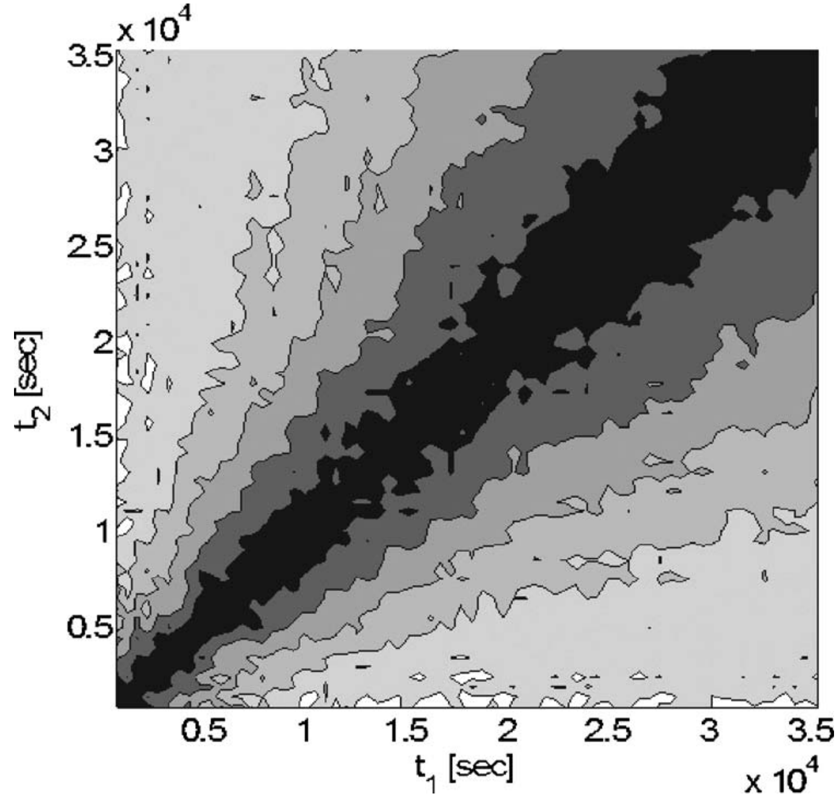
Quenched Cu_3Au

A. Fluerasu et al., Phys. Rev. Lett. **94**, 055501 (2005)
M. Sutton et al., Opt. Exp. (2003)

Non-Equilibrium (aging) XPCS, cont'd:

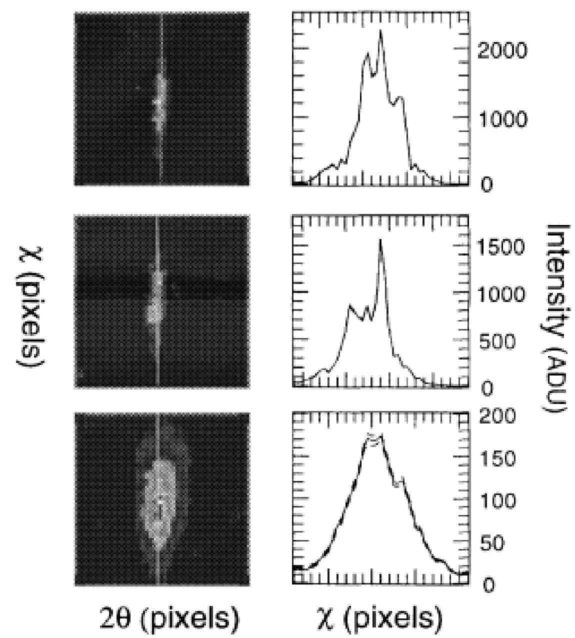
CuPd binary alloy:





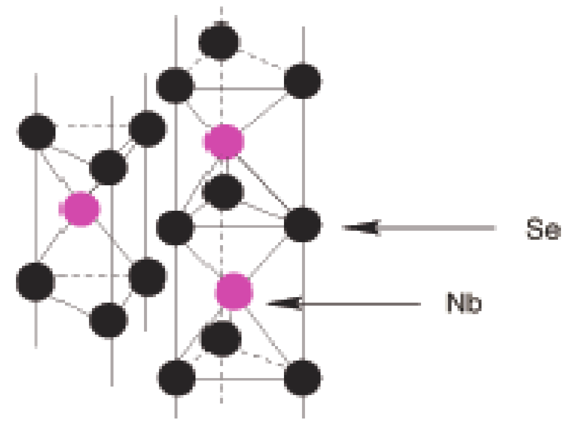
Ludwig et al., PRB 72, 144201 (2005)

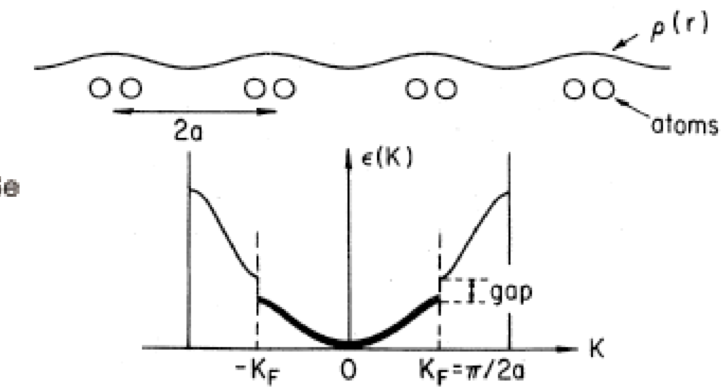
Charge and Spin-ordered systems:



Nb_3Se (classic CDW system)

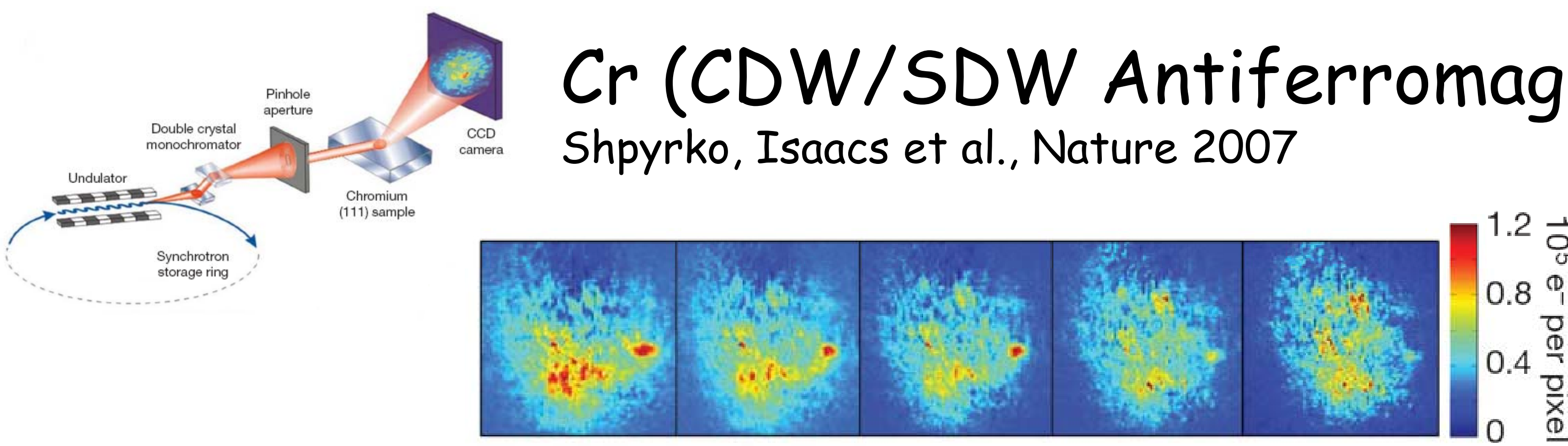
Sutton, Brock, Thorne et al., J. Phys. 2002, PRB 2001



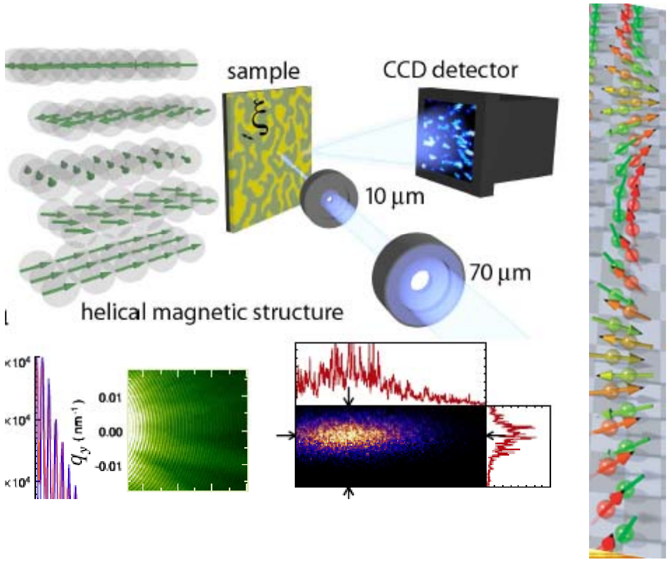


Cr (CDW/SDW Antiferromagnet)

Shpyrko, Isaacs et al., Nature 2007



Charge and Spin-ordered systems:



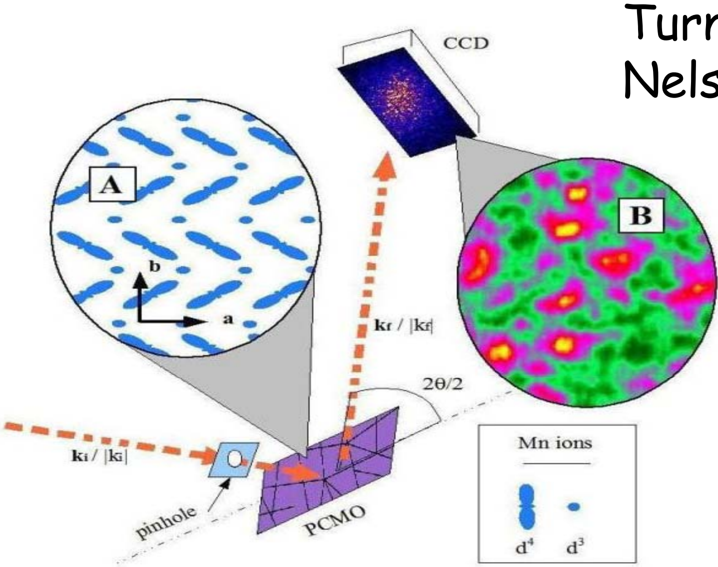
Ho films (helical AFM)

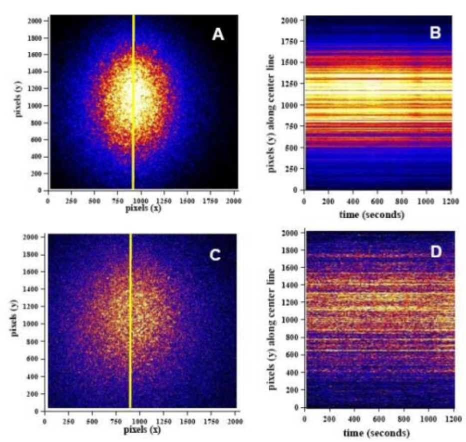
Koning, Goedkoop, PRL 2007

$Pr_{0.5}Ca_{0.5}MnO_3$ (Charge- & Orbital-Order)

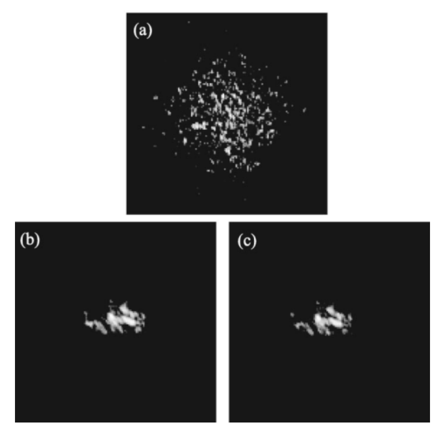
Turner, Hill, Kevan et al., arxiv (?) 2008

Nelson, Hill, Livet et al., PRB 2002

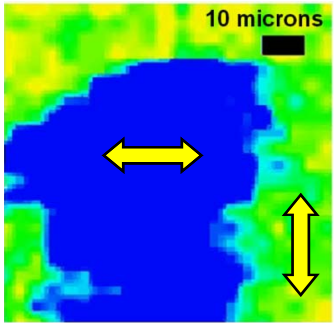




$Pr_{0.6}Ca_{0.4}MnO_3$, T = 150 K



- Studies of *antiferromagnets* are more challenging than those of ferromagnets
  Net magnetic moment = 0



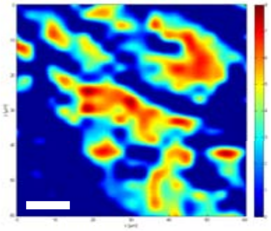
Spin domains in Cr
P. G. Evans, E. D. Isaacs et al., *Science* **295** 1042 (2002)

- Complex relationship between mesoscale phases (spin, charge, lattice) and physical properties

How can we study mesoscale dynamics in the bulk?

