NMR Studies of the Iron Based Superconductors

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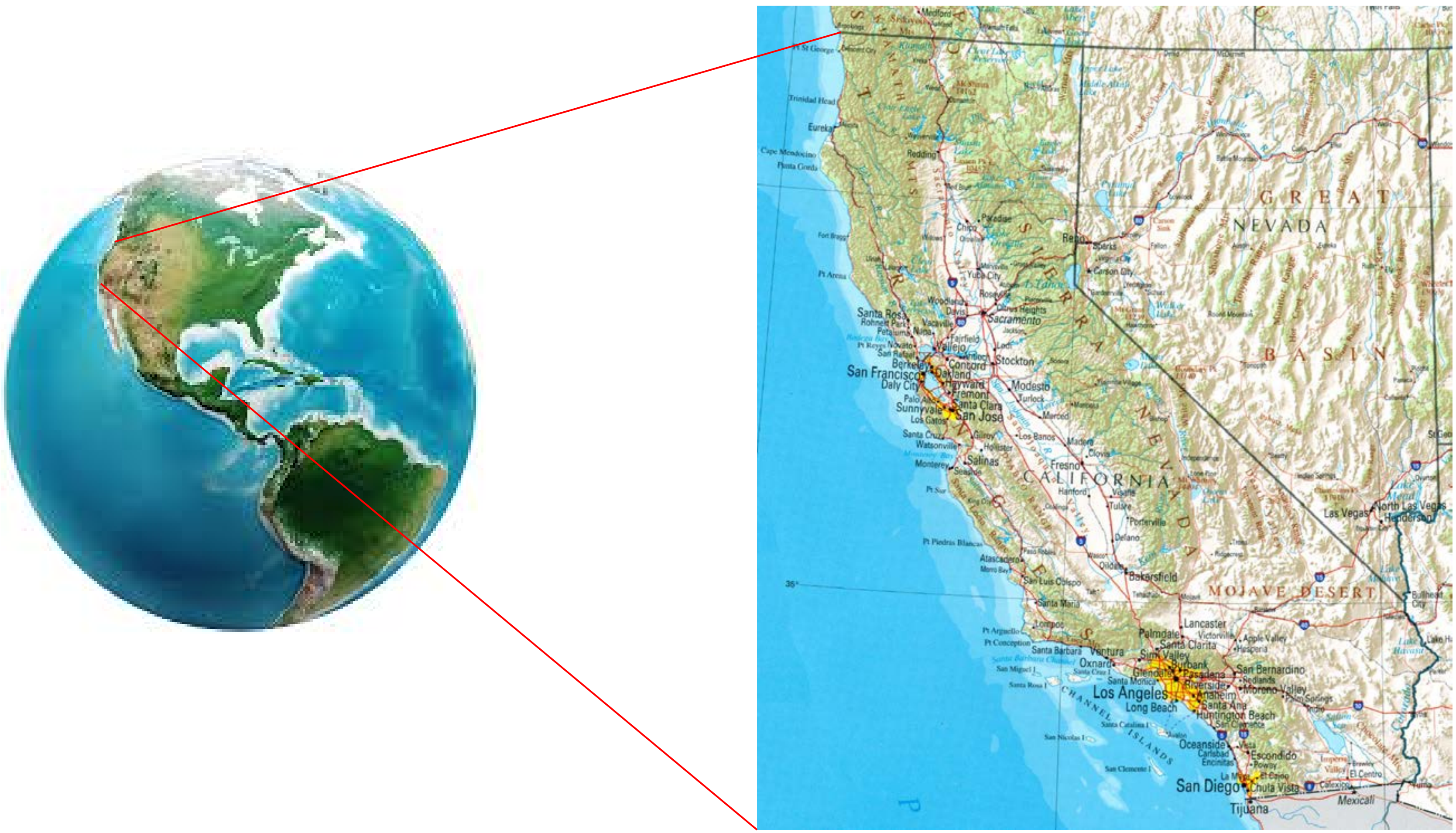
Cade o UC Davis?



Universidade da California

10 campuses
238700 Undergraduates
50400 Postgraduate
19700 Academic Staff

the state must bring own water!

Acknowledgements

NMR:
Adam Dioguardi
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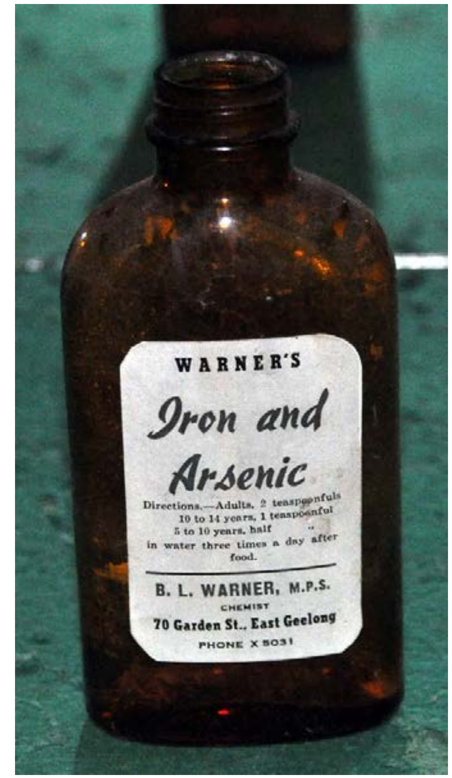
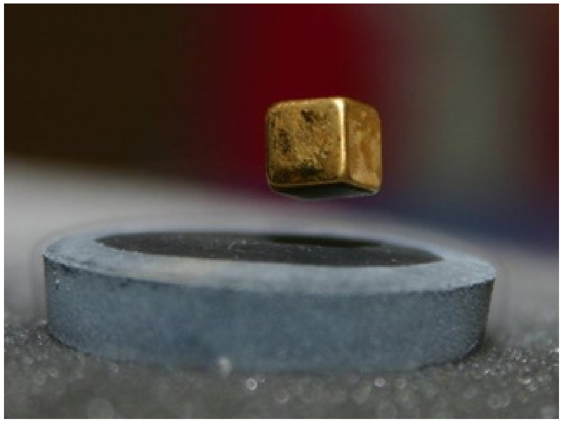
Erica Carlson (Purdue)
Karin Dahmen (UIUC)

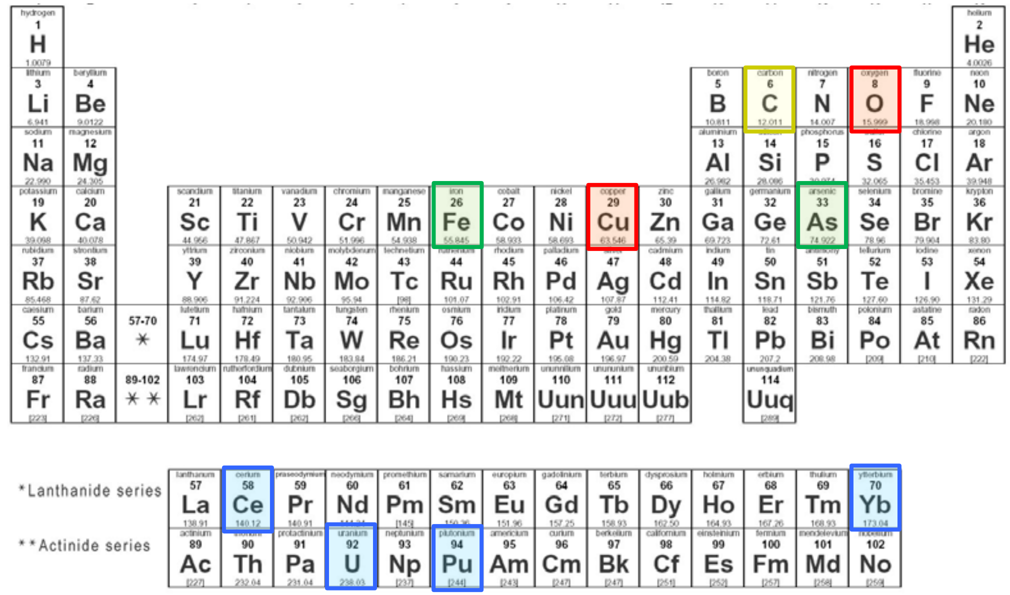
Outline

- The Iron Superconductors
- Nuclear Magnetic Resonance
- Glassy Dynamics and Inhomogeneity
- Nematicity and Disorder



Superconductor families

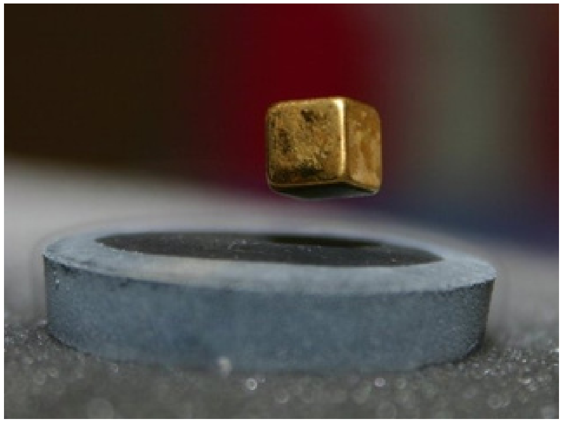


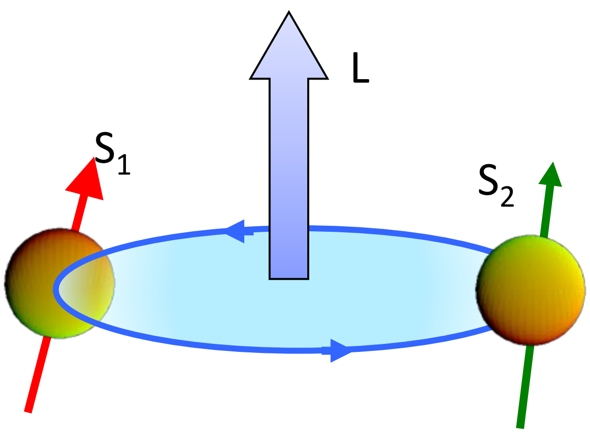


Unconventional superconductor families:

Heavy fermions	T_c ~ 2 K	1979
Organics	T_c ~ 10 K	1990
Cuprates	T_c ~ 100 K	1987
Iron Arsenides	T_c ~ 40 K	2008

Superconductor families





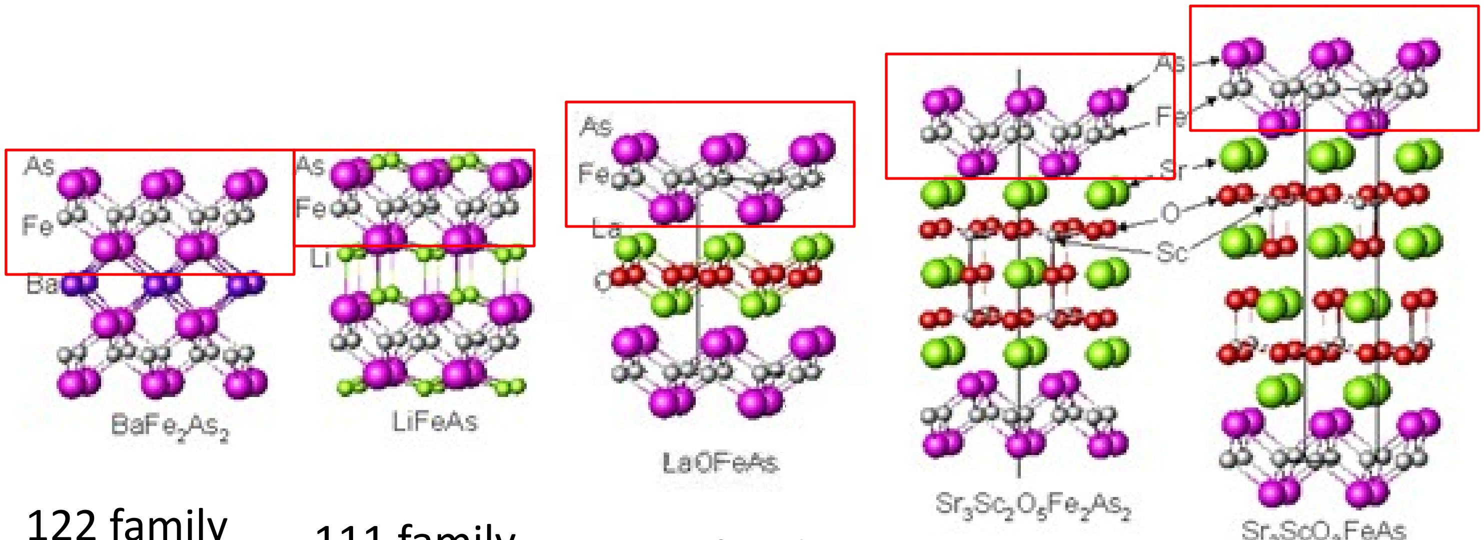
Conventional:

