Argonne NATIONAL LABORATORY

# Single Crystal Diffuse Scattering

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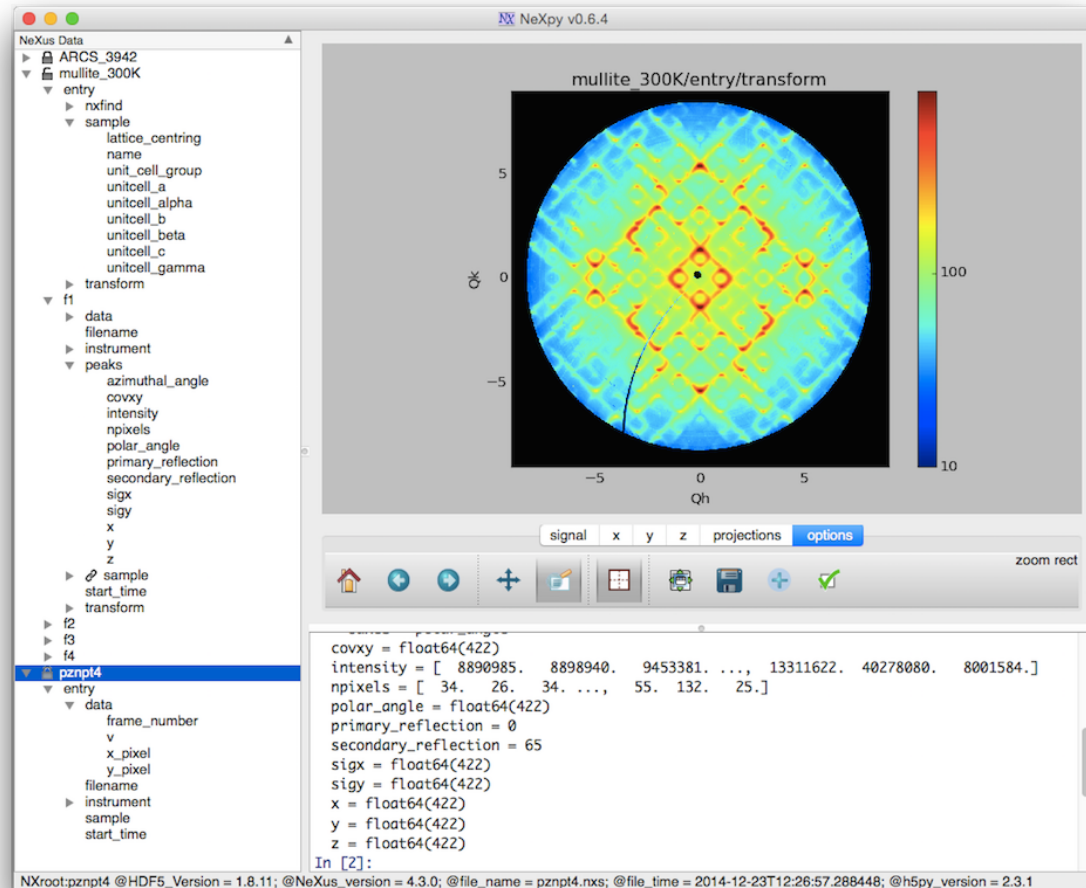
Argonne National Laboratory



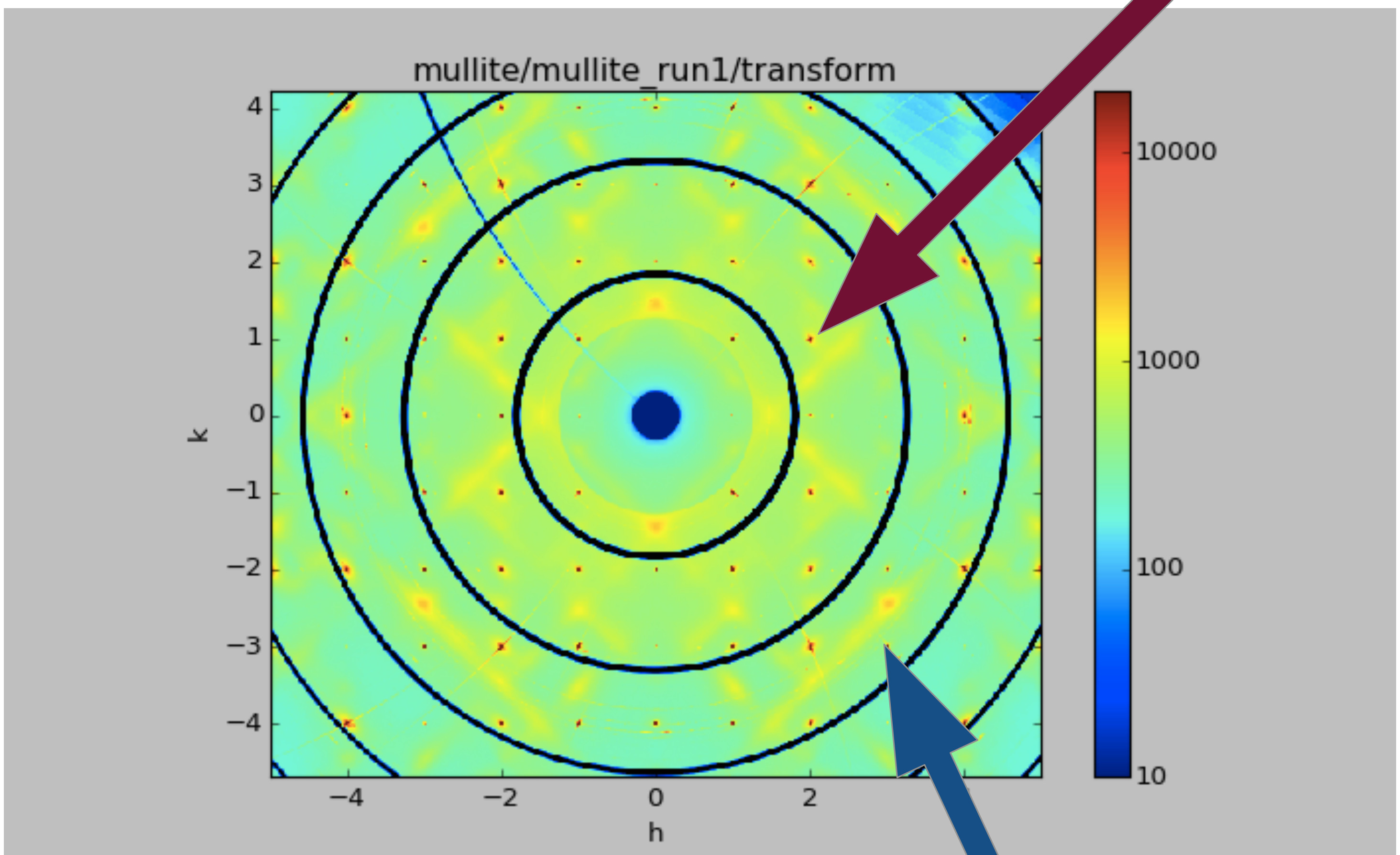

U.S. DEPARTMENT OF ENERGY

# Outline

- What is diffuse scattering?
  - What does it look like?
  - What causes it?
  - Who started it?
- What is it good for?
  - A random walk through disordered materials
- How do I model it?
  - A few equations
  - Rules of thumb
- Case Study 1: Diffuse scattering from vacancies in mullite
- Case Study 2: Huang scattering in bilayer manganites
- How do I look at static disorder?
  - Neutrons *vs* X-rays
  - Corelli - Diffuse scattering with elastic discrimination
- Diffuse scattering - the musical

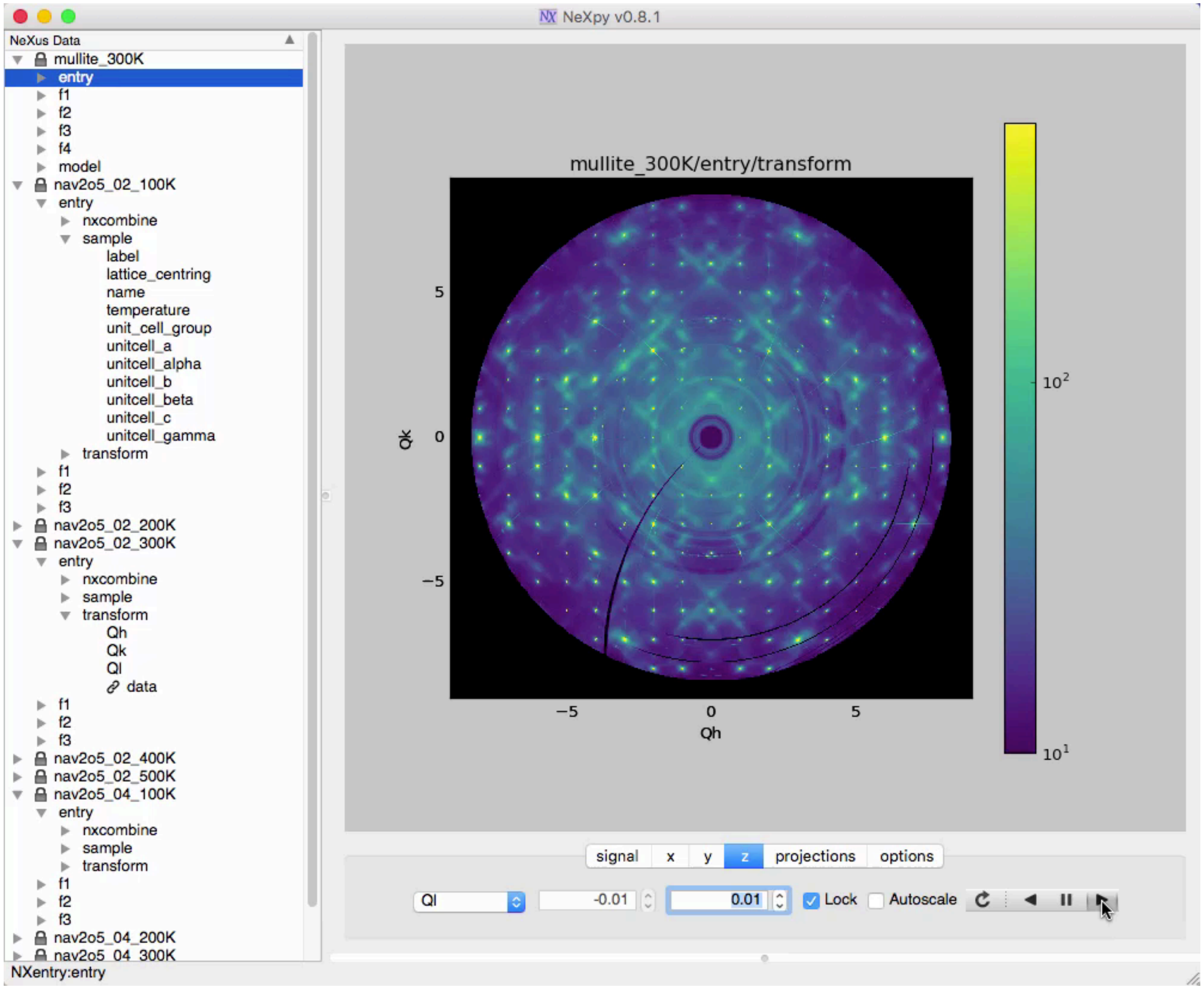
# Bragg Scattering *vs* Diffuse Scattering

