First Experiments at CSX

Upgrades are in the air . . .

Earthquakes and intermittency

Hidden domain symmetries and Barkhausen cascades

Thermally-driven magnetic intermittency near an SRT

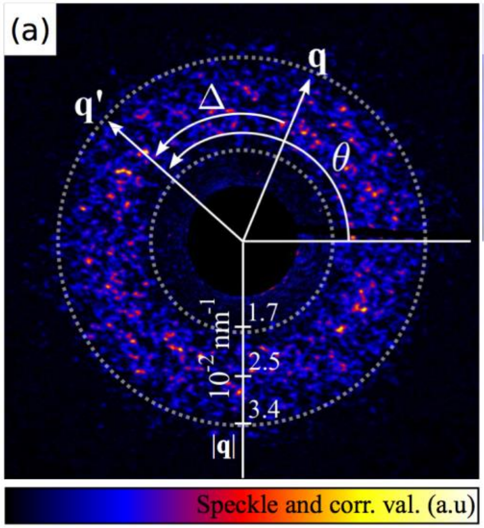
Plans for the future

Steve Kevan

Division Deputy for Science
Advanced Light Source
Lawrence Berkeley National Lab

Professor of Physics
University of Oregon
Eugene, OR.

‘Hidden’ Symmetries in Magnetic Domains

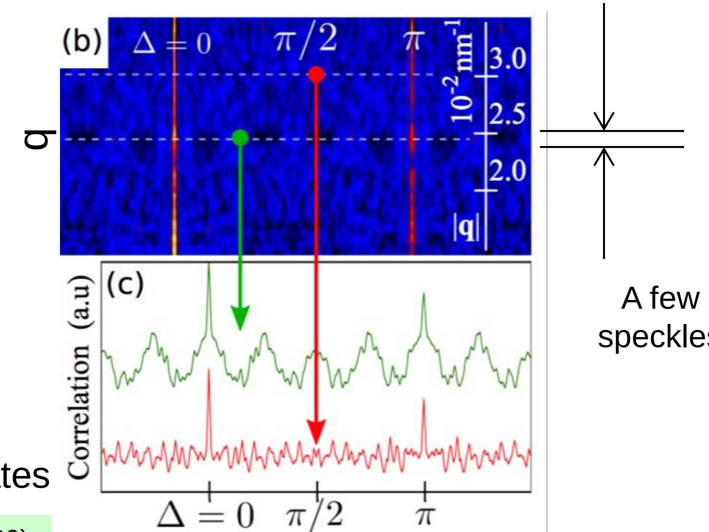


$$ACF(q,\Delta)=\frac{\sum I(q,q+\Delta)\,I(q,q)}{\sum\left[I(q,q)\right]^2}$$

Rotational Autocorrelation function

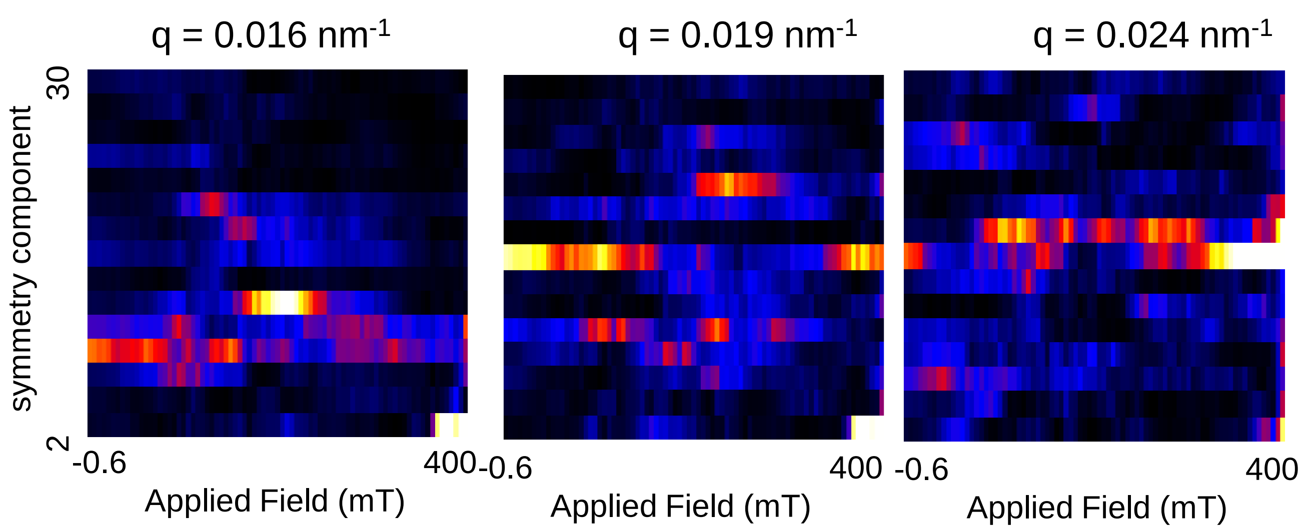
-- in polar coordinates

Wochner, et. al., PNAS 108, 11511 (2009).