- Well described by BCS theory
- Cooper pairing driven by phonons
- Typically elements or simple compounds
- (Al, Hg, MgB_2, Nb_3Sn, Nb-Ti alloy…)
- Zero spin and angular momentum

Unconventional:

- Unknown pairing mechanism (spin fluctuations?)
- Finite spin or angular momentum
- Often found in close to (anti)ferromagnetism

The Iron Arsenide Family



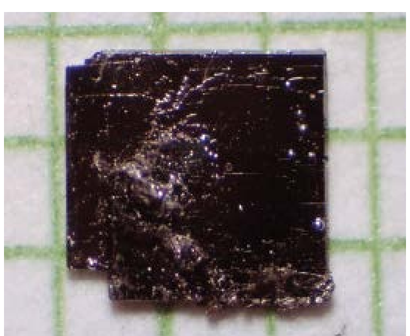
122 family

111 family

1111 family

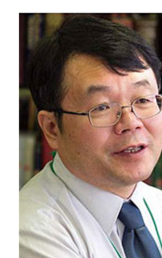
Well characterized single crystals

T_c up to 55 K in SmFeAsO



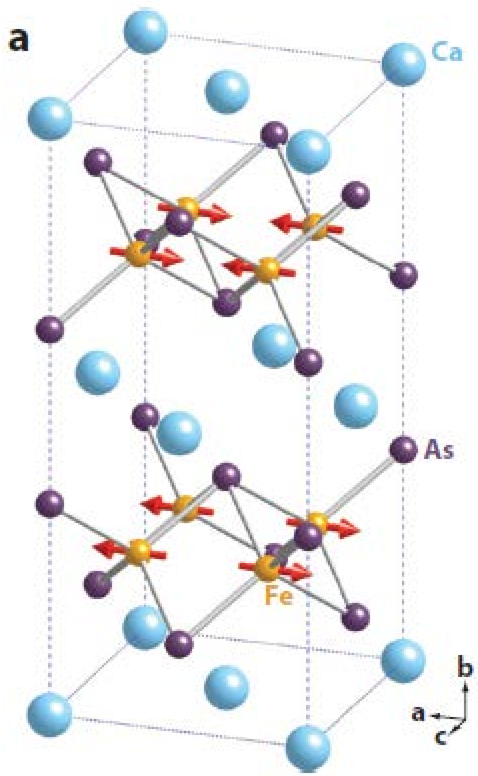
Canfield and Bud'ko, Annu. Rev. Condens. Matter Phys. (2010)

Hideo Hosono, Tokyo Inst. Tech.



Superconductivity and Magnetism

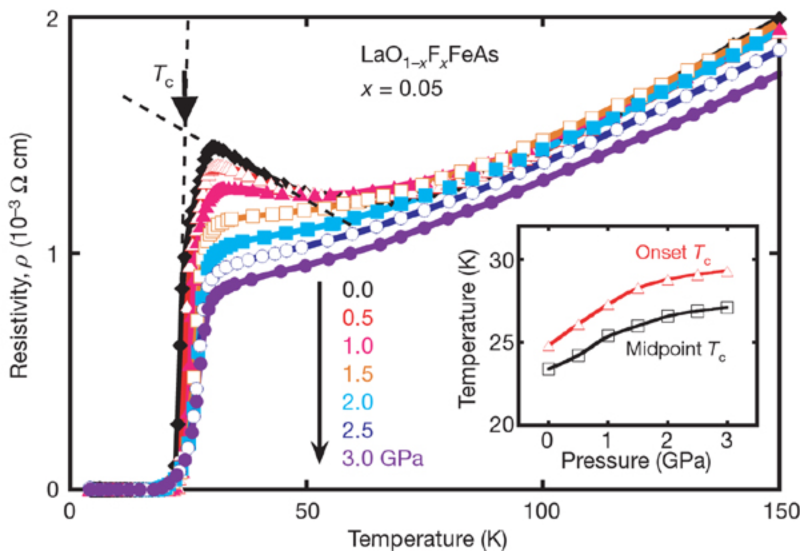
Antiferromagnetic metal



Goldman et al, PRB 79 24593 (2008)

Electron or hole doping
Or pressure

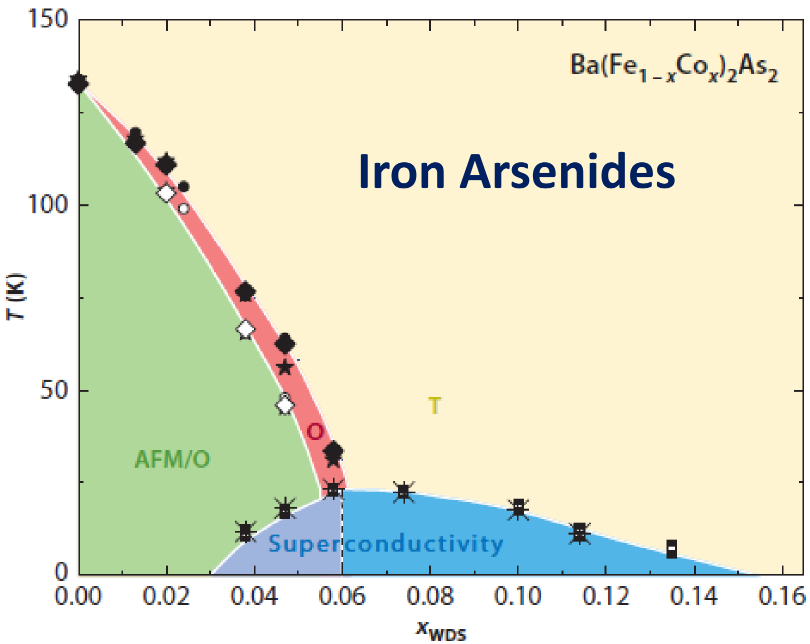
Zero resistance



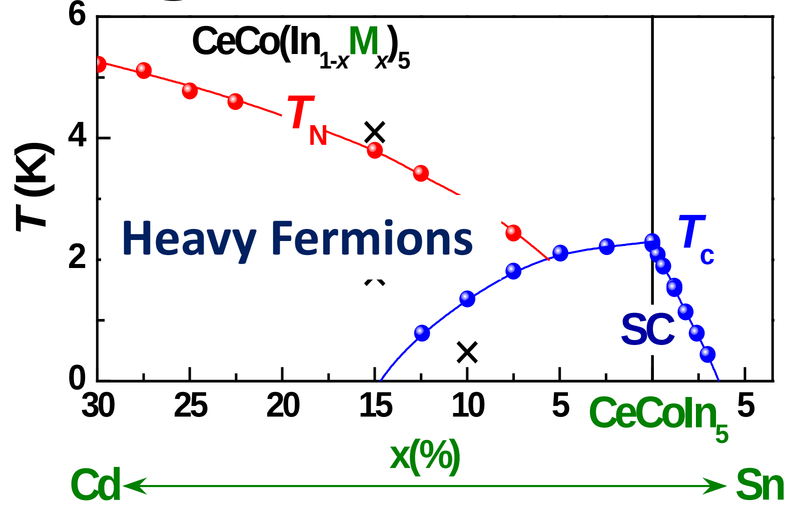
Hosono et al., Nature 2008

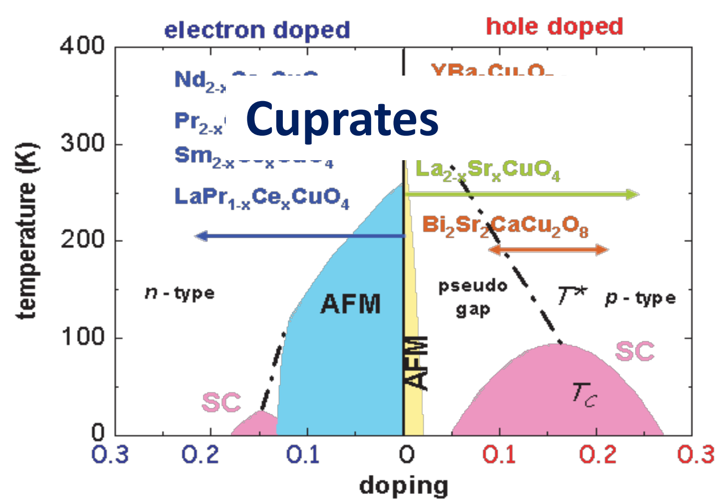
Phase Diagram

Superconductivity and Antiferromagnetism are ubiquitous



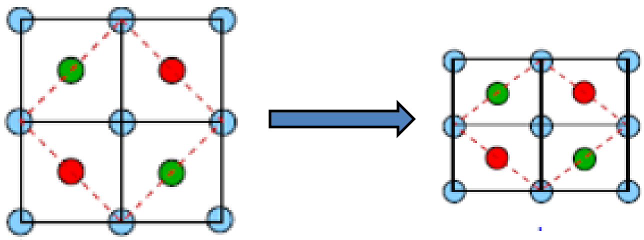
Electron doping



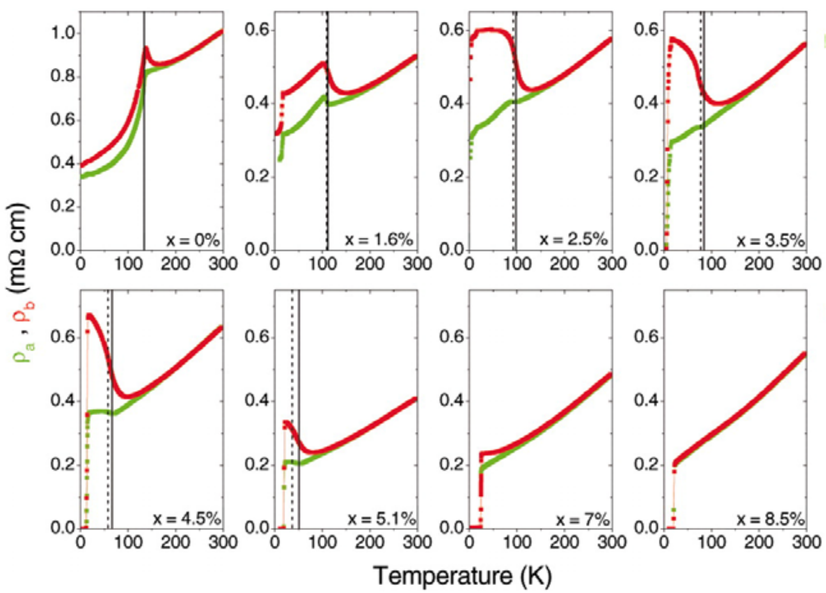


But the details are very different!