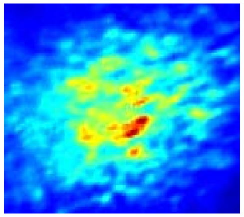
X-rays:

- Scanning X-ray Microscopy (slow dynamics)



Charge/spin density wave domains

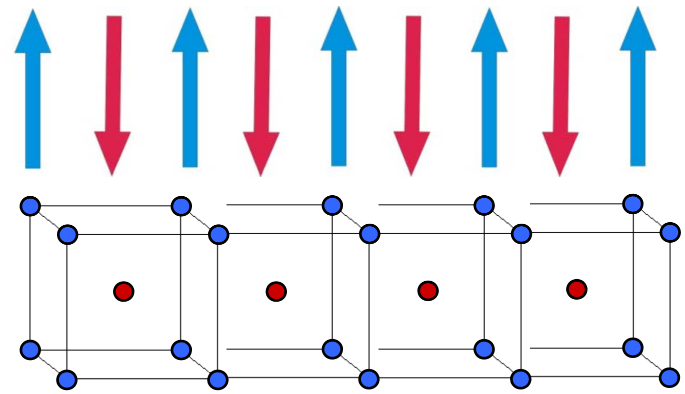
- X-ray Photon Correlation Spectroscopy or XPCS (faster)



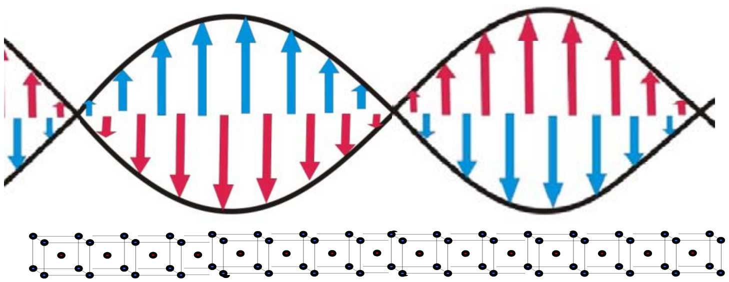
Coherent x-ray speckle

Spin Density Wave (SDW) in Chromium:

Commensurate SDW (C-SDW)
Wave follows periodicity of underlying atomic lattice

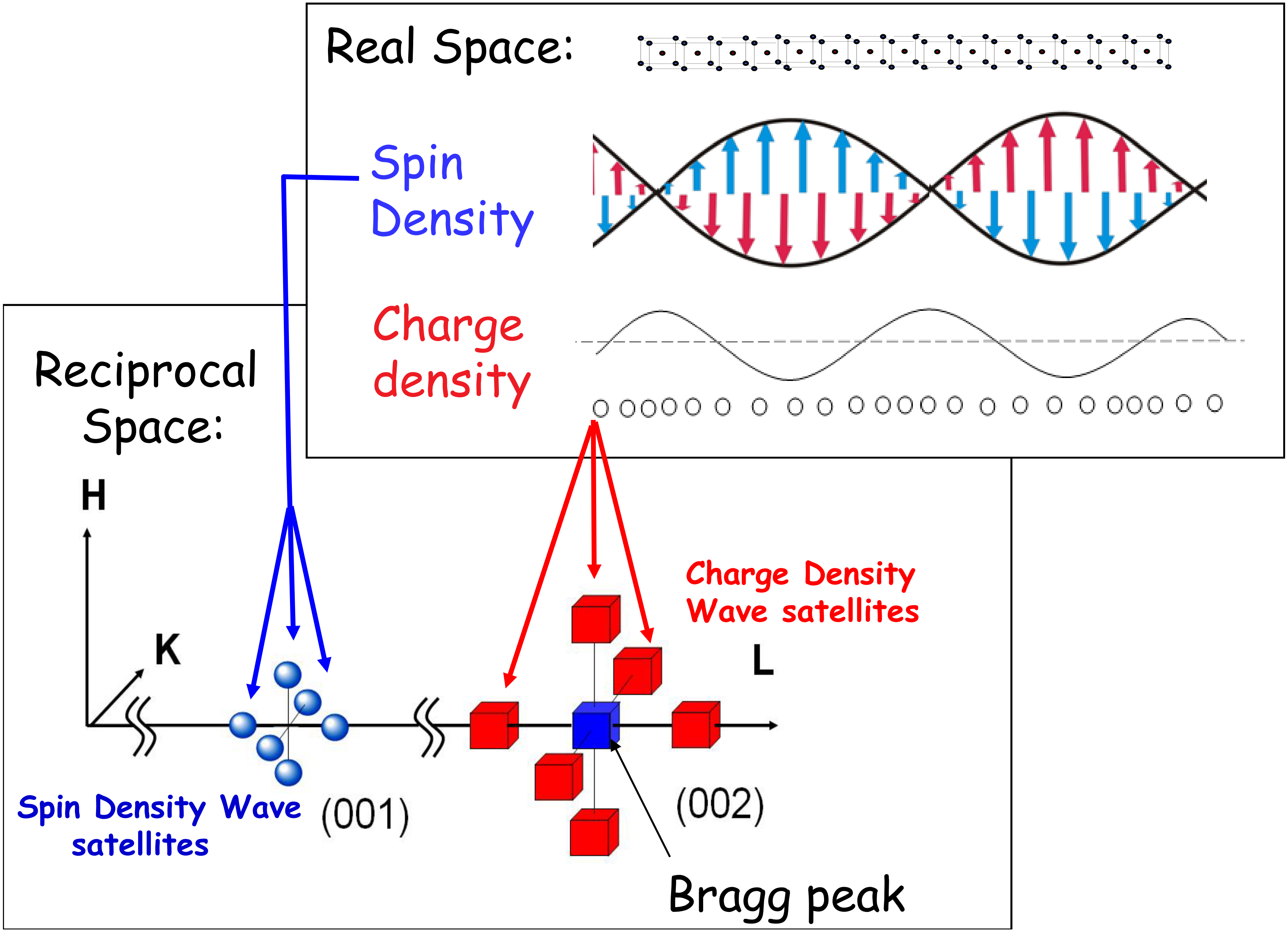


Incommensurate SDW (IC-SDW)
Modulation period incommensurate with lattice periodicity



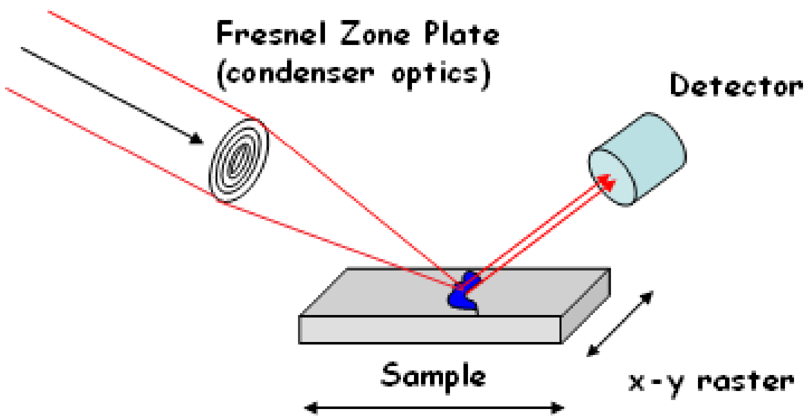
For chromium incommensurability parameter is δ=0.037 at room T (period is δ^{-1}~28 times the lattice constant)

Charge, Spin and Lattice order parameters:



Microscopic Magnetic Domains in Chromium:

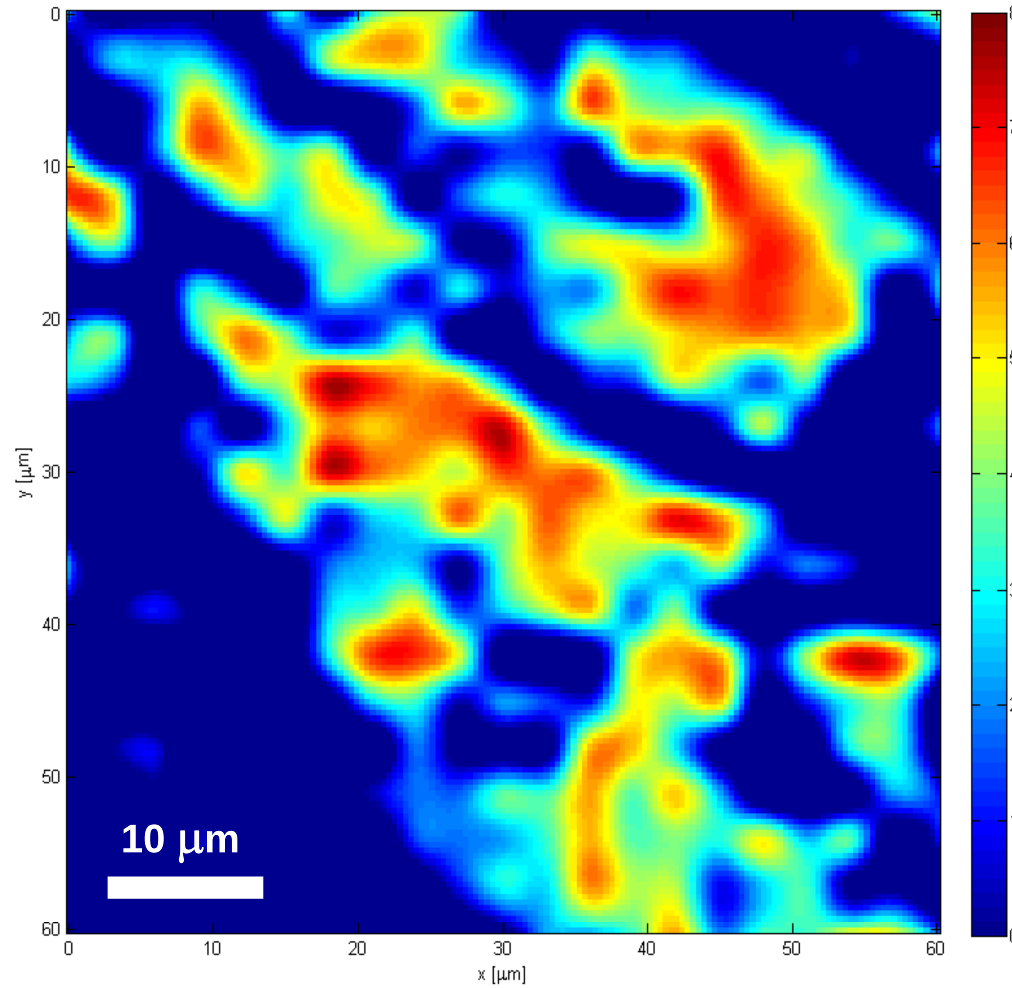
Scanning X-ray Microscopy:



