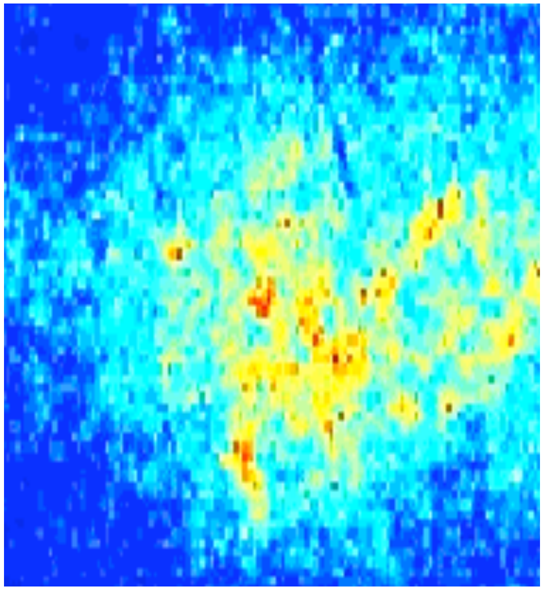
Slow dynamics using coherent x-rays



Eric D. Isaacs
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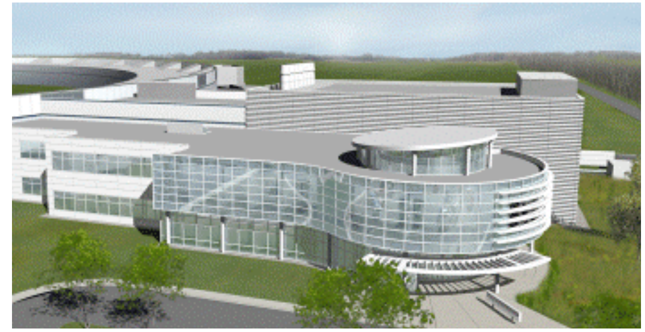
The University of Chicago

Collaborators



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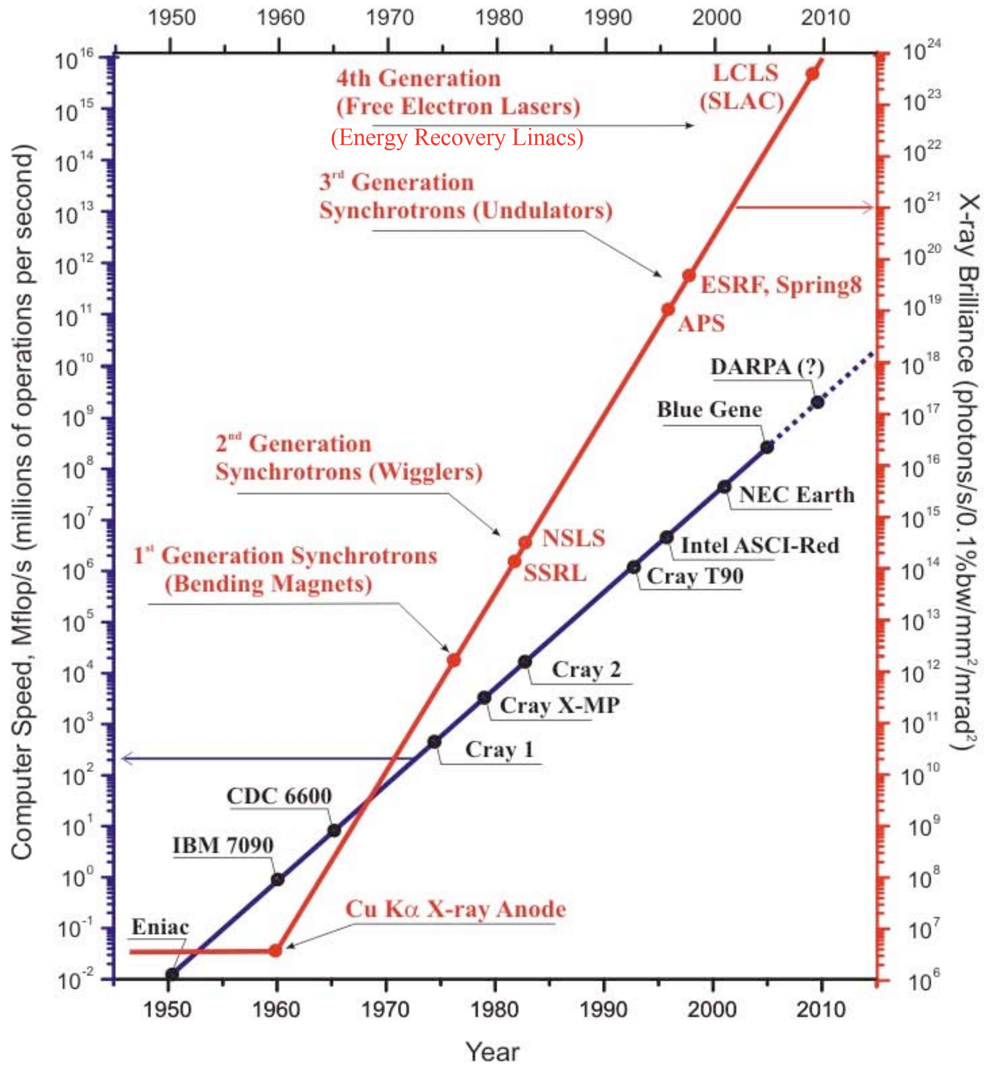
Outline

- Condensed matter physics - texture and multiphase coexistence
- X-ray Photo-correlation spectroscopy - fluctuations of domain walls at the nanoscale
- Wider implications
- What we would really like - spatio-temporal resolution using coherence

Moore's law for X-ray Sources

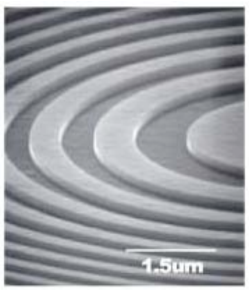
12 orders
of magnitude
In 6 decades



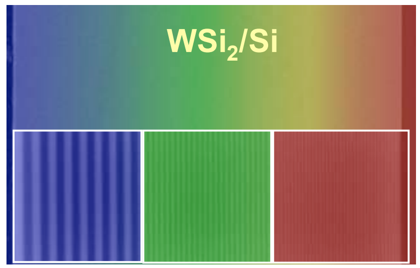
18 orders
of magnitude
In 5 decades!

Developments for Nanoscience

1. Nano-scale focusing - CNM's Hard X-ray Nanoprobe at the APS (Workshop on Thursday - Maser, Stephenson, Streiffer)

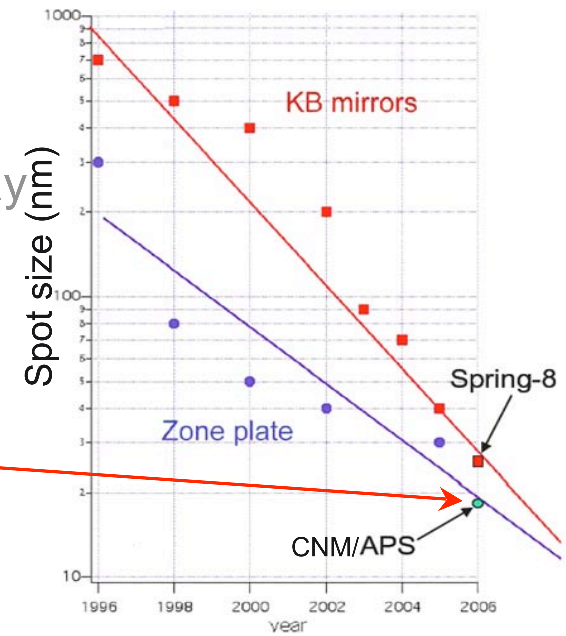


Zone plate



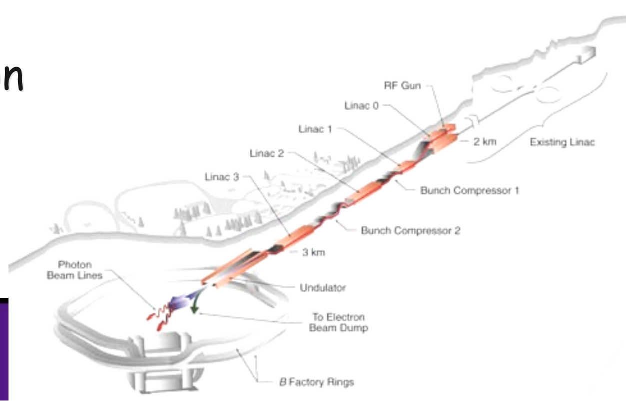
Multi-layer Laue lens

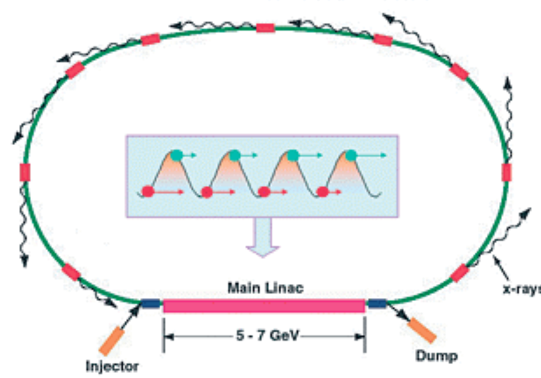
Hard x-ray spot size vs. year



2. Coherence (X-ray "Lasers")
   - Lens-less imaging
   - X-ray photo correlation spectroscopy

X-ray Free Electron Laser at SLAC (opening in 2009)

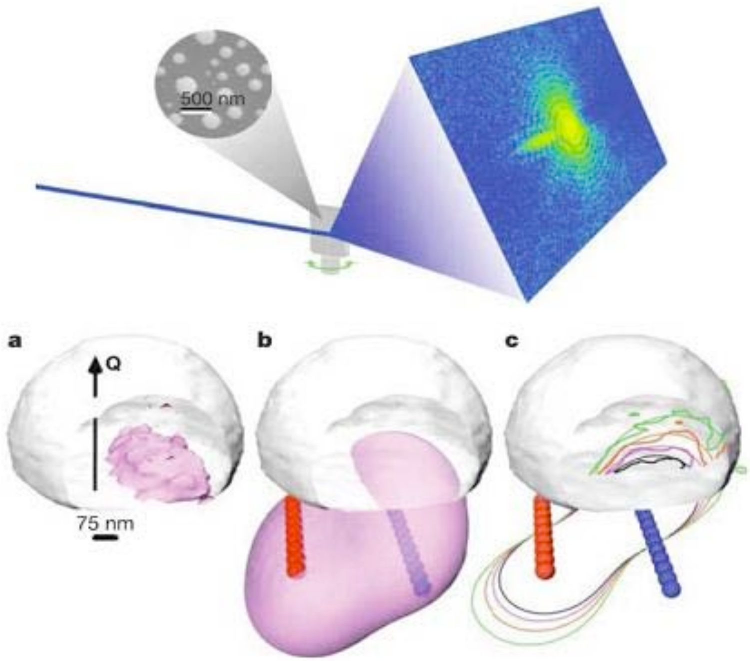




Proposed Energy Recovery Linac at Cornell, Argonne

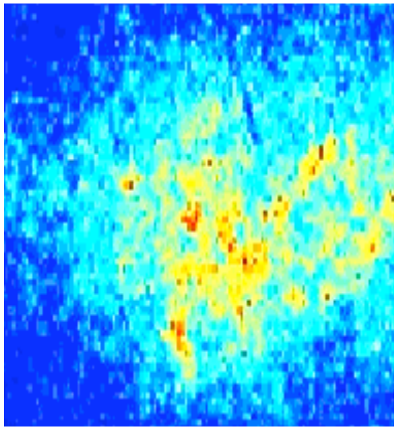
Coherent X-ray Scattering

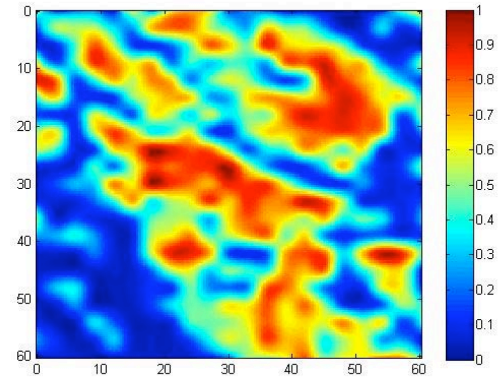
Imaging nanoparticles - long-range order no longer required