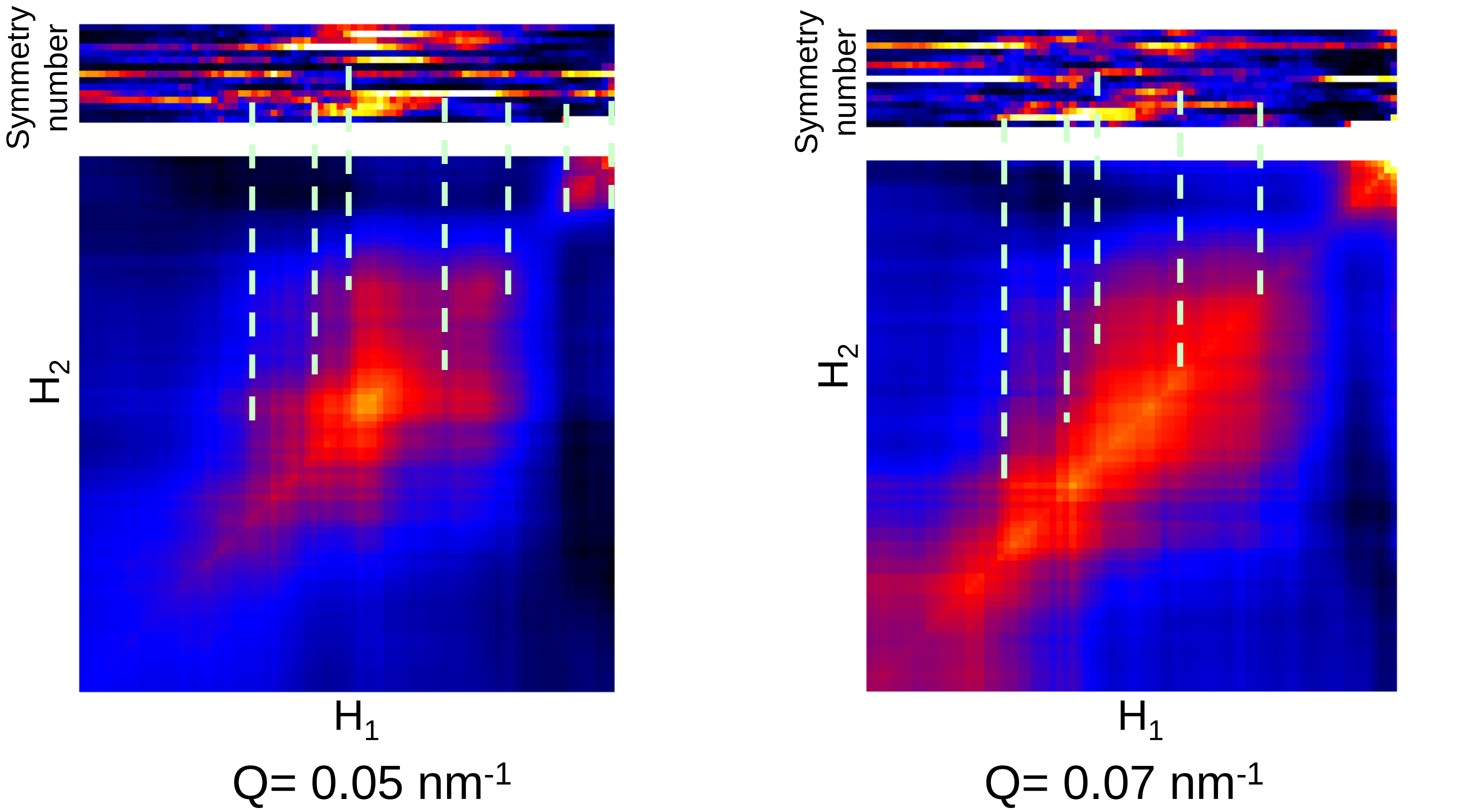


R. Su, et. al., PRL **107**, 257204 (2011)

Are these hidden symmetries related to intermittency and Barkhausen events?

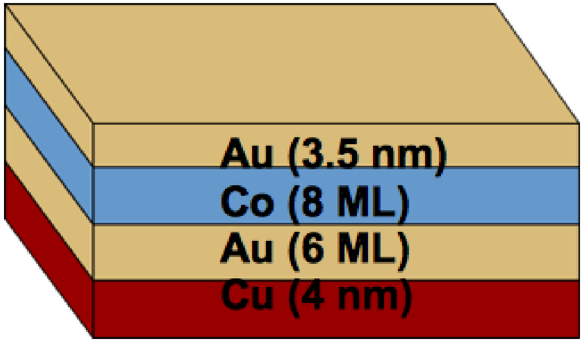


Correlations between Correlation Functions



Is there a relationship between symmetry number and the field increment of a Barkhausen cascade?

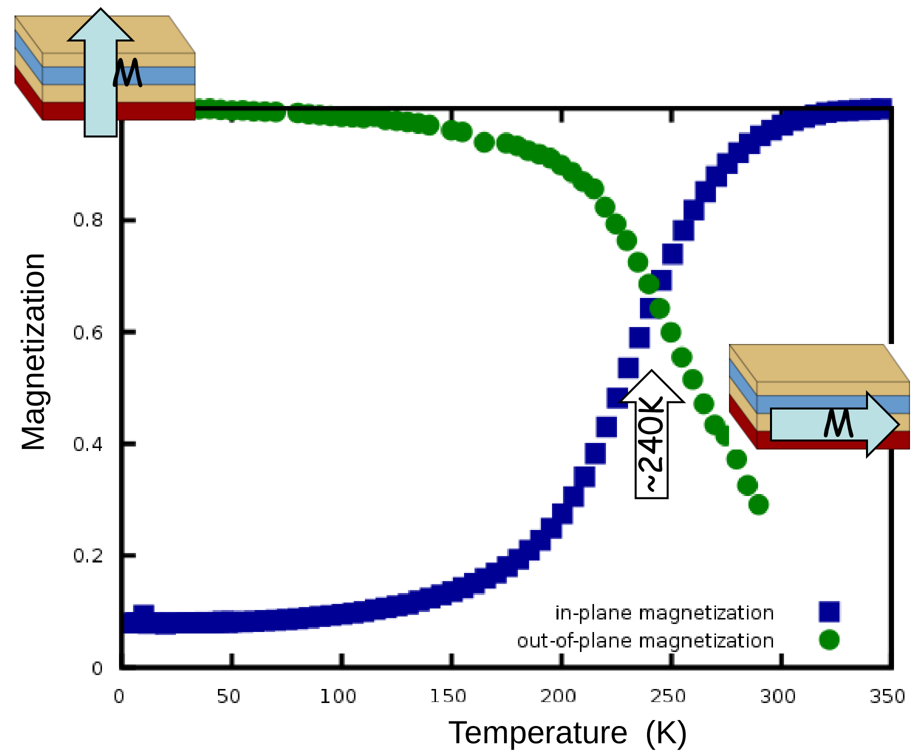
Spin Reorientation Transition in Au:Co:Au



$$E = \{K_1(T) - 2pM_s(T)^2\}\sin^2(q) + K_2(T)\sin^4(q)$$

Ultrathin Co layers -> spin-reorientation transition. Preferred magnetization direction is determined by competition between shape and crystalline/surface anisotropy (Pescia *et al. PRL* ***65, 2599).***

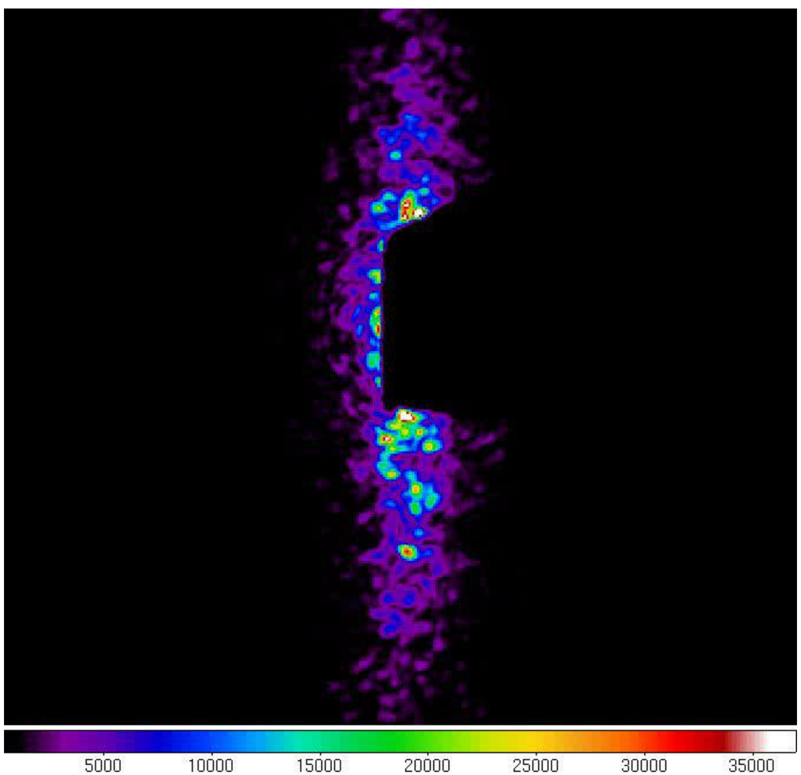
Magnetization rotates from out-of-plane to in-plane as a function of increasing temperature (Park *et al. APL 86 042504).*