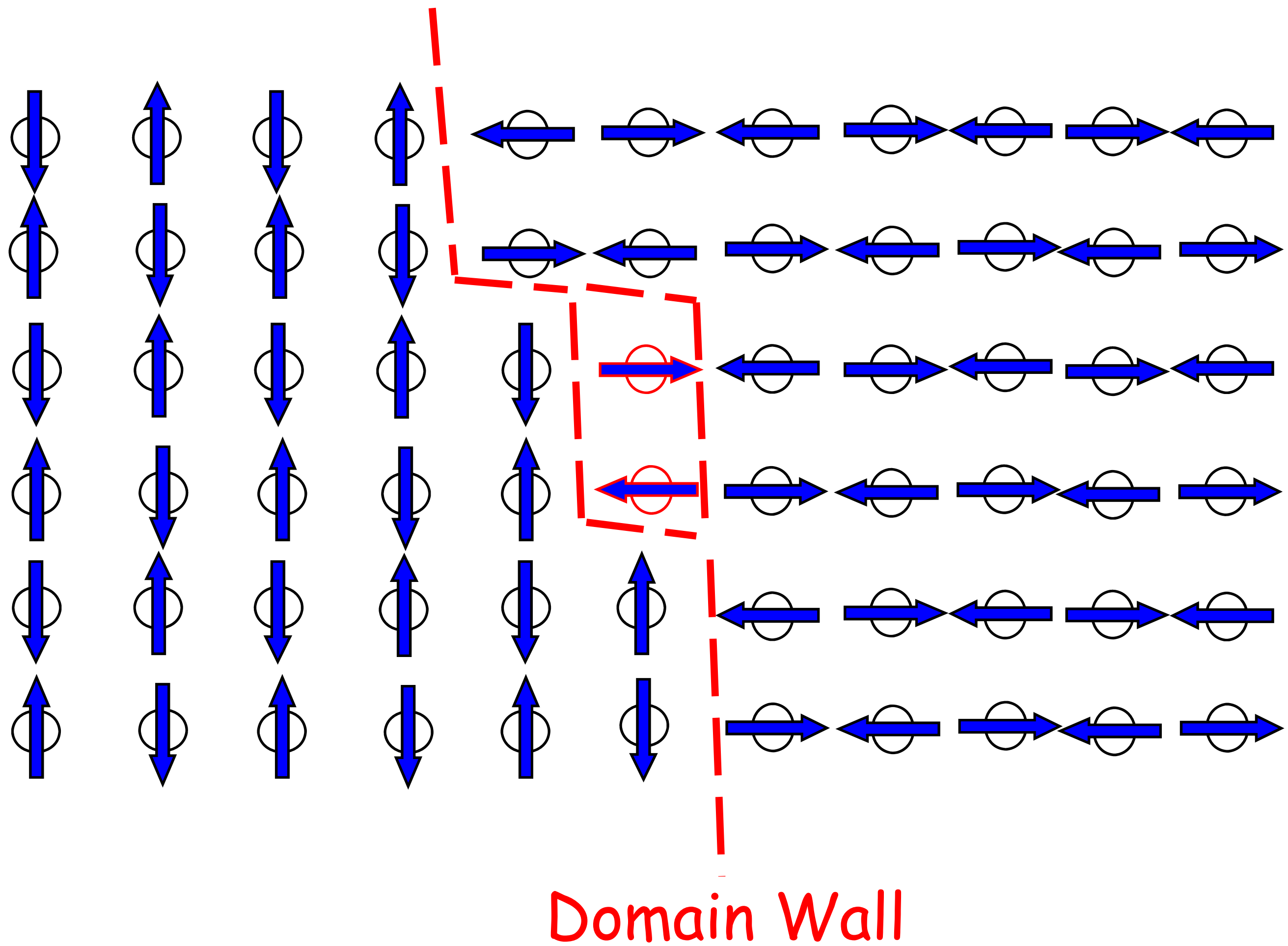
• bulk probe (micron-sized penetration depth)

• spin, charge, lattice and chemical sensitivity

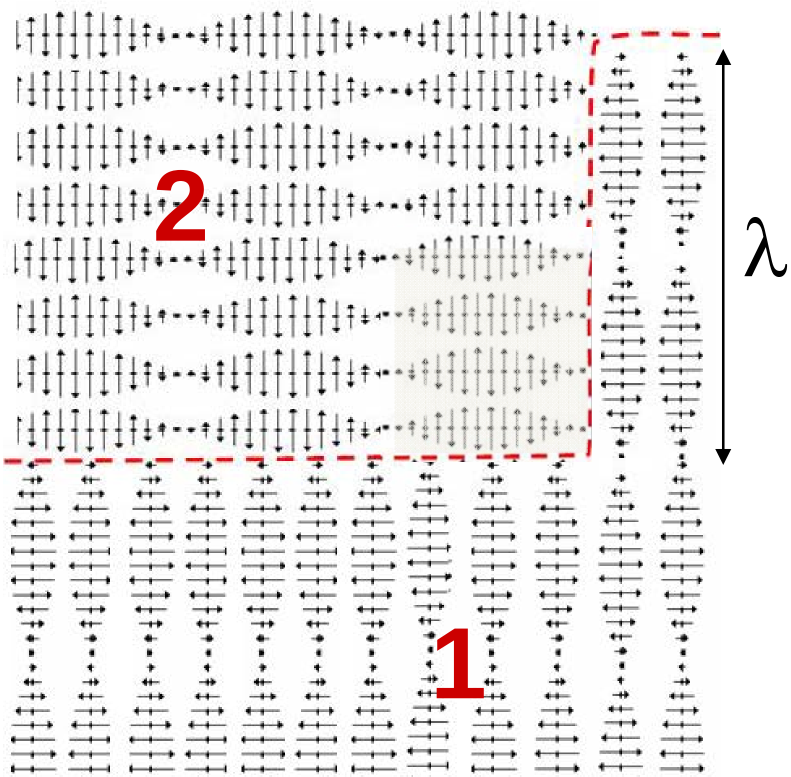
[0, 0, 2-2δ] Charge-density wave satellite

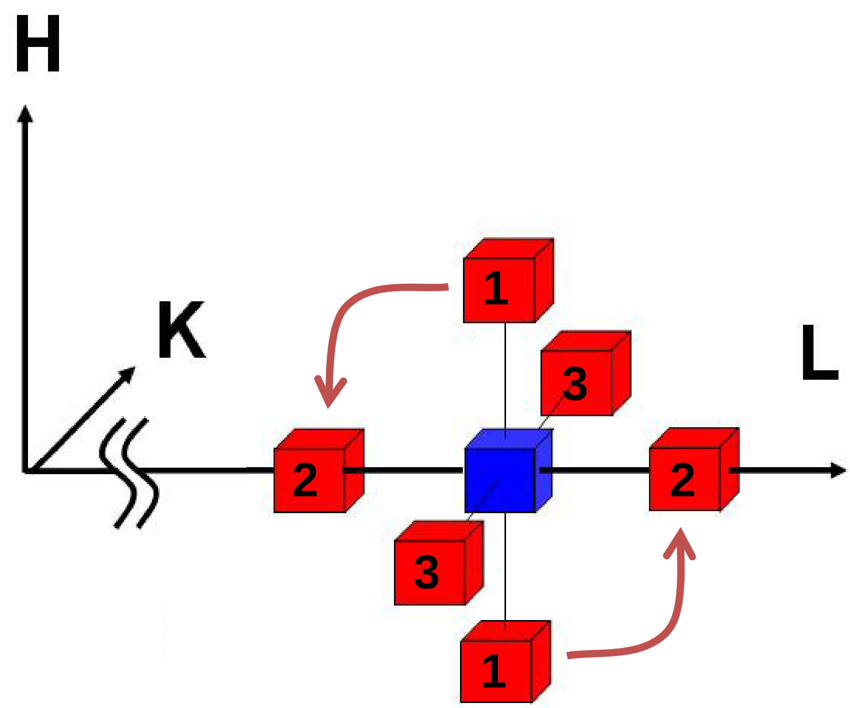


Domain Wall Fluctuations in Antiferromagnets



Magnetic domain wall fluctuations in real and reciprocal space:





Real Space:

elemental switching block, w/ volume $(\lambda/2)^3$, λ=3-4 nm

Momentum Space:

transfer of intensity from satellites 1 to 2 due to switch

Random Telegraph Noise in Cr (thin films):

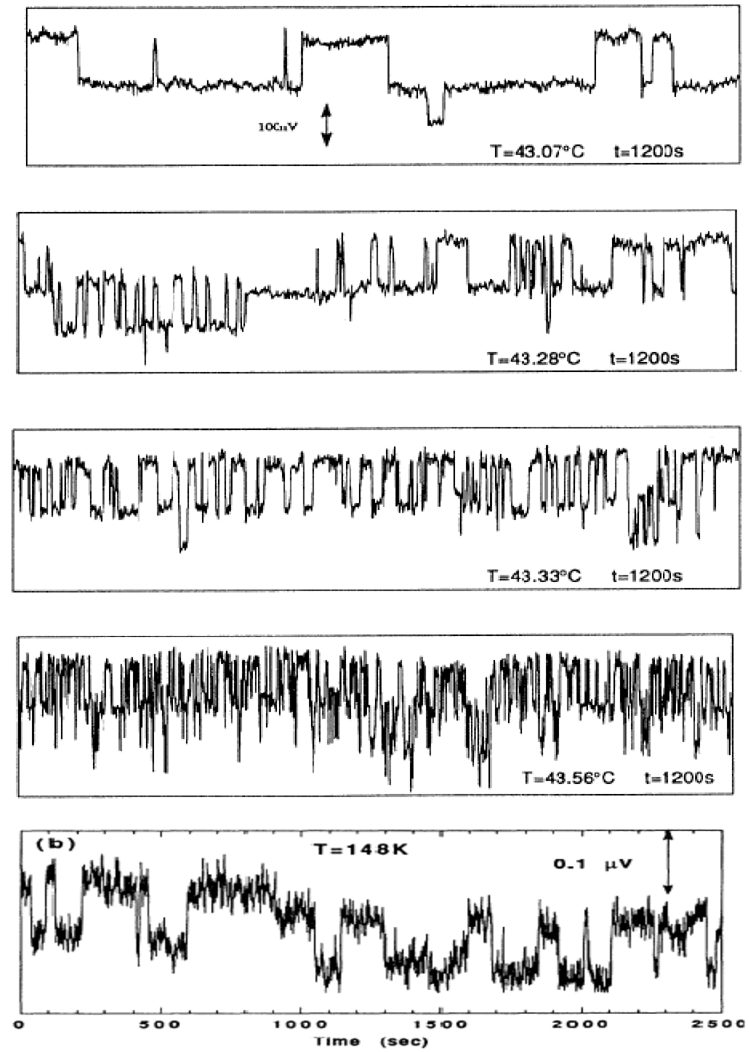
Chromium:

Discrete steps in electrical resistivity

Slow (1 s -100 s)

$\delta R/R \sim 10^{-5}$

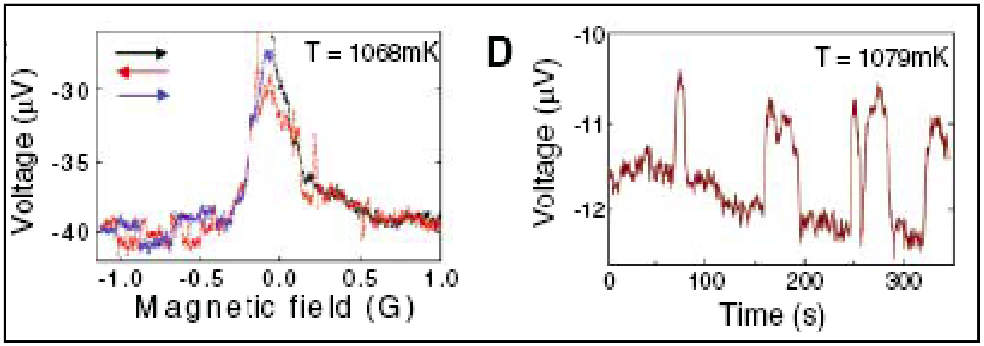
Is this domain switching?



R. Michel, M. Weissman, *Phys. Rev. B* **44**, 7413 (1991).

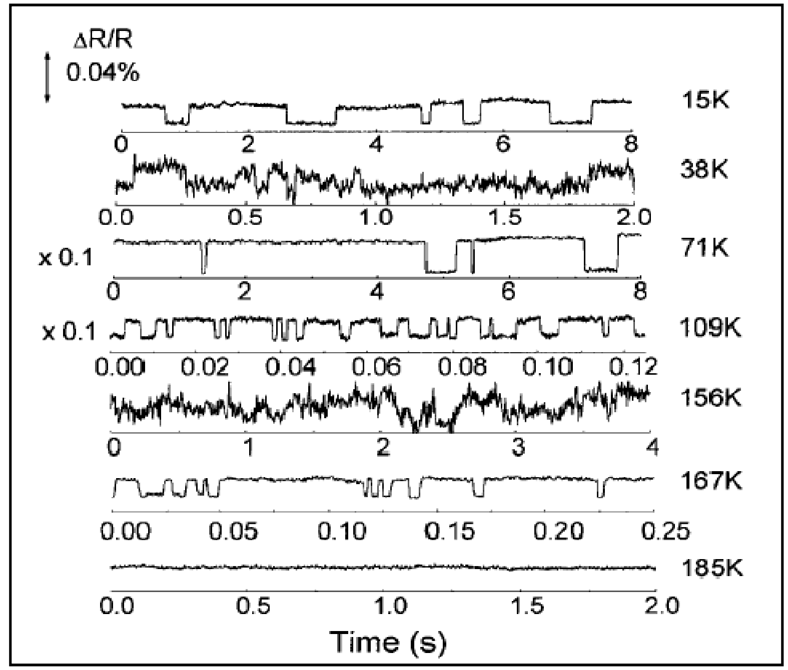
Random Telegraph Noise in other materials:

Ruthenates (Sr_2RuO_4):