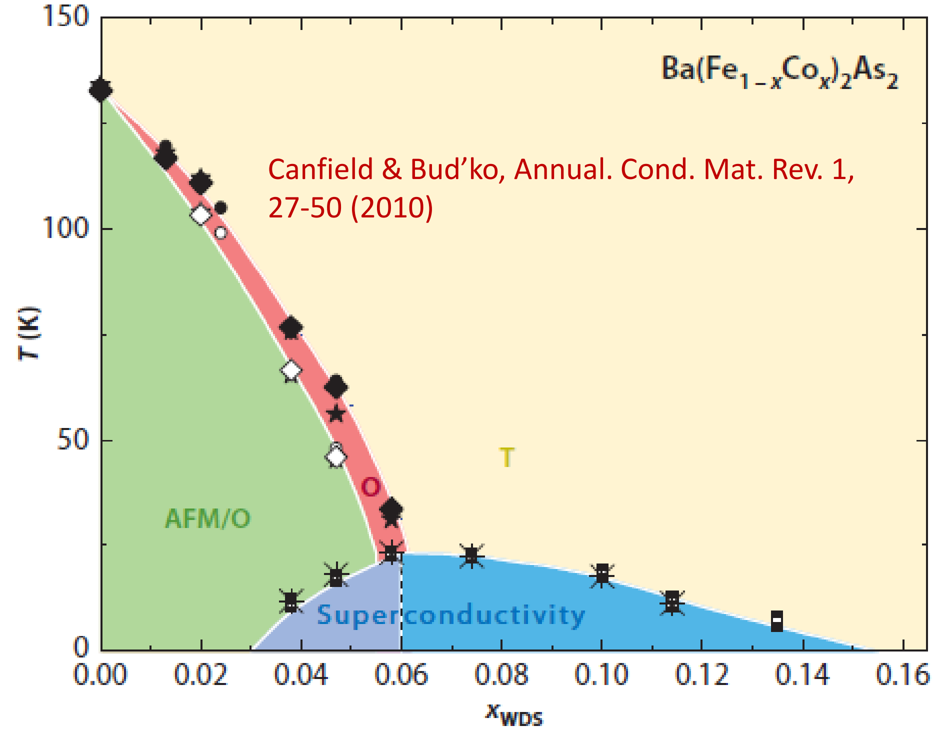
Orthorhombic Distortion



I4/mmm F/mmm



Fisher et al., Science (2010)



Canfield & Bud'ko, Annual. Cond. Mat. Rev. 1, 27-50 (2010)

(a-b)/a ~ 1%

Magnetic Order

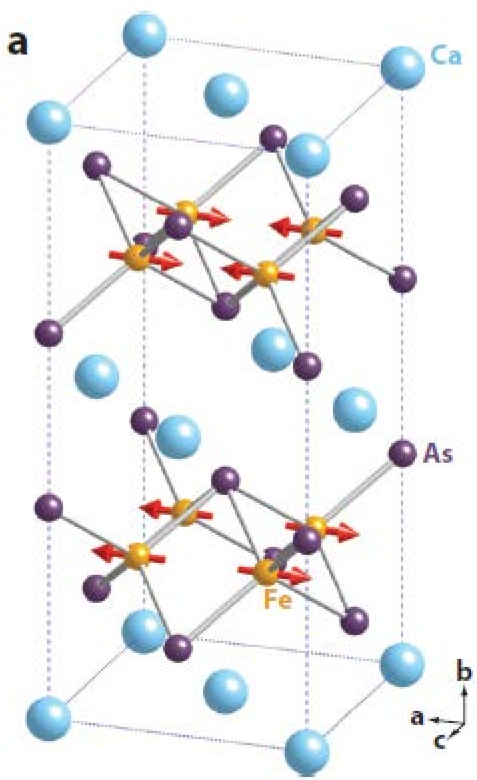
Stripe ordering:

$$\mathbf{Q}_{AF} = (\pi/a, 0, \pi/c)$$

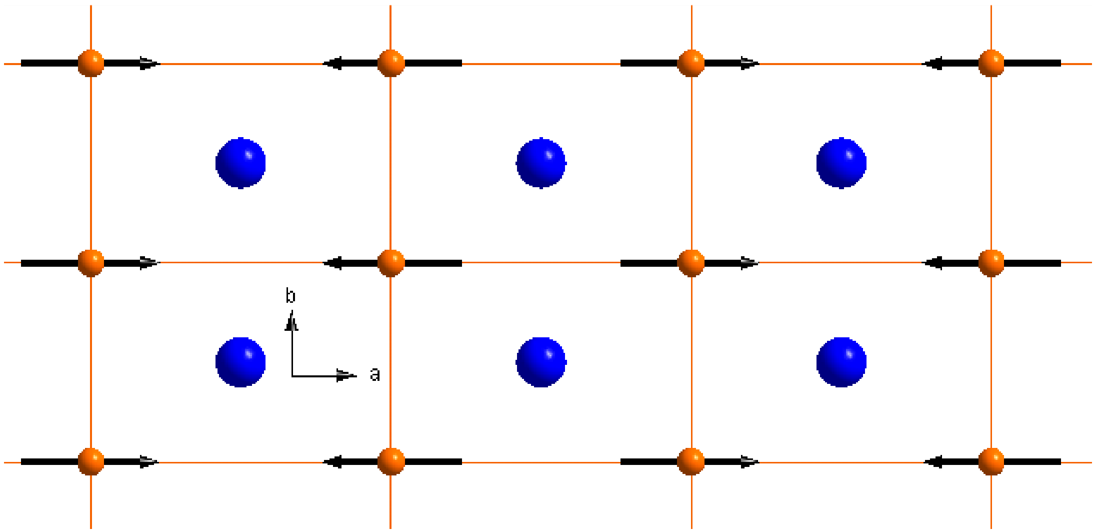
Moments point along (100)

First order for pure compound

Material	Ordered Moment
$CaFe_2As_2$	0.80 μ_B
$BaFe_2As_2$	0.87 μ_B
$SrFe_2As_2$	1.01 μ_B
LaFeAsO	0.4 μ_B



Goldman et al, PRB 79 24593 (2008)



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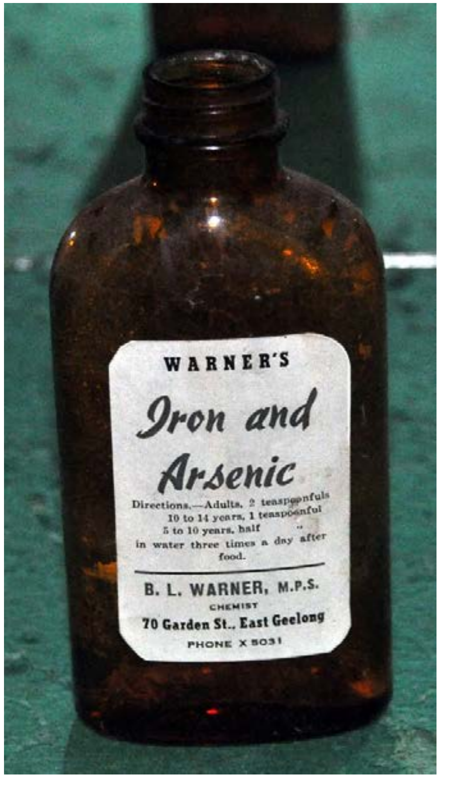
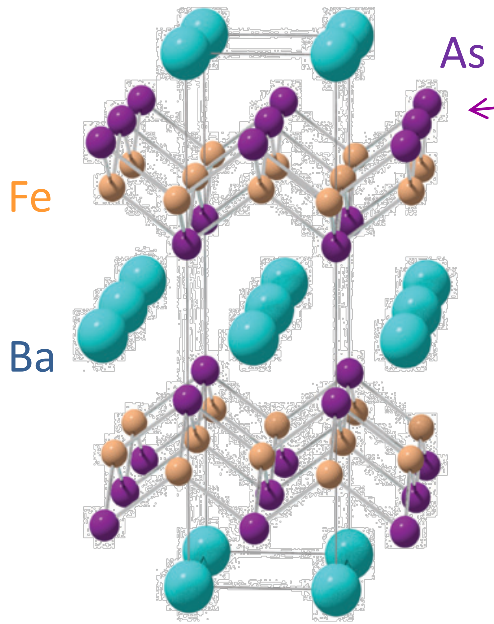
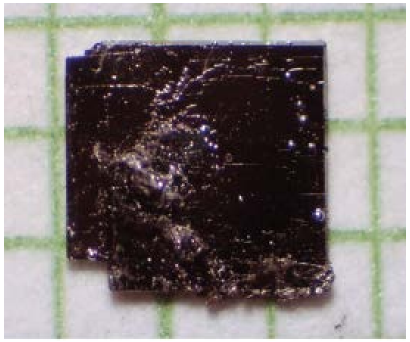


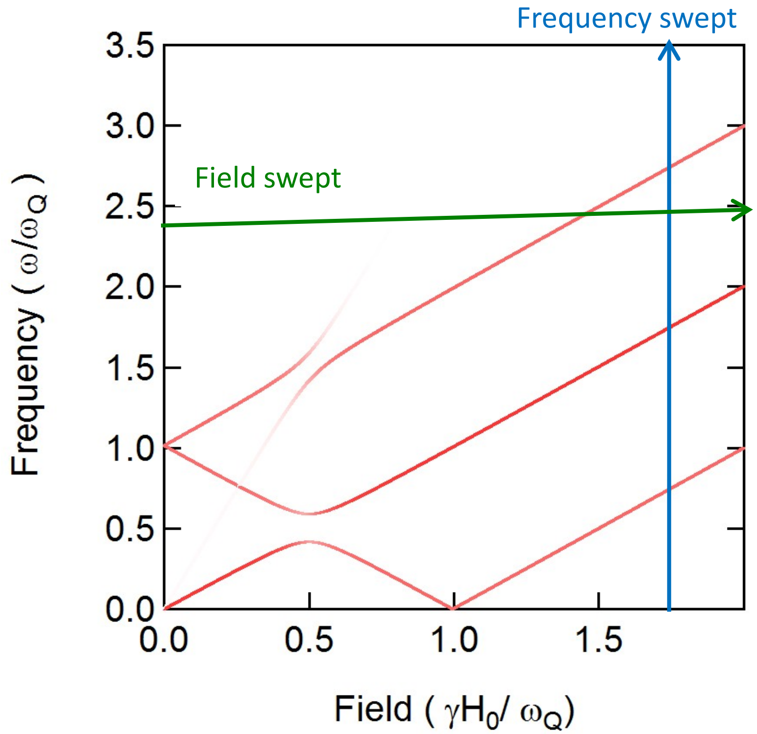
As NMR

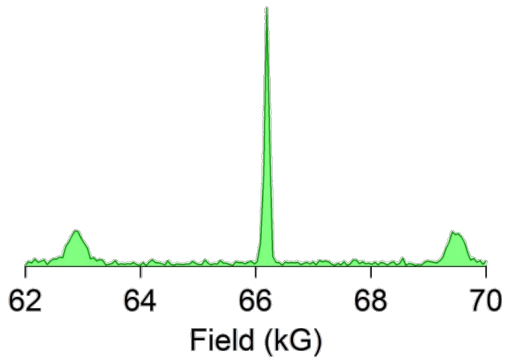


^{75}As I=3/2 is 100% abundant



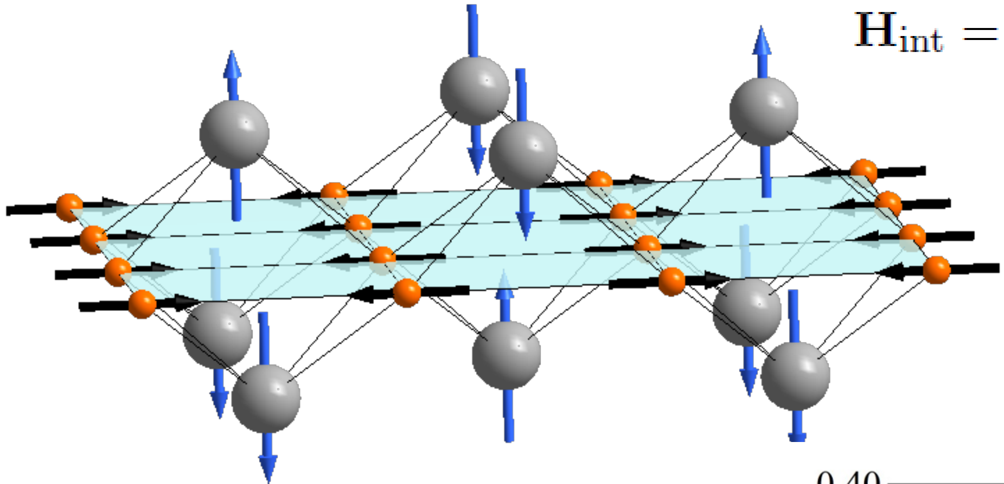
Canfield and Bud'ko, Annu. Rev. Condens. Matter Phys. (2010)