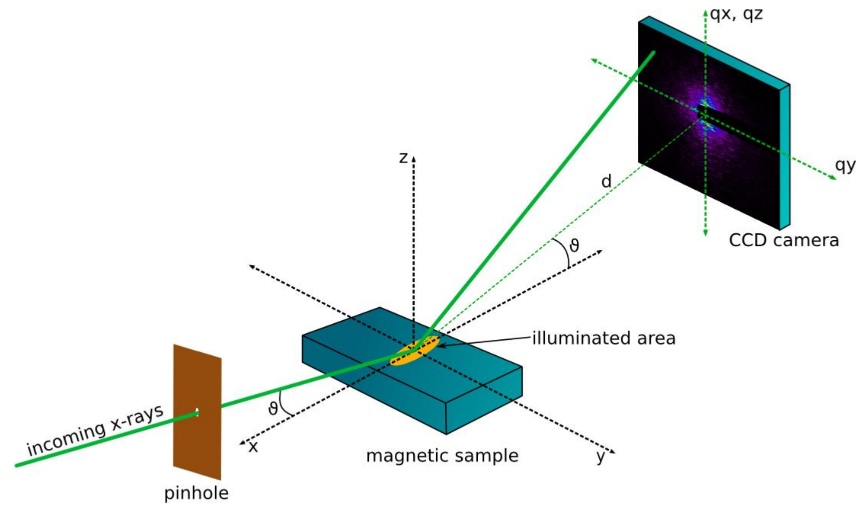


Does Barkhausen noise appear near the thermally-driven SRT?

Fluctuations near an SRT in Au/Co/Au Heterostructures

- Low angle diffuse reflectivity ($2\theta \sim 18^{o}$)
- Resonant: X-rays tuned to Co L_3 edge to provide elemental and magnetic sensitivity
- Scattered light is measured with a CCD camera: movies with q resolution



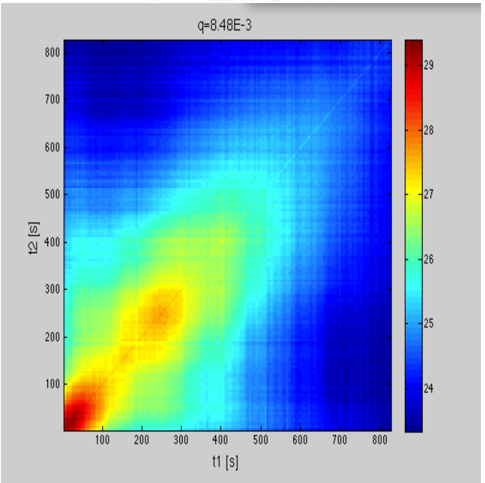


The intensity-intensity time-autocorrelation function directly measures the intermediate scattering function F(q,t):

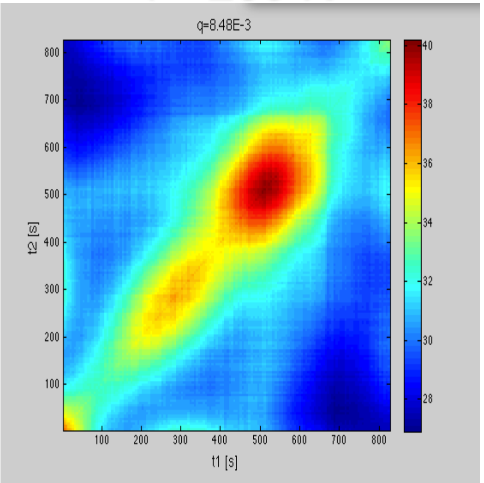
$$\frac{\left\langle I(q,t) I(q,t+t) \right\rangle_t}{\left\langle I(q,t) \right\rangle_t^2} = 1 + A\, F(q,t)^2$$