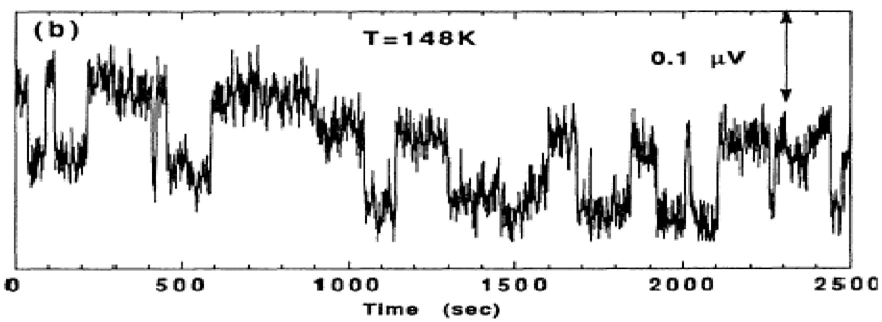
F. Kidwingira, D. J. Van Harlingen et al., *Science* **314**, 1267 (2006)

Manganites ($La_{1-x}Ca_xMnO_3$):

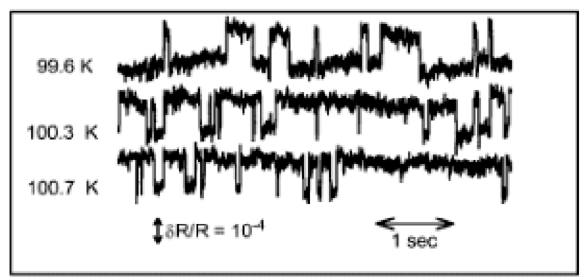


B. Raquet et al., *Phys. Rev. Lett.* 84, 4485 (2000)

Chromium:

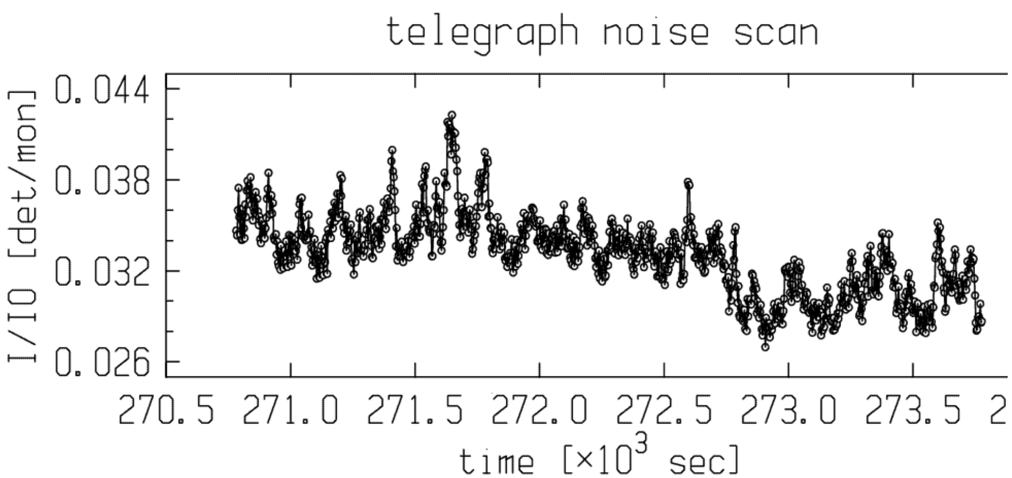


R. Michel, *Phys. Rev. B* **44**, 7413 (1991)

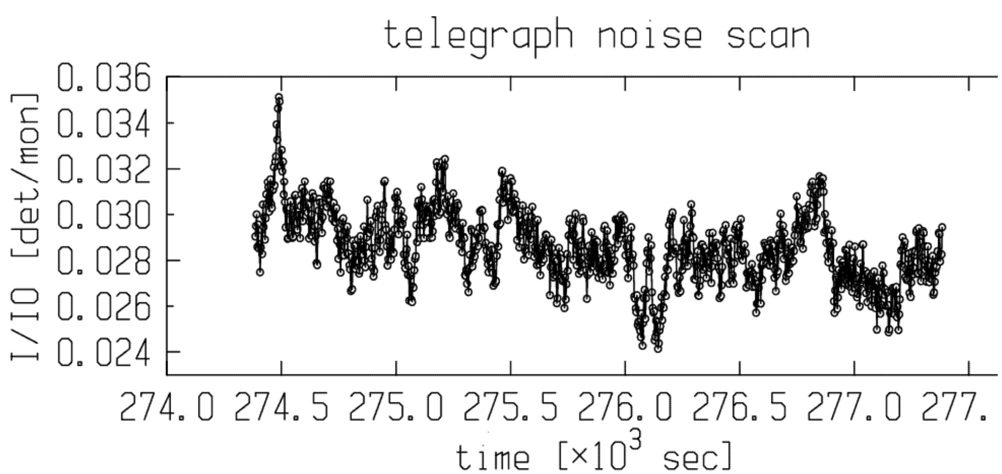


R. D. Merithew et al., *Phys. Rev. Lett.* **84**, 3442 (2000)

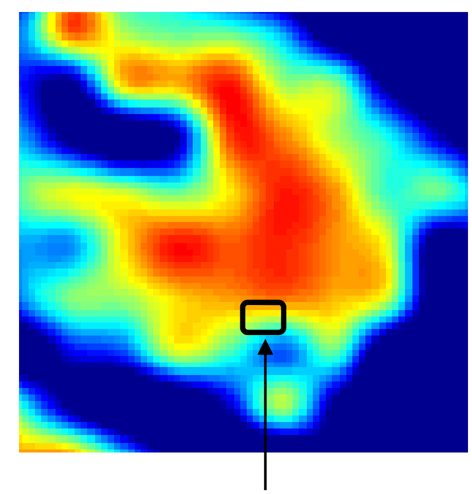
Random Telegraph Noise measurements:
Focus on the Domain Wall