M. A. Pfeifer et al., *Nature* **442**, 63-66 (2006).
E.D. Isaacs, News&Views, Nature **442** (2006).

Slow dynamics with high spatial resolution

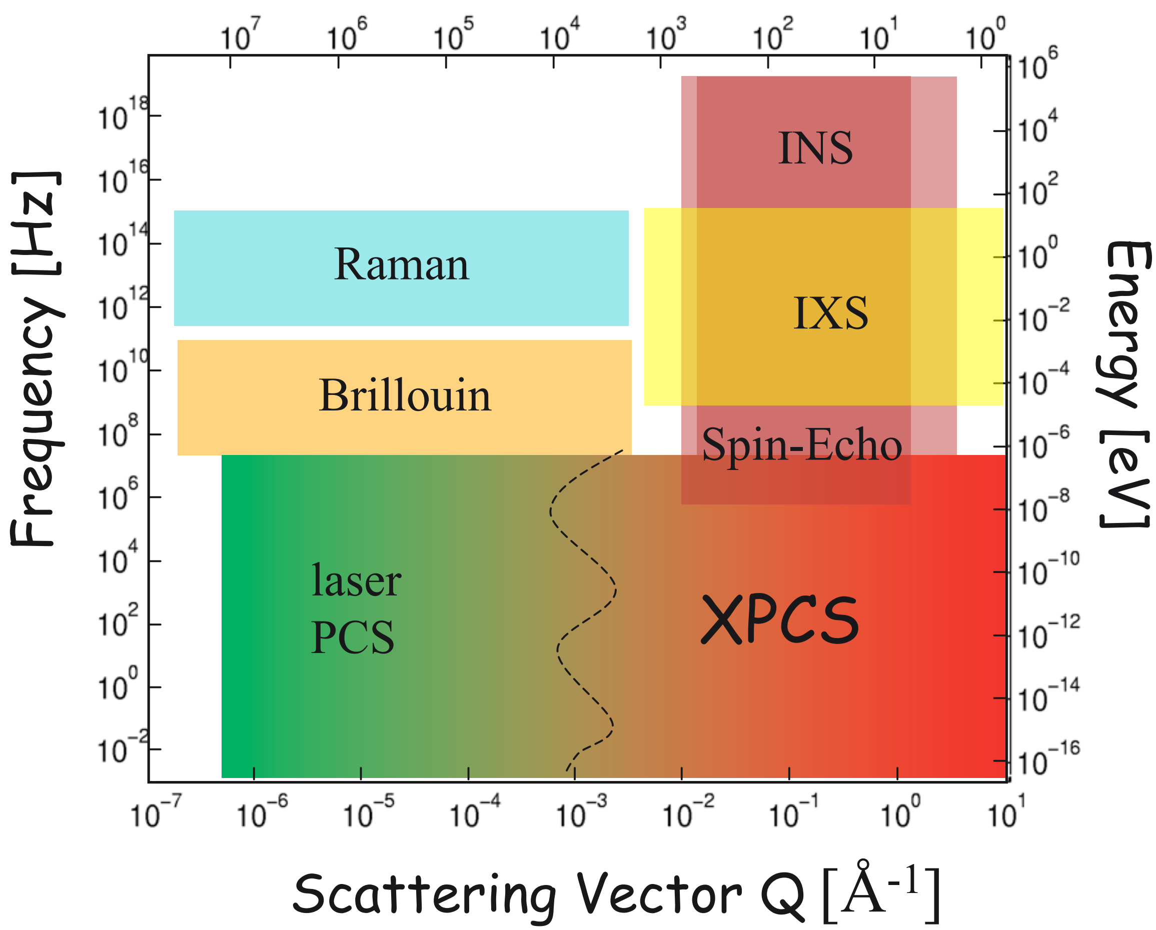




O. Shpyrko, et al *Nature* **447**, 68-71 (2007)

XPCS and other spatio-temporal probes

S(q, ω) map:



Advantages

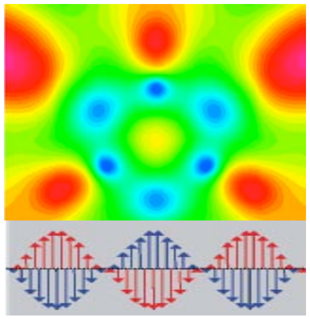
- Shorter lengthscales
- Non-transparent materials
- Charge, Spin, Chemical and atomic structure sensitivity

Disadvantages

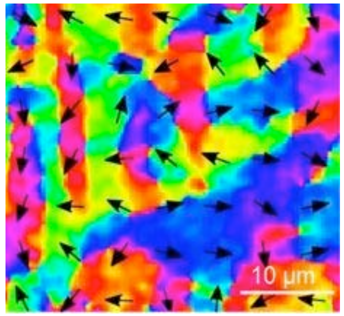
- Need coherent x-ray sources!

Collective dynamics in the presence of quenched disorder

Charge-, Spin-density waves (10^{-10}-10^{-7} m)

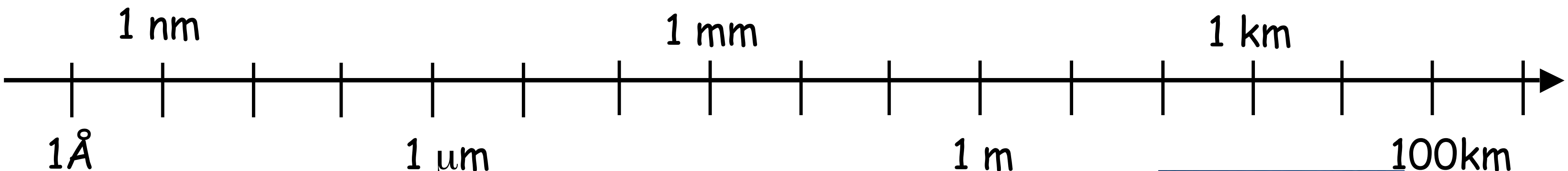


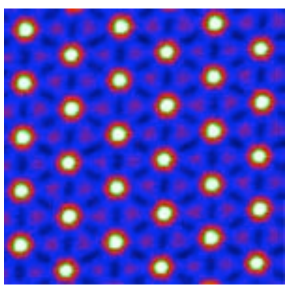
Magnetic domains (10^{-8}-10^{-4} m)



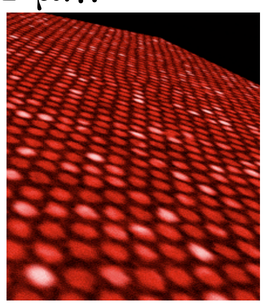
Sandpiles (10^{-3}-10 m)

tectonic plates (10^{2}-10^{6} m)





Abrikosov vortex lattice (10^{-7} m)

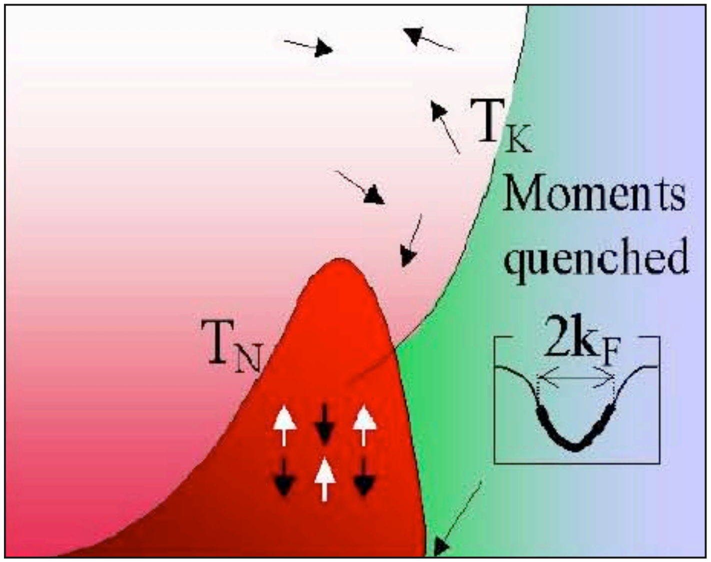


Jamming, shear flow in granular materials, colloids (10^{-7}–10^{-2} m)

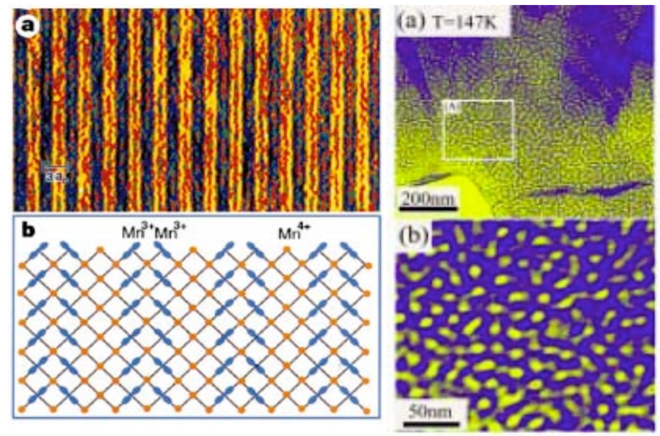
Liquid droplets pinned on rough substrates (10^{-4} – 10^{-2} m)

Avalanches (10-10^{3} m)

Mesoscale Structure in Strongly Interacting Fermi Systems

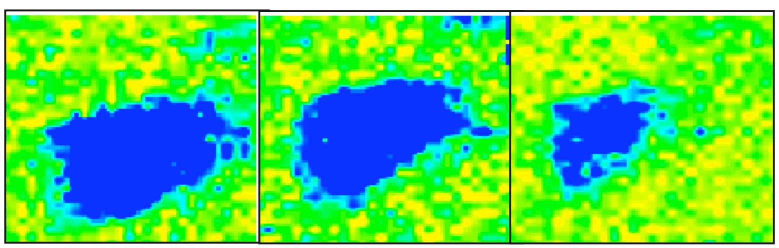


CMR manganites

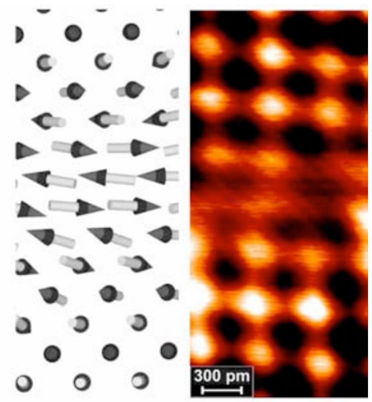


S. Mori et al., *Nature* **392**, 473 (1998)
M. Uehara et al., *Nature* **399**, 560 (1999)

AF chromium



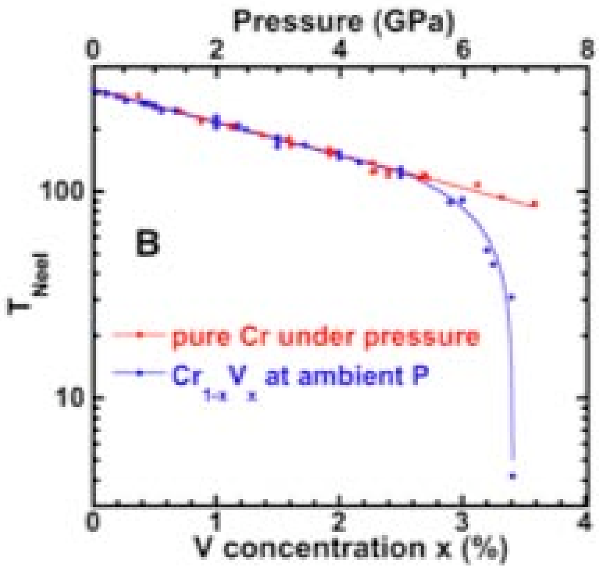
P. G. Evans et al., *Science* (2002)