Temperature Dependent 2-time CF in SRT System

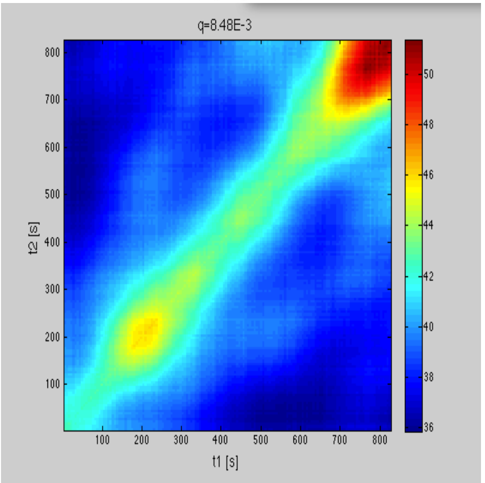
T= 240 K



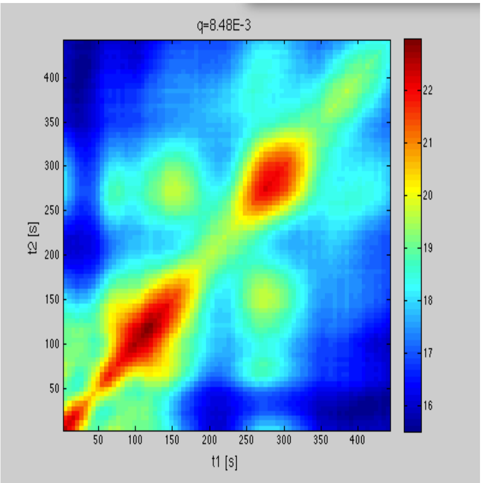
T= 260 K

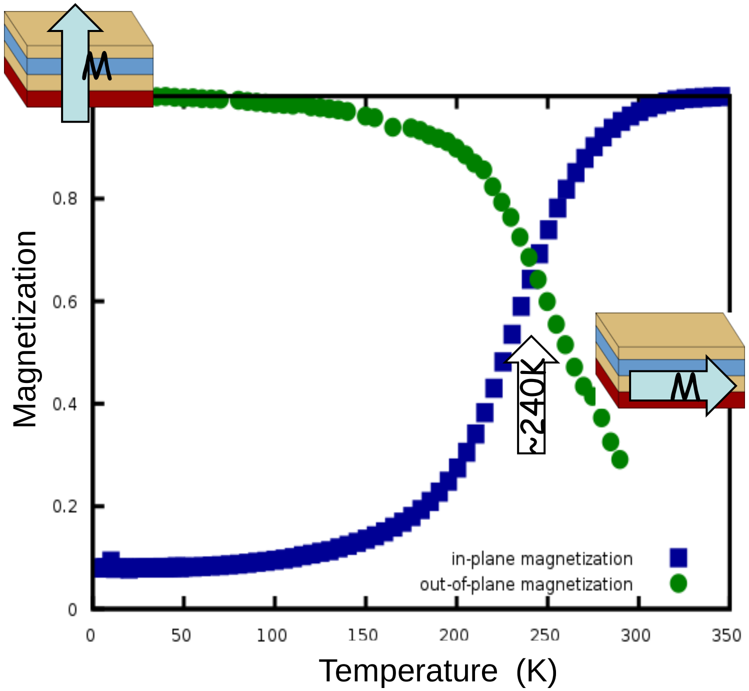


T= 280 K



T= 300 K

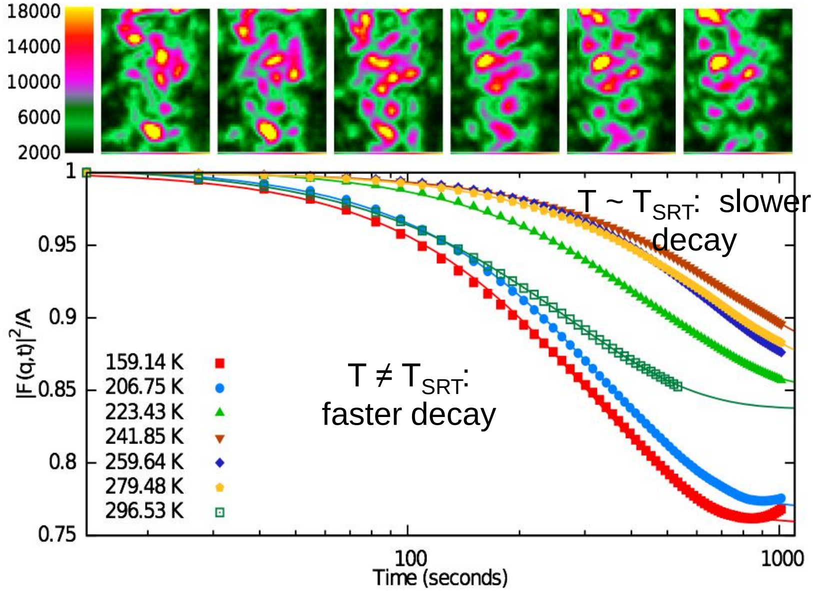




Truncated square 'blobs': crossover between thermal and athermal system?

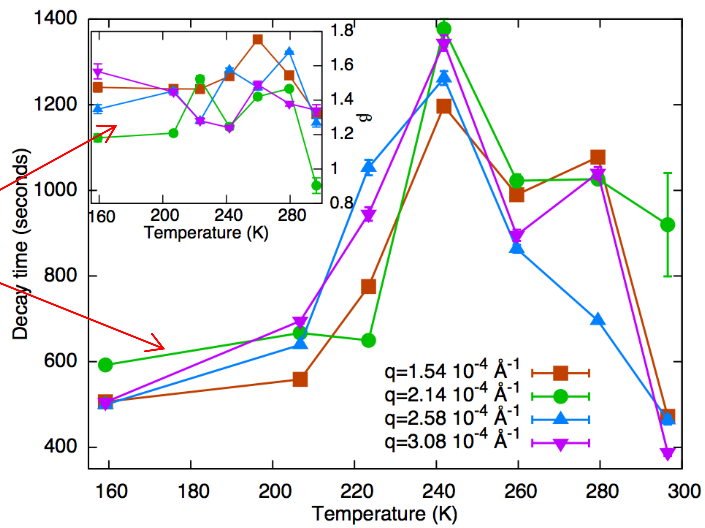
Complex Fluctuations near an SRT

$q = 2.58 \times 10^{-4}$ Å^{-1}



- F(q,t) measures the time the system takes to decorrelate due to diffusive motion of the magnetization.
- F(q,t) probes complex magnetization dynamics, possibly with a non-ergodic component.
- Stretched exponential provides a decent fit. . .

$$F(q,t) \propto e^{-(t/\tau)^{\beta}}$$

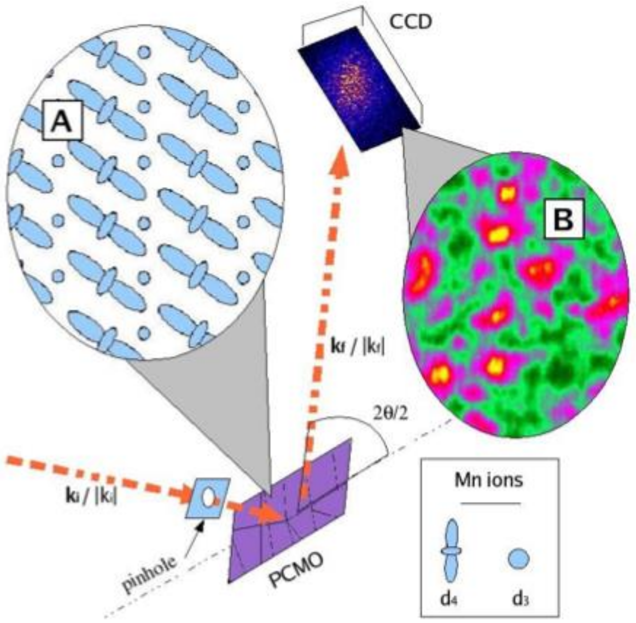


- Increase in decay time at the transition: vestige of critical slowing down?
- Stretching exponent > 1 : collective dynamics; too low for a jamming transition (Nature **447 68**)
- No significant q-dependence? Need larger dynamic range, better pinhole & smaller blocker. . .

How Does an Orbital Lattice Melt?

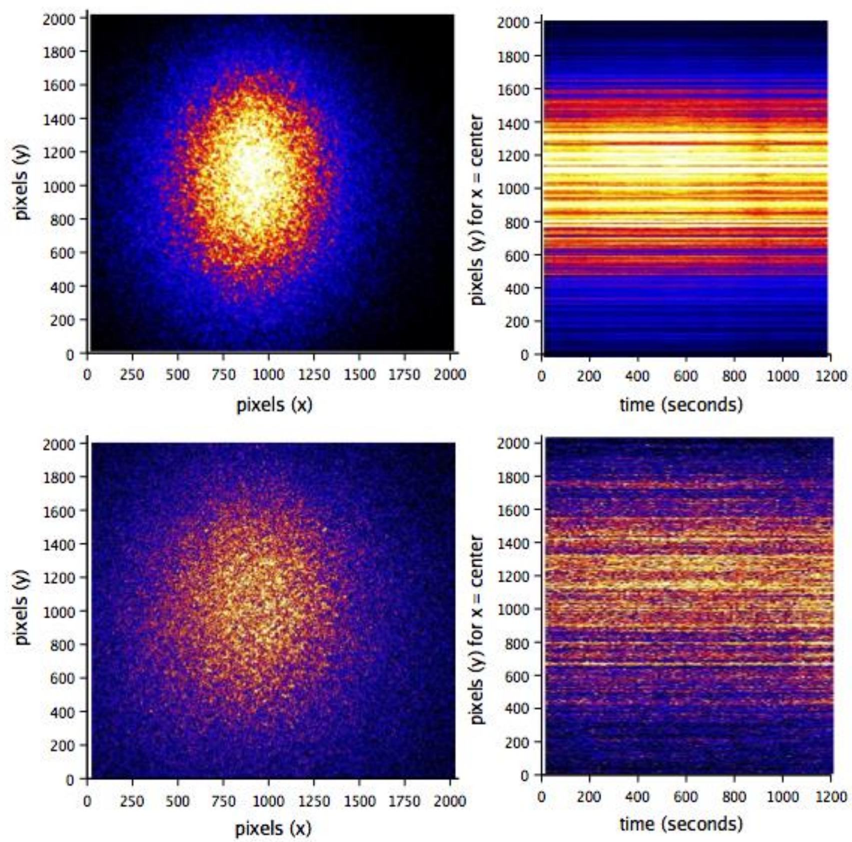
Left: well below (top) and near the ordering transition.

Right: Intensity vs. time through the the Bragg peak



(0,1/2,0) orbital-order Bragg peak broadened by finite-sized orbital domains.

From J.J. Turner, et. al., NJP **10**, 053023 (2008).



System remains mostly static, with a small fluctuating component, even while the orbital peak broadens due to reduced OO correlation length.