~100 nm

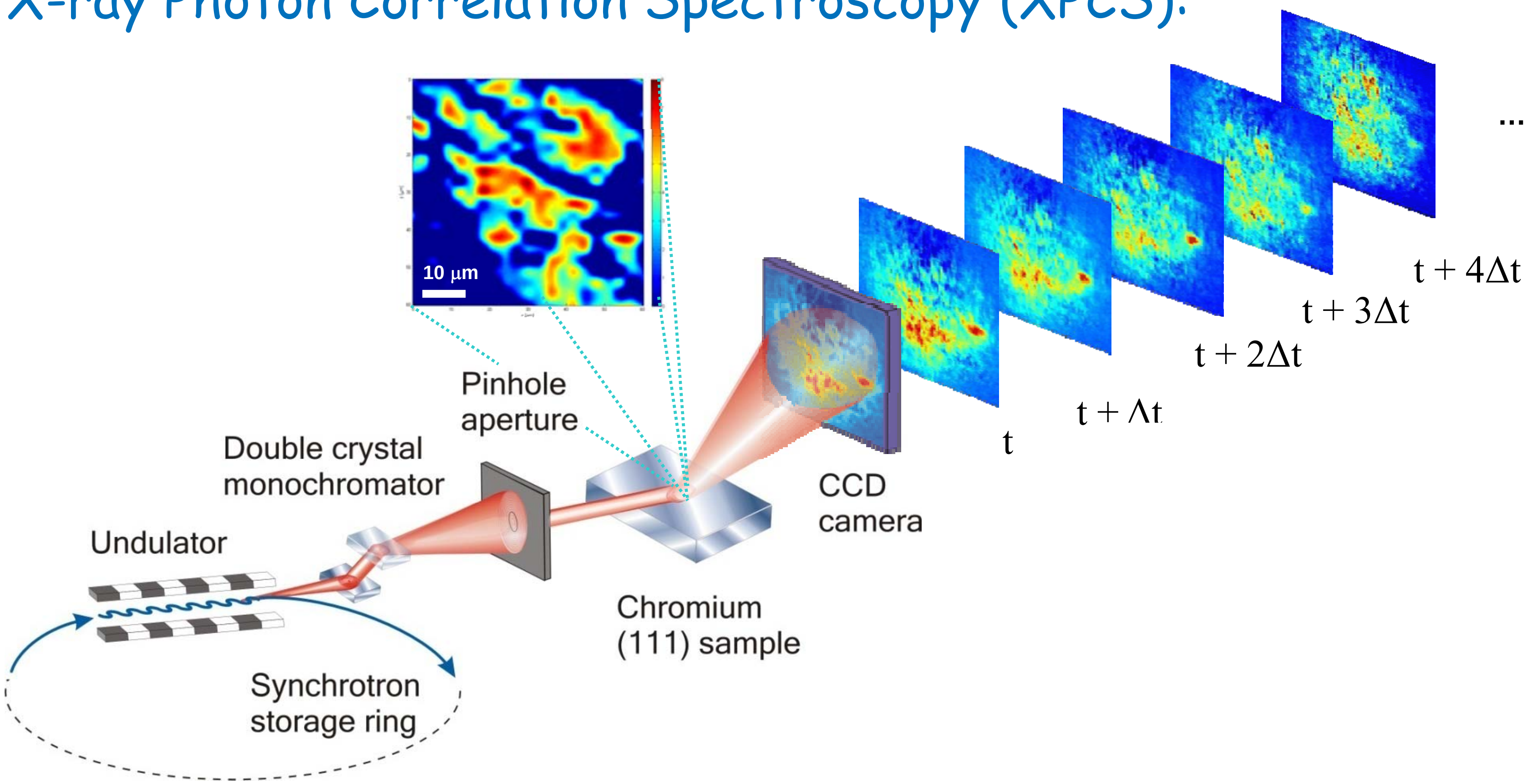


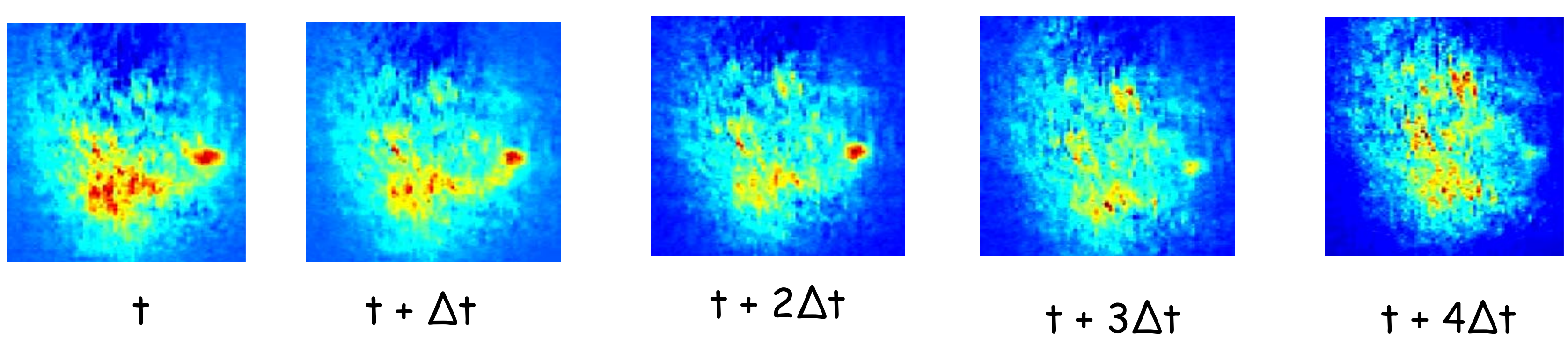
~100 nm



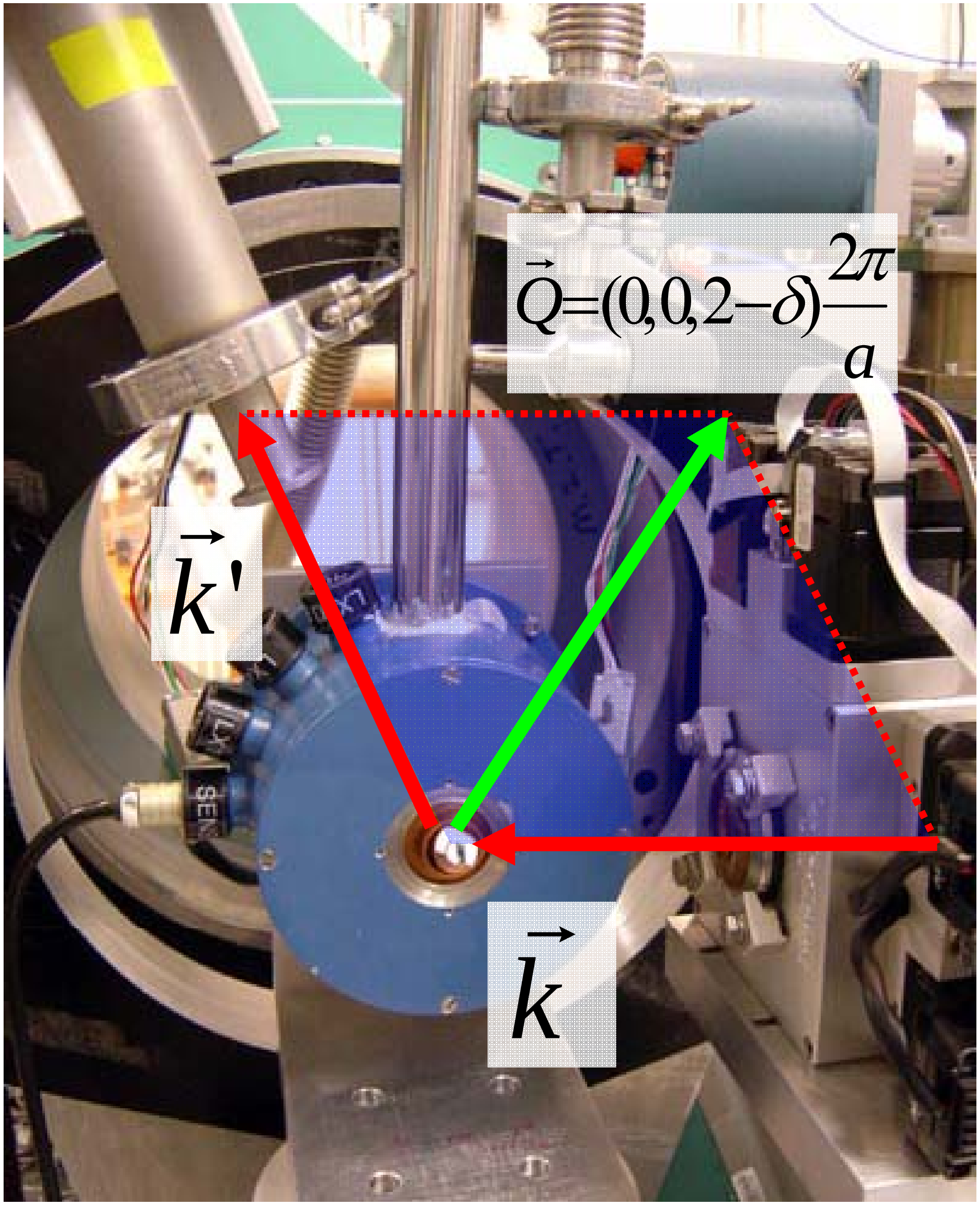
focused x-ray beam
(0.5 μm)

X-ray Photon Correlation Spectroscopy (XPCS):

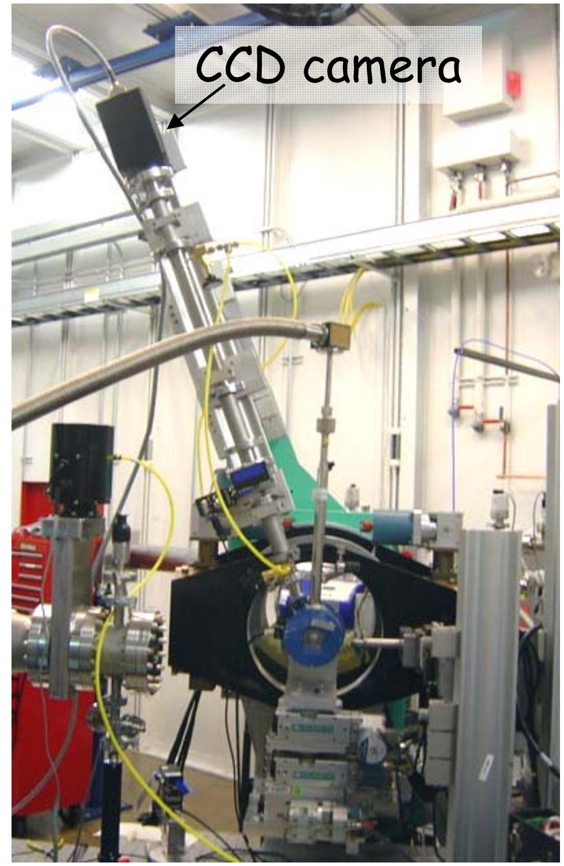




O. G. Shpyrko et al., *Nature* **447**, 68 (2007)



$\vec{Q}=(0,0,2-\delta)\frac{2\pi}{a}$
$\vec{k}'$
$\vec{k}$

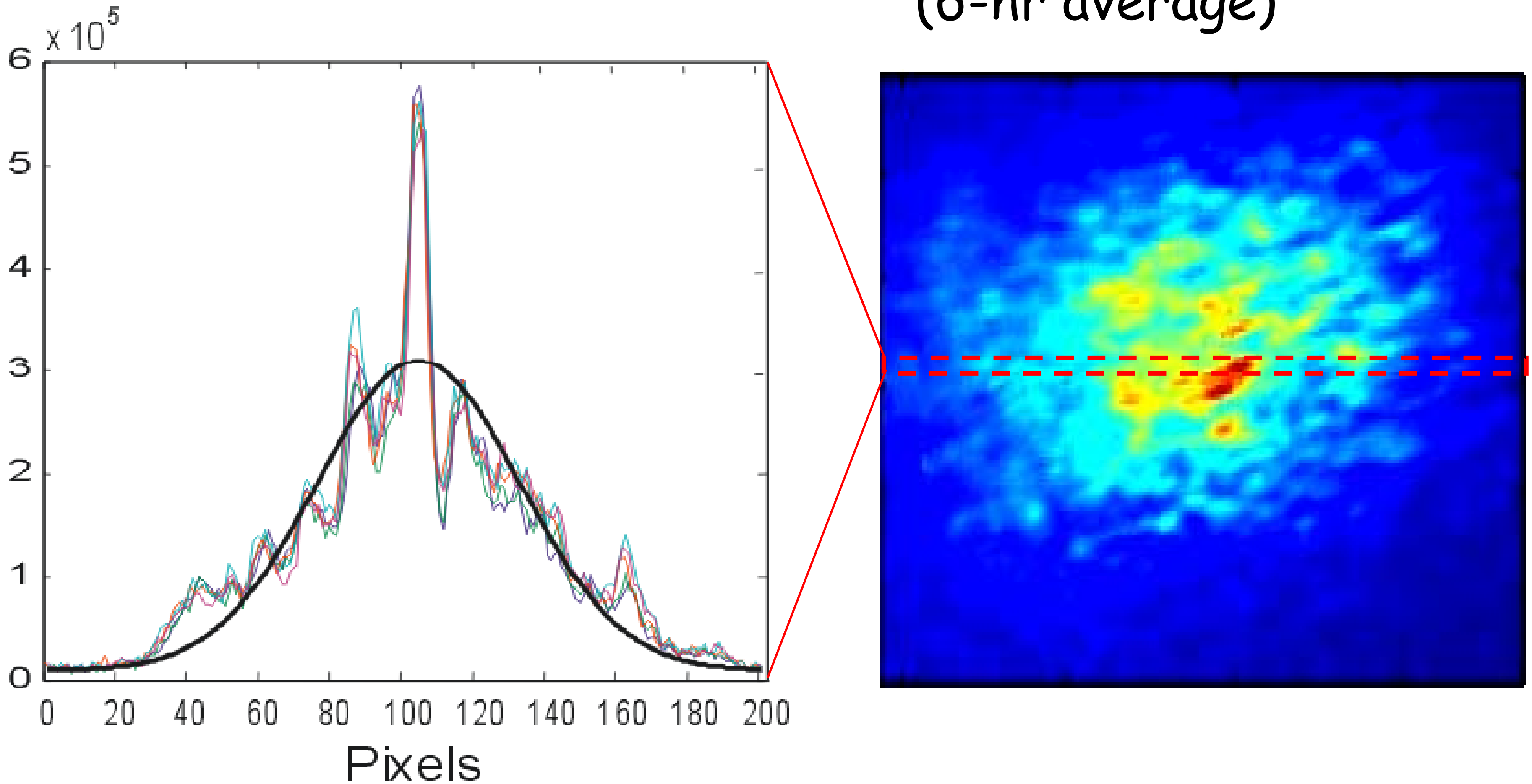


CCD camera

Control experiment: Bragg Speckle

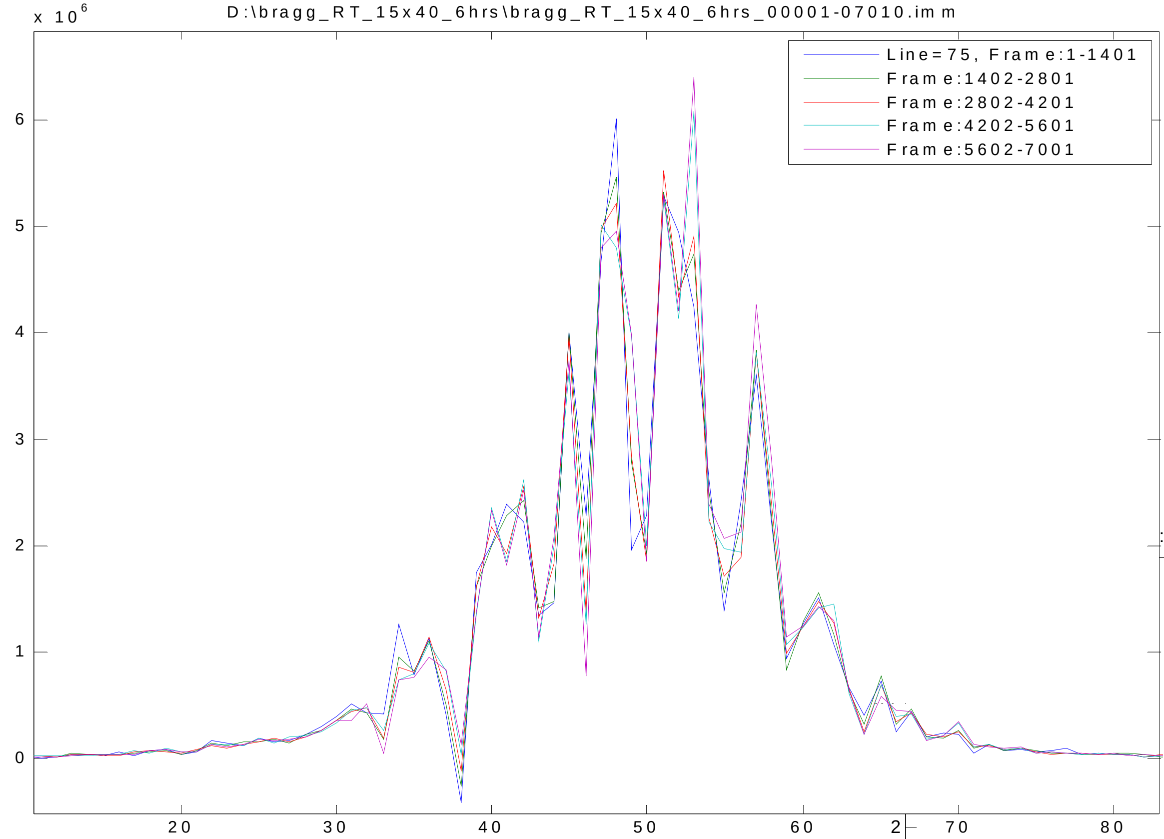
Quasi-static Brag speckle
(line scans from 2D image):

X-ray Bragg speckle
(6-hr average)