Bragg Scattering
Average Structure



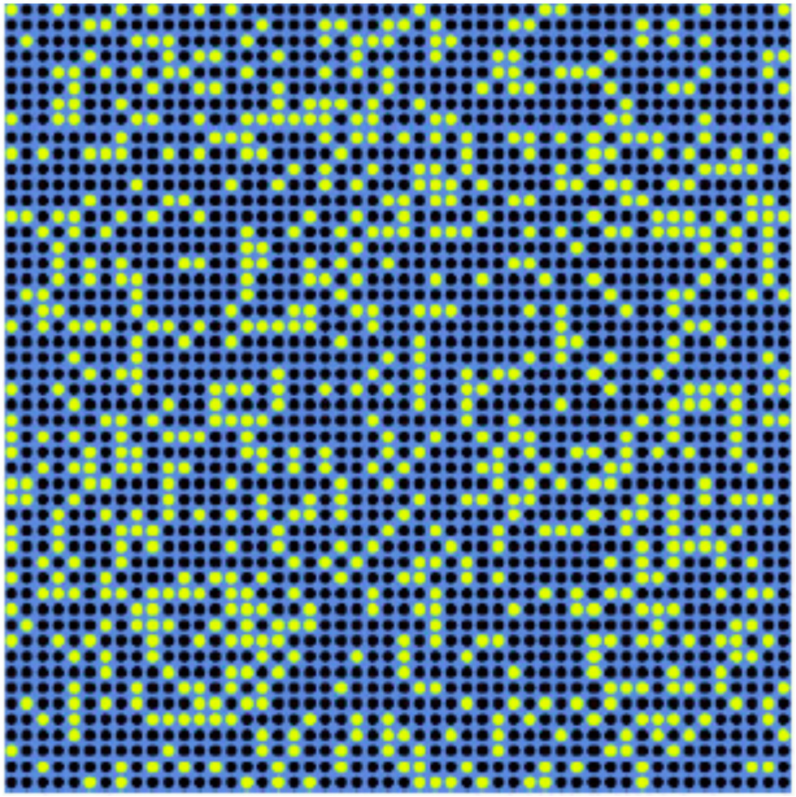

Diffuse Scattering
Deviations from the Average Structure

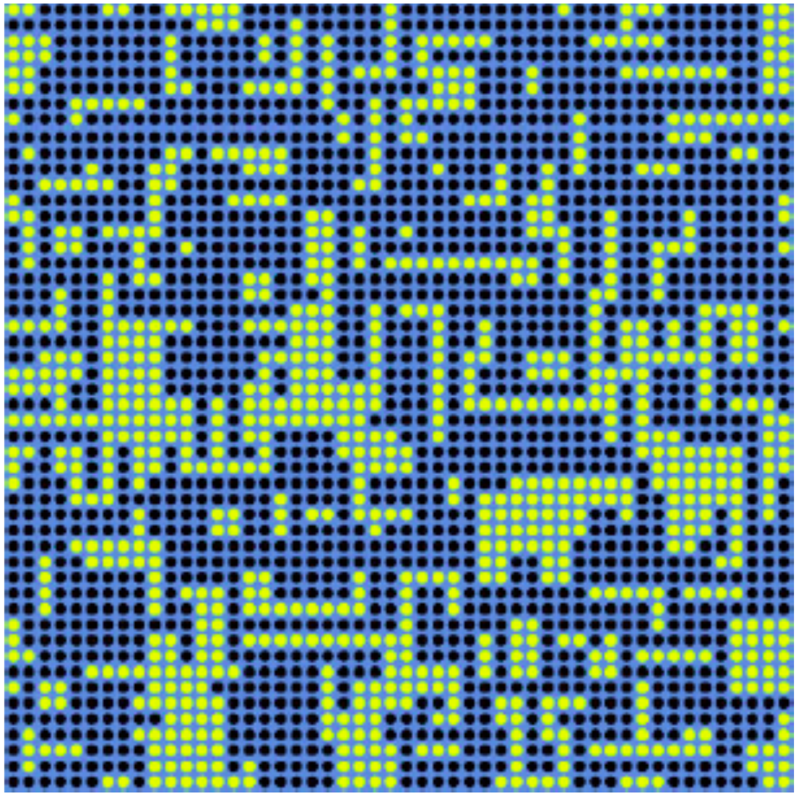
# Single Crystal Diffuse Scattering in 3D



# Simple Example of Disorder

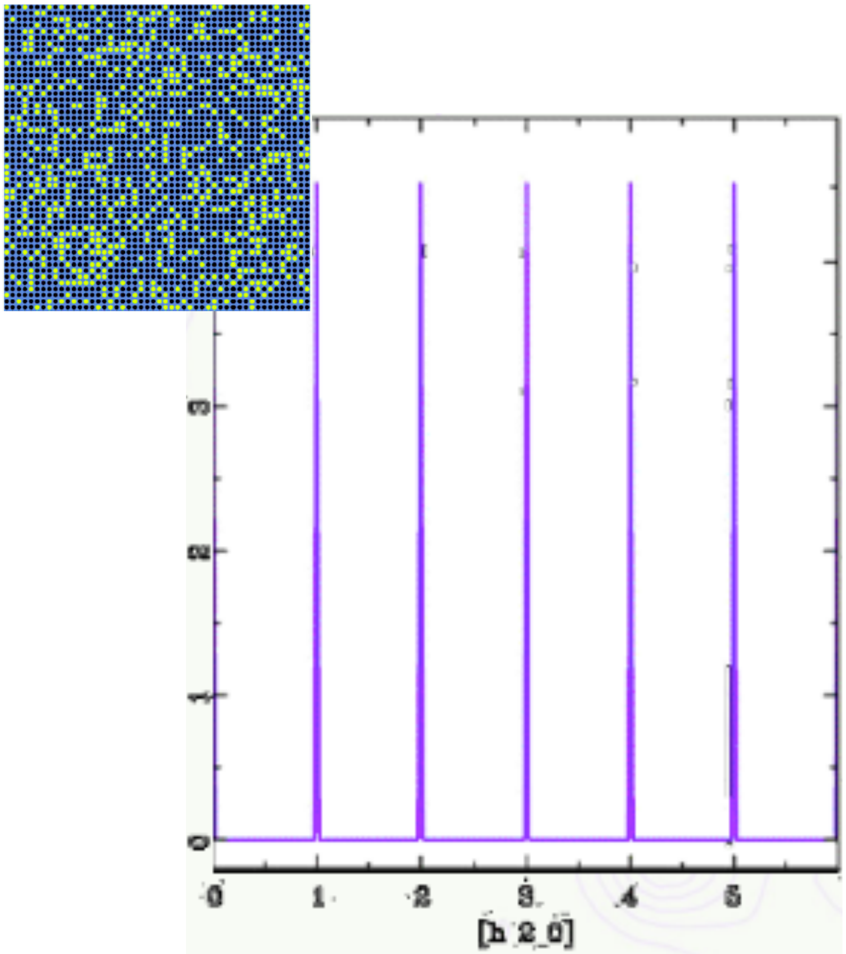
- In these examples, 30% of atoms (blue dots) have been replaced by vacancies (green dots)
  - Left-Hand-Side: random substitution
  - Right-Hand-Side: high probability of vacancy clusters
    - Thanks to Thomas Proffen