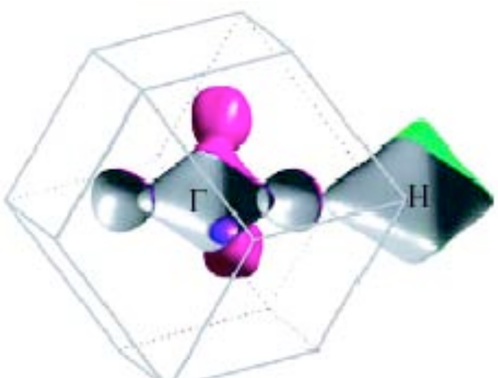


AF iron

M. Bode, et al., *Nature (2006)*

No need to look at complicated material to find complexity





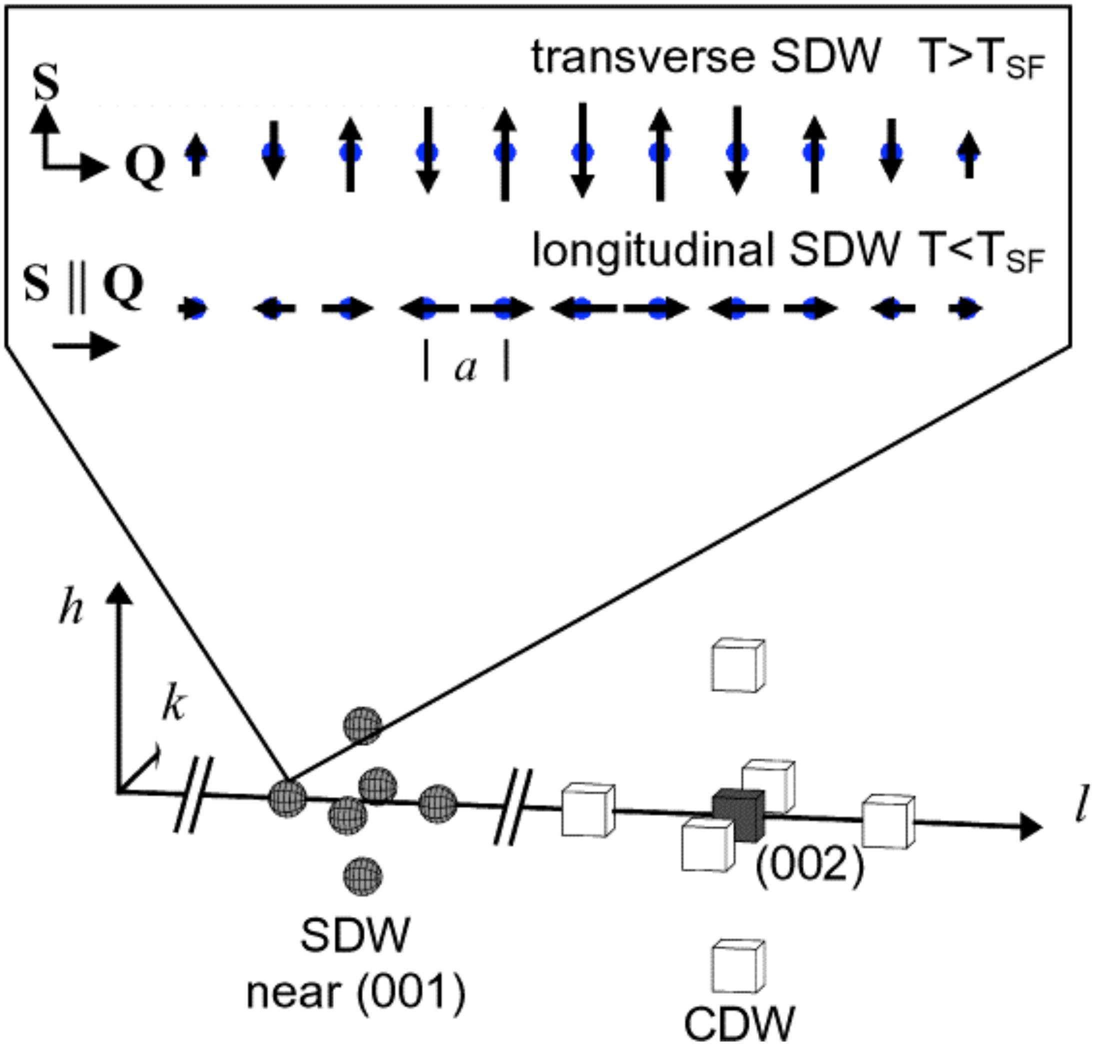
Chromium and its common alloys are ‘simple’ bcc metals, exhibiting complex behaviors including:

• Only elemental material w/SDW.

• Spin-density wave ground state at 311 K due to Fermi-surface nesting.

•Spin-flip transition at 123 K.

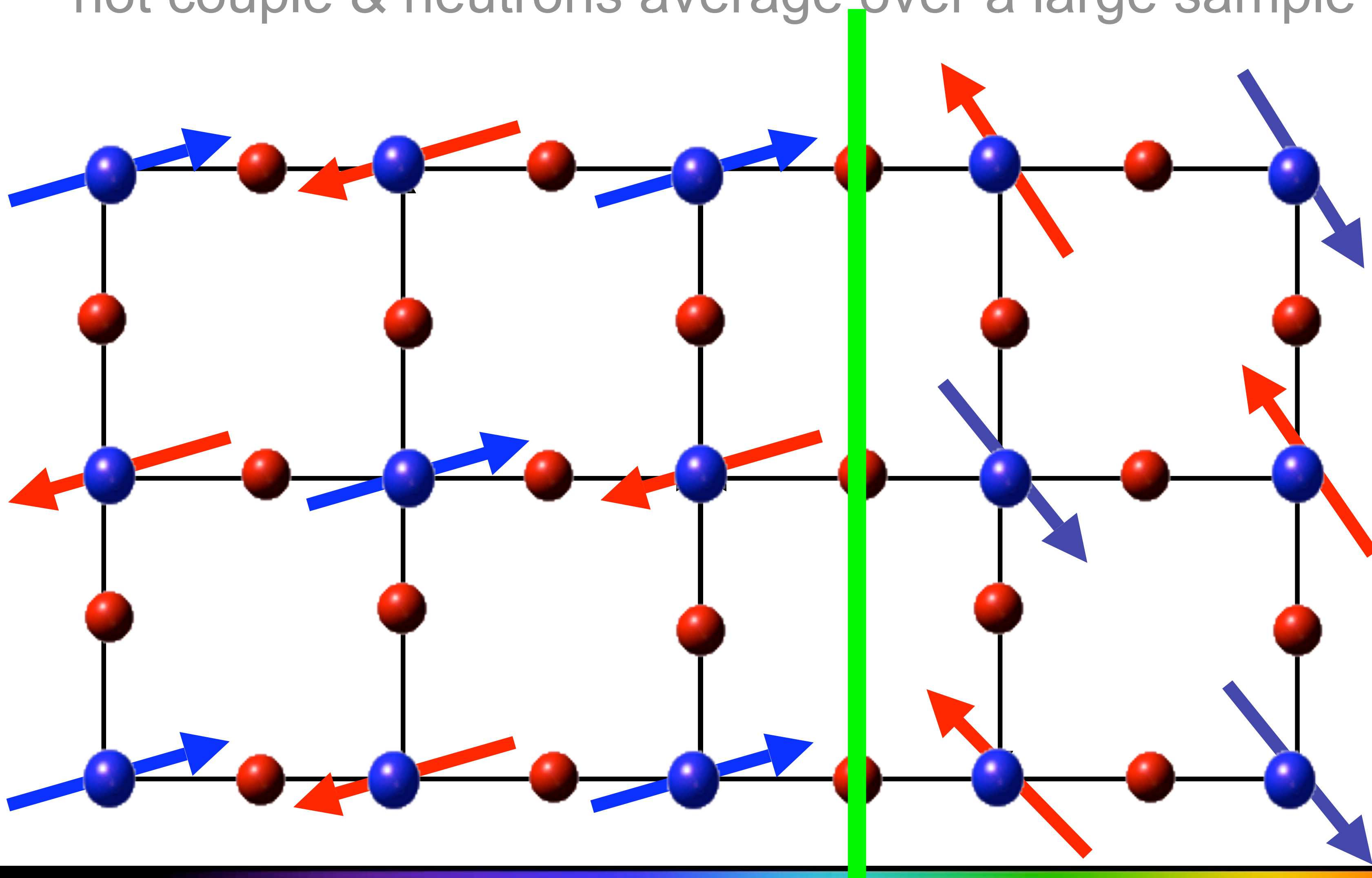
• Quantum critical behavior:
drive T_N to zero by **doping with V** or by **applying pressure**.



transverse SDW T>T$_{SF}$
S
Q
longitudinal SDW T<T$_{SF}$
S || Q
a
h
k
l
(002)
SDW
near (001)
CDW

Texture and multiphase coexistence

For engineering & science, need to image individual domains & walls between them - but visible light does not couple & neutrons average over a large sample