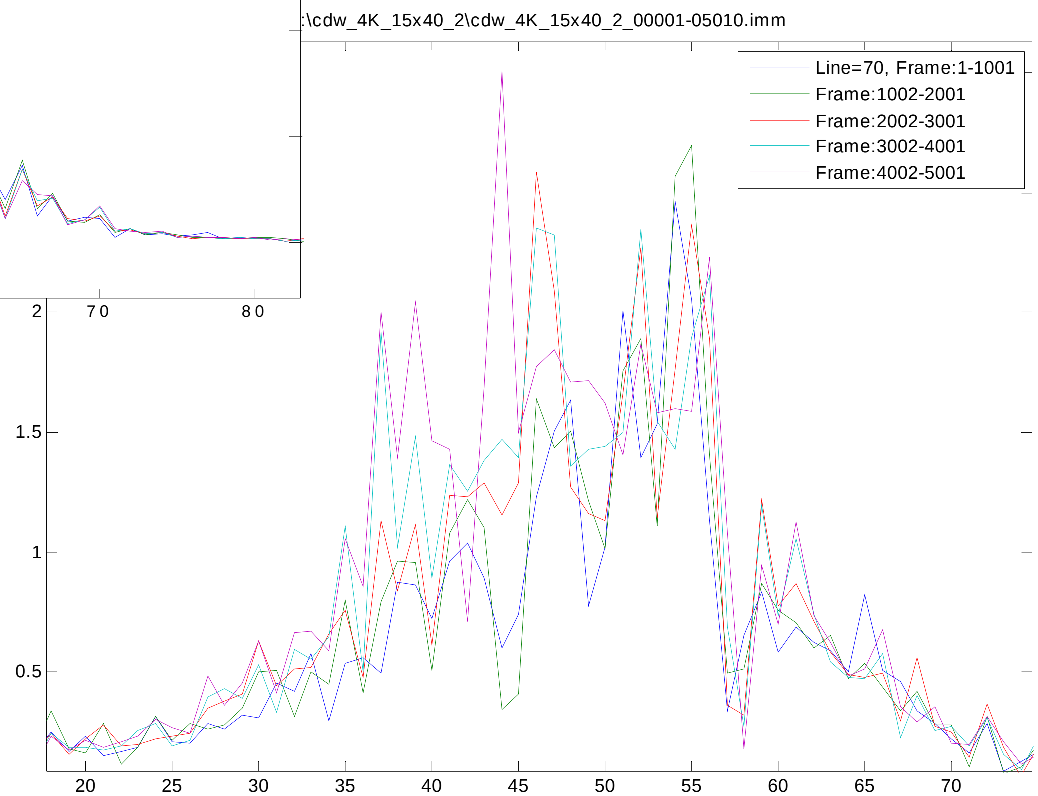


O. G. Shpyrko et al., *Nature* **447**, 68 (2007)

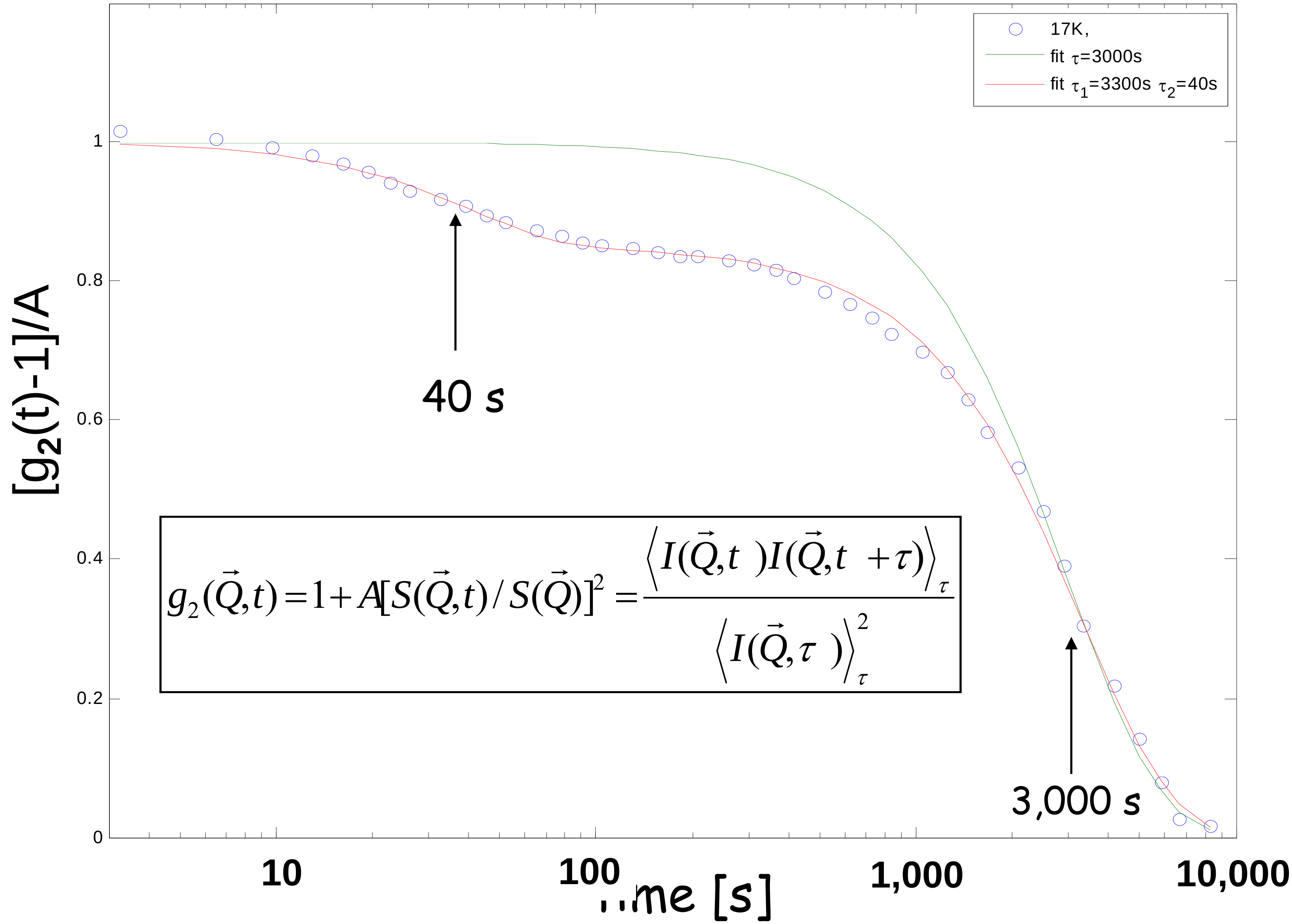
Bragg, 300K: (total 6 hrs) linescans



CDW, 4K: 6 hrs

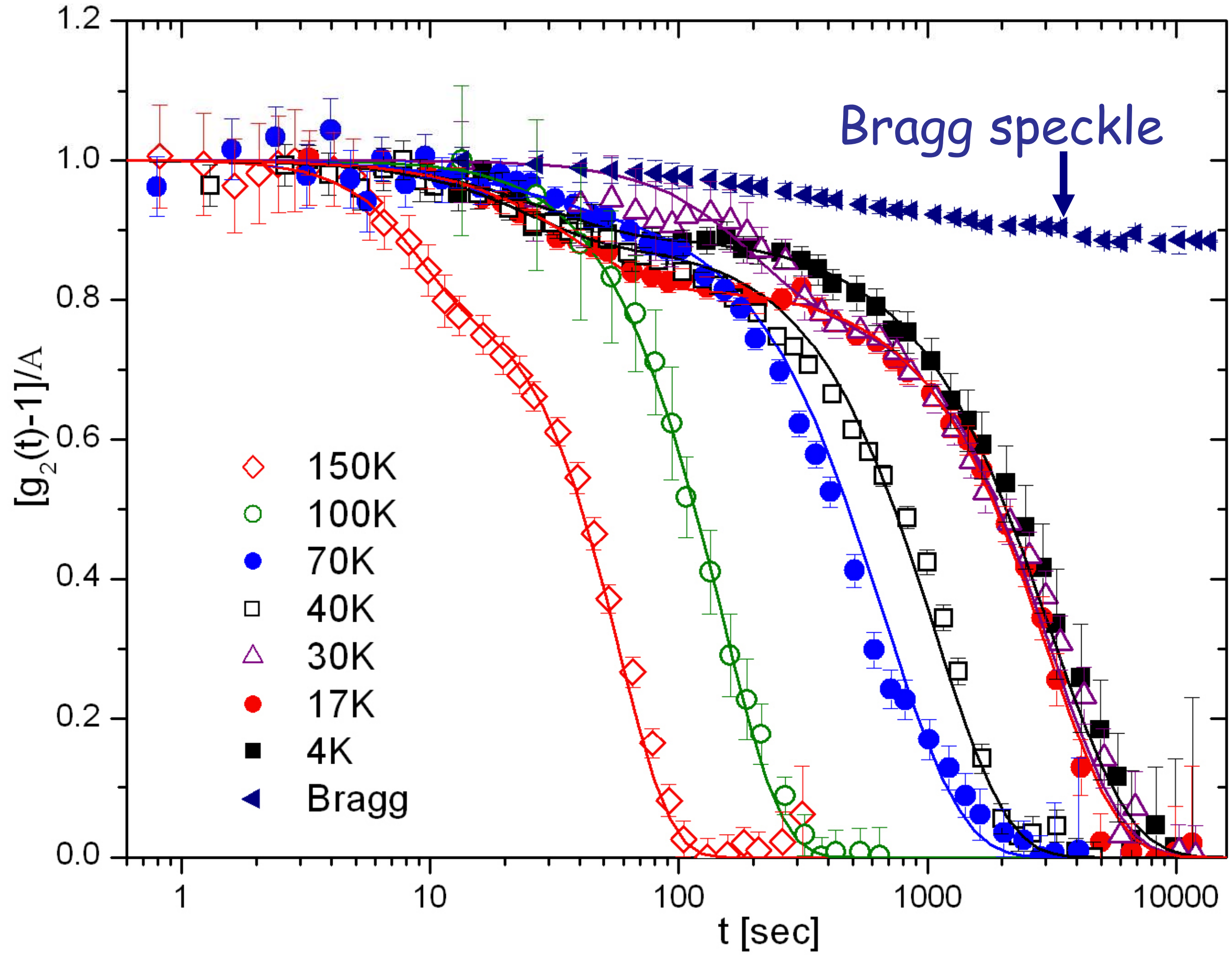


Autocorrelation function $g_2(t)$:
Multiple relaxation timescales

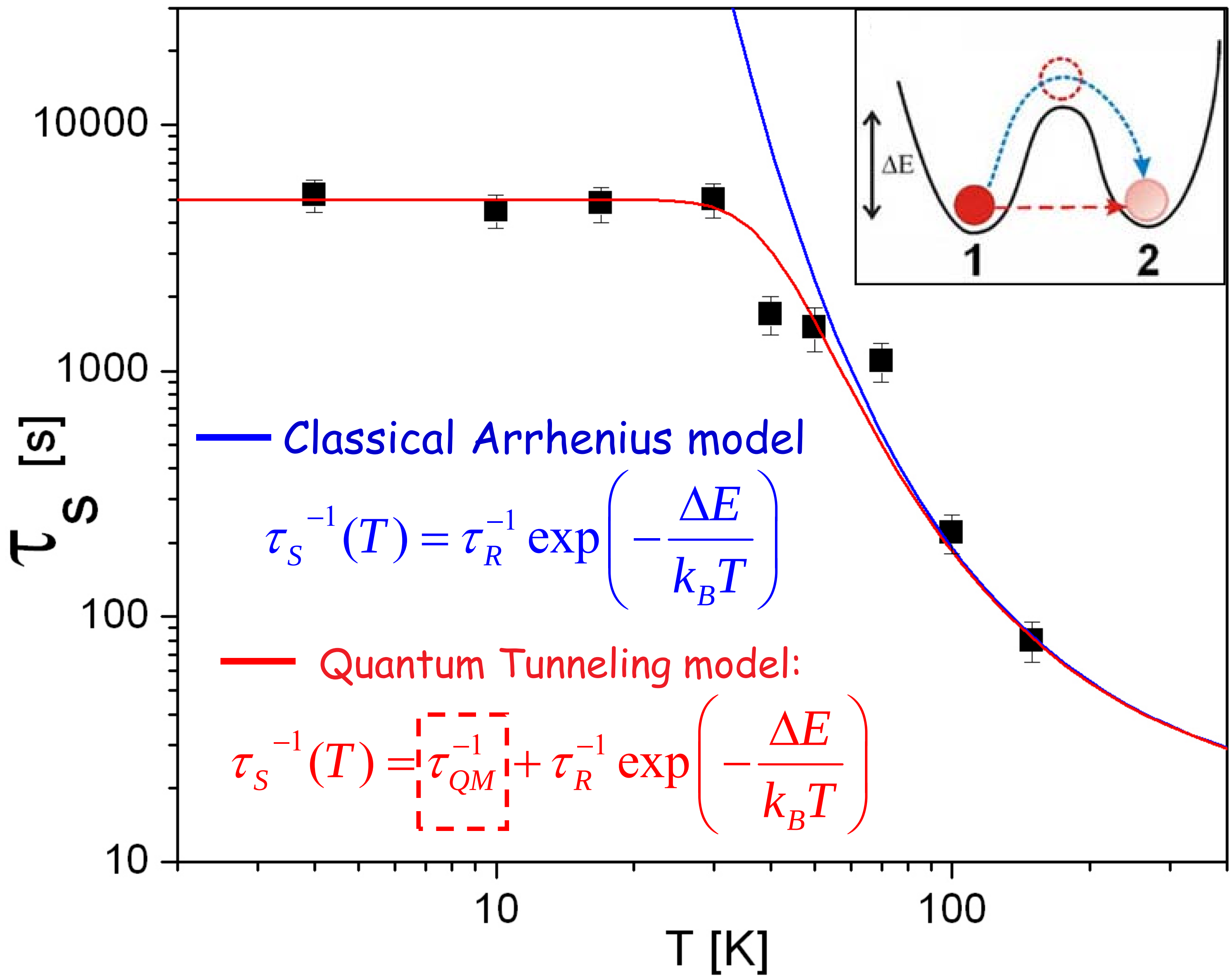


$$g_2(\vec{Q},t) = 1 + A[S(\vec{Q},t)/S(\vec{Q})]^2 = \frac{\left\langle I(\vec{Q},t\;)I(\vec{Q},t\;+\tau)\right\rangle_\tau}{\left\langle I(\vec{Q},\tau\;)\right\rangle_\tau^2}$$