Intermittency, Thermal Equilibrium, and the Mesoscale

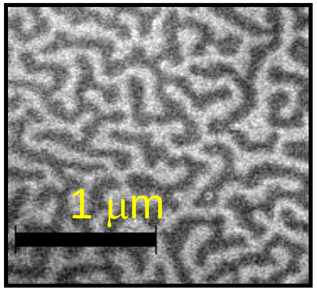
- Interplay between *frozen and fluctuating degrees of freedom* is of prime importance.

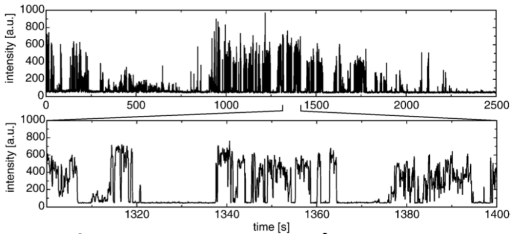
- Externally driven mesostructured systems will often exhibit *unusual patterns* in space an time.

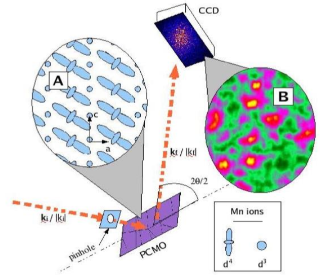
- *Mesoscale intermittency* often connects (ultra)fast dynamics with slow, complex kinetic behaviors

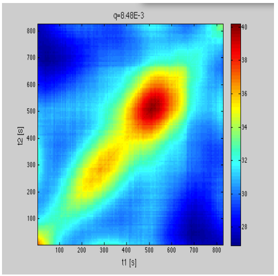
- Coherent x-ray beams provide a good way to *project this complexity* in both space and time with charge, chemical, orbital, and magnetic contrast.

- Unfortunately, with existing sources, we rarely have enough signal to probe a large *dynamic range in either space or time.*



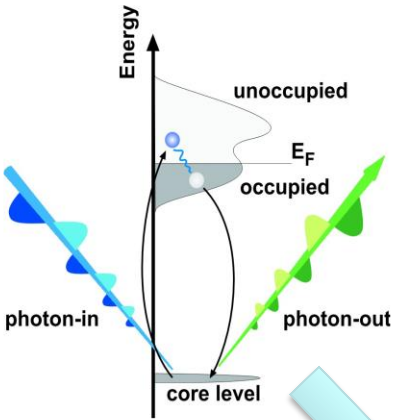






Connecting XPCS and RIXS

RIXS



3eV
- *Mott gap*

- *dd excitations*
- *Orbital waves*

1eV

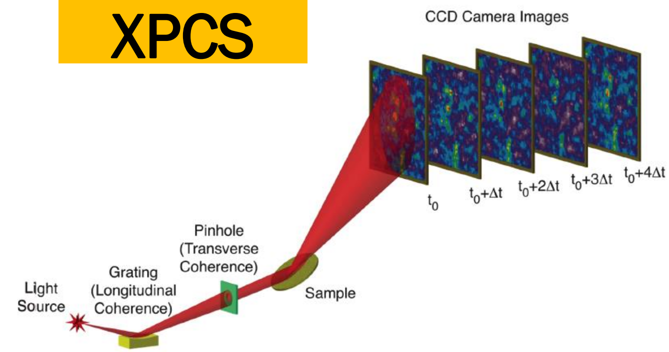
- *Multi-phonons*
- *Multi-magnons*
- *Pseudogap*

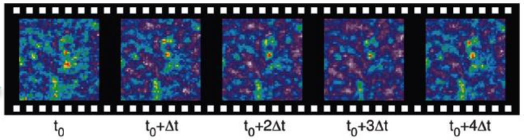
100meV

- *Optical phonons*
- *Magnons*
- *Local spin flip*
- *Superconducting gap*

0eV

XPCS





$$\frac{d^2\sigma}{d\Omega_{k'}\, d(\hbar\omega'_k)} = \frac{\omega'_k}{\omega_k}\sum_{|f\rangle}\left|\sum_{|n\rangle}\frac{\langle f|T^\dagger|n\rangle\langle n|T|i\rangle}{E_i - E_n + \hbar\omega_k + i\frac{\Gamma_n}{2}}\right|^2 \delta(E_i - E_f + \hbar\omega_k - \hbar\omega'_k)$$

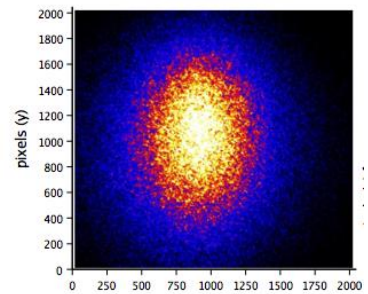
S(q,ω)

S(q,t)

Thoughts about Early Experiments at NSLS-II CSX

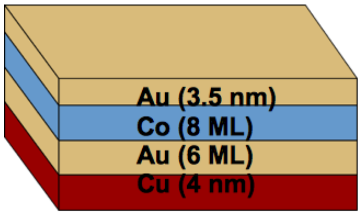
Domain fluctuations near phase boundaries in complex oxides

- Thermal *vs*. athermal degrees of freedom
- Probe short length scale domain wall motion
- Static disorder *vs*. frozen-in disorder
- Does not need a field



Exotic magnetic phases near the SRT as a function of (T,H)

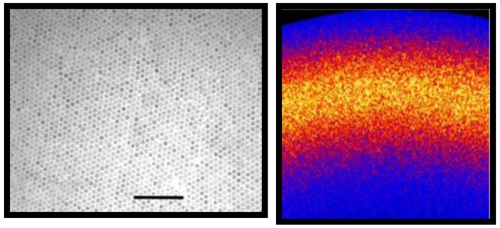
- Tune system further to approach zero anisotropy
- Seek exotic LC phases near the SRT
- Broad length/time scale to vary stretching exponent
- 1 vs 2 transitions?
- Does not require a field but would benefit from one



$$E = \left\{K_1(T) - 2pM_s(T)^2\right\}\sin^2(q) + K_2(T)\sin^4(q)$$

Superparamagnetism in nanoparticle arrays

- Easy to produce, high (charge) scattered signal
- Probably rife with cascades, intermittency, fluctuations
- Need EPU, magnetic field