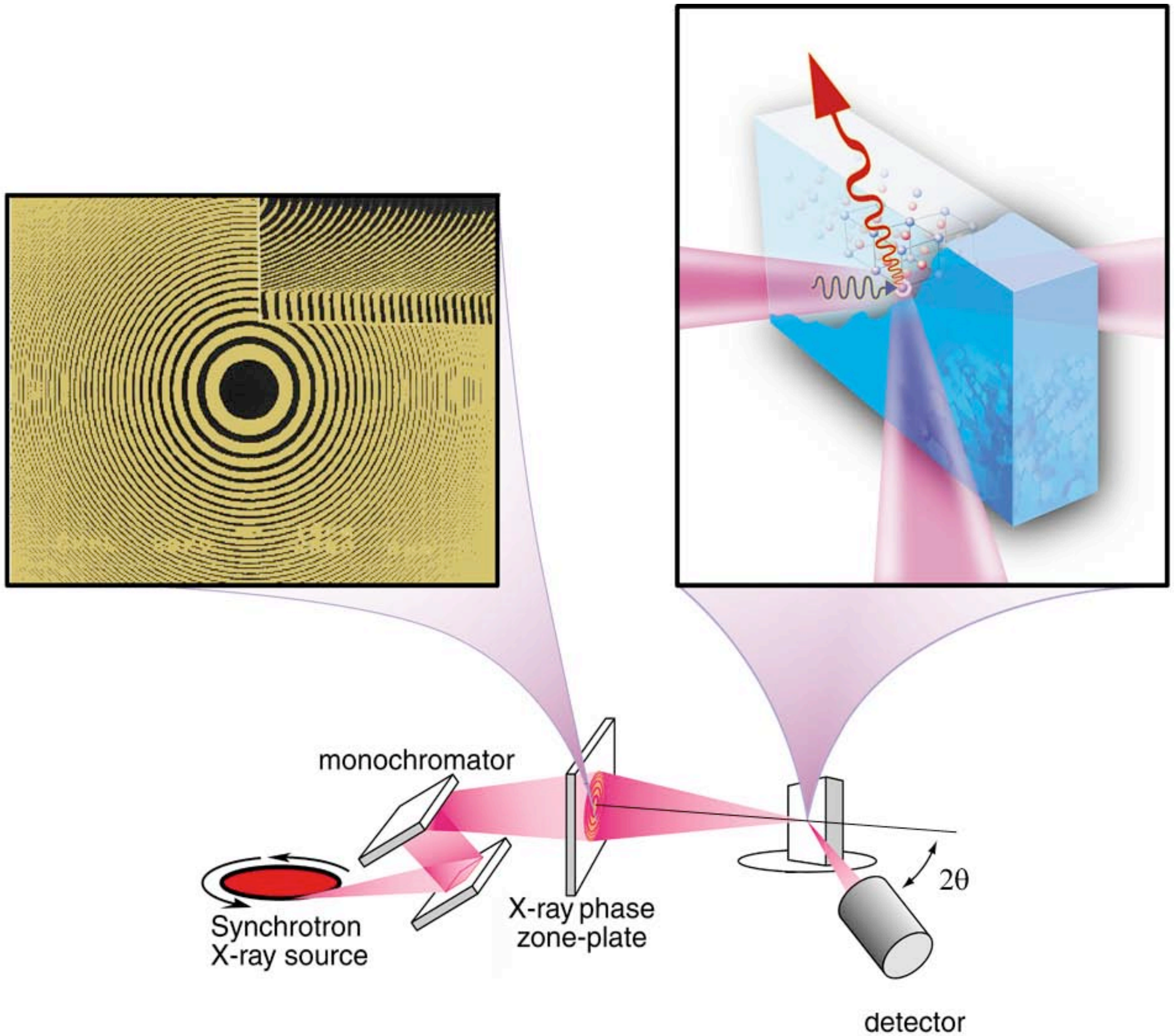


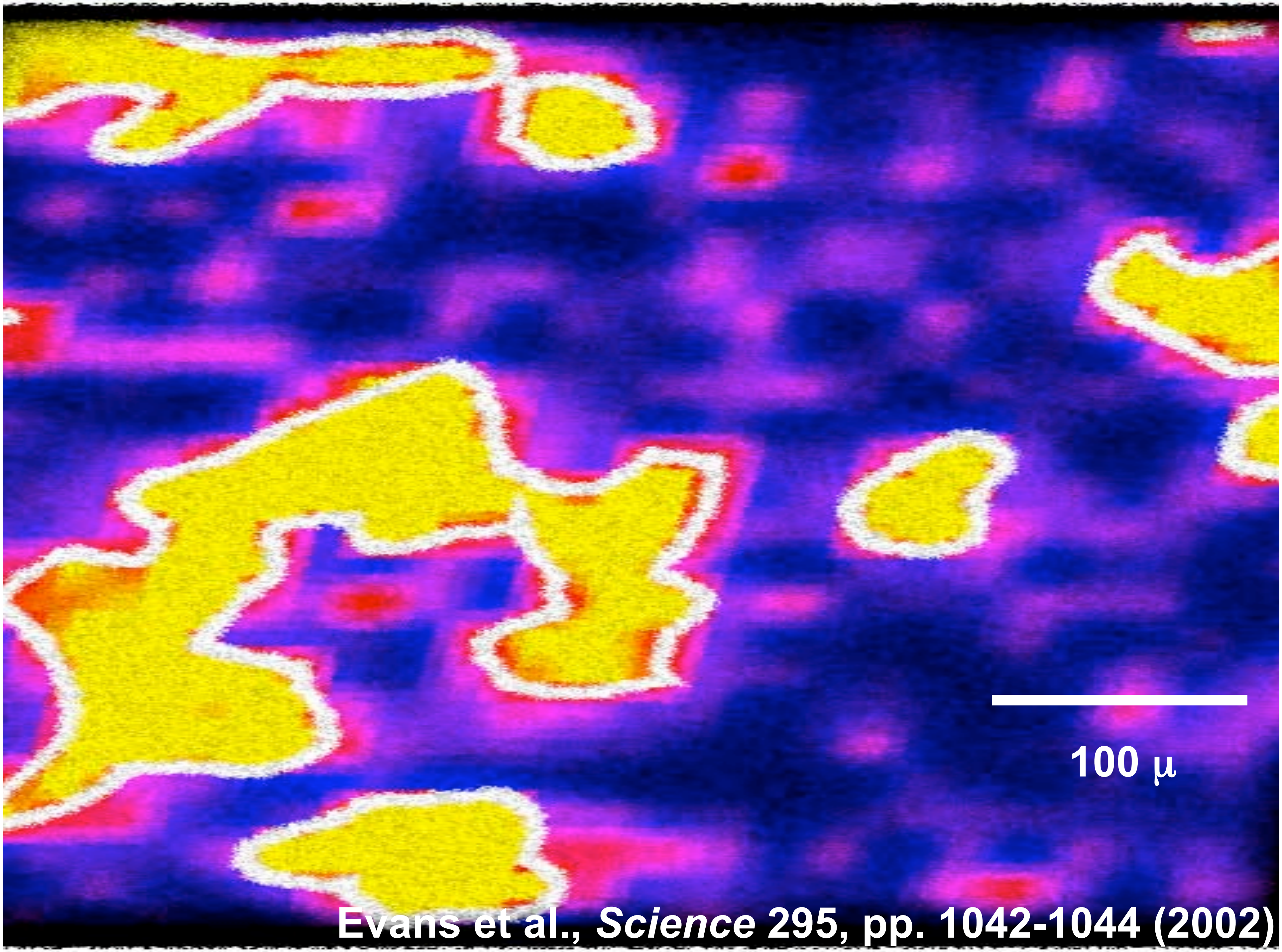
Atomic-scale light - X-rays

outermost zone

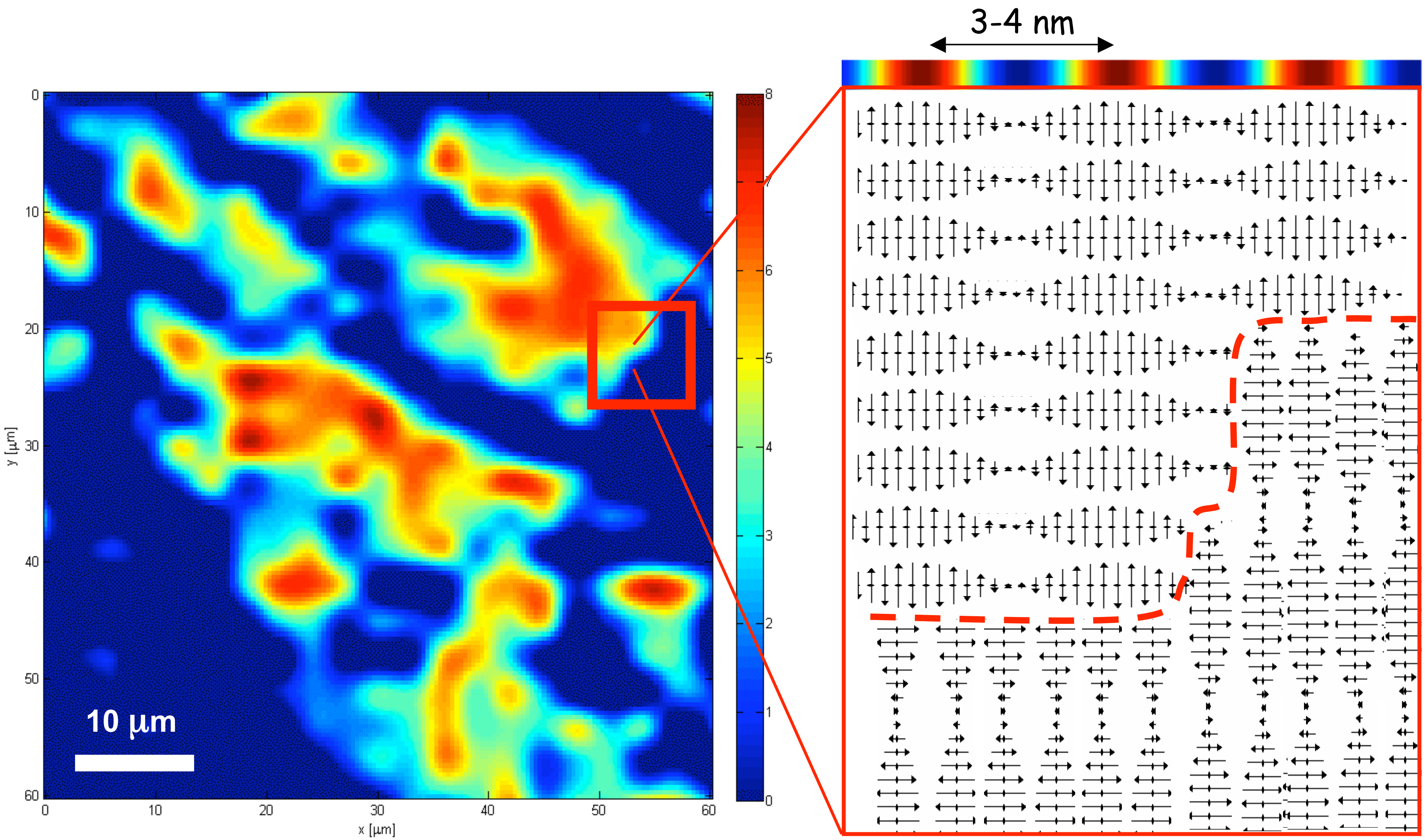
1992 - 0.5 mm

now - 20 nm




100 μ
Evans et al., *Science* 295, pp. 1042-1044 (2002)