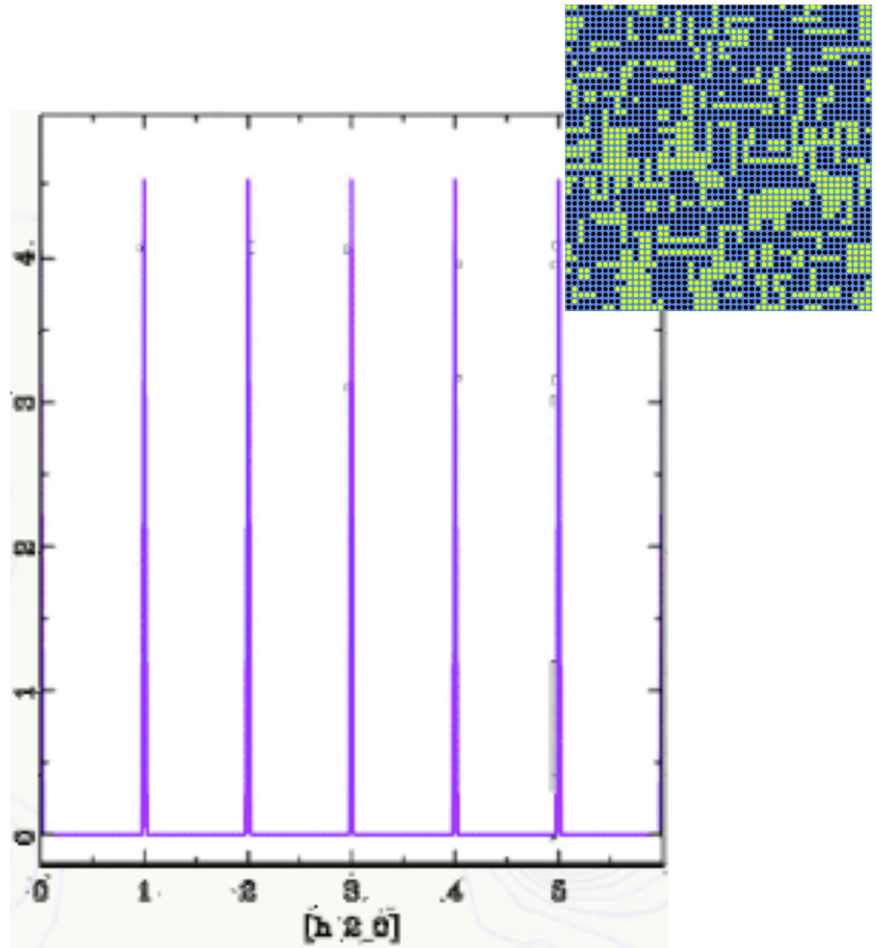




# Bragg Scattering

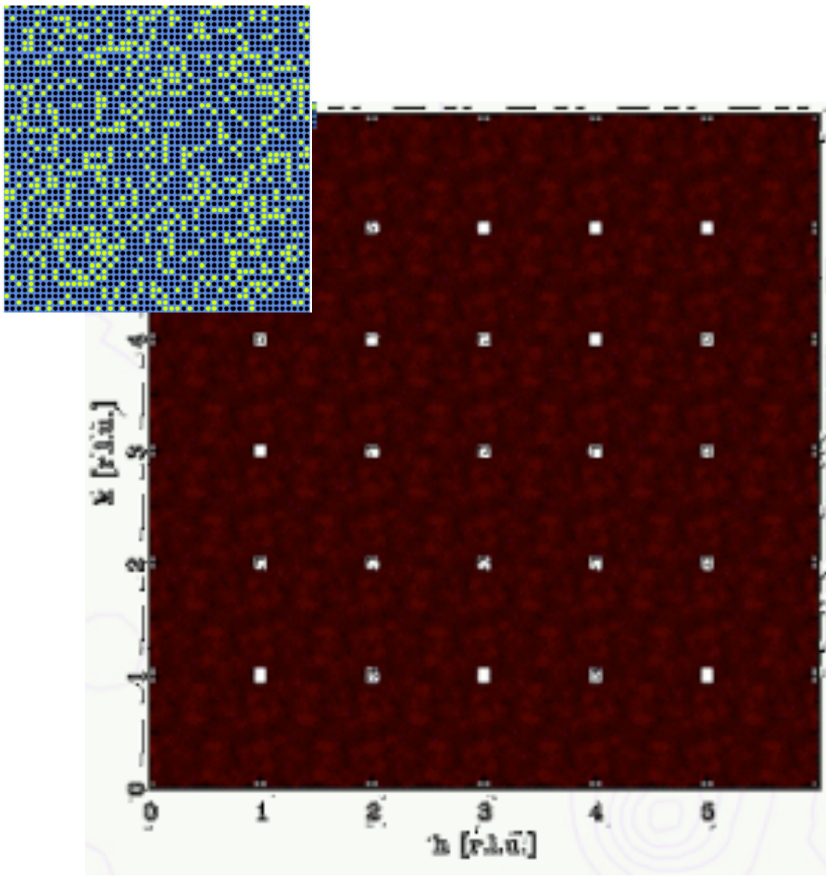
- Bragg scattering is determined by the average structure.
  - Since the average vacancy occupation is identical, both examples have identical Bragg peaks

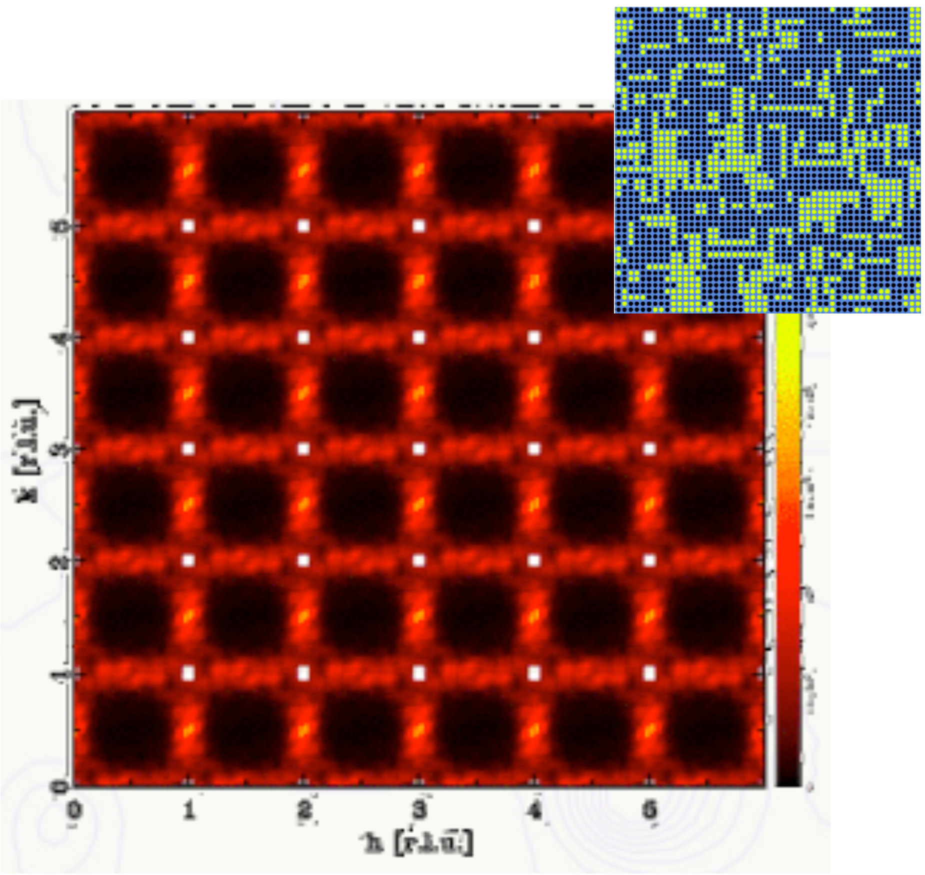


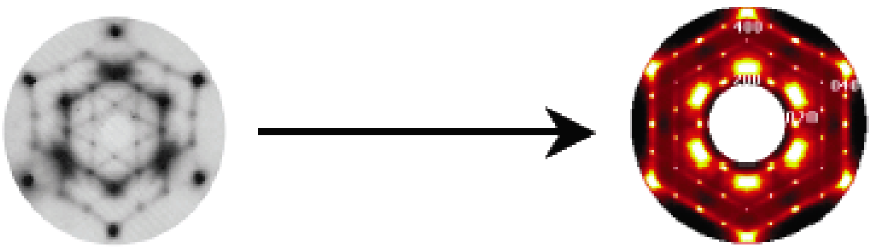
# Diffuse Scattering

- The diffuse scattering is quite different in the two examples
  - Random vacancy distributions lead to a constant background (Laue monotonic scattering)
  - Vacancy clusters produce rods of diffuse scattering connecting the Bragg peaks



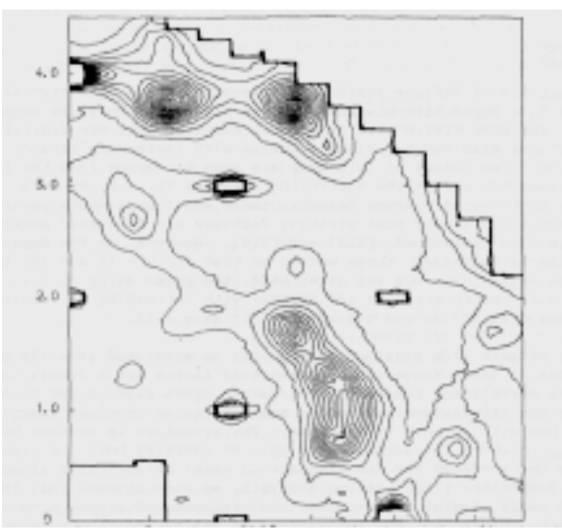


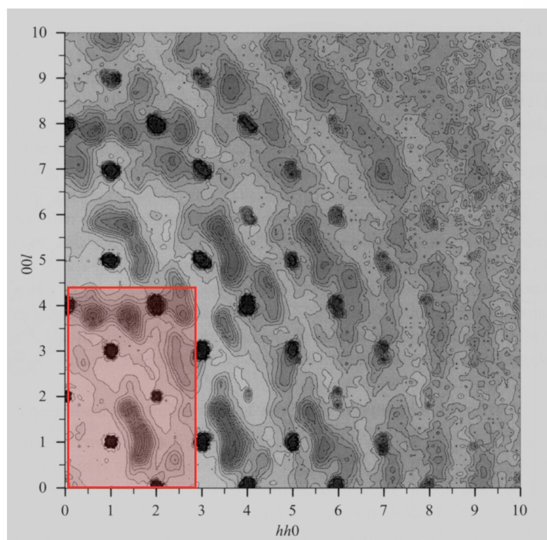
# An Ultra-Short History of Advances in Diffuse Scattering