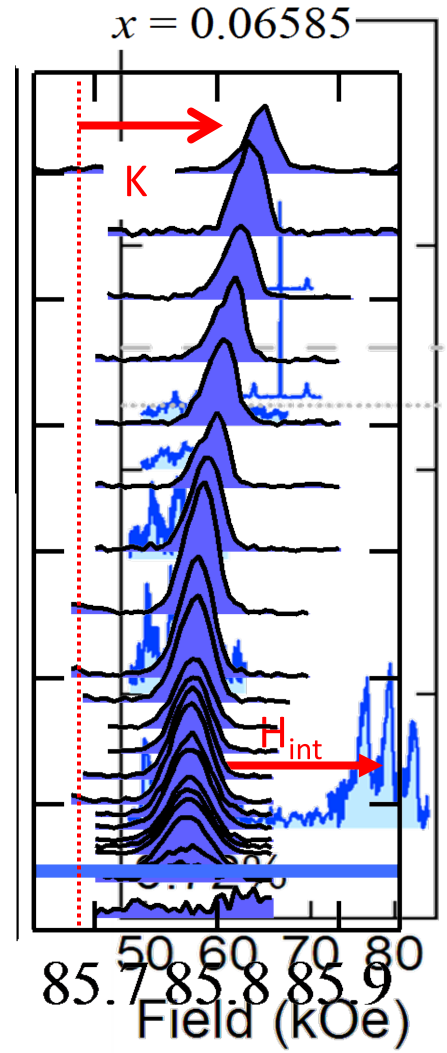
+1/2 to -1/2 transition

As Hyperfine Coupling

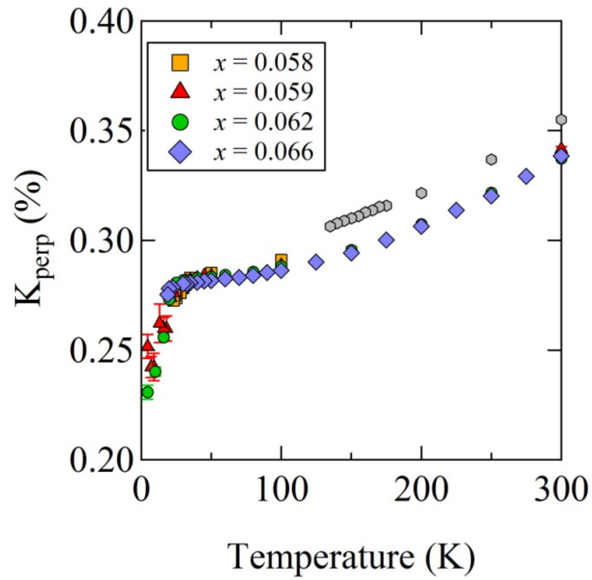


$$\mathbf{H}_{\rm int} = \sum_{i \in nn\mathrm{Fe}} \mathbb{B}_i \cdot \mathbf{S}(\mathbf{r}_i)$$

$K_\alpha = B_\alpha \chi_\alpha$



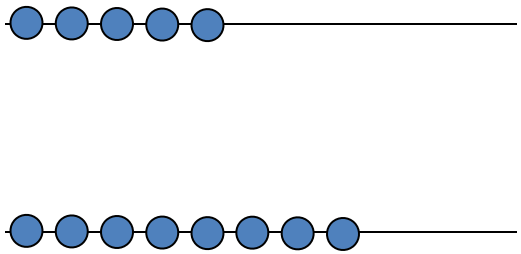
Knight shift in paramagnetic state probes static susceptibility



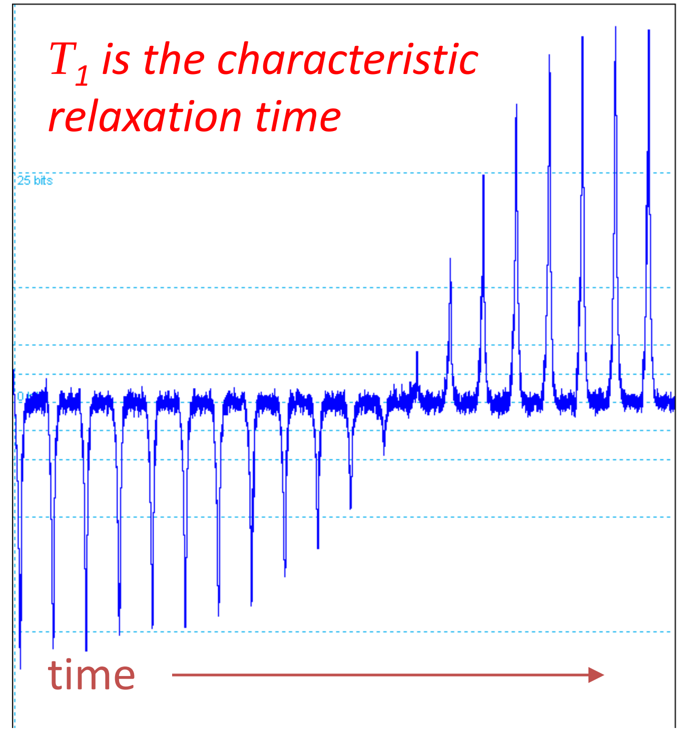
Nuclear Spin Dynamics

$| I_z = +½>$

$| I_z = -½>$



By applying rf pulses, we can perturb the equilibrium Boltzmann distribution, and then watch as the system relaxes to a finite spin temperature



$$M(t) \sim 1 - e^{-t/T_1}$$

$$(T_1 T)^{-1} \sim \lim_{\omega \to 0} \frac{\chi''(\mathbf{q}, \omega)}{\omega}$$

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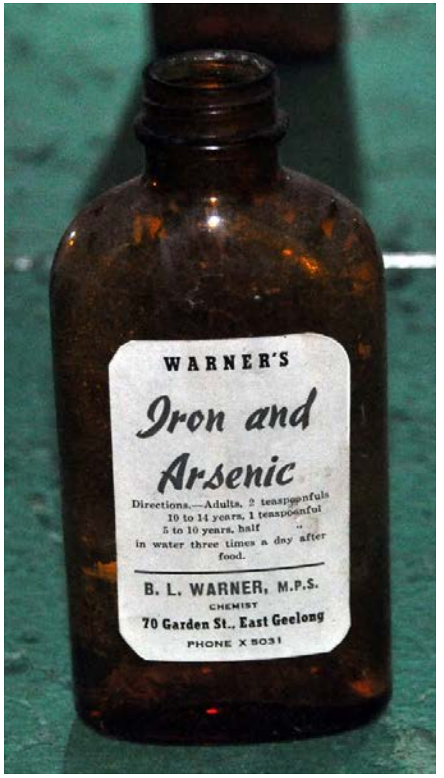
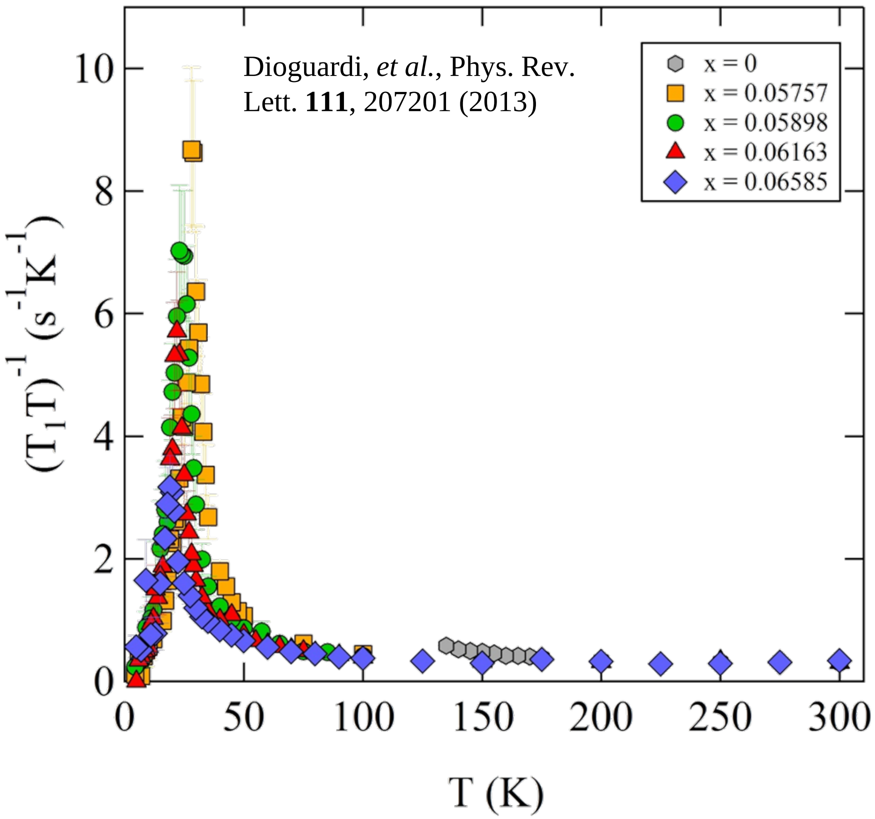
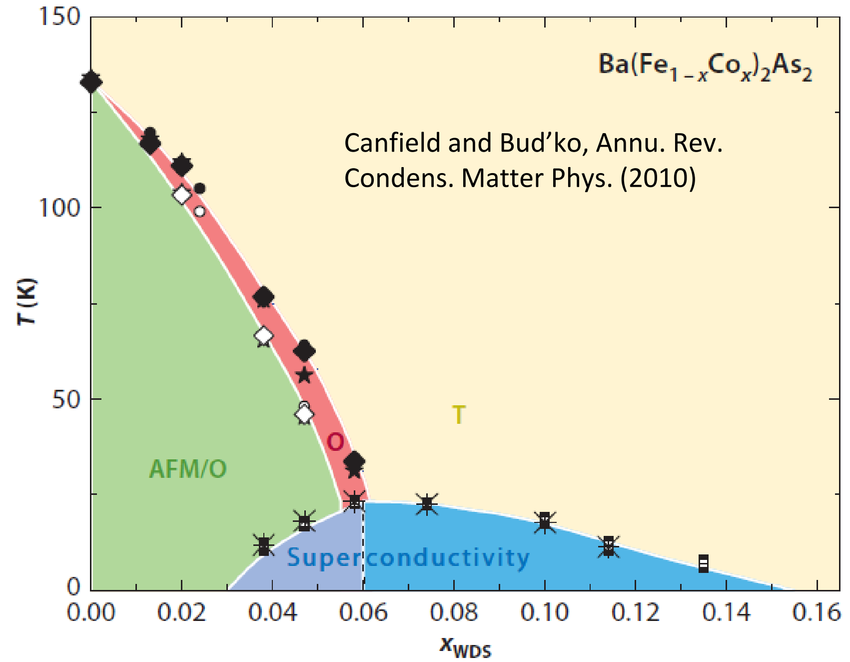


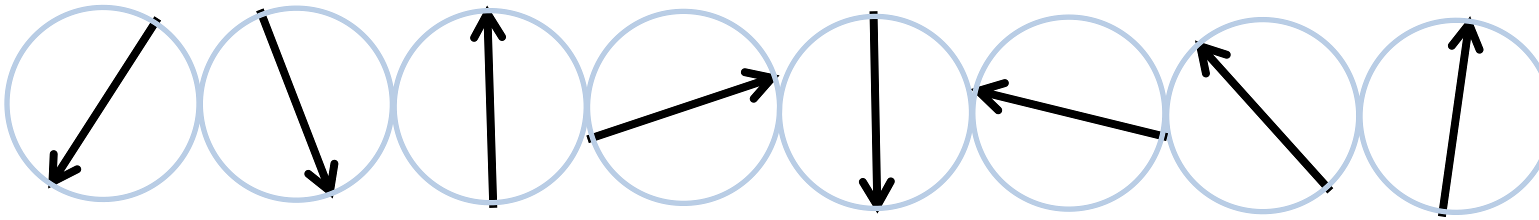
Spin Lattice Relaxation



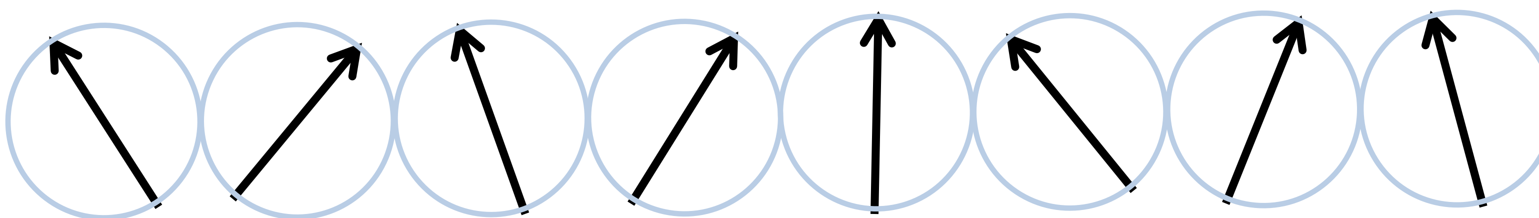


Divergence reveals critical slowing down of magnetic fluctuations at AFM phase transition