Q-domains

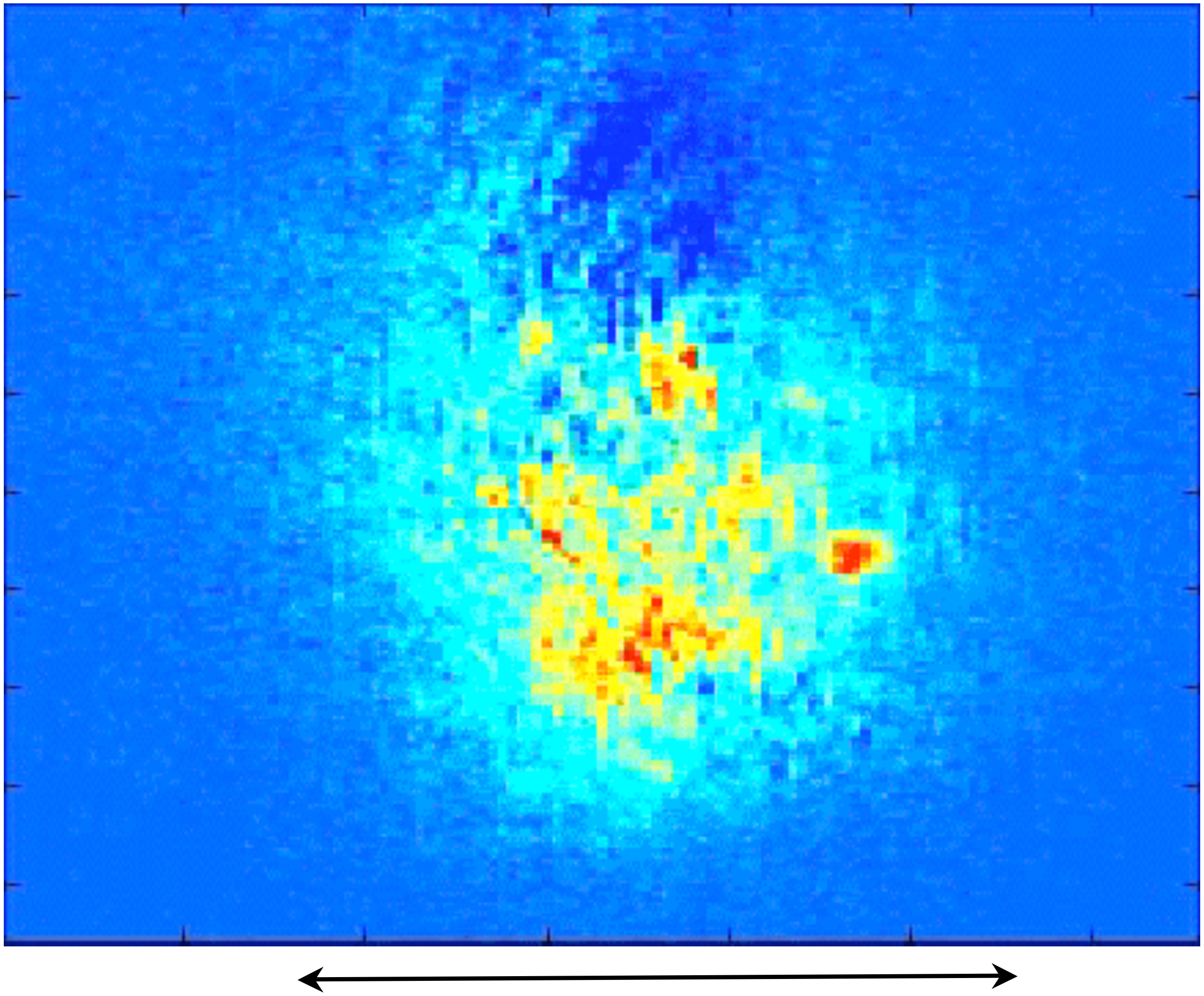


Speckle Pattern and Spatial Resolution

Resolution:
$\sim \pi / \Delta Q$

$\sim 50nm$

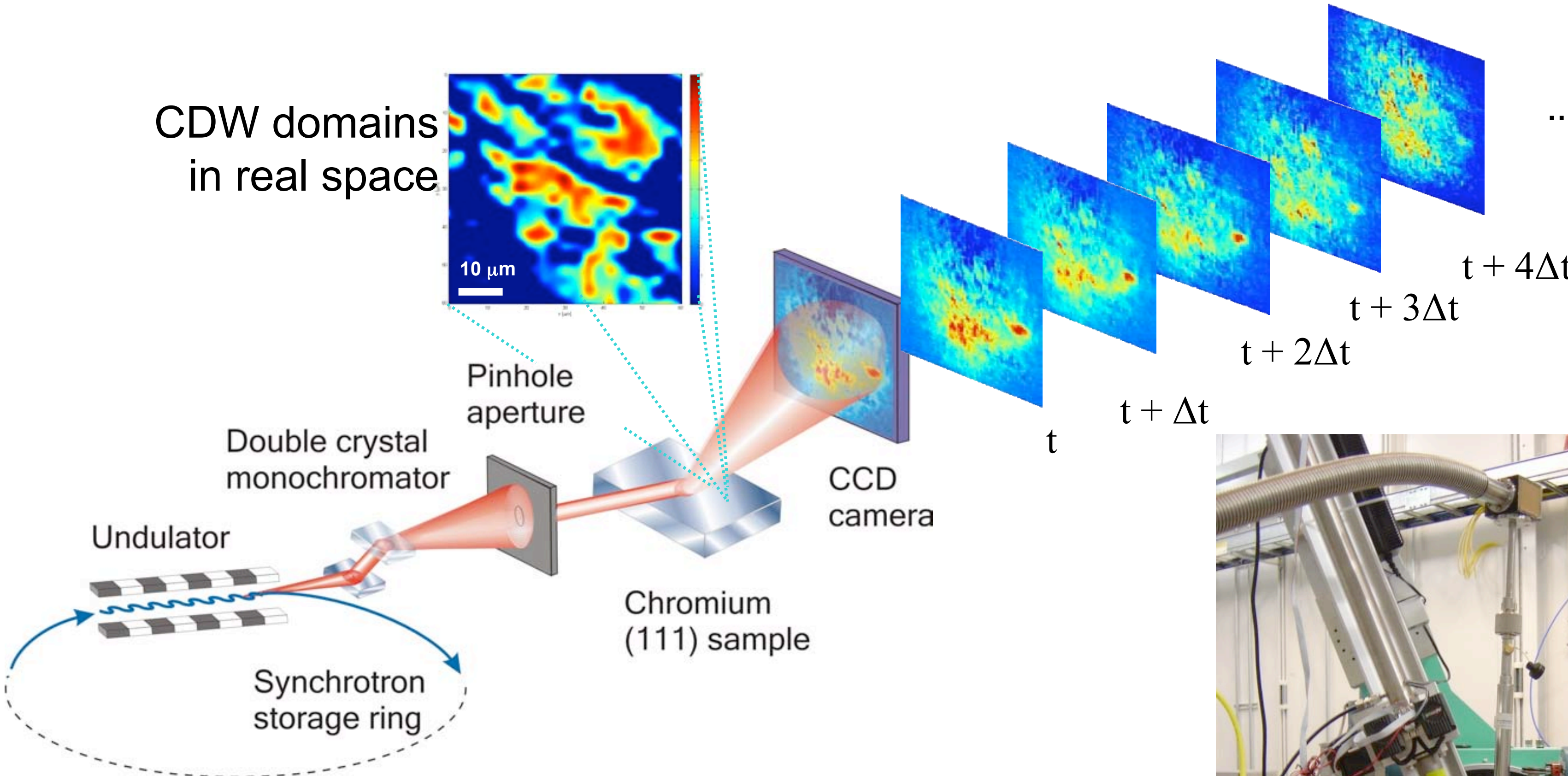
Resolution is coherent flux-limited!

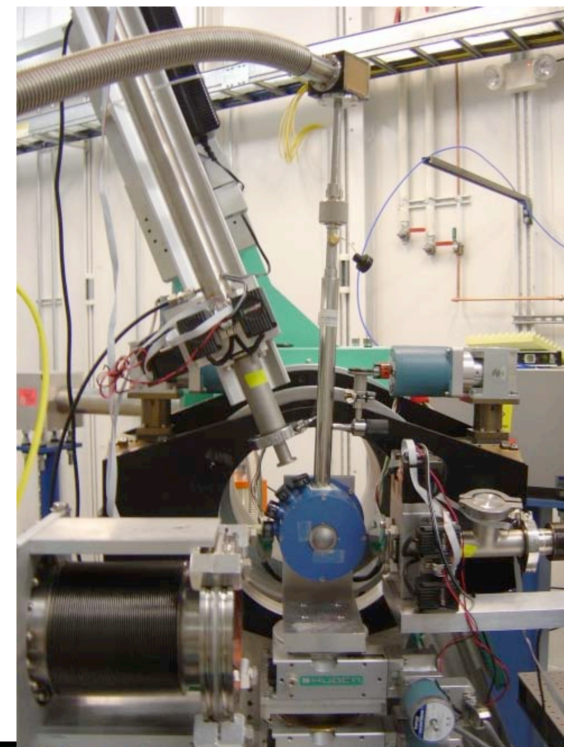


Q (10^{-2} $Å^{-1}$)

CCD image of scattered x-rays

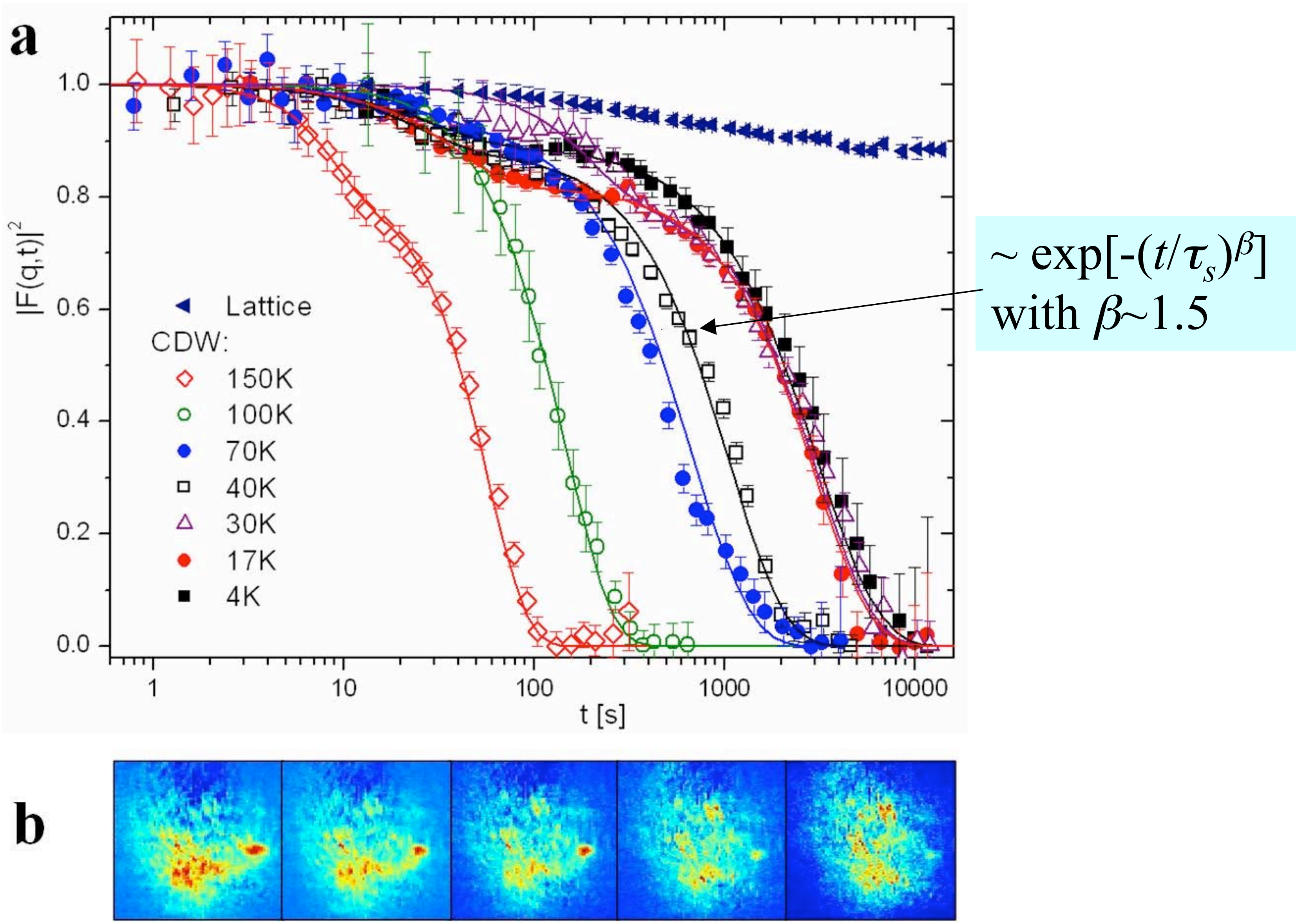
X-ray Photo Correlation Spectroscopy (XPCS)