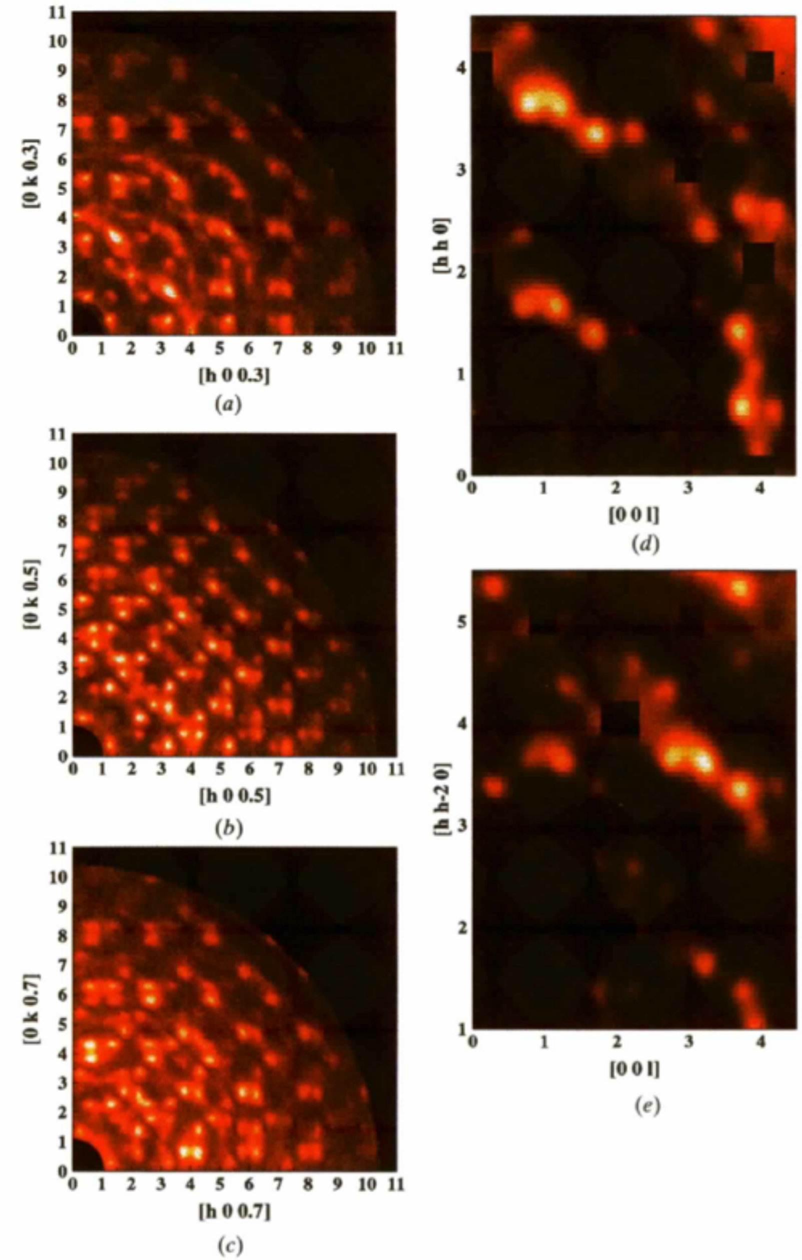


1941 BENZIL 2001

Yttria-Stabilized Zirconia





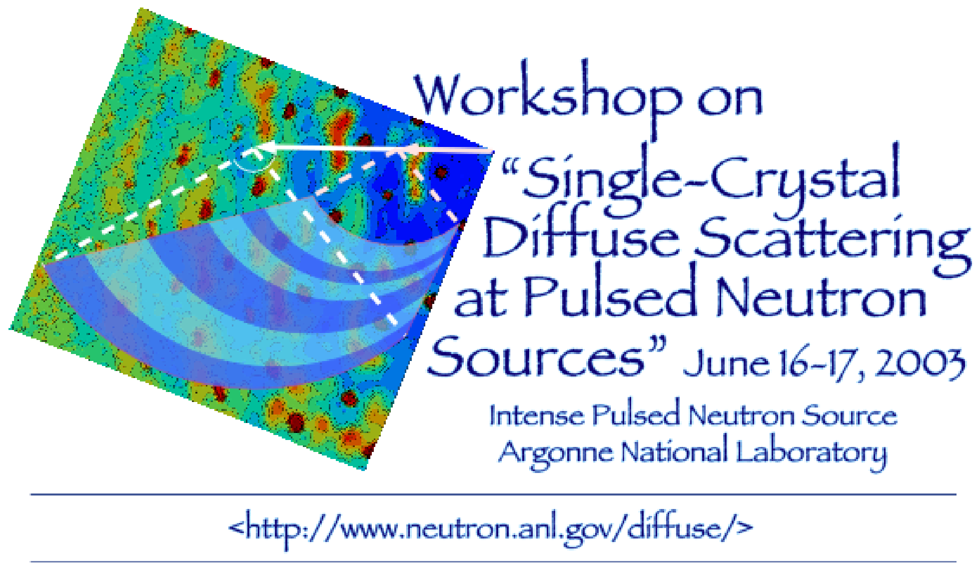




T. Proffen and T. R. Welberry J. Appl. Cryst. **31**, 318 (1998)

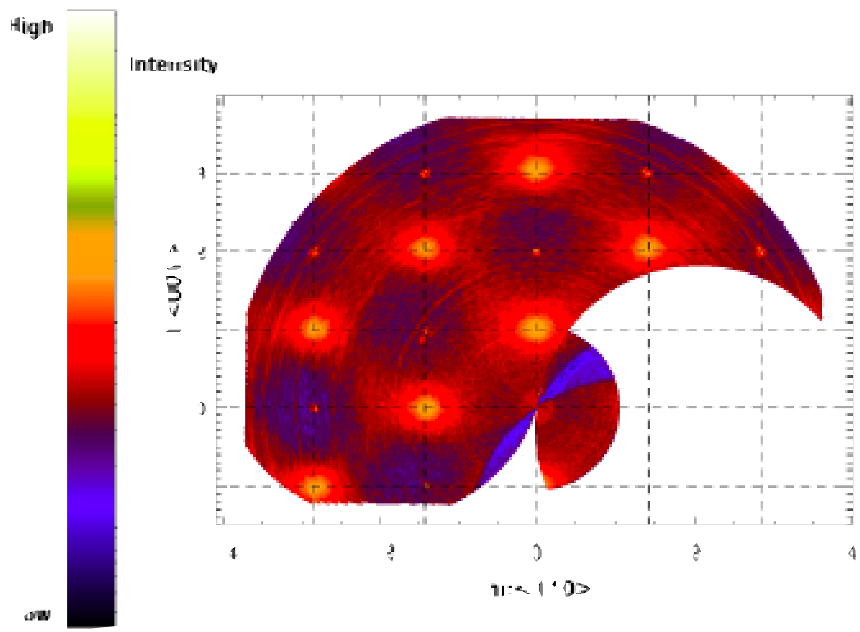
# What is it good for?

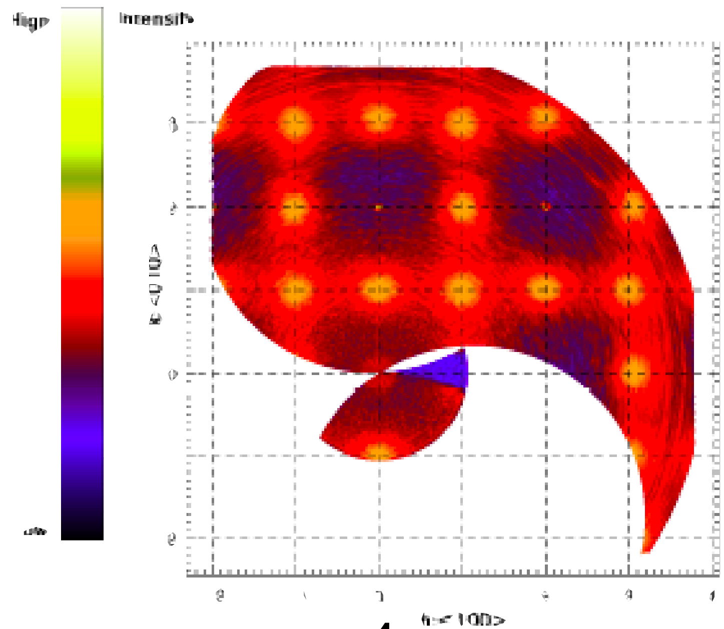
# Science Impacted by Diffuse Scattering

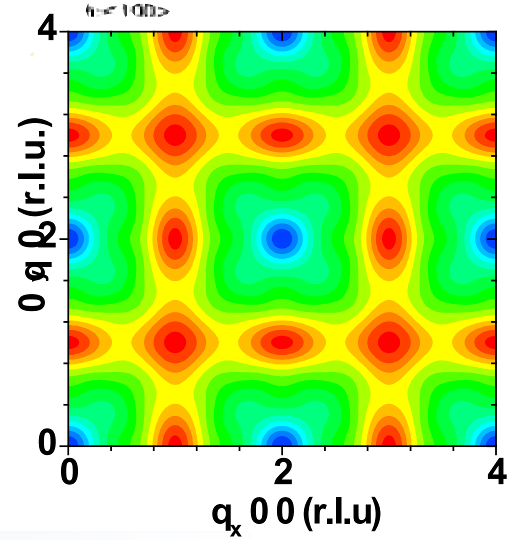
- Subjects identified at the *Workshop on Single Crystal Diffuse Scattering at Pulsed Neutron Sources*
  - Stripes in cuprate superconductors
  - Orbital correlations in transition metal oxides (including CMR)
  - Nanodomains in relaxor ferroelectrics
  - Defect correlations in fast-ion conductors
  - Geometrically frustrated systems
  - Critical fluctuations at quantum phase transitions
  - Orientational disorder  in molecular crystals
  - Rigid unit modes in framework structures
  - Quasicrystals
  - Atomic and magnetic defects in metallic alloys
  - Molecular magnets
  - Defect correlations in doped semiconductors
  - Microporous and mesoporous compounds
  - Host-guest systems
  - Hydrogen-bearing materials
  - Soft matter - protein configurational disorder using polarization analysis of spin-incoherence
  - Low-dimensional systems
  - Intercalates
  - Structural phase transitions in geological materials