Autocorrelation data:



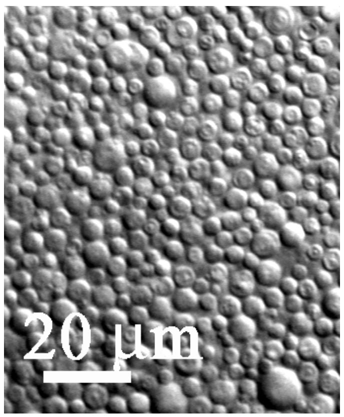
O. G. Shpyrko et al., *Nature* **447**, 68 (2007)

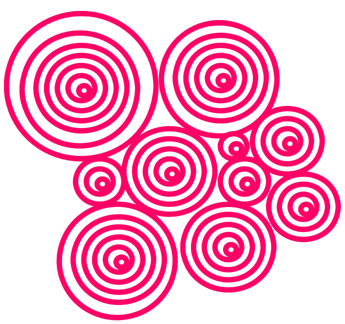


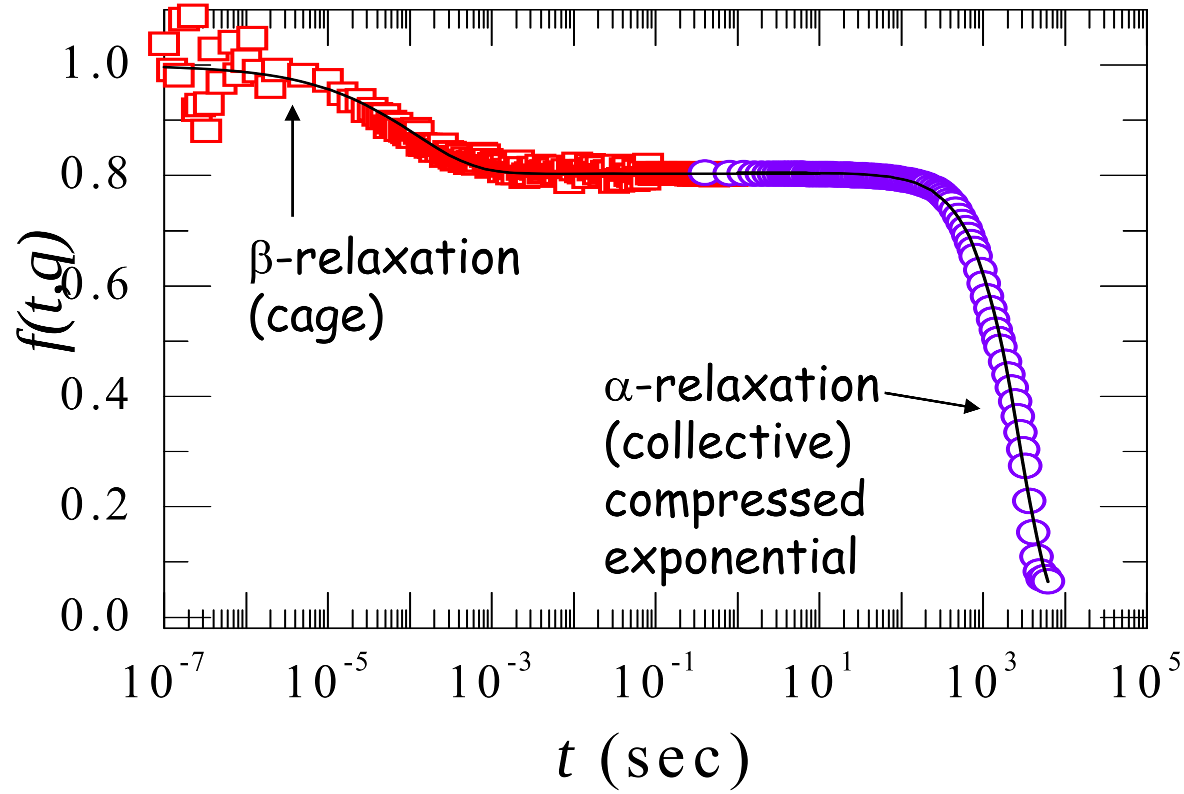
O. G. Shpyrko et al., *Nature* **447**, 68 (2007)

Slow Dynamics in Soft Matter

Onion gel







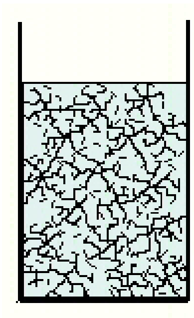
Final relaxation: compressed exponential

$f(q,t)=\exp[-(t/\tau_f)^{\beta}]$ with β~1.5 and $\tau_f \propto q^{-1}$

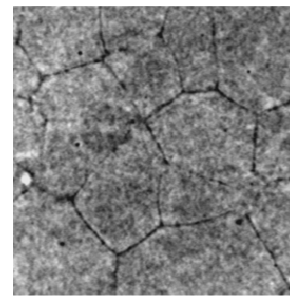
L. Ramos and L. Cipelletti, *Phys. Rev. Lett.* **87**, 245503 (2001)

Aging of Soft Matter under jamming transition (using Laser speckle PCS)

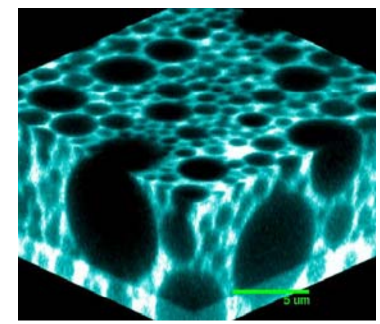
reviewed in L. Cipelletti *et al*., Faraday Discuss. **123** (2003)



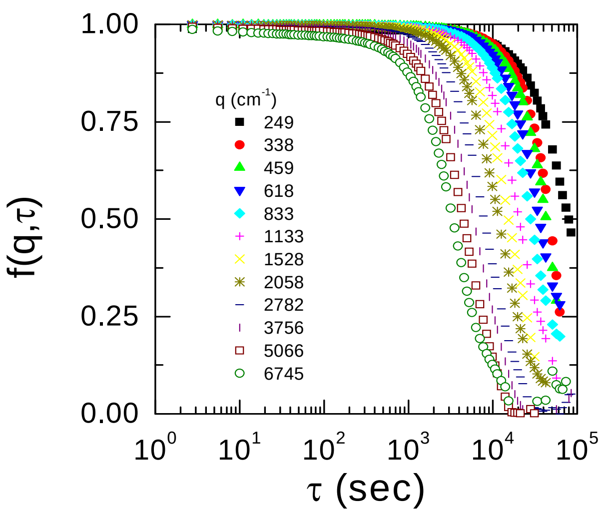
Colloidal gels

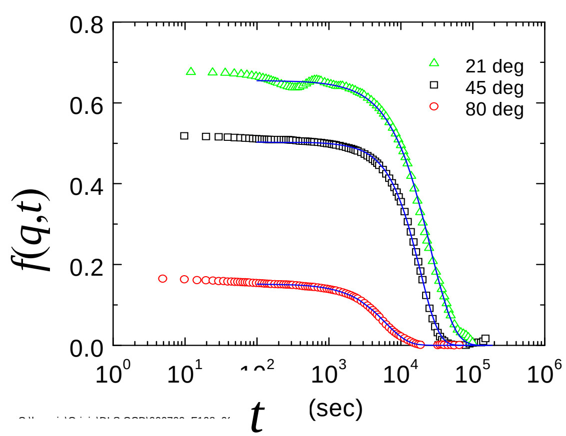


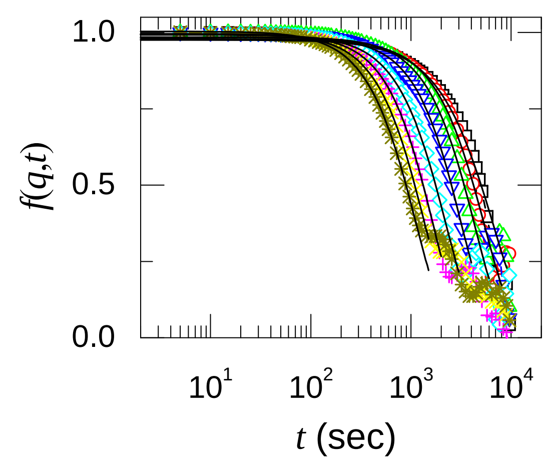
Micellar polycrystal



Concentrated Emulsions







$$f(q,\tau) \propto \exp[-(t/\tau_f)^{1.5}], \quad \tau_f \propto q^{-1}$$

What does next generation of sources (NSLS-II) bring us?

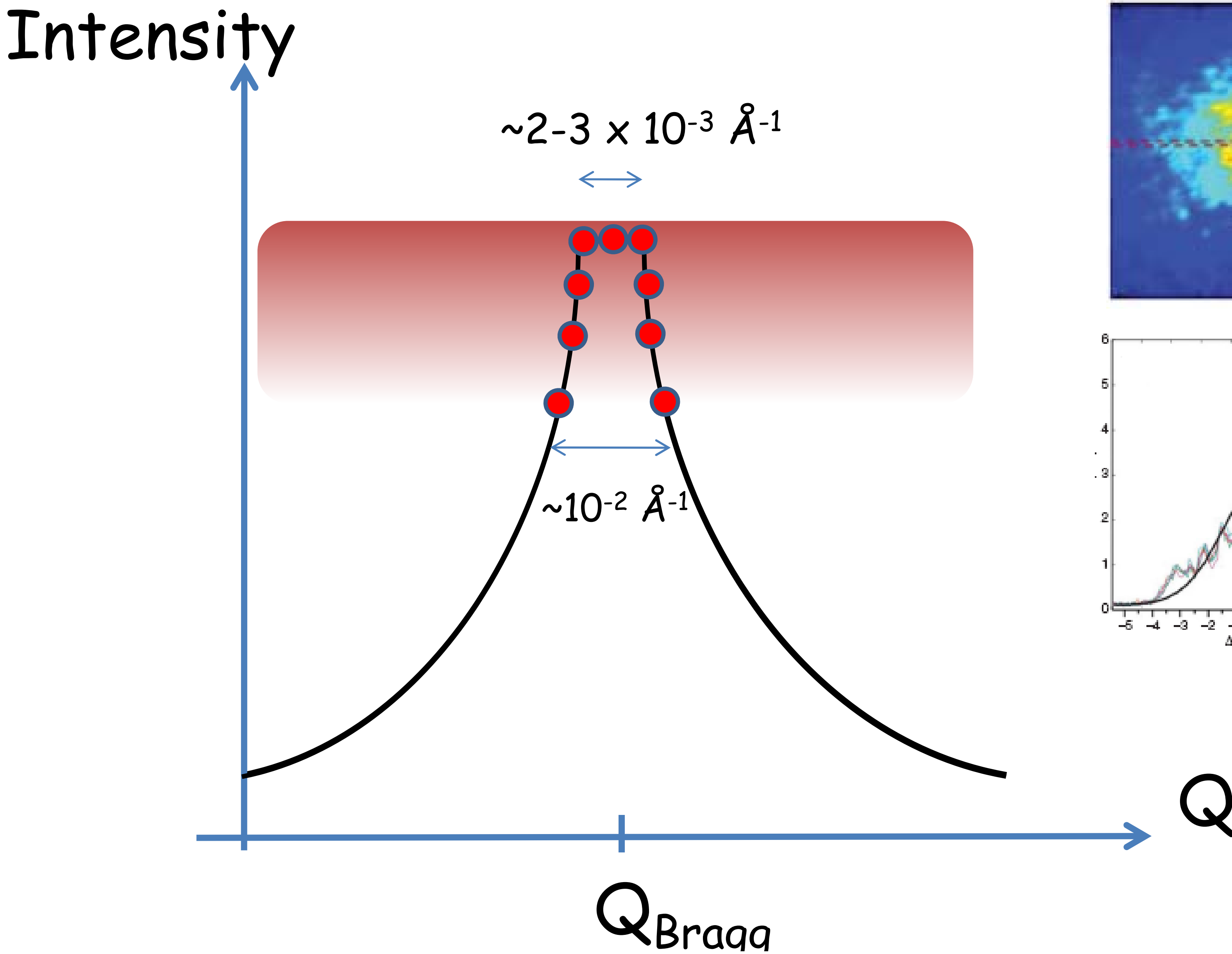
Brightness=Coherent Flux

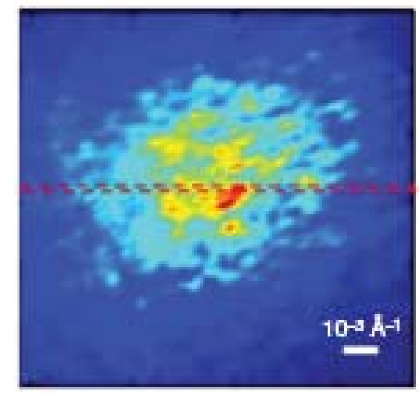
brightness=10^{21} Photons/sec/mm^2/mrad^2/0.1%BW or
=Flux/emittance/0.1% BW