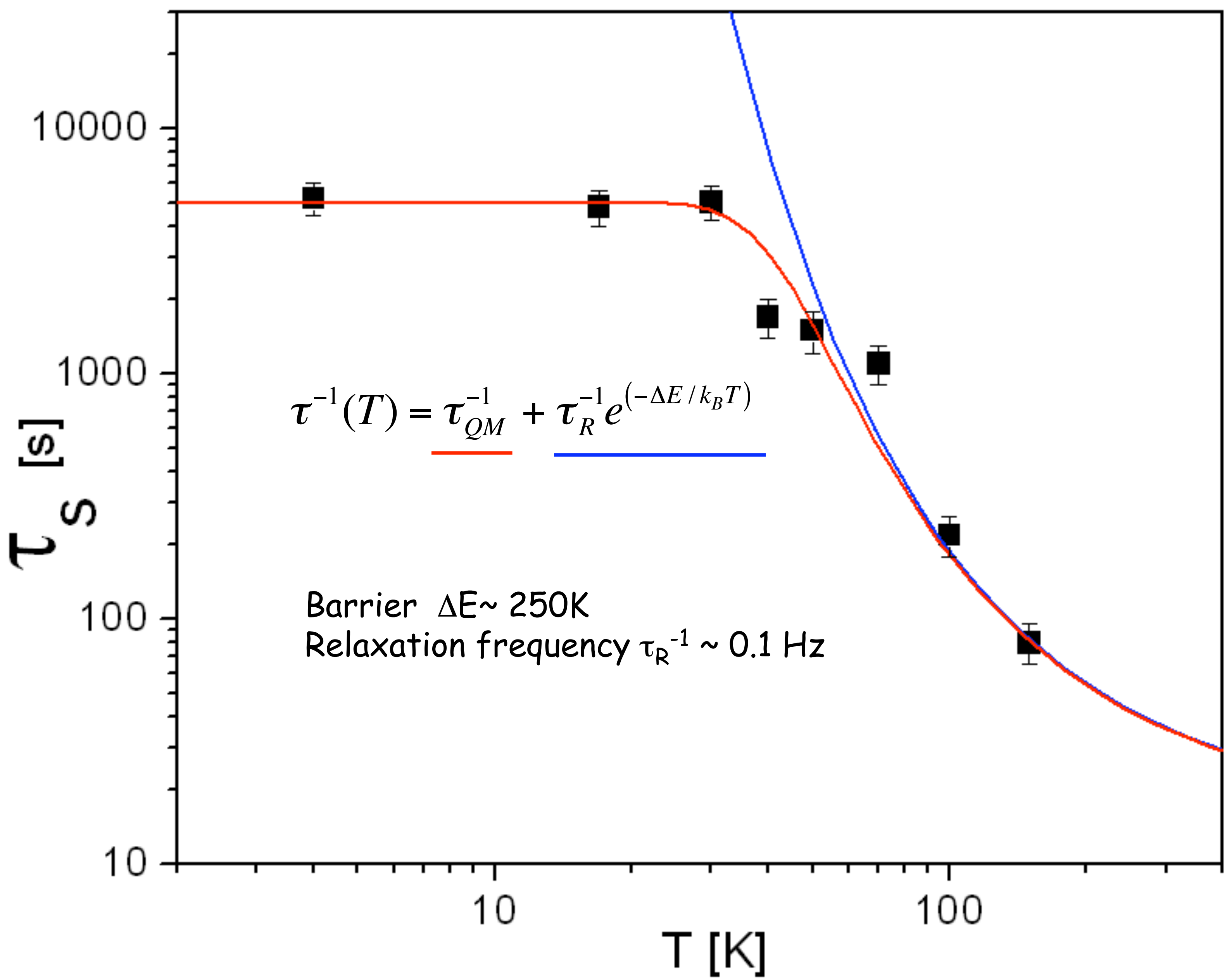


autocorrelation function

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

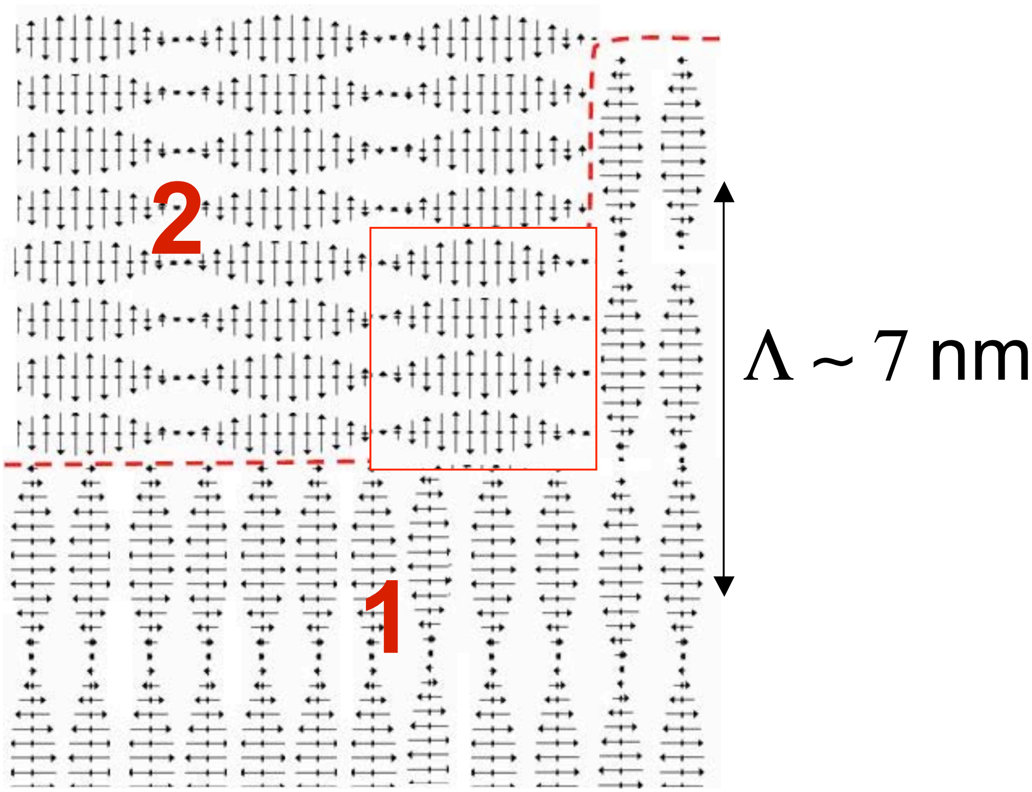


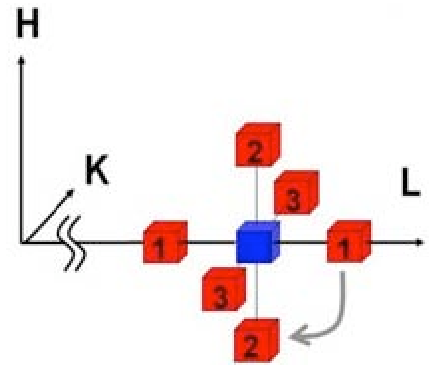
O. Shpyrko et al., Nature, 447, 68 - 71 (2007)

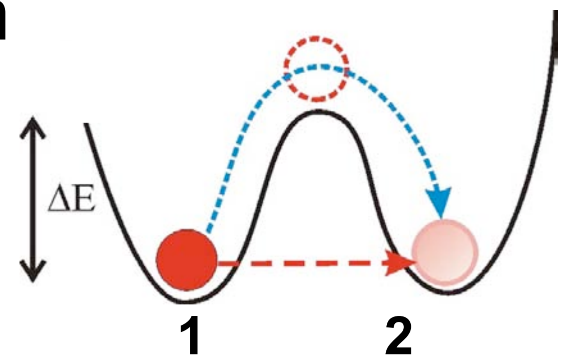


$\tau^{-1}(T) = \tau_{QM}^{-1} + \tau_R^{-1} e^{(-\Delta E / k_B T)}$
Barrier ΔE~ 250K
Relaxation frequency τ_R^{-1} ~ 0.1 Hz
τ_S [s]
T [K]
10000
1000
100
10
10
100

Where could this come from?







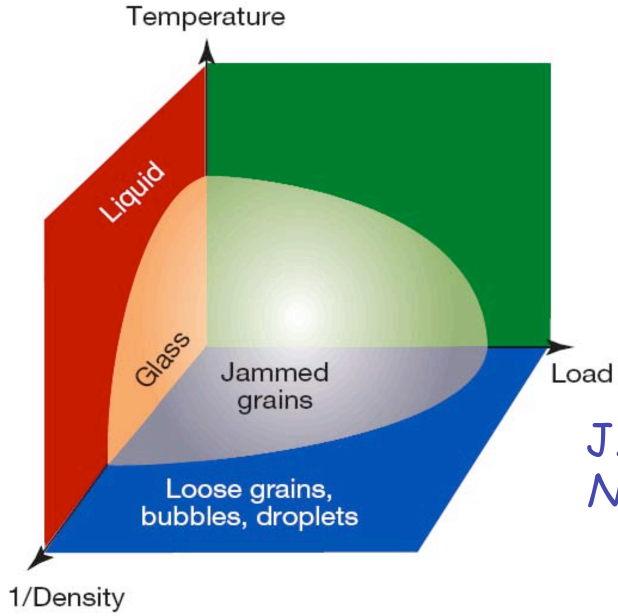
$$\tau^{-1}(T) = \tau_{QM}^{-1} + \tau_R^{-1} e^{(-\Delta E / k_B T)}$$

where ΔE=25 meV

Quantum rotor (WKB):

$\tau_R/\tau_{QT} = exp\text{-}(S/h)$ where $S=(I\ \Delta E)^{1/2}$ is the tunneling action

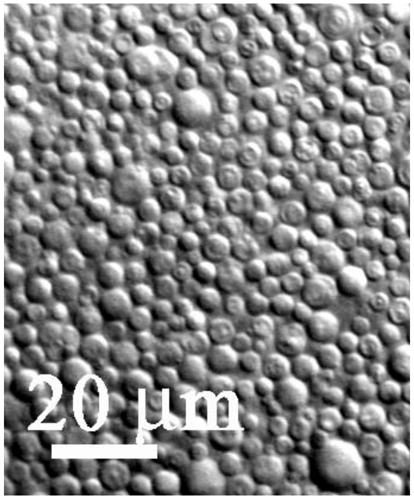
Wider implications…
dynamics in disordered soft materials

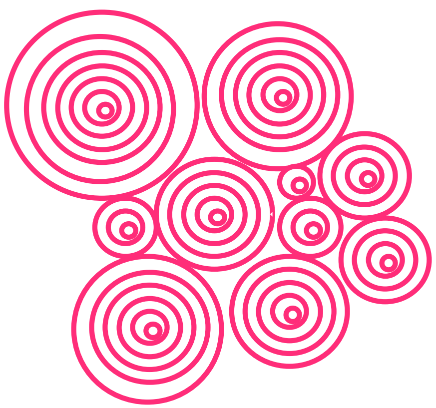


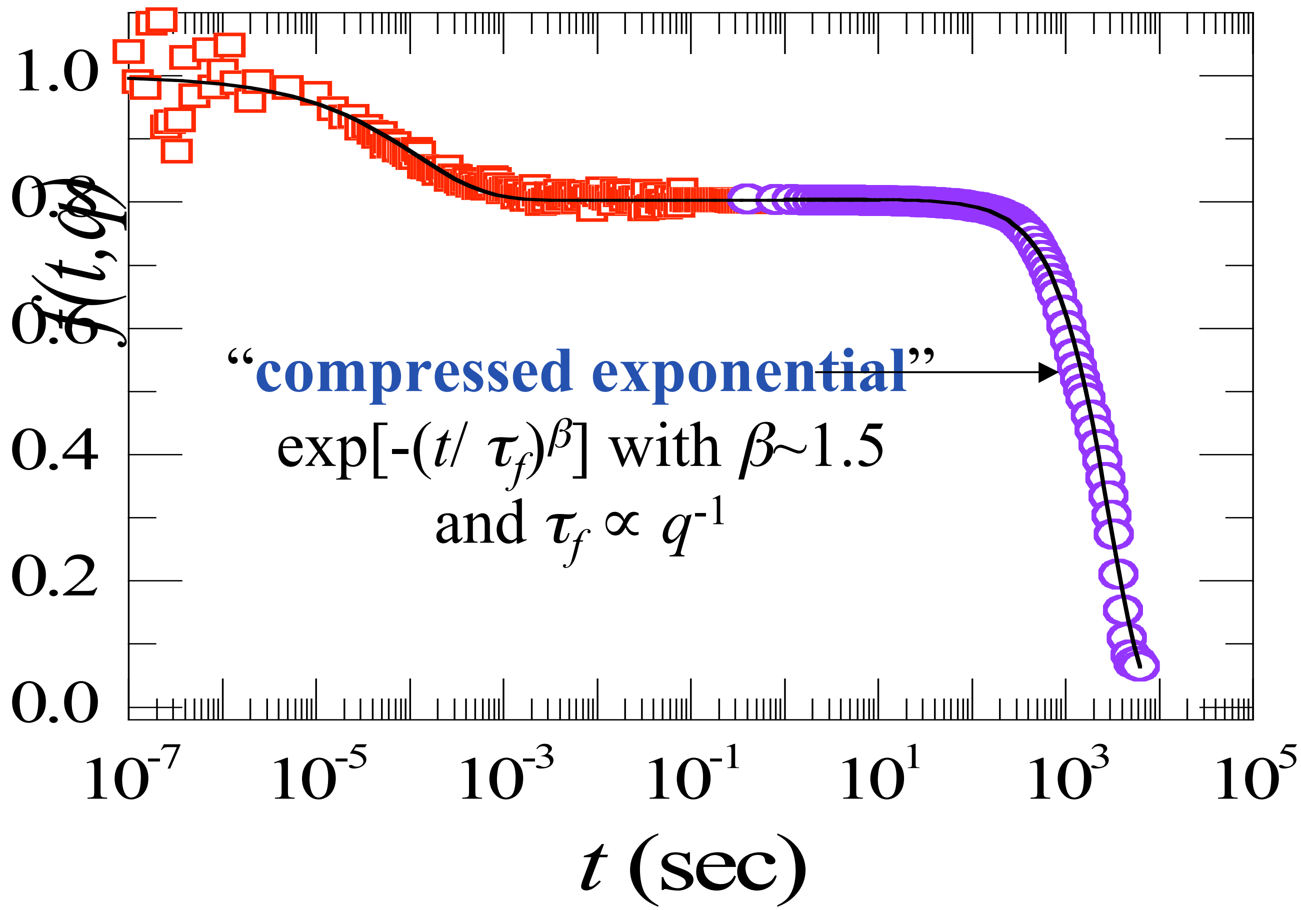
J. Liu and S. Nagel,
Nature **396**, 21 (1998)