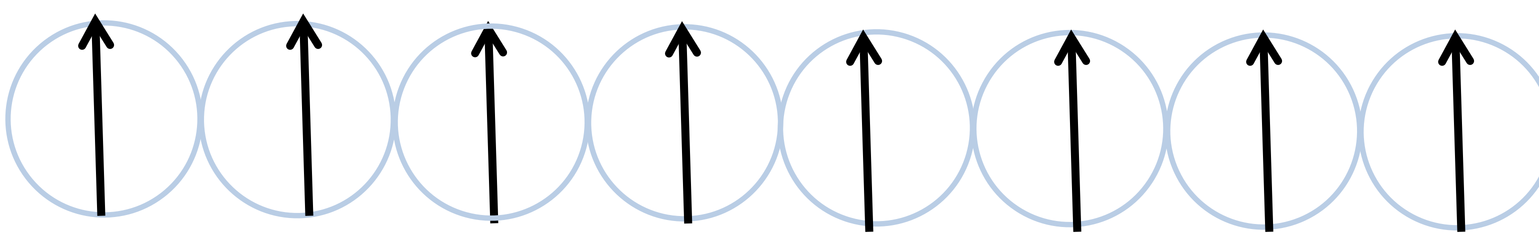
Critical Slowing Down



High temperature, random fluctuations

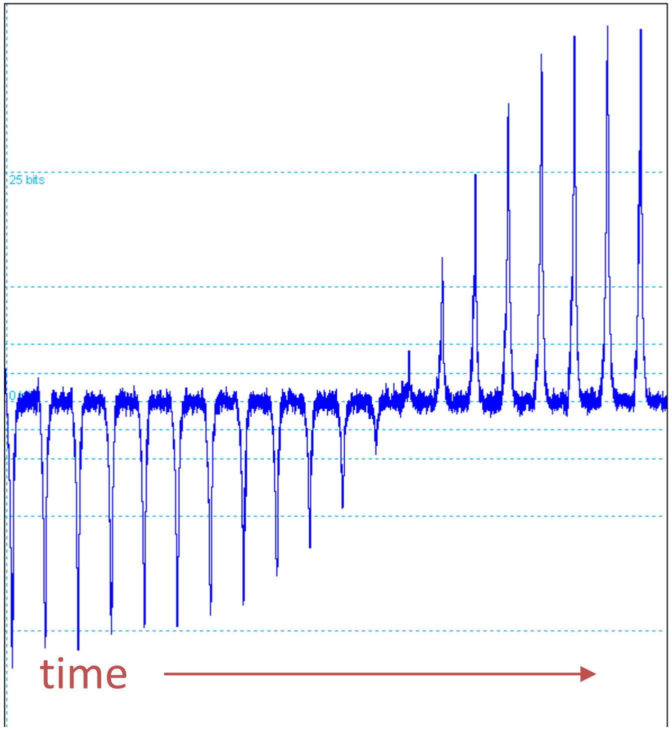


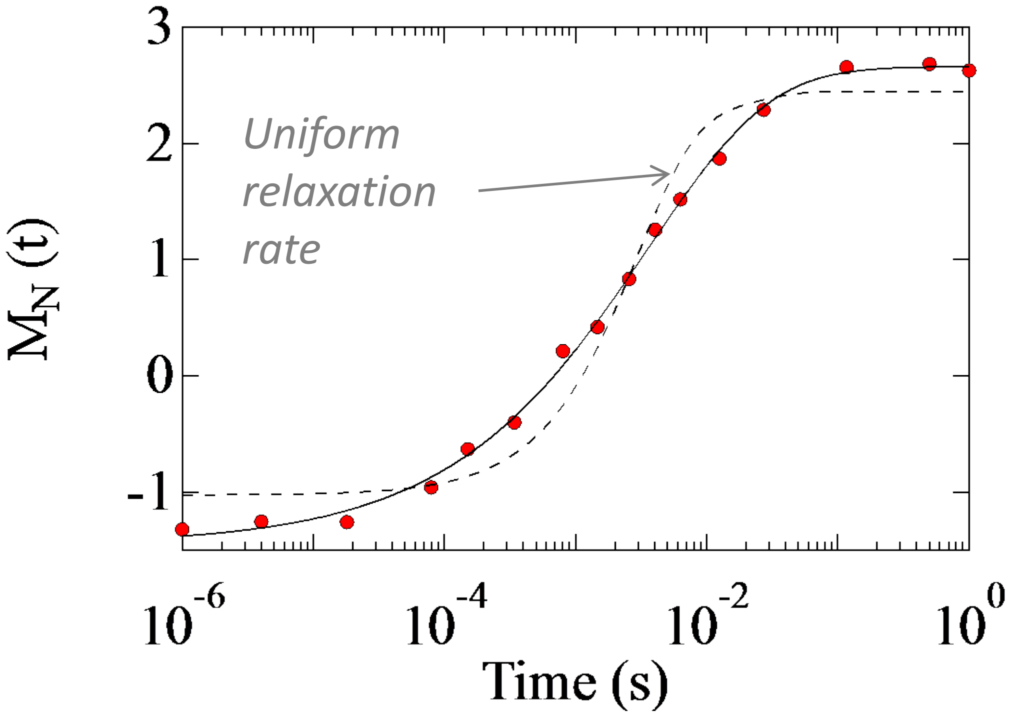
Near transition, slow correlated fluctuations



Low temperature, long-range order

Under the Rug: A Closer Look





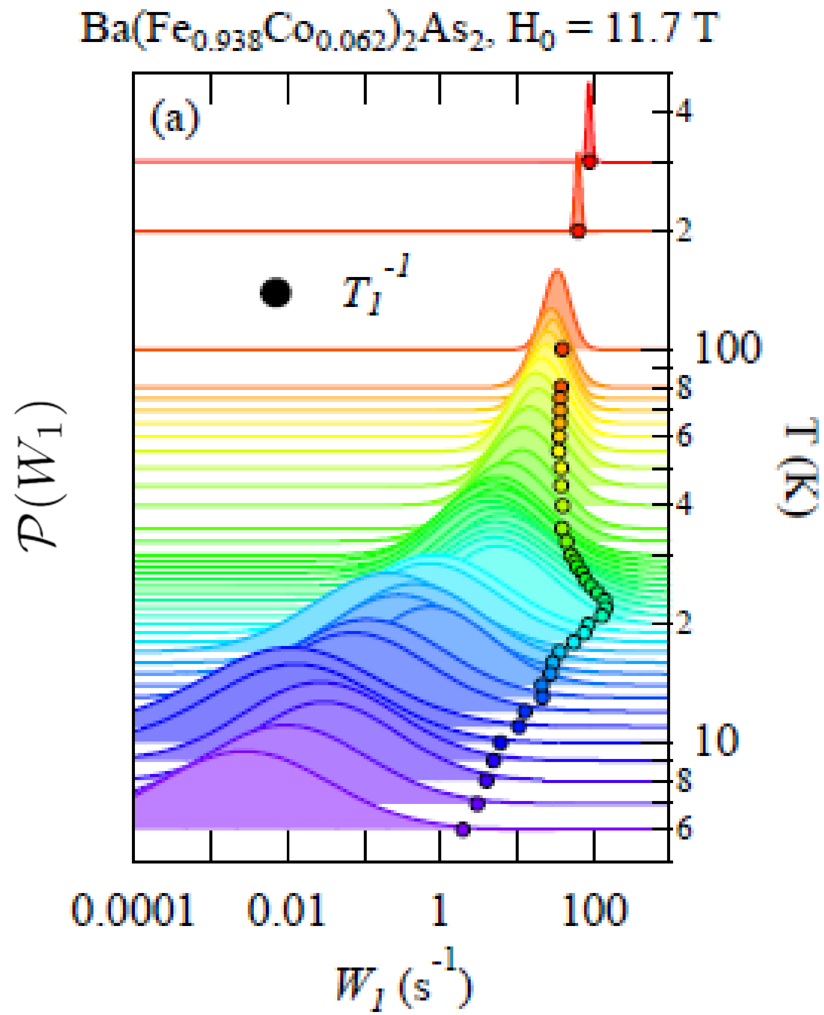
<u>Not all the nuclei see the same fluctuations!</u>

Dynamical Heterogeneity

$$M(t) = \int \mathcal{P}(W_1) f(W_1 t) dW_1$$

$\mathcal{P}(W_1)$: *Distribution of relaxation rates*

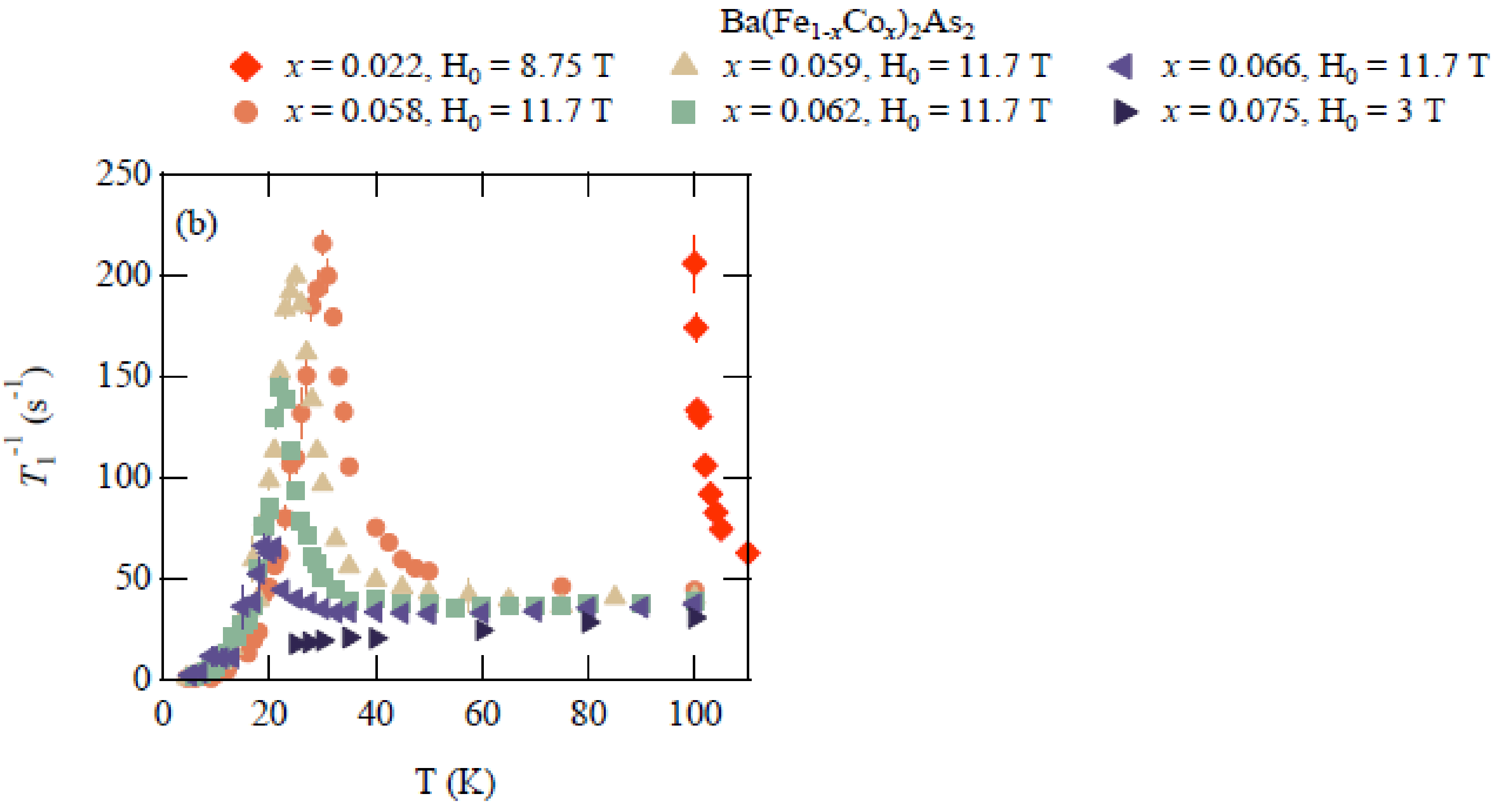
$f(W_1 t)$: $1 - e^{-W_1 t}$



$\mathcal{P}(W_1)$ *characterized by two parameters (fit to log-normal distribution):*