# Diffuse Scattering from Metallic Alloys



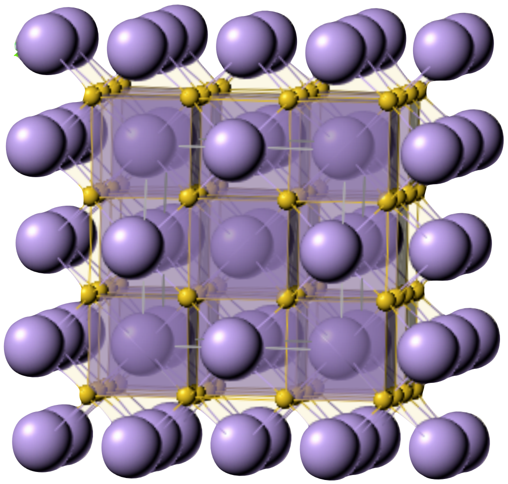




## Short-range Order in Null Matrix $^{62}Ni_{0.52}Pt_{0.52}$

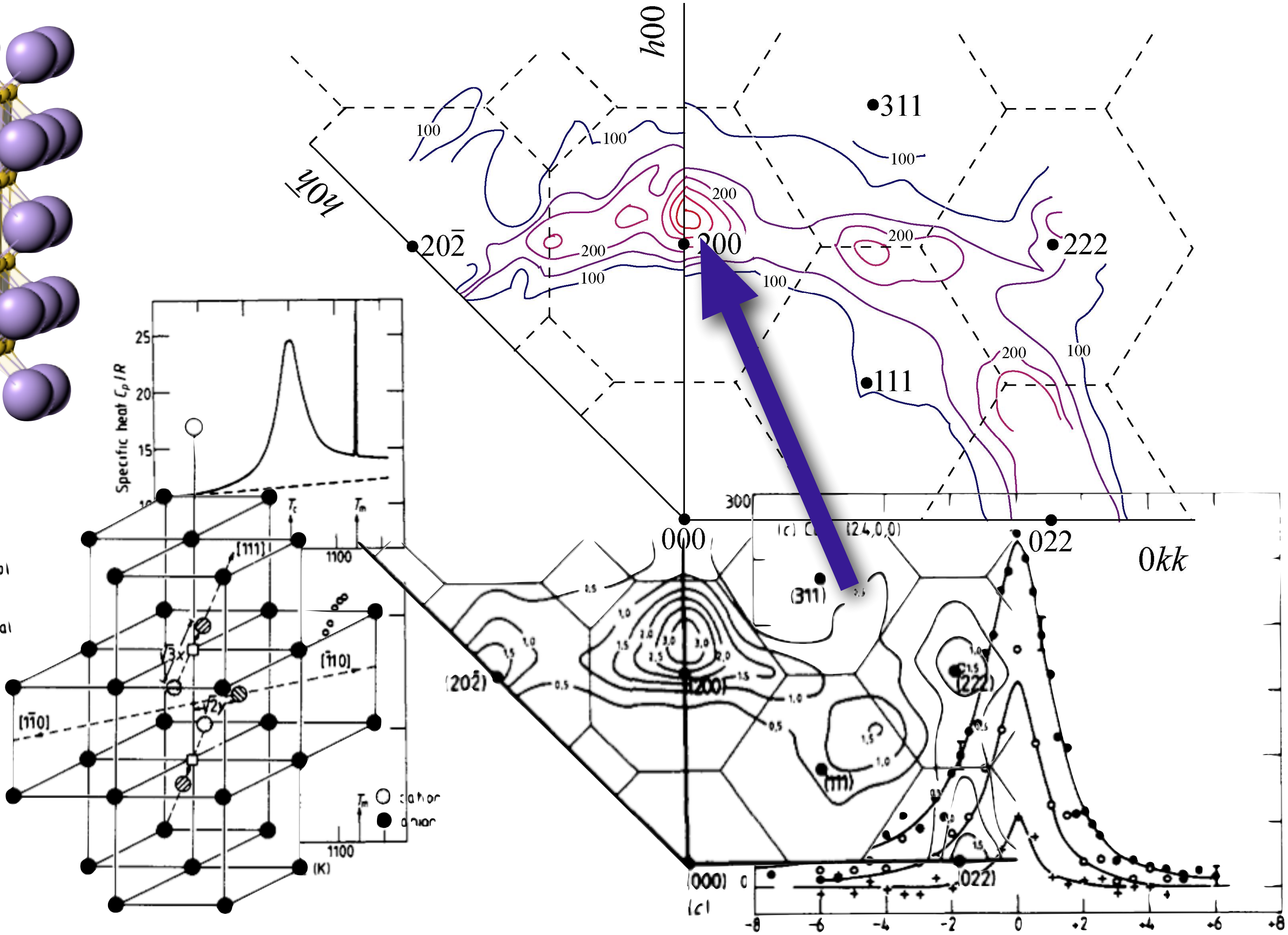
J. A. Rodriguez, S. C. Moss, J. L. Robertson, J. R. D. Copley, D. A. Neumann, and J. Major
Phys. Rev. B **74**, 104115

# Diffuse Scattering from a Fast-Ion Conductor



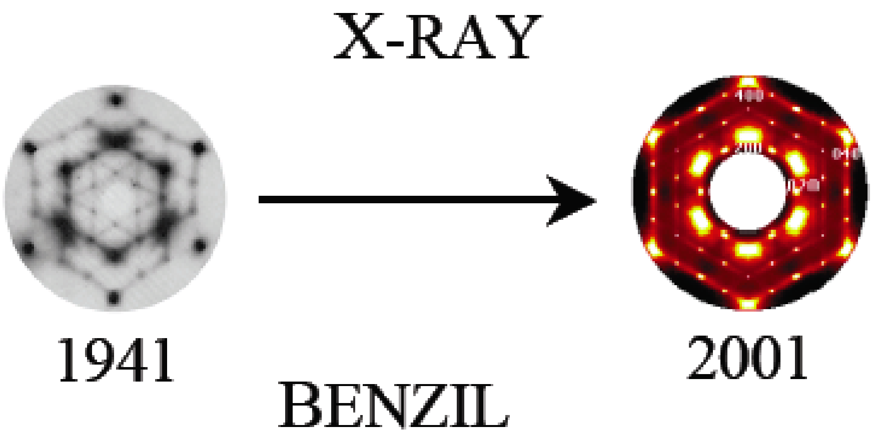
$CaF_2$

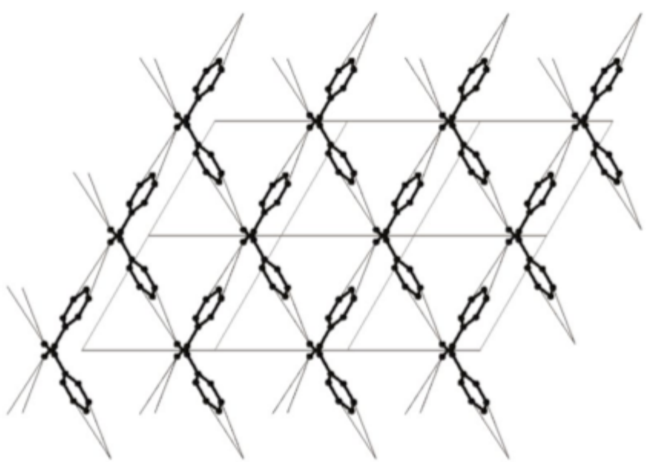
Frenkel pair: vacancy, interstitial
Relaxed anion: vacancy, interstitial