Slow Dynamics in Soft matter

Onion gel



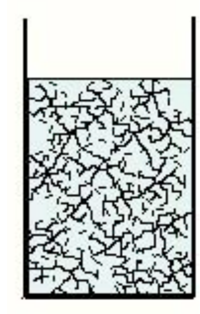




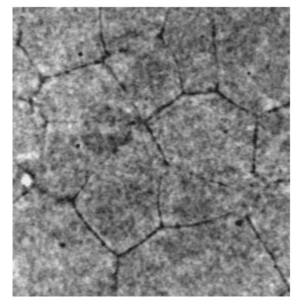
L. Ramos & L. Cipelletti, PRL 2001

Other soft systems undergoing 'jamming' transitions

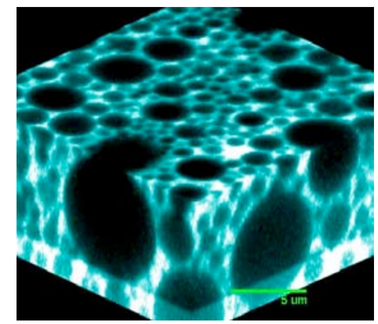
review: Cipelletti *et al.*, Faraday Discuss. **123** (2003)



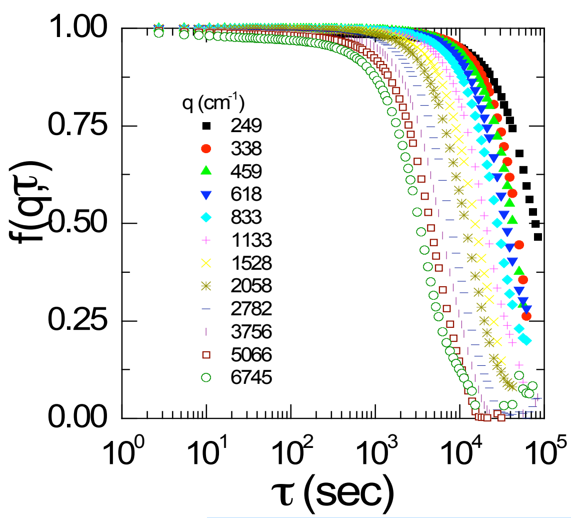
Colloidal particles gel

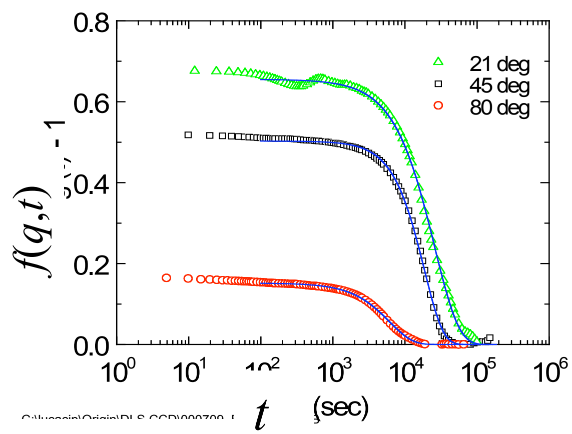


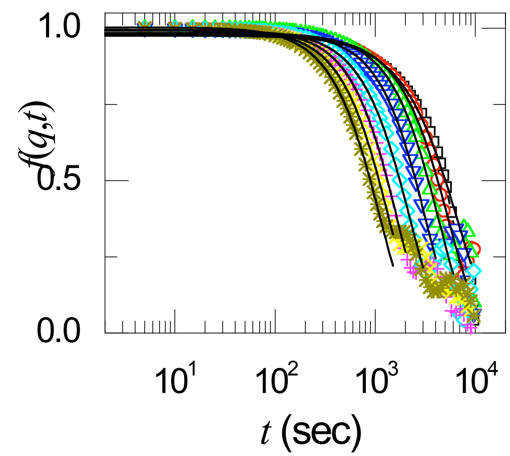
Micellar polycrystal



Conc. Emulsion







$$\mathbf{f}(q,\tau) \propto \exp[-(t/\tau_f)^{3/2}],\ \tau_f \propto q^{-1}$$

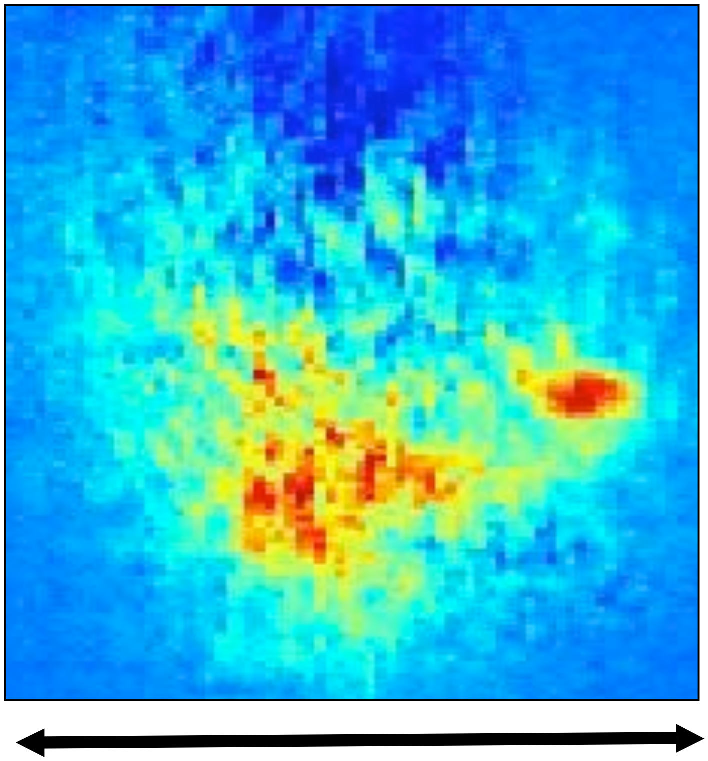
summary

- X-ray photo correlation spectroscopy (XPCS) allows measurement of dynamics of antiferromagnets at tens of nanometers length scales (finite-q).
- Dynamics strongly reminiscent of ‘glassy’ collective behavior in disordered systems seen universally in soft matter, but, …
- … in solid-state system, quantum tunneling provides additional channel for relaxation.
- Beginning of domain wall engineering in antiferromagnets

Speckle Pattern and Spatial Resolution

Spatial resolution: $\sim \pi / \Delta Q \sim 50 nm$

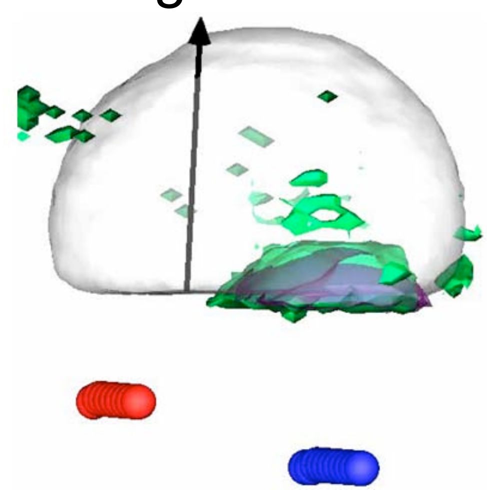
= smallest object that can contribute to speckle



$\Delta Q \sim 10^{-2}$ Å^{-1}

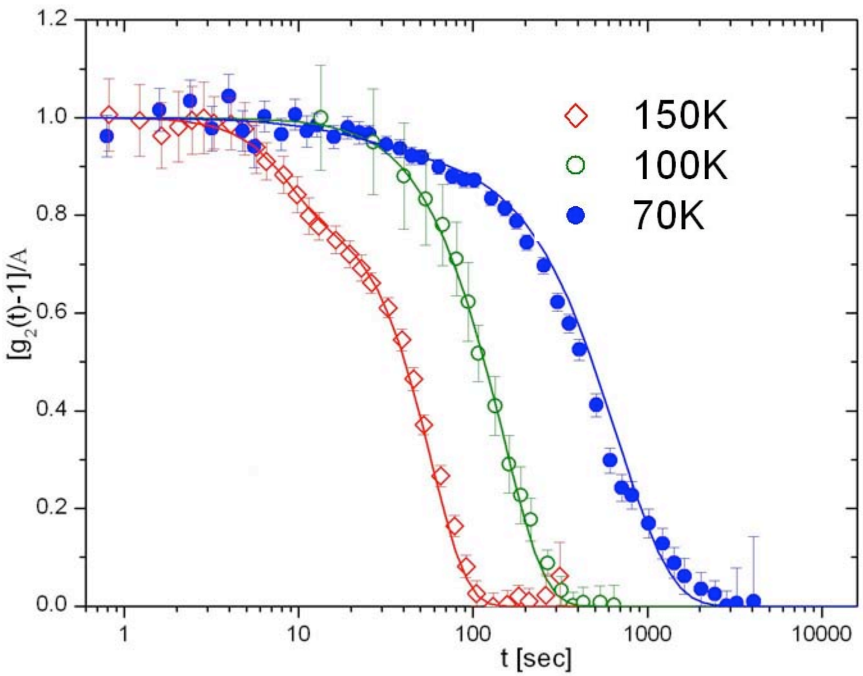
Resolution is coherent flux-limited:
$I_{Bragg} \sim 1/q^2$
Current resolution: ~ 50 nm
⇒ we need factor of 100 in coherent flux to achieve 5 nm.

Can we image disorder directly?



M. A. Pfeifer et al., *Nature* **442**, 63-66 (2006).

Autocorrelation Function and Temporal Resolution

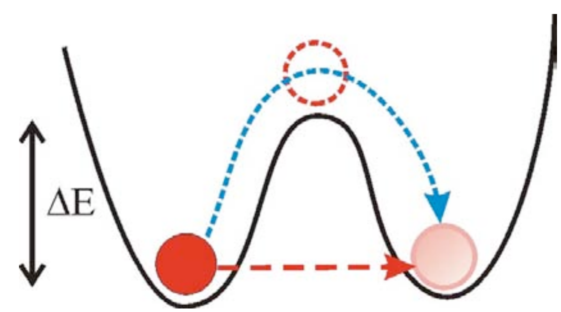


Resolution is coherent flux-limited:
$g_2(t)$ ~ intensity-intensity correlations

Statistics:
5% error bars ⇔ 1 second resolution

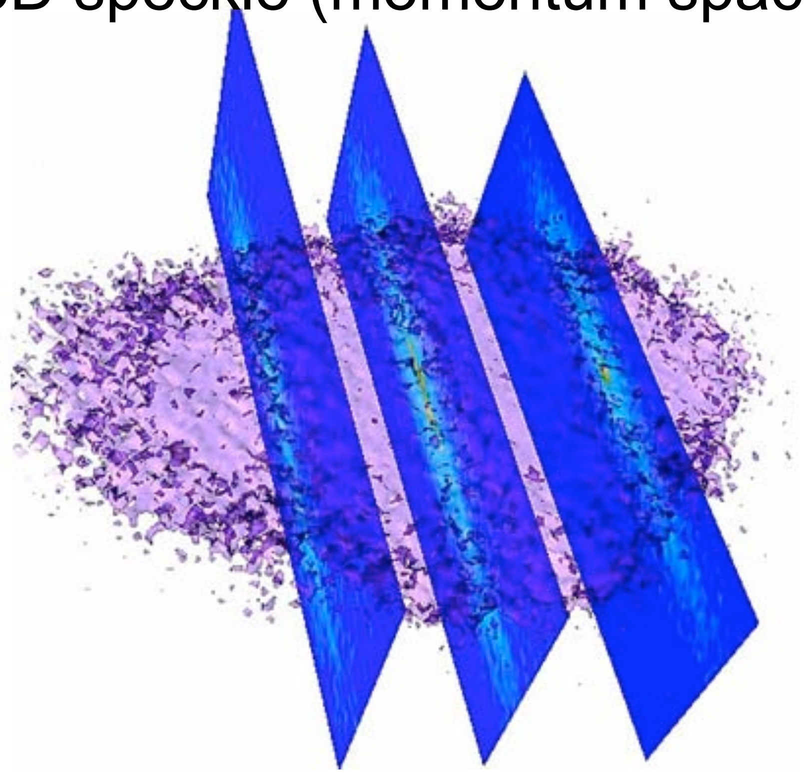
⇒ we need factor of 100 in coherent flux to achieve msec resolution.
⇒ **spatial + temporal: need 10,000 x**

Can we image quantum tunneling directly?