T_1^{-1} *and* σ_1

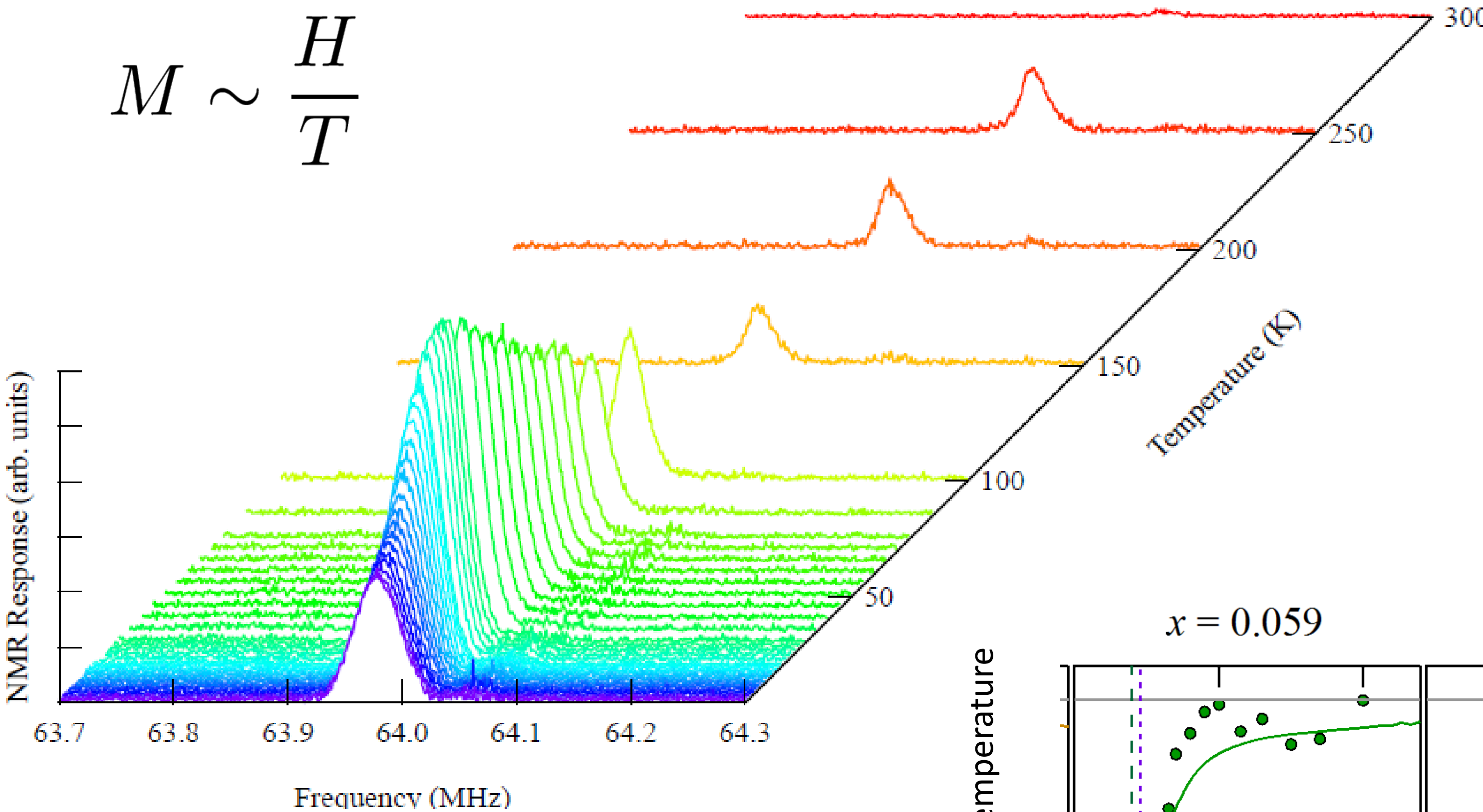
Temperature Dependence

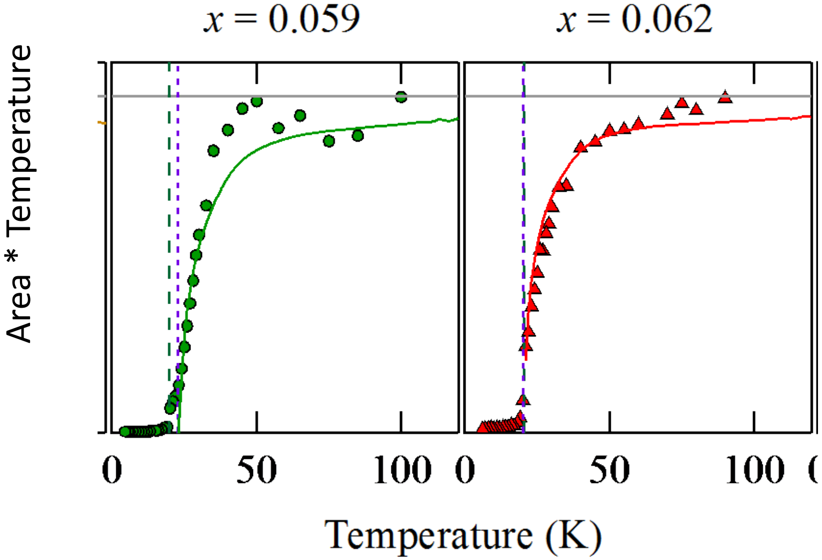


Standard deviation σ_1 increases by 2 orders of magnitude below 100 K

Signal Wipeout

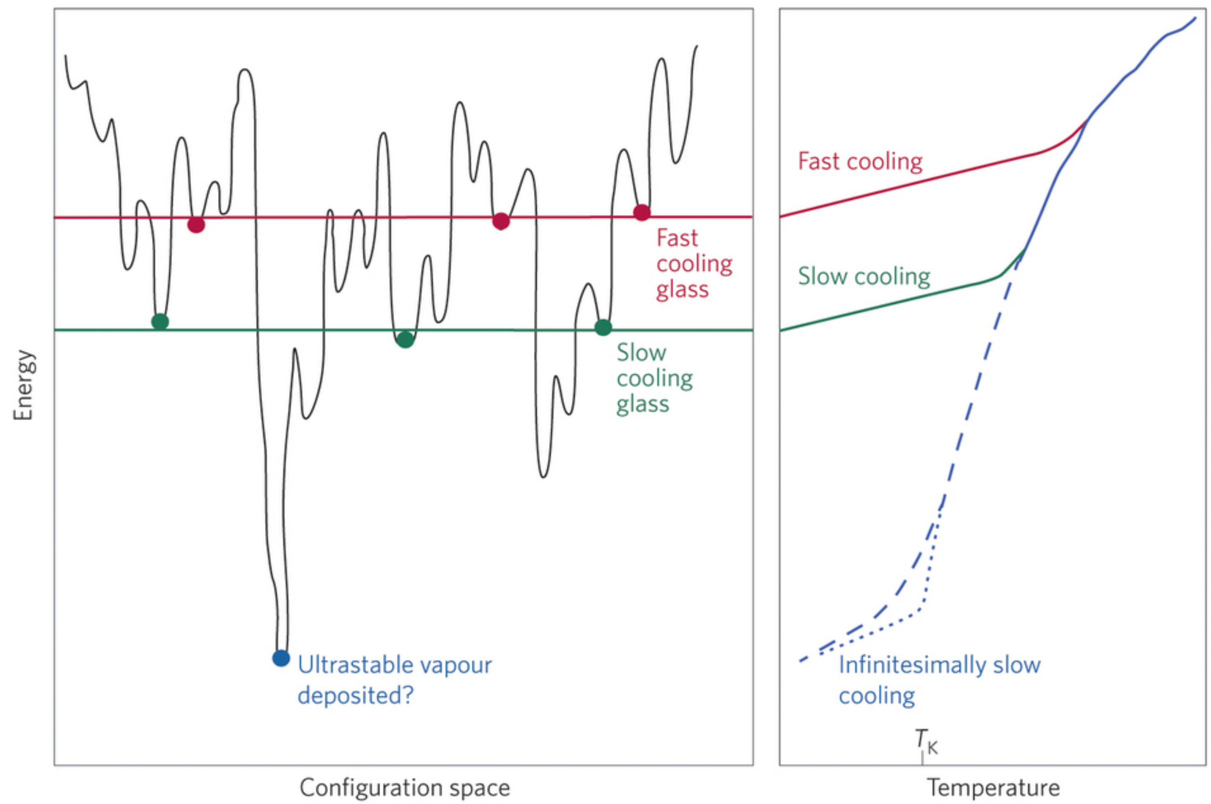
$$M \sim \frac{H}{T}$$





Wipeout coincides with onset of dynamical heterogeneity

Glassy Behavior



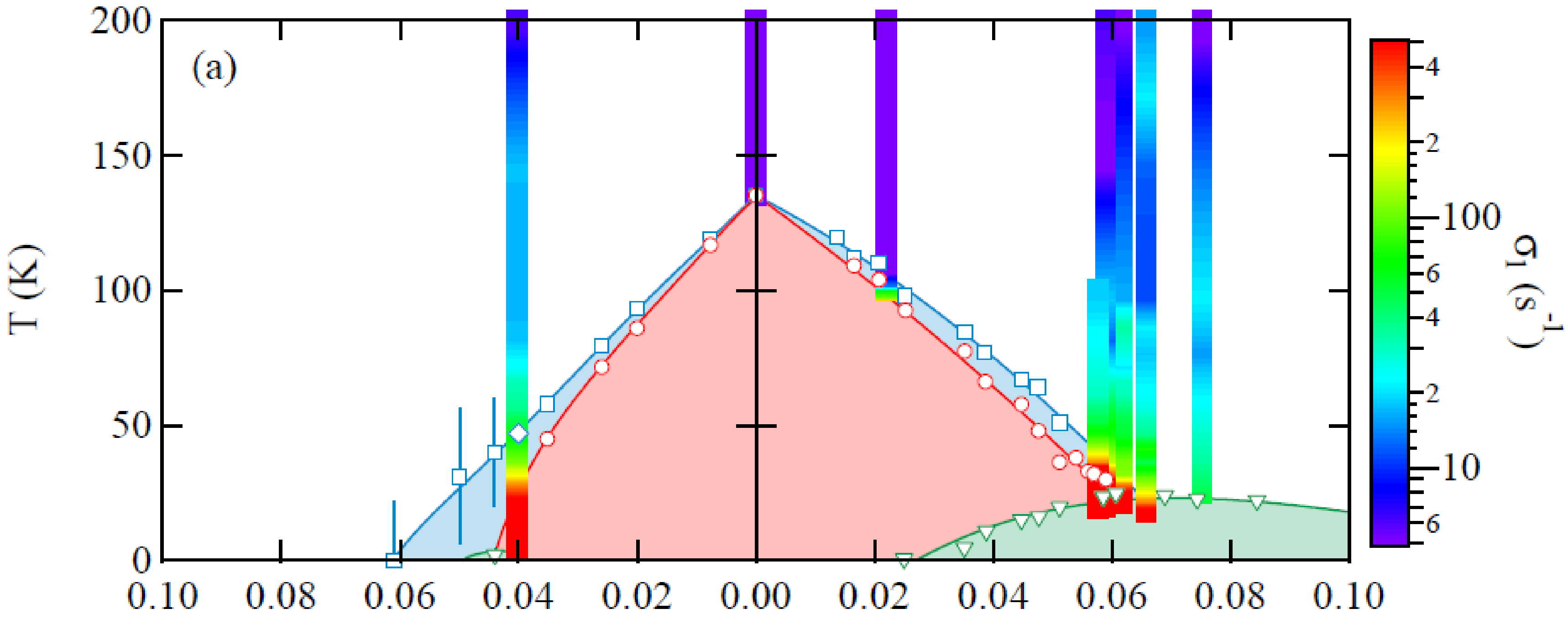
•General feature in statistical mechanics when ergodicity is broken (structural glasses, polymers, spin glasses, etc.)