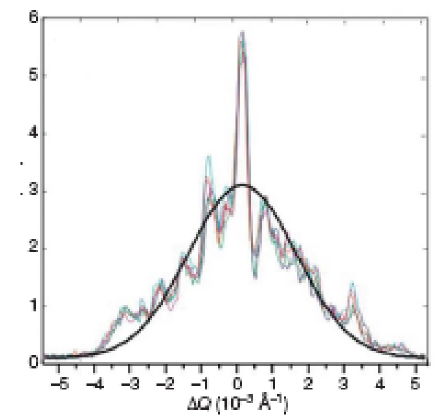
Ratio of source emittance to diffraction limited emittance $\lambda^2/4\pi$ is coherent fraction

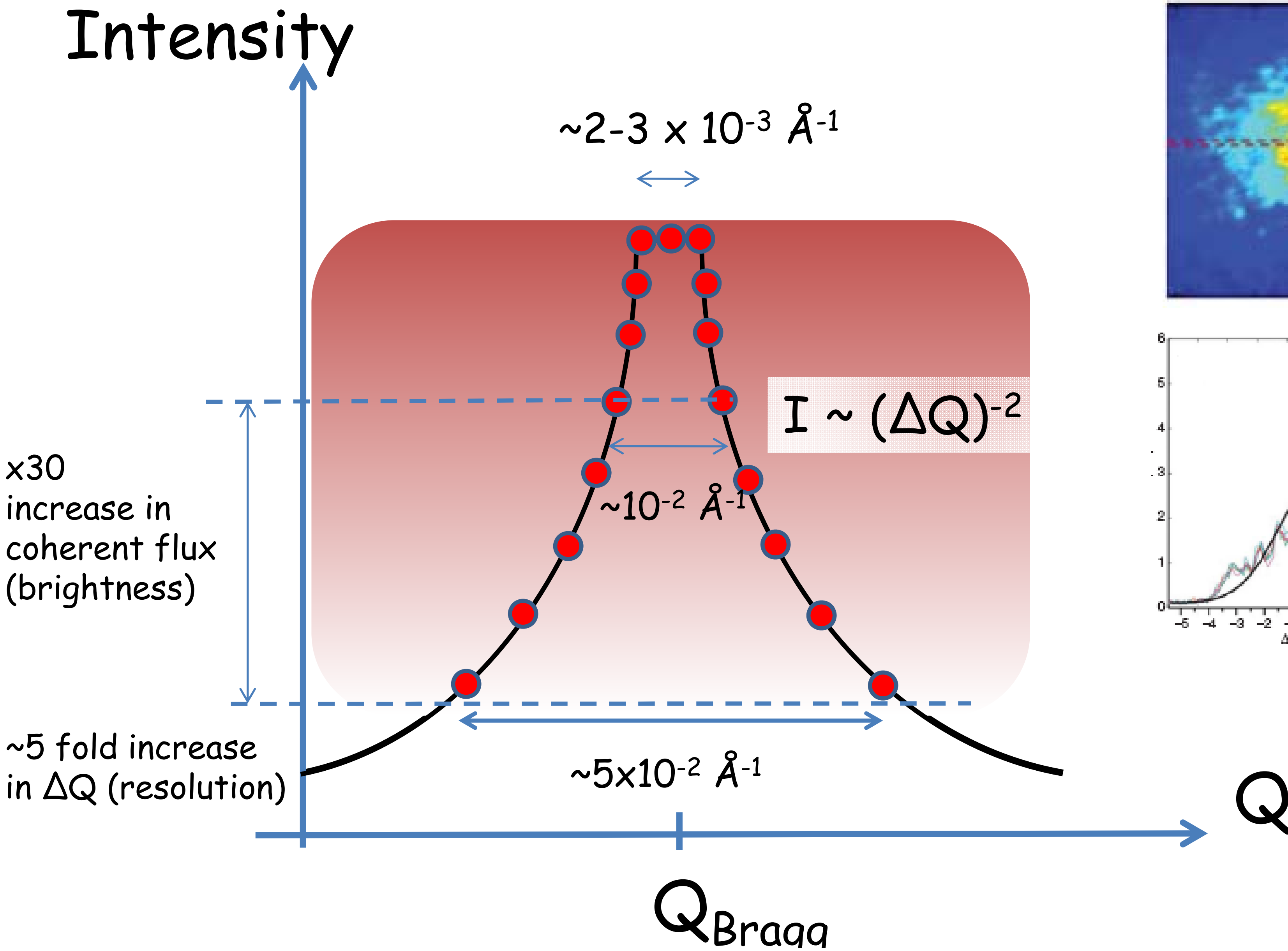
1. Enhanced spatial resolution (for the same temporal scale) – scales as $\Delta r_{min} \sim 1/\sqrt{I}$

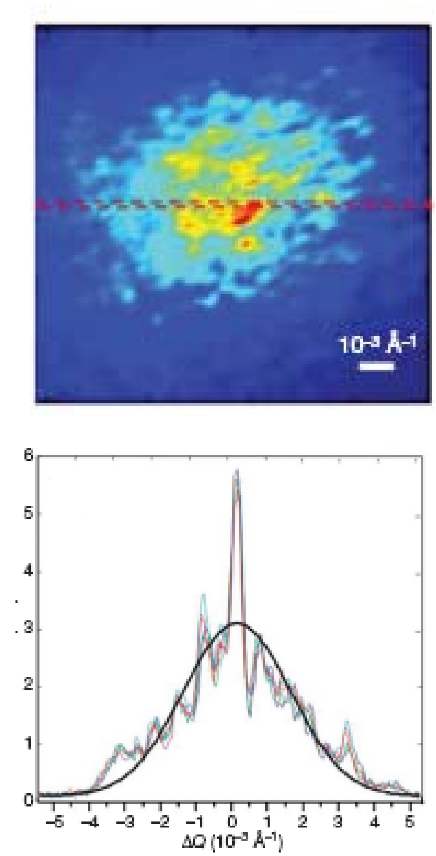
2. Enhanced temporal resolution – scales as $\Delta\tau_{min} \sim 1/I^2$


Intensity
~2-3 x 10^-3 Å^-1
~10^-2 Å^-1
Q
Q_Bragg



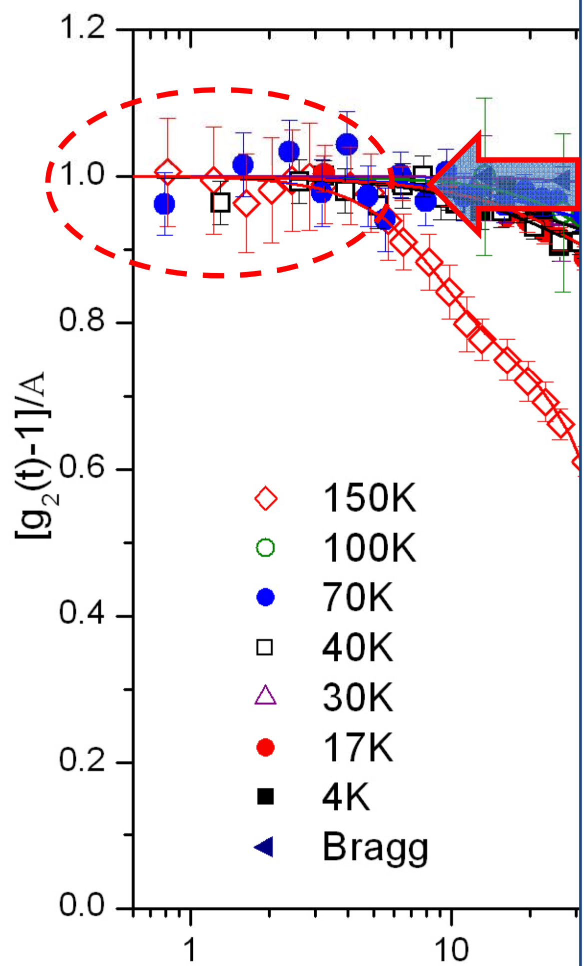






Instead of $\pi/10^{-2}$Å^{-1} ~30 nm, resolution becomes ~6 nm

Enhanced time resolution:



For CDW in Cr we could get reasonable statistics at <1 second, possibly down to ~100 ms

With x30 factor enhancement in brightness (NSLS-II vs. APS), temporal resolution is improved by a factor $x(30)^2=1,000$

Could get into sub-1 ms regime

(in theory – need detectors!)

O. G. Shpyrko et al., *Nature* **447**, 68 (2007)

Other Order Parameters:

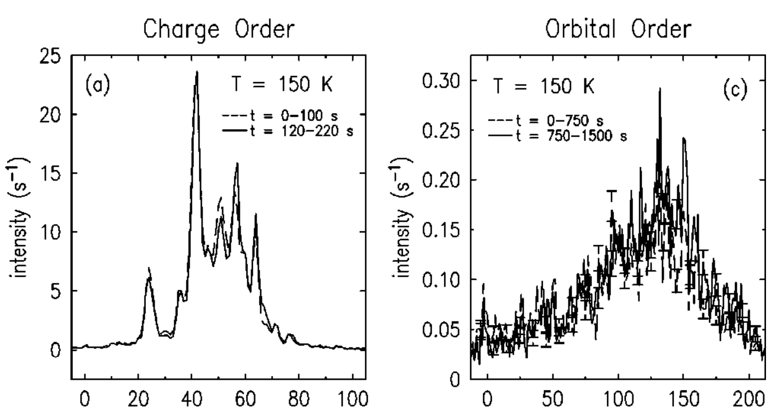
Magnetic (non-resonant) scattering

For Cr SDW satellite at APS ~ 1 ct/sec (coherent flux)

Factor of 30 helps, but realistically need a factor of ~10^3+ (!)

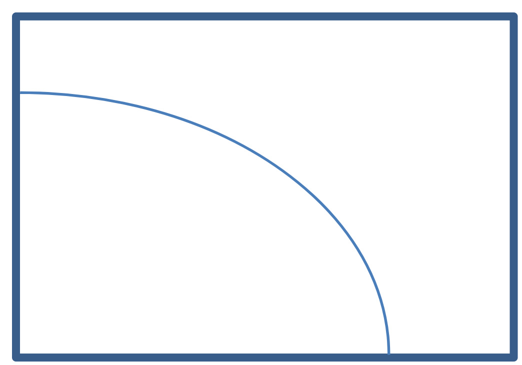
Orbital Order:

$Pr_{0.6}Ca_{0.4}MnO_3$

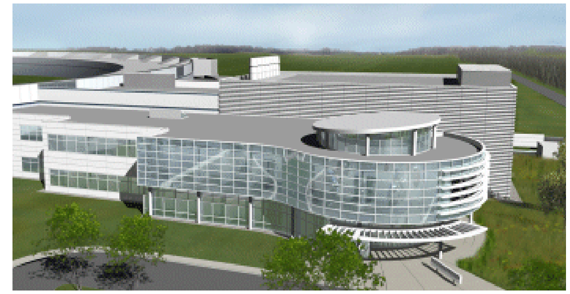


Nelson, Hill et al., PRB **66,** 134412 (2002)

Second Order Phase Transitions:



Chromium Work -
"X-ray Speckle" Collaboration:



Oleg Shpyrko and Prof. Eric Isaacs (Center for Nanoscale Materials, Argonne and Physics Dpt., University of Chicago)

Yejun Feng, Rafael Jaramillo, Jonathan Logan and Clarisse Kim
Prof. Thomas Rosenbaum (University of Chicago)

Paul Zschack, 33-ID
Michael Sprung, 8-ID
Suresh Narayanan, 8-ID
Alec R. Sandy, 8-ID
(Advanced Photon Source, Argonne)

Gabriel Aeppli
(U. College London)