Coherent (lens-less) X-ray Imaging

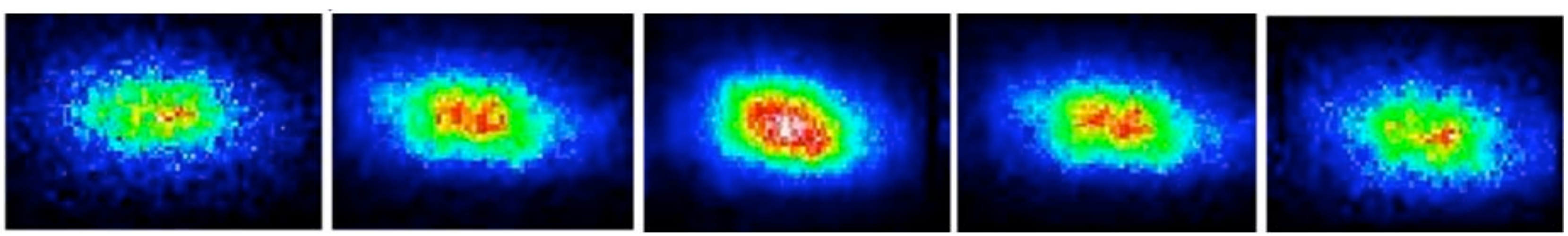
3D speckle (momentum space):



Can we invert speckle of embedded, irregular structures to obtain 3D real-space images? (ptychography)

1. Reveal internal CDW phase information (topological defects, phase strain) with ~ 50 nm resolution currently

2. 3D movies of nanoscale fluctuations (FEL, ERL)

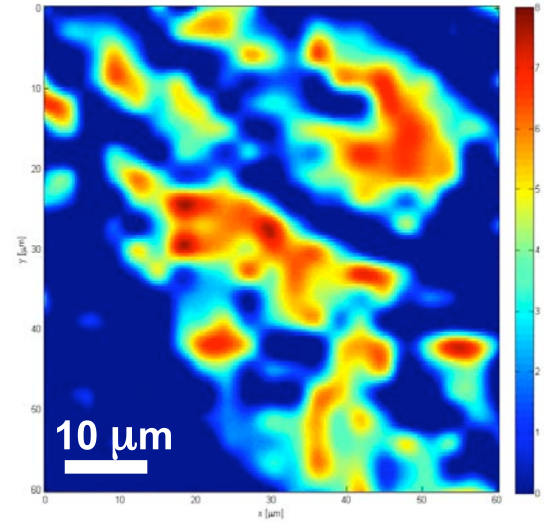


O. G. Shpyrko et al., in preparation (2006)

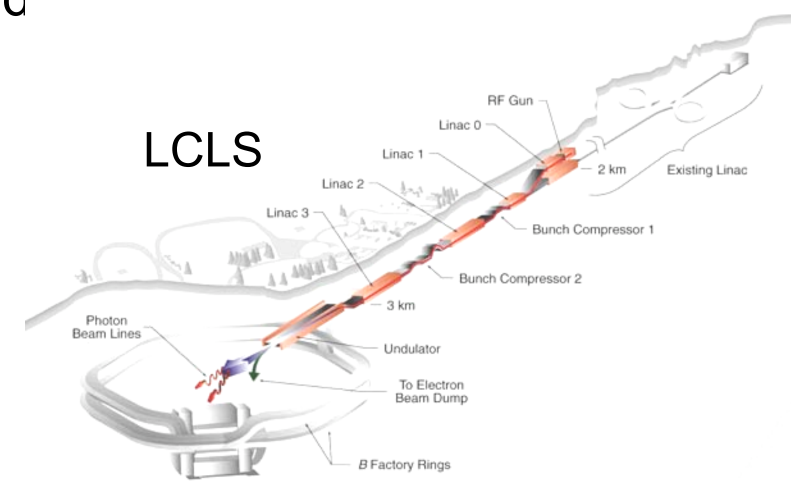
Conclusions

- Coherence may transform our ability to use x-rays for,
  - Imaging (Nanoprobe, coherent diffraction - lensless imaging of non-periodic structures)
  - Dynamics
- Many interesting problems in strongly correlated Fermi systems, soft materials, phase transitions (eg., jamming)…
  - Many of these are embedded structures
- Dedicated beamline at APS would important start
- Detectors, too!
- Future: FEL, ERL

Slow dynamics

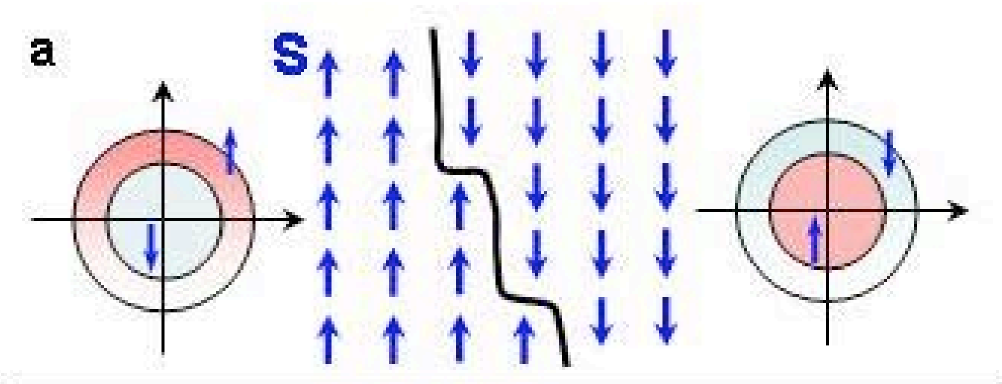


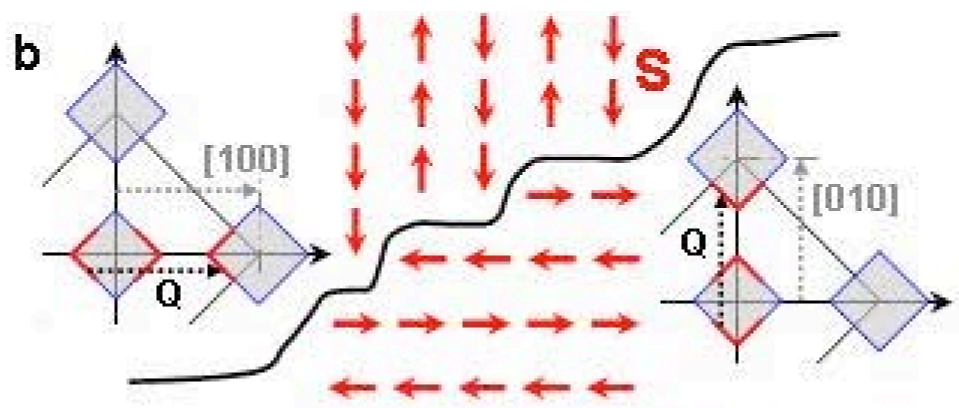
LCLS



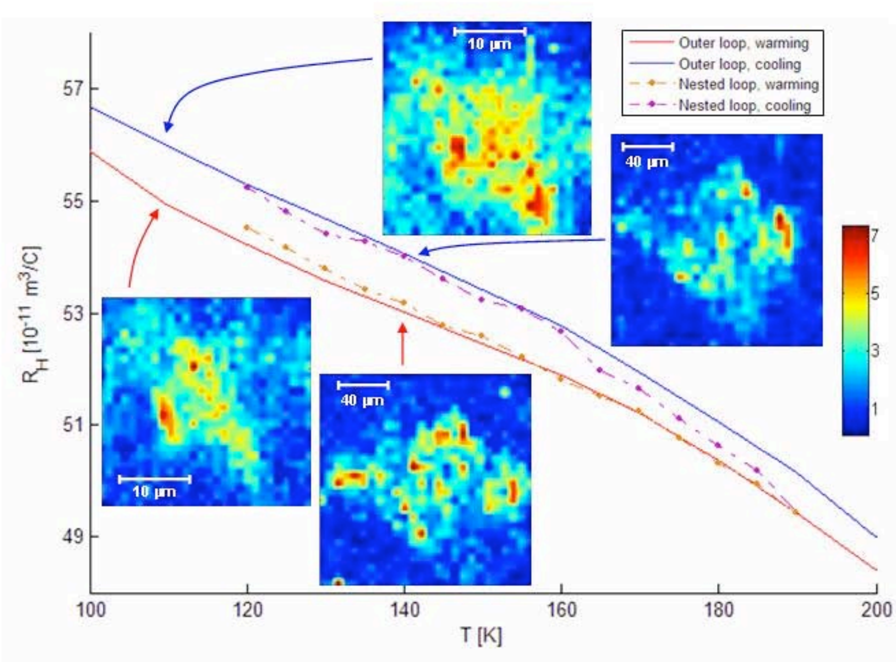
Wider implications…

domain wall resistivity


a
S


b
S
[100]
Q
[010]
Q

Preliminary estimate of domain wall resistivity



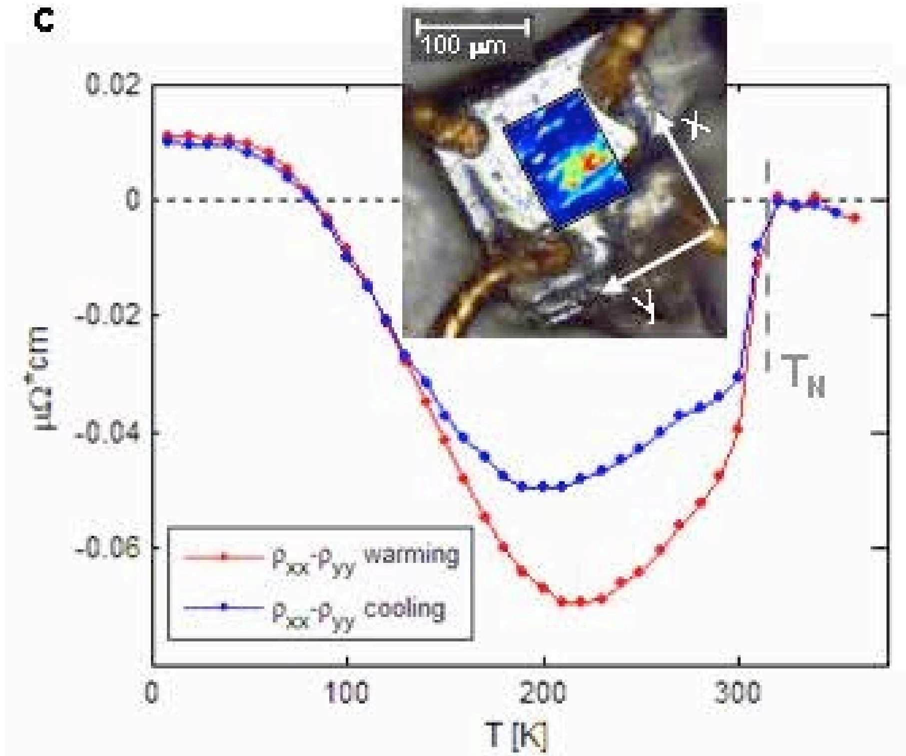
Hysteresis loop size at 100K ~ 50 nanoOhm-cm.

Typical scale of domain wall length change ~ 50% of 10 micron.

Therefore,

resistance of typical wall = 2 X 50 nanoOhm-cm X 10 micron/Area

= 10^{-4} microOhm-cm^2/Area



Resistivity 300K - 11.7 μΩ-cm

10K - 0.24 μΩ-cm

195x180X45 μm^3