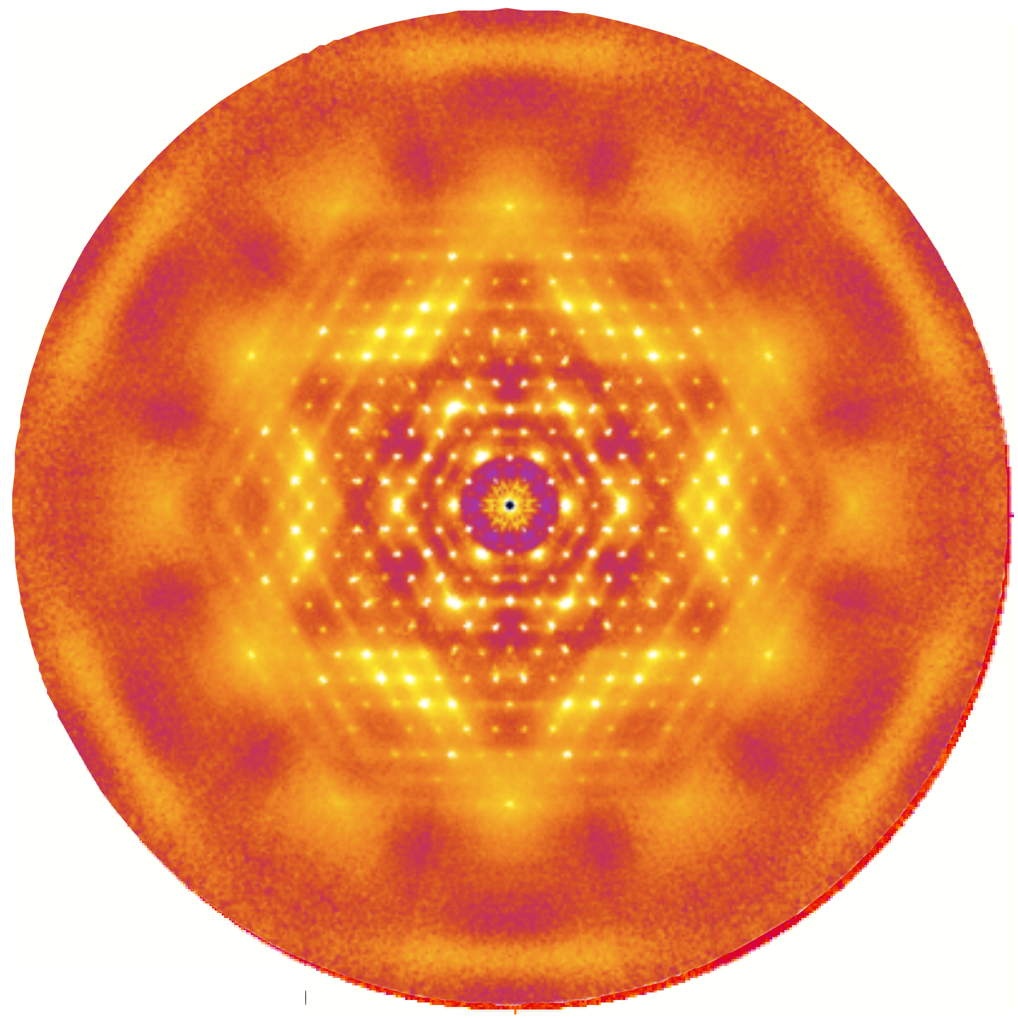



M. T. Hutchings *et al* J. Phys. C **17**, 3903 (1984)

# Diffuse Scattering from Molecular Solids

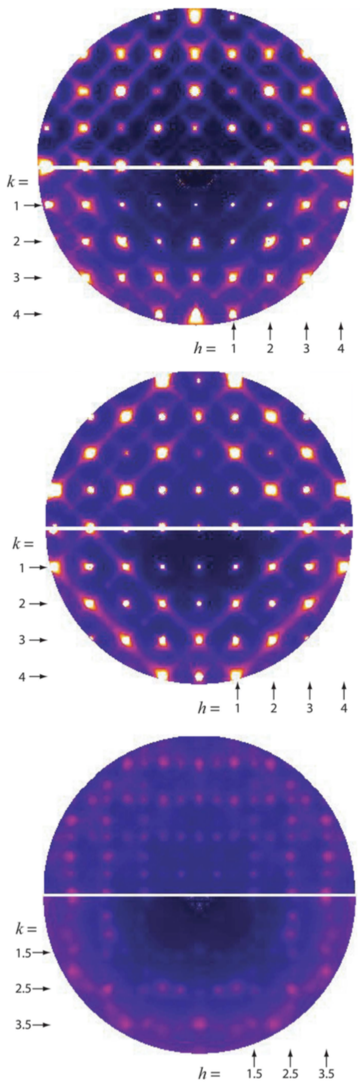


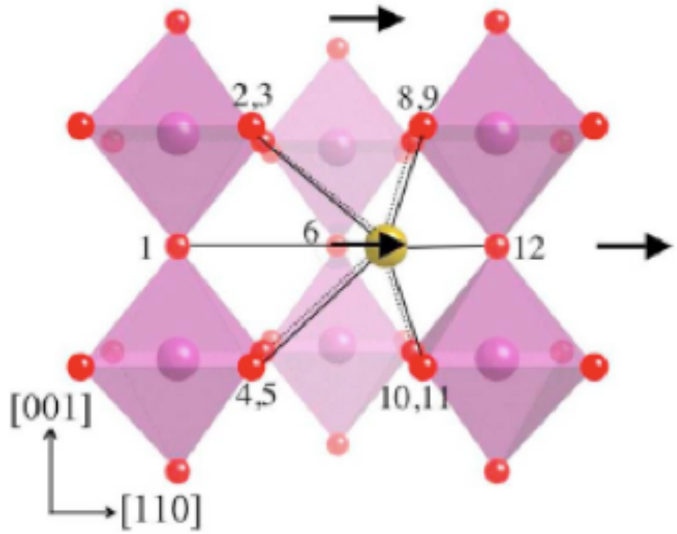





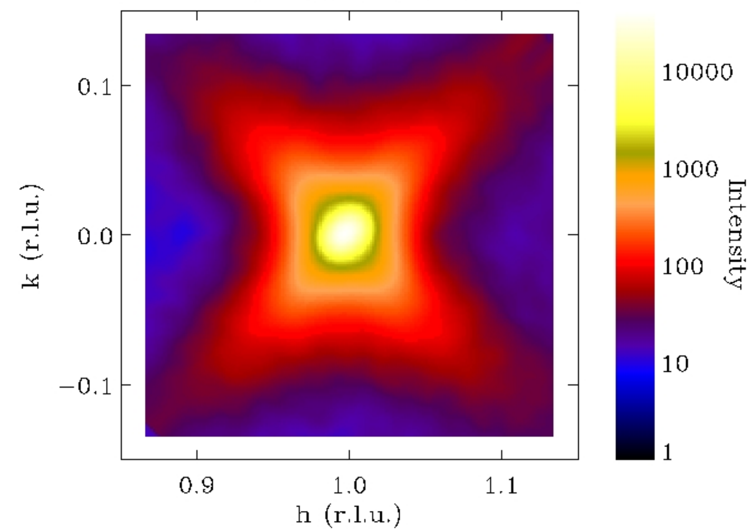
T. R. Welberry *et al* J. Appl. Cryst. **36**, 1400 (2003)

# Diffuse Scattering from Relaxor Ferroelectrics

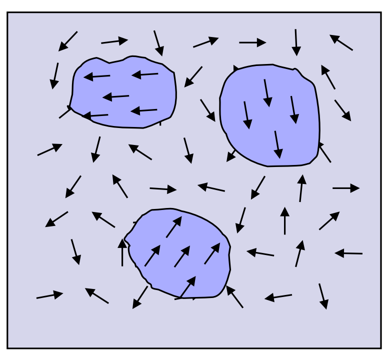




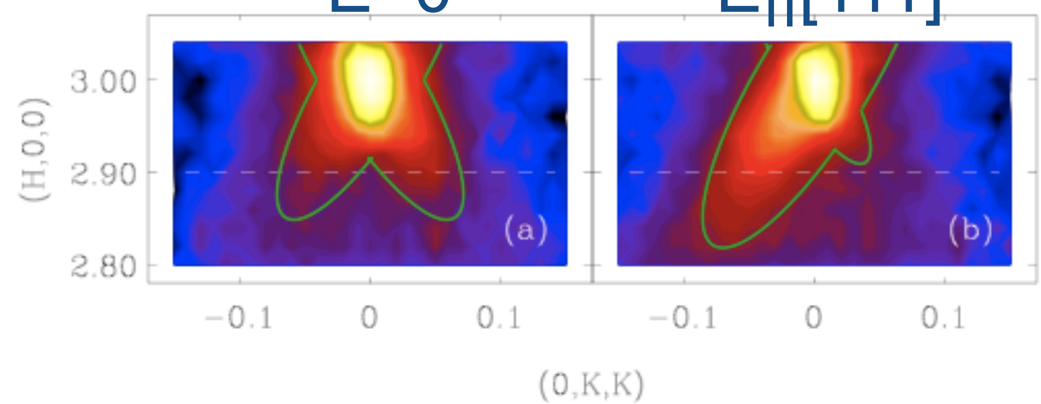

## Lead Magnesium-Niobate




## Lead Zinc-Niobate



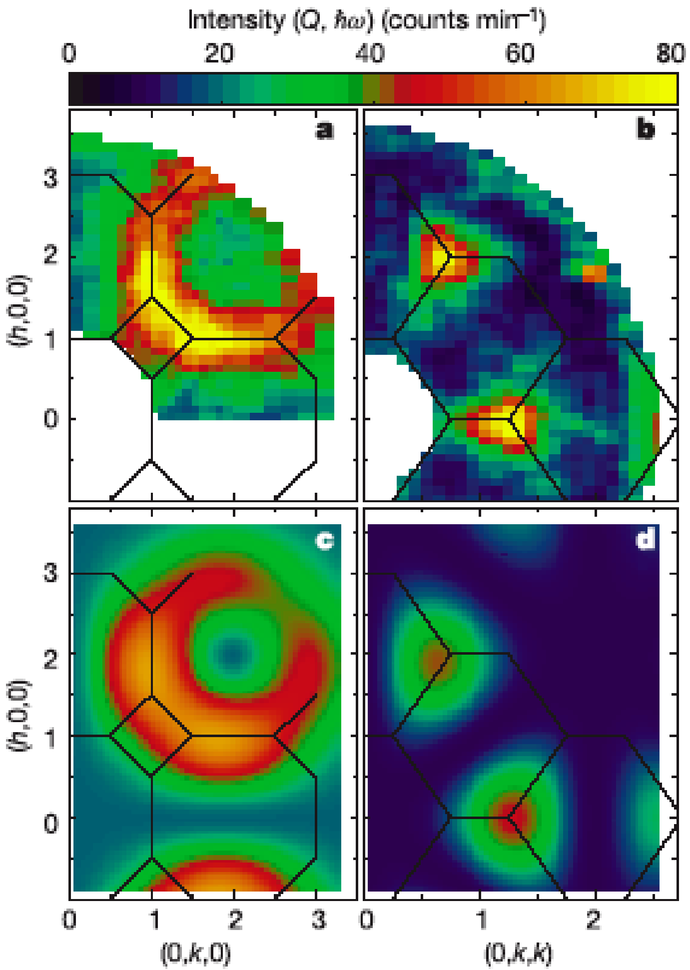
E=0 E||[111]