•symmetry breaking in systems with ***disorder***

Dynamical Heterogeneity

Parisi and Sciortino, Nat. Mat. 2013

Doping Dependence



x in $Ba(Fe_{1-x}Cu_x)_2As_2$ x in $Ba(Fe_{1-x}Co_x)_2As_2$

Dynamical inhomogeneity develops below 100 K, and is more pronounced near the critical doping x = 0.07

- Glassy behavior also has been reported via NMR in: LaFeAs(O,F) (Hammerath PRB 2013) , $Ba(Fe,Rh)_2As_2$ (Bossoni, PRB 2013), and $Ba(Fe,Cu)_2As_2$ (Imai, PRL 2014)

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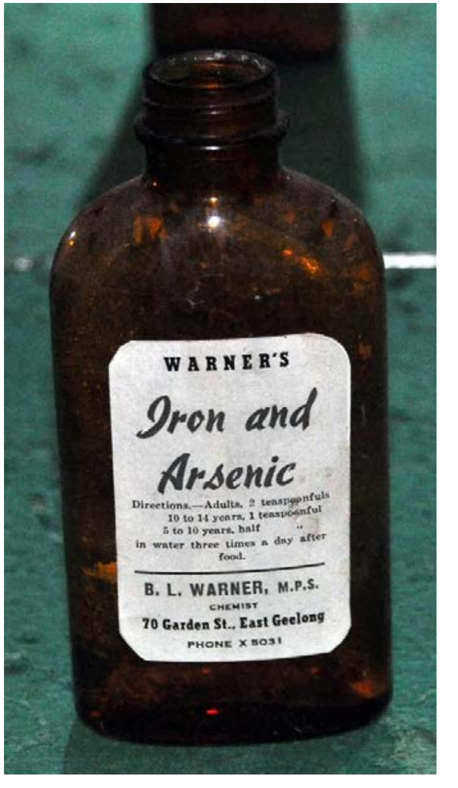
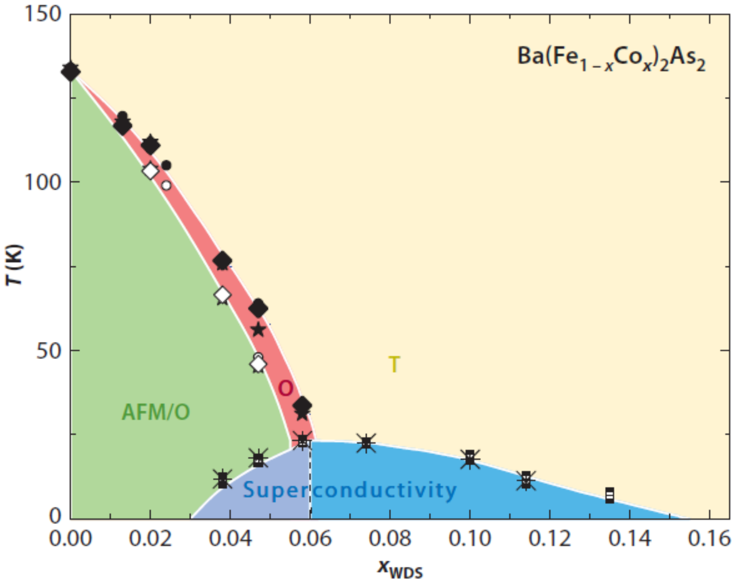
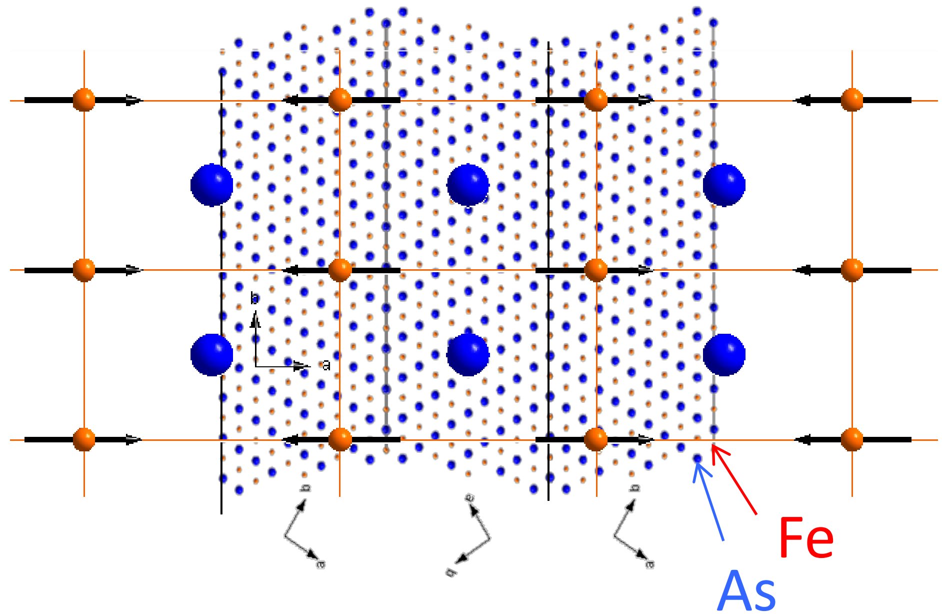
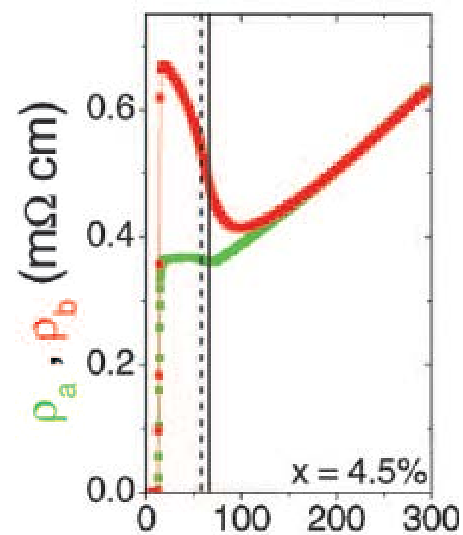
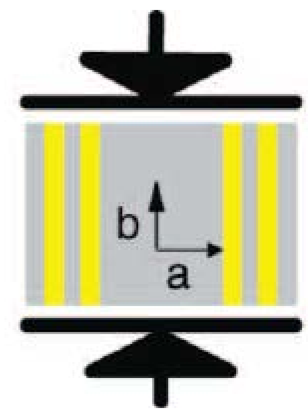


Nematic Order



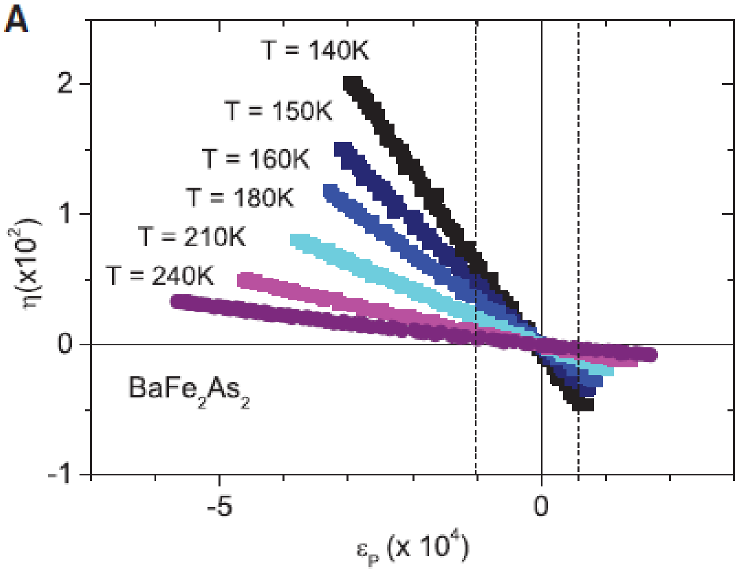






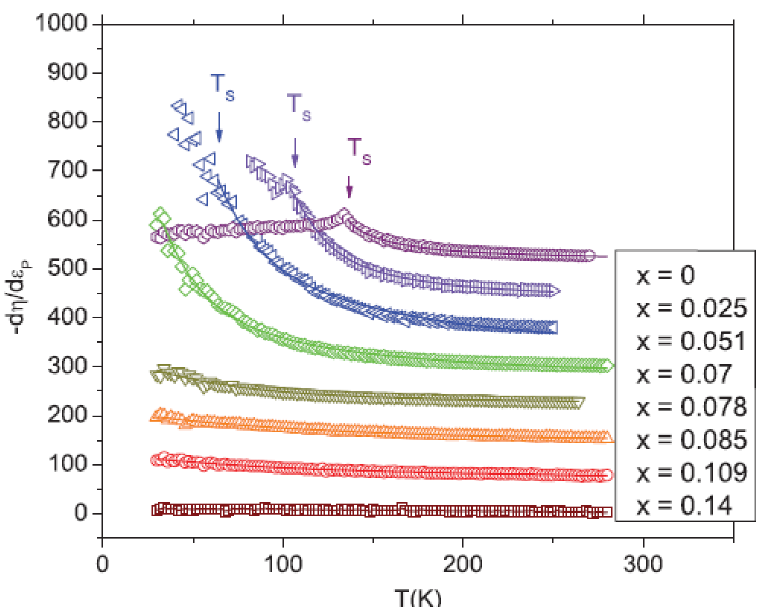
Detwin under uniaxial strain
Chu et al., Science 2010