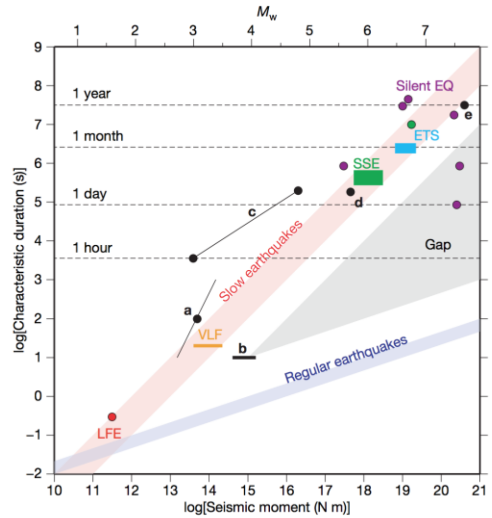
Collaborators and Funding

$$ DOE, ALS/CXRO/LBNL $$

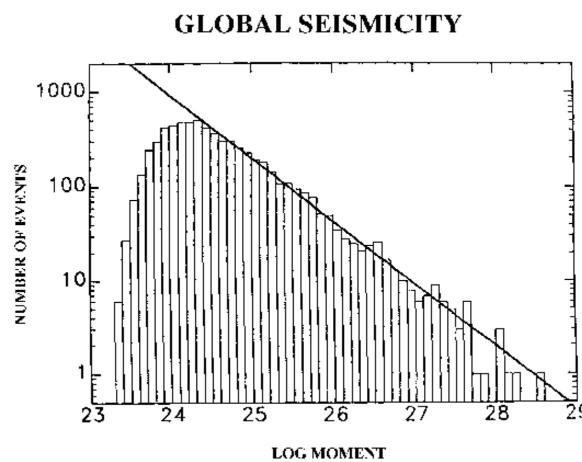
Dan Parks	UO, ALS
Run Su	UO, ALS
Keoki Seu	UO, ALS
Josh Turner	UO -> LCLS
Sujoy Roy	ALS
Eric Fullerton	UCSD
Jimmy Kan	UCSD
Charlie Falco	U. Az.
Sunkyun Park	Pusan Univ.
John Hill	BNL

Intermittency at the Macroscale

Earthquakes are intermittent. Are they random events?



Ide, et. al., Nature 447, 76 (2007).



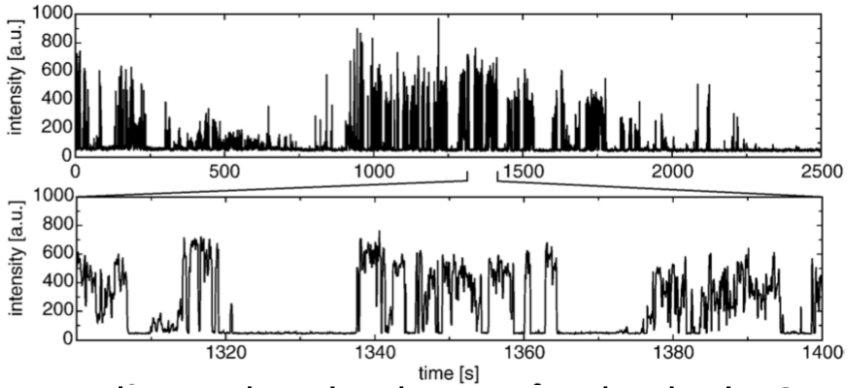
[Lay and Wallace, Modern Global Seismology, Academic Press, San Diego, CA, 1995.]

Gutenberg-Richter relationship: power law histogram

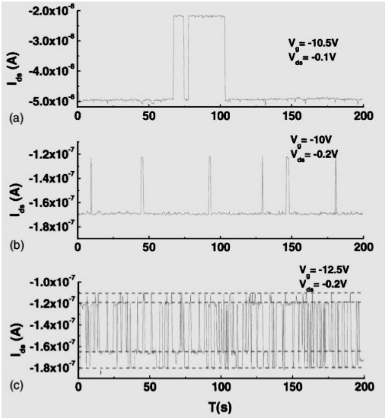
Intermittency often exhibits power law scaling (over some range)

Power law behaviors can cause bad things to happen.

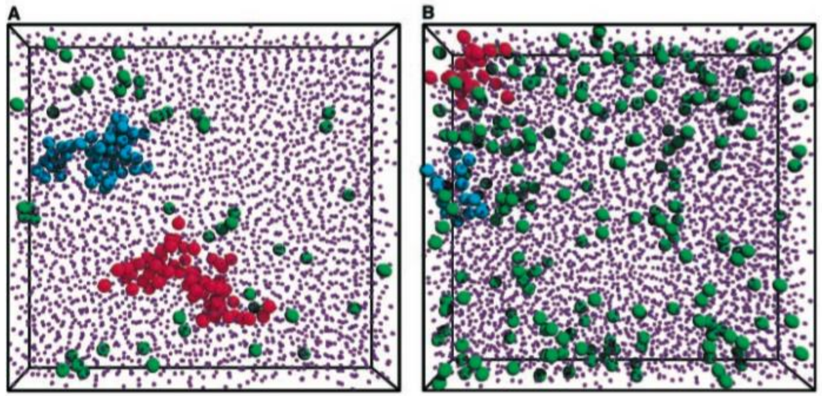
Nanoscale Intermittency Everywhere



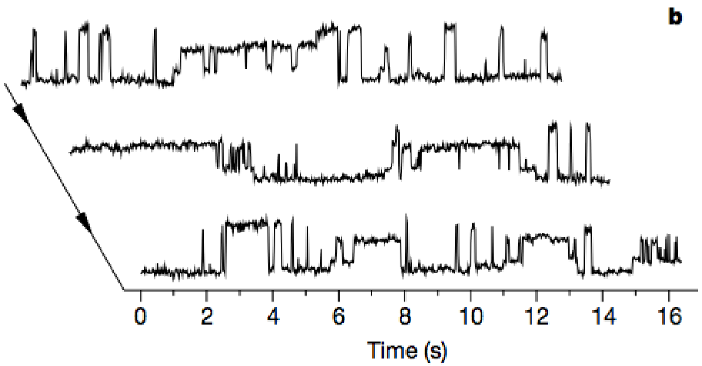
Intermittent photoluminescence in single QD
*R. Verberk, et. al. Phys Rev B **66**, 233202 (2002).*



Random telegraph signal in a CNT FET
Liu et. al. Appl. Phys. Lett. 86, 163102 (2005)



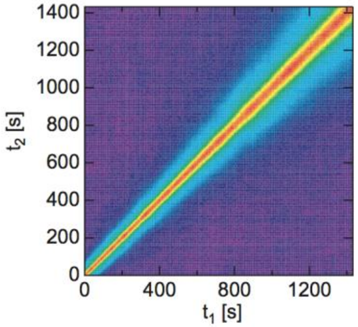
Fast diffusers near a colloidal glass transition
*Weeks, et. al., Science **287**, 627 (2000).*



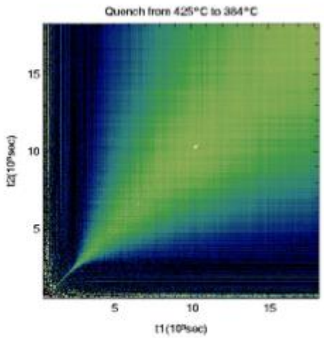
Dynamical heterogeneity, e.g., in polymer films.
*Russell and Israeloff, Nature **408**, 695 (2000).*

- Systems driven thermally or with a quasi-static external field
- Power law behaviors are common: multiscale (fractal) in space and time
- Need techniques with large dynamic range in space and time (not pump probe)

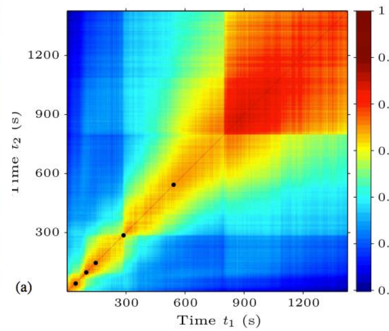
Probing Intermittency with High Order Correlations Functions



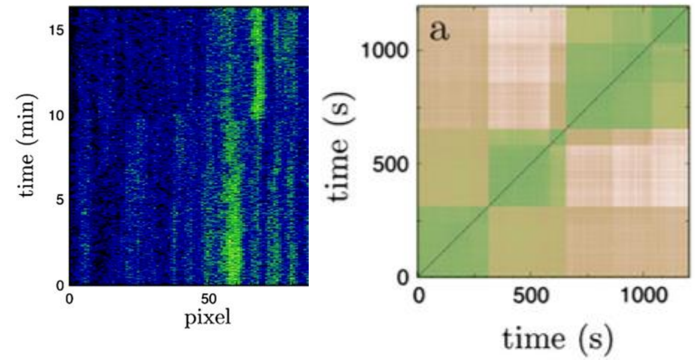
Aging in a Colloidal Gel
NJP 12, 055001 (2010).