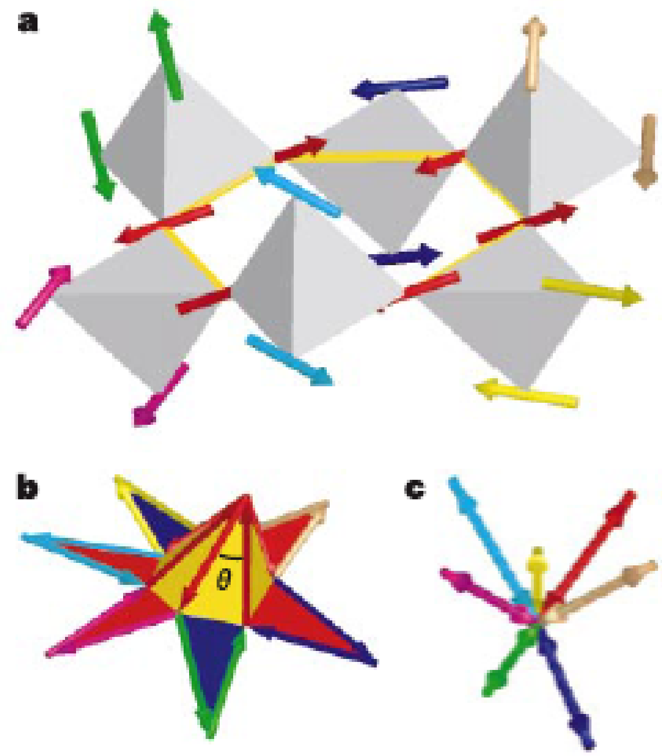



T. R. Welberry *et al* J. Appl. Cryst. **38**, 639 (2005)

G. Xu, P. M. Gehring, G. Shirane, Phys. Rev. B **72**, 214106 (2005).

# Magnetic Diffuse Scattering from Geometric Frustration



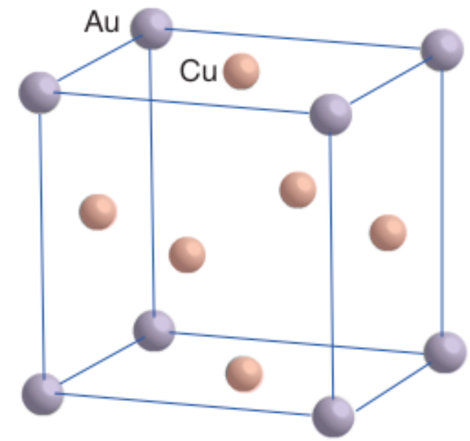

$ZnCr_2O_4$

S.-H. Lee *et al* Nature **418**, 856 (2002)

# How do I model it?

# A Few Equations

V. M. Nield and D. A. Keen *Diffuse Neutron Scattering From Crystalline Materials* (2001)
T. R. Welberry *Diffuse X-ray Scattering and Models of Disorder* (2004)




J. M. Cowley, J. Appl. Phys. **21**, 24 (1950)

$$I = \sum_i \sum_j b_i b_j \exp(i\mathbf{Q} \cdot \mathbf{r}_{ij})$$

- **Laue Monotonic Diffuse Scattering**

$$I = \bar{b}^2 \sum_{ij} \exp(i\mathbf{Q} \cdot \mathbf{r}_{ij}) + N(\overline{b^2} - \bar{b}^2);\ \bar{b}^2 = (c_A b_A + c_B b_B)^2;\ \overline{b^2} = c_A c_B (b_B - b_A)^2$$

- **Cowley Short-Range Order**

$$I_{diffuse} = N c_A c_B (b_B - b_A)^2 + \sum_{ij} \alpha_i c_B c_A (b_B - b_A)^2 \exp(i\mathbf{Q} \cdot \mathbf{r}_{ij});\qquad \alpha_i = \left(1 - \frac{p_i}{c_A}\right)$$

- **Warren Size Effect**

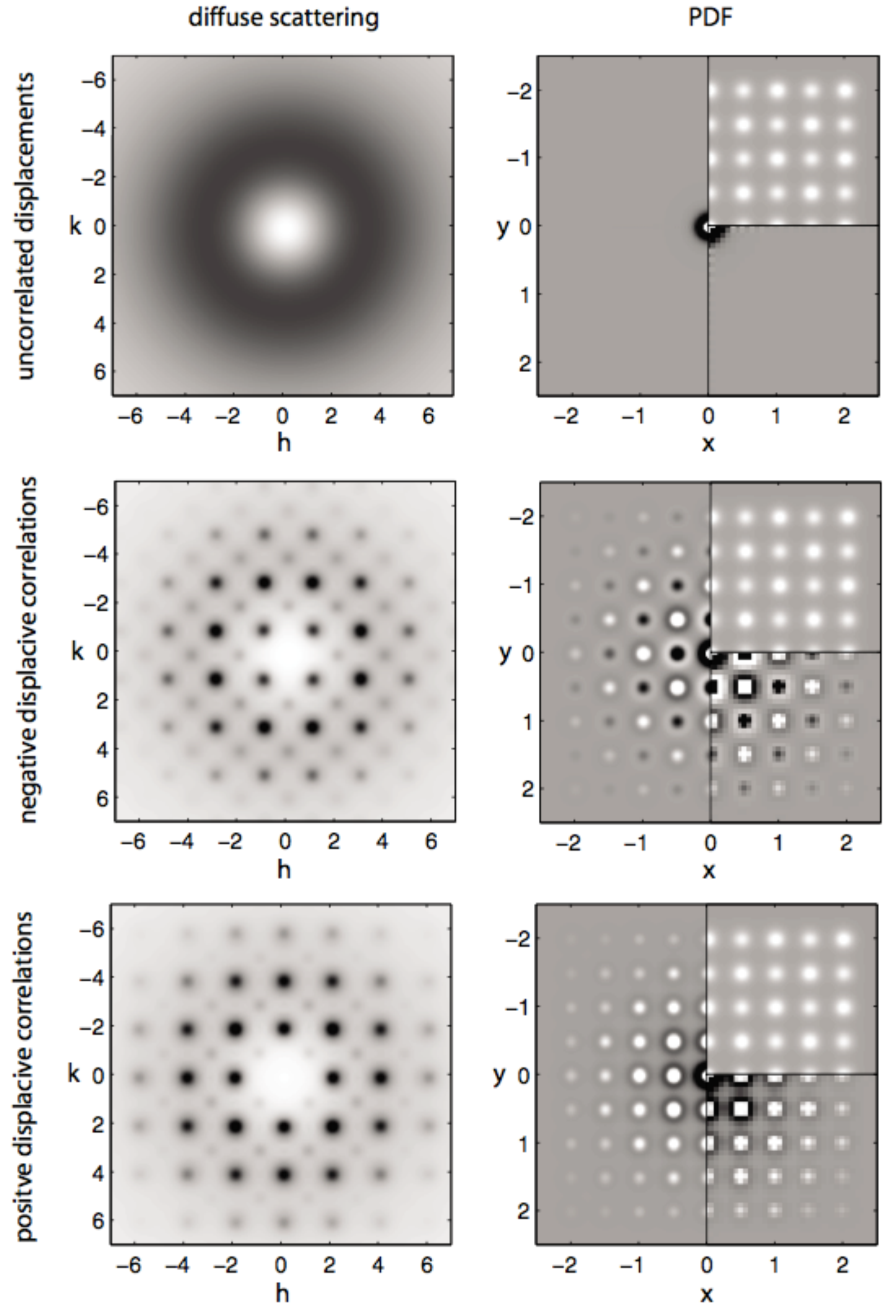
$$I_{diffuse} = N c_A c_B (b_B - b_A)^2 \left(1 + \sum_{ij} \alpha_i \exp(i\mathbf{Q} \cdot \mathbf{r}_{ij} + \sum_{ij} \beta_i \exp(i\mathbf{Q} \cdot \mathbf{r}_{ij}\right);\ \beta_i = f(\epsilon^i_{AA}, \epsilon^i_{BB})$$

- **Borie and Sparks Correlations**

$$I = \sum_i \sum_j b_i b_j \exp\left(i\mathbf{Q} \cdot (\mathbf{R}_i - \mathbf{R}_j)\right) \left[1 + i\mathbf{Q} \cdot (\mathbf{u}_i - \mathbf{u}_j) - \frac{1}{2}\left(\mathbf{Q} \cdot (\mathbf{u}_i - \mathbf{u}_j)\right)^2 + ...\right]$$

# Three-Dimensional Pair Distribution Functions

- The ability to measure three-dimensional S(**Q**) over a wide range of reciprocal space provides the 3D analog of PDF measurements.
  - Total PDFs if Bragg peaks and diffuse scattering can be measured simultaneously
  - Δ-PDFs if the Bragg peaks are eliminated
    - using the punch and fill method
- This would allow a model-independent view of the measurements in real space.