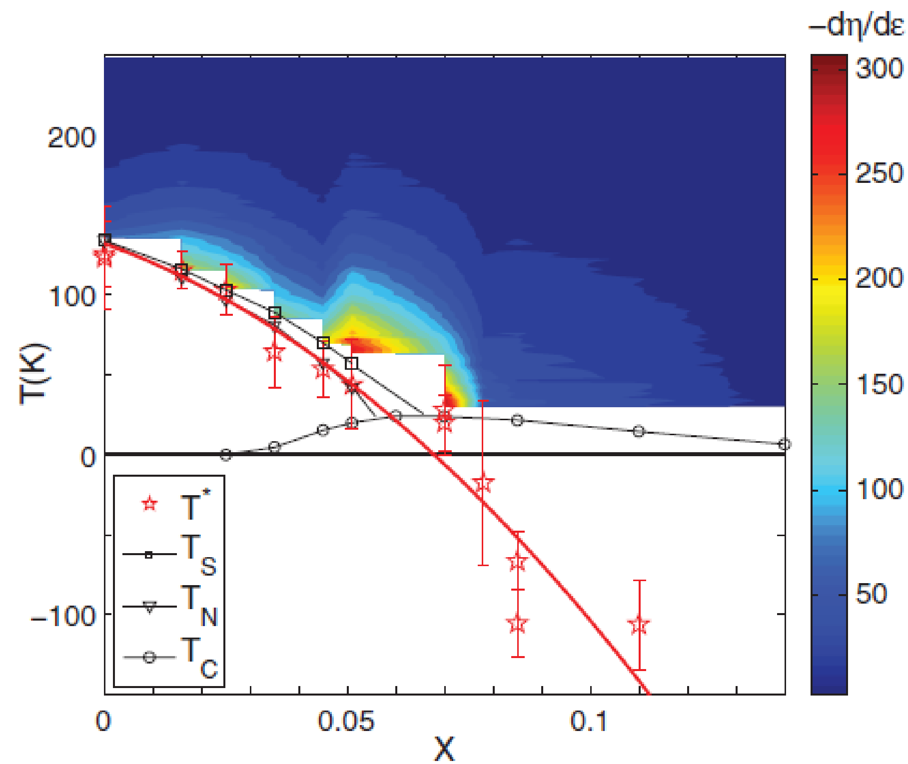
Nematic Susceptibility



Chu et al., Science 2012

Apply strain ε_p , measure nematicity $\eta = \Delta\rho/\rho_0$

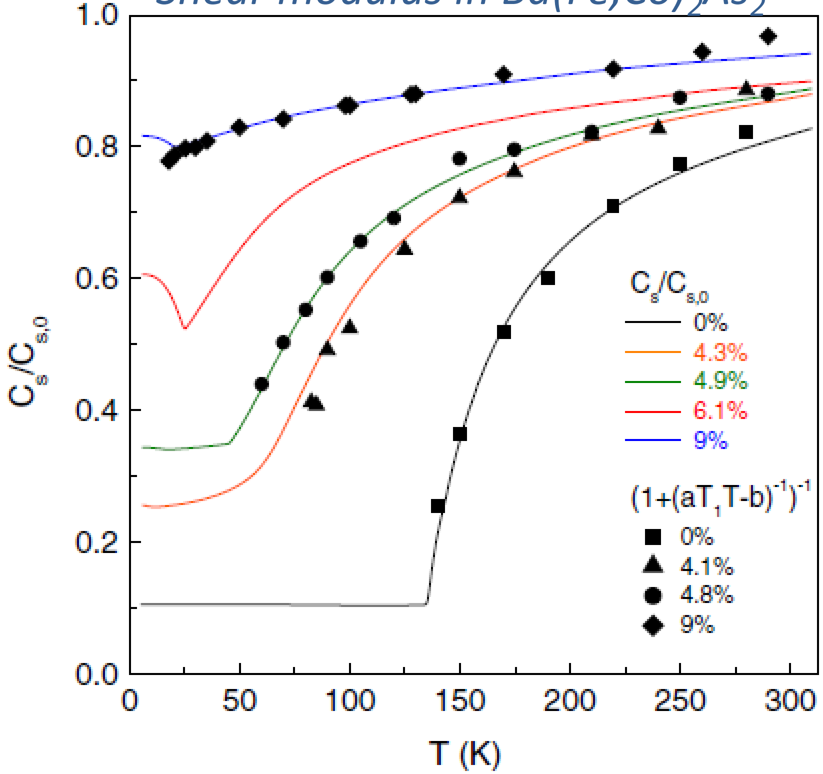


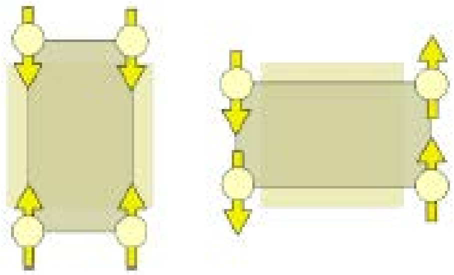


Fluctuation-dissipation theorem:
nematic fluctuations in paramagnetic state

Nematic Fluctuations Drive Spin Fluctuations

Shear modulus in $Ba(Fe,Co)_2As_2$

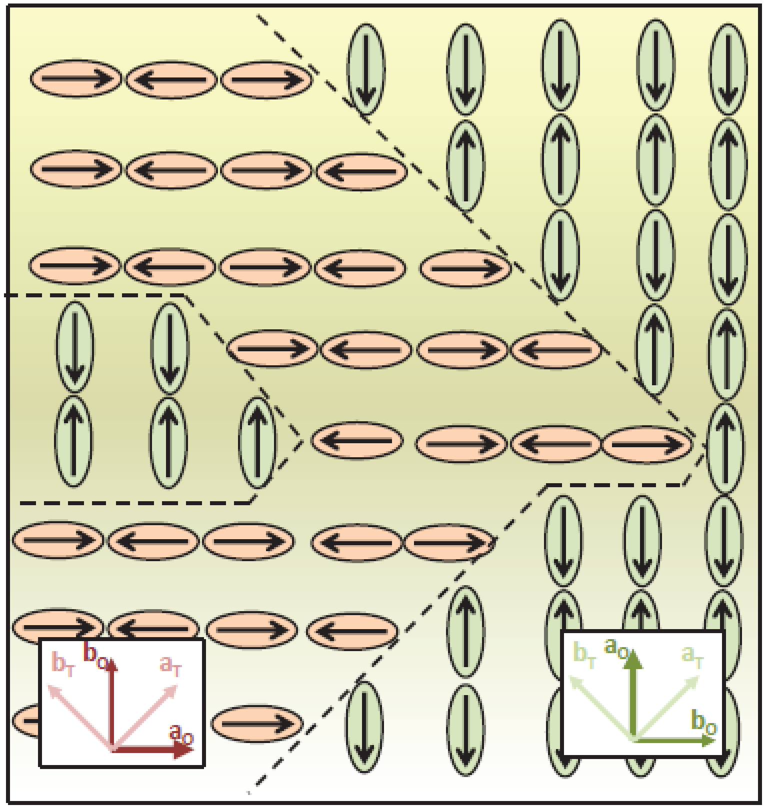




Fernandes et al., PRL 2013

Magnetoelastic coupling leads to scaling between shear modulus and NMR T_1T

Effect of Disorder



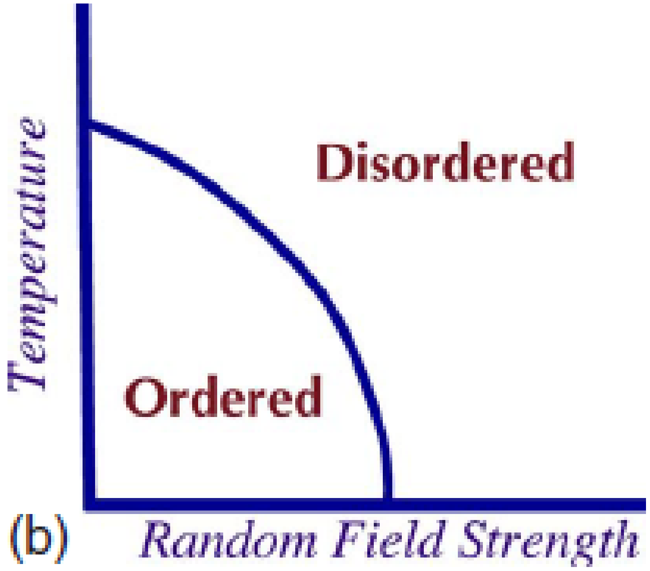
- Nematic order has Ising symmetry
- Dopants/disorder introduce local field gradients -> act as random field
- Random fields in Ising model (Imry & Ma PRL 1975):
- Suppression of long range nematic order
- Inhomogeneous glassy dynamics

Carlson and Dahmen, Nat. Comm. 2010
Carlson et al., PRL 2006
Mezard & Monnason, PRB 1994

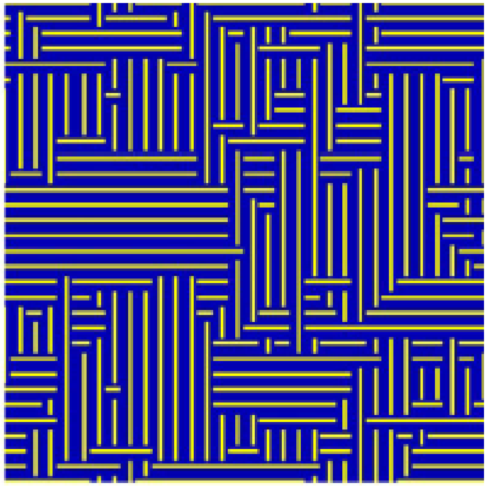
Random Field Ising Model

$$H = -J\sum_{\langle i,j\rangle}\sigma_i\sigma_j - \sum_i (h + h_i)\sigma_i$$

randomly distributed field from local disorder/dopants



(a)Color visualization



(b)Stripe visualization

Kivelson et al., PRL 2006;
Loh, Carlson and Dahmen, PRB 2010

Temperature Dependence

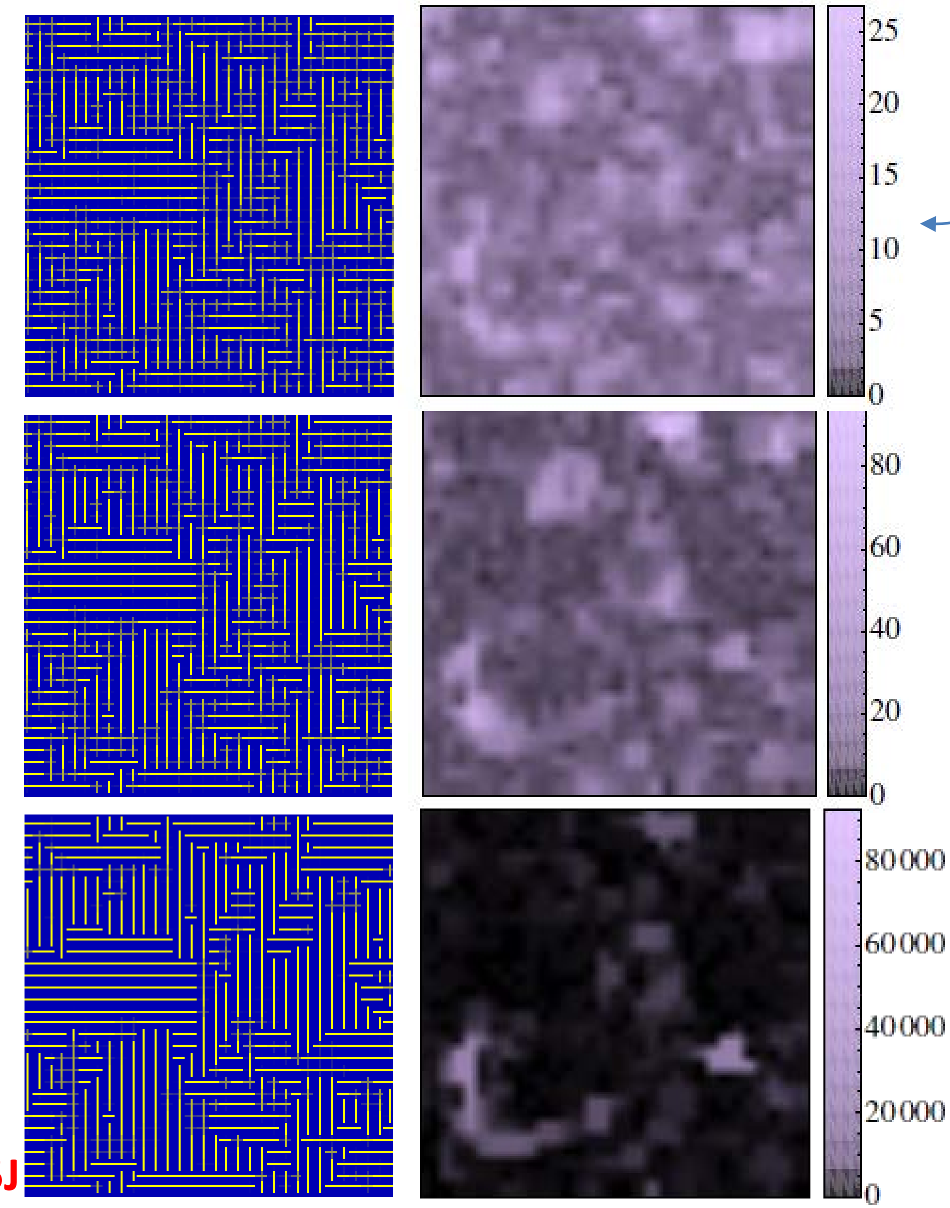
Local nematicity

Local correlation time

T = 2J

T = 1.5J

T = 0.5J

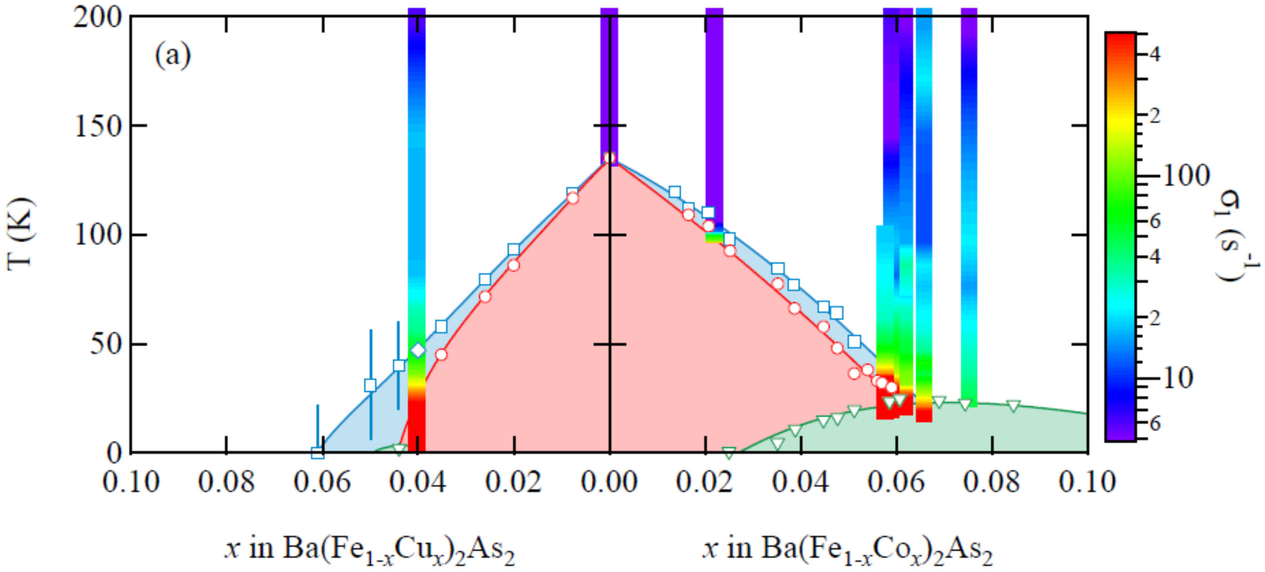


Dynamical heterogeneity!

σ_1 is the standard deviation of this distribution

Loh, Carlson and Dahmen, PRB 2010

Conclusions



•NMR reveals ***dynamical inhomogeneity***

•Glassy dynamics persists up to 100 K in a broad range of materials (Ni, Co, Cu, Rh, P doped $BaFe_2As_2$, $LaFeAsO_{1-x}F_x$)

•Frozen AF clusters coexist with SC

•Likely origin is ***disorder in the vicinity of the nematic quantum critical point***