Aging in Cu_3Au,
Sutton, et. al.



Aging in an Au:Cd Alloy
PRL 107, 105701 (2011).



Intermittency in a Martensitic Transition
PRL **107**, 015702 (2011)

$$C_2(t_1,t_2)=\frac{\langle I(t_1)I(t_2)\rangle_q}{\langle I(t_1)\rangle\langle I(t_2)\rangle} \overset{?}{=} \frac{\langle I(0)I(t_2-t_1)\rangle_t}{\langle I(t_1)\rangle\langle I(t_2)\rangle}$$

Two-time correlation function

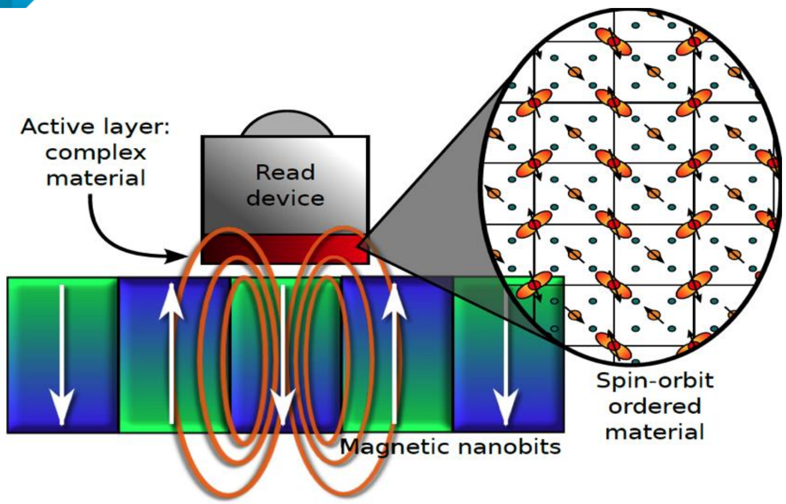
- compares system with itself at t_1 and t_2
- probes stationarity/ergodicity/aging
- detects intermittent cascades

M.Sutton et al. Optics Express 11, 2268 (2003).
A. Madsen et al, NJP 12, 055001 (2010).

Depressingly narrow dynamic range in length and time scale due to low coherent flux.

One natural time scale for chemical intermittency is $h/k_BT \sim 1$ ps

Yin and Yang of Mesoscale Devices: Field- vs. Thermally-Driven (Anomalous) Dynamics



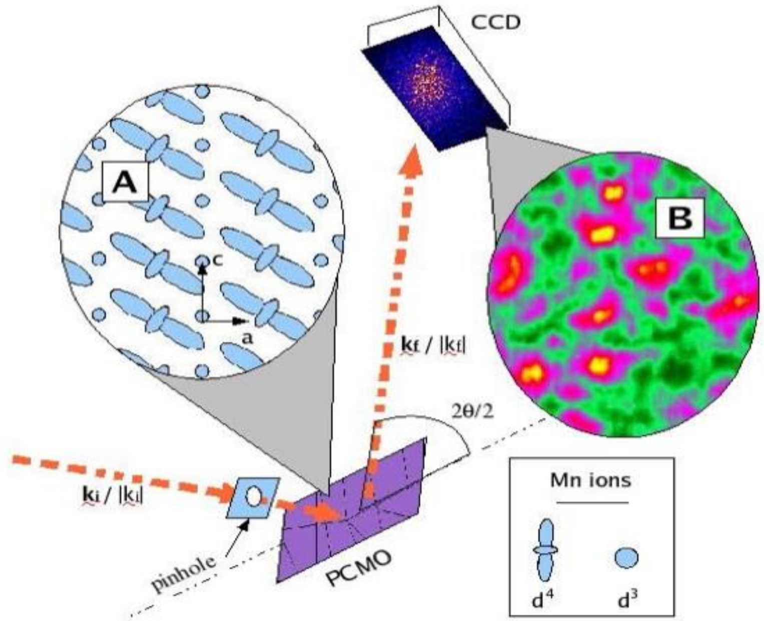
‘Field drive’ to control a complex system
(Cartoon courtesy of Sujoy Roy/ALS)

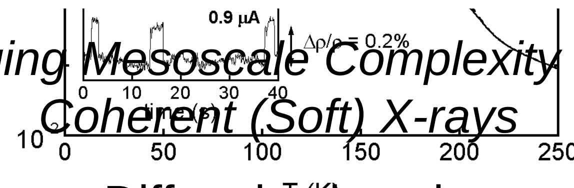
Will impact many mesoscale devices

Connects dynamic and kinetic time scales

So, thermally driven mesoscale dynamical heterogeneity is important.

How do we predict, measure, and control it?

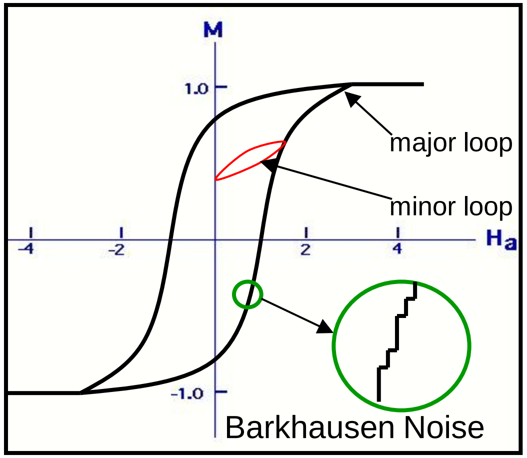


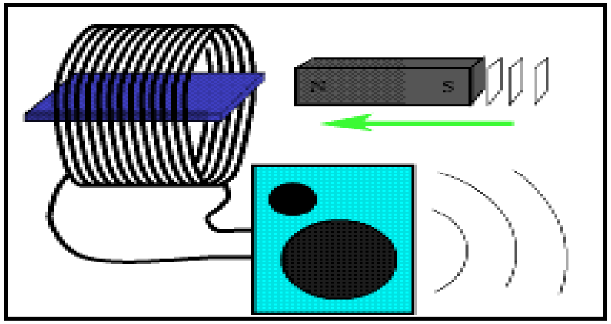


Imaging Mesoscale Complexity with Coherent (Soft) X-rays

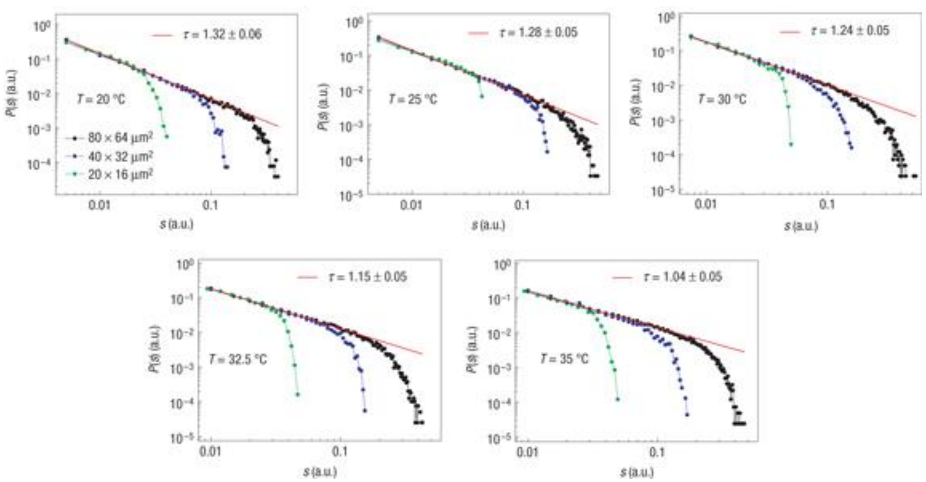
- Diffractive imaging
- Speckle metrology
- Correlation spectroscopy

Intermittency in Magnets

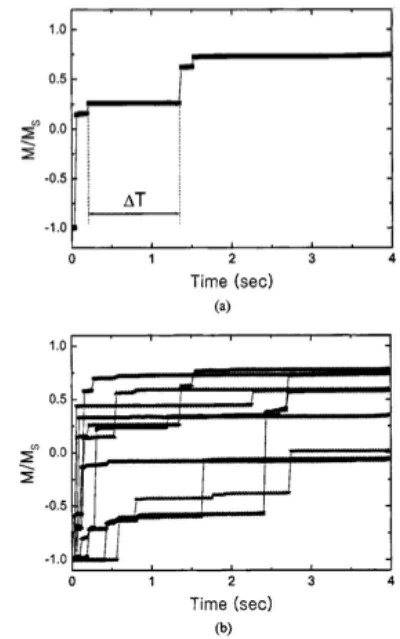




Listening to Barkhausen events
[Feynman Lectures on Physics
vol. 2, Fig. 37-11]



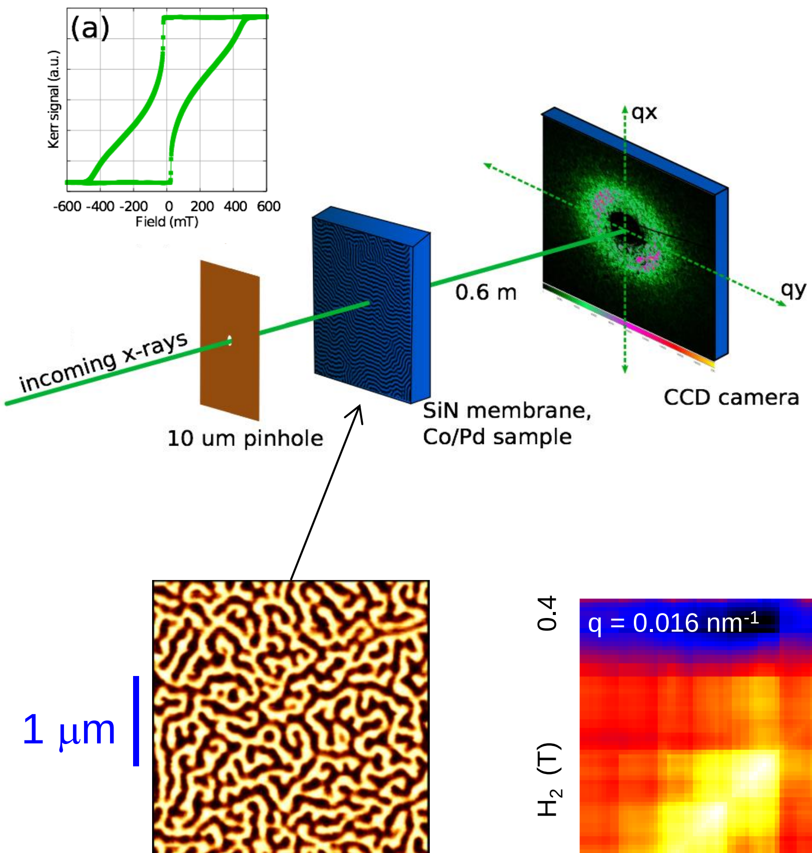
Histograms of sizes of Barkhausen events: scaling and self-similarity?
[Ryu, Akinagas, and Shin, Nature Phys. 3, 547 (2007).]

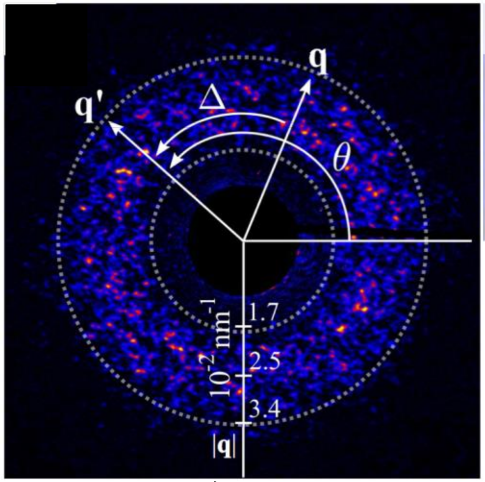


Barkhausen events in a Co film
[Kim and Shin, J. Appl. Phys. 95, (2004).]

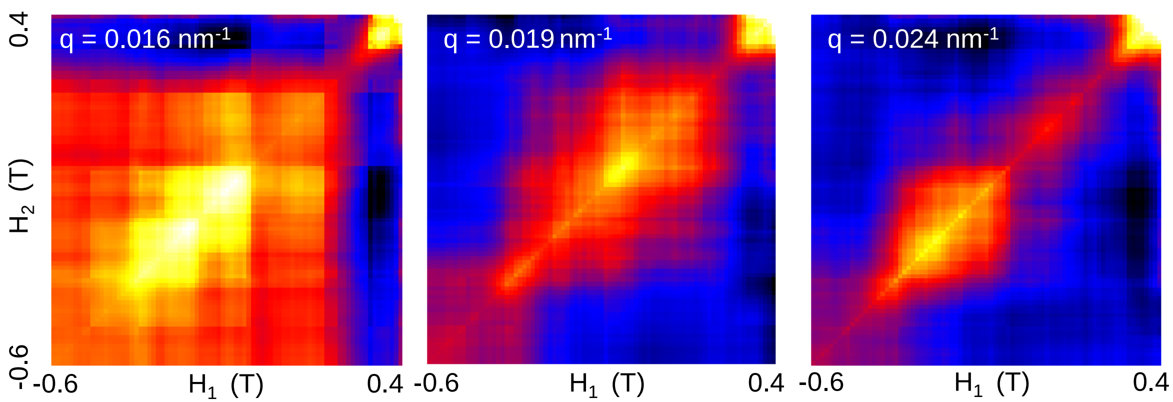
With a microscopic probe can we understand why a particular cascade is large while another is small?

Barkhausen Cascades and Two-Field Correlation Functions





$$C_2(H_1, H_2, q) = \frac{\langle I(H_1, q)\, I(H_2, q)\rangle_q}{\langle I(H_1, q)\rangle_q \langle I(H_2, q)\rangle_q}$$



Broad distribution of overlapping cascades;
highly q-dependent