238 Z. Kristallogr. **2012**, *227*, 238–247 / **DOI** 10.1524/zkri.2012.1504

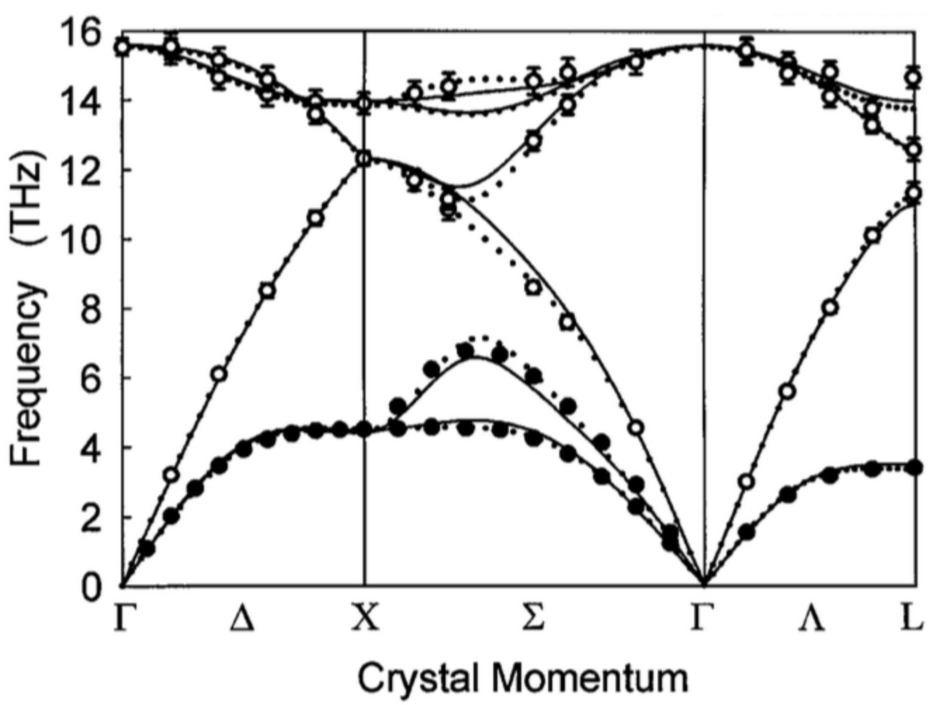

**The three-dimensional pair distribution function analysis of disordered single crystals: basic concepts**

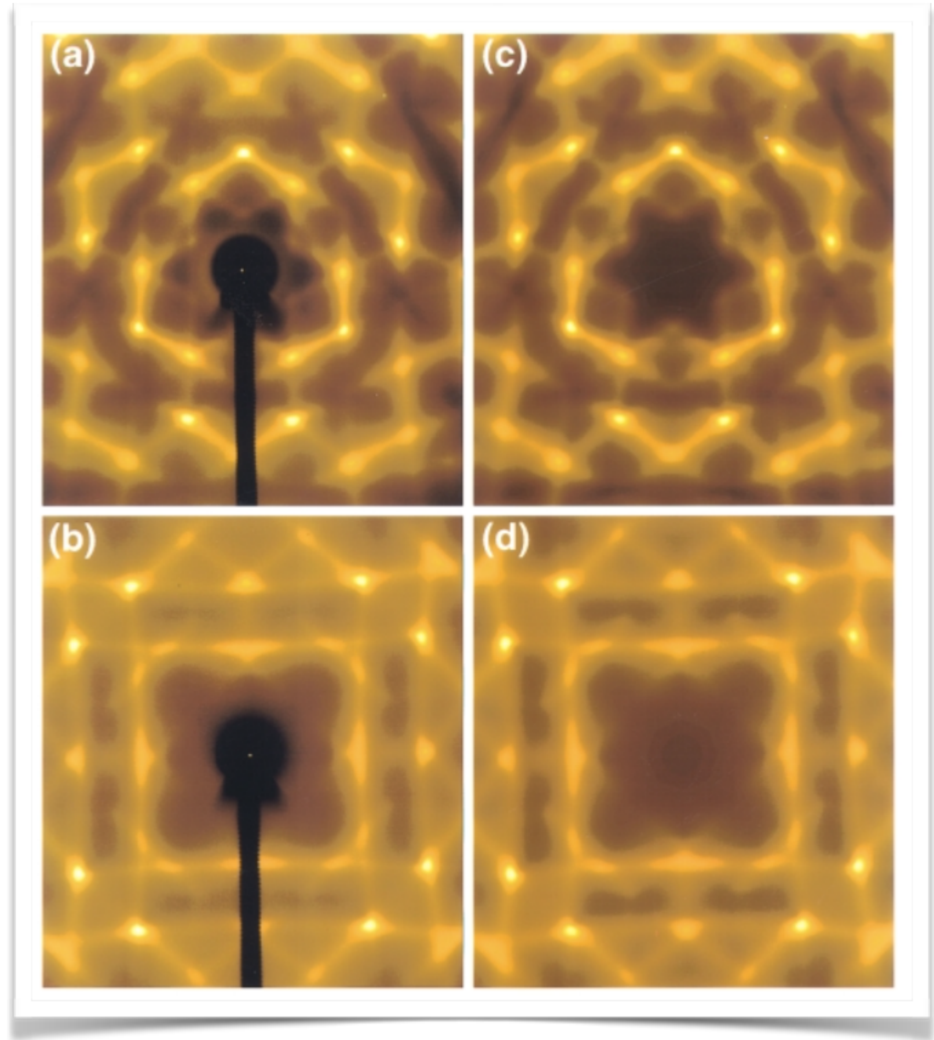
Thomas Weber* and Arkadiy Simonov

Laboratory of Crystallography, ETH Zurich Wolfgang-Pauli-Str. 10, 8093 Zurich, Switzerland

# Thermal Diffuse Scattering

- Lattice vibrations produce deviations from the average structure even in perfect crystals
- X-ray scattering intensity is given by the integral over all the phonon branches at each **Q**




$$I_0 \propto f^2 e^{-2M} \sum_{j=1}^{6} \frac{|\mathbf{q} \cdot \hat{\mathbf{e}}_j|^2}{\omega_j} \coth\left(\frac{\hbar\omega_j}{2k_B T}\right).$$

M. Holt, *et al*, Phys Rev Lett **83**, 3317 (1999).

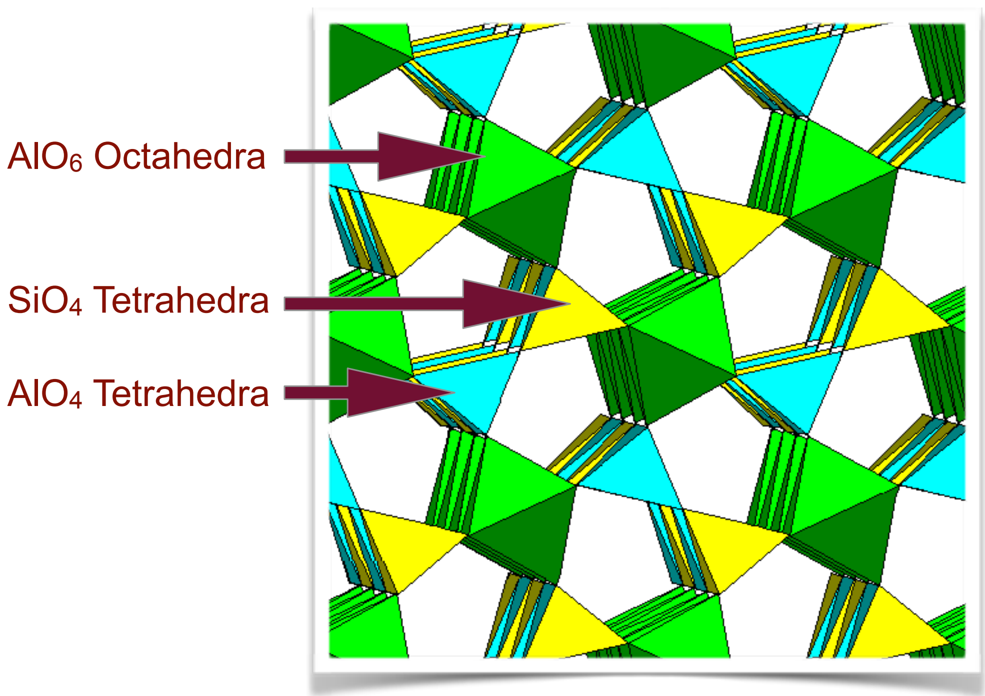
# Some Rules of Thumb (*thanks to* Hans Beat Bürgi)

| Reciprocal space | | Direct space |
|---|---|---|
| Only sharp Bragg reflections | → | 3D-periodic structure<br>• no defects |
| Sharp diffuse rods | → | 2D-periodic structure<br>• perpendicular to the streaks<br>• disordered in streak directions |
| Sharp diffuse planes | → | 1D-periodic structure<br>• perpendicular to the planes<br>• disordered within the plane |
| Diffuse clouds | → | 0D-periodic structure<br>• no fully ordered direction |

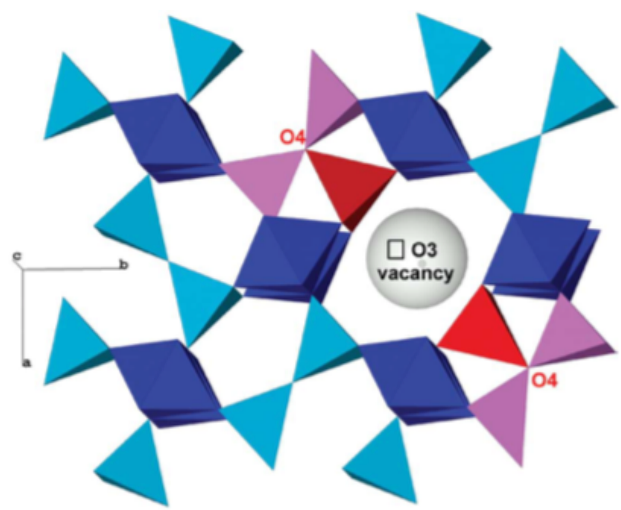
# Case Study 1: Mullite

# Mullite - A Case Study

- Mullite is a ceramic that is formed by adding $O^{2+}$ vacancies to Sillimanite
  - Sillimanite has alternating $AlO_4$ and $SiO_4$ tetrahedra
  - Mullite has excess $Al^{3+}$ occupying $Si^{2+}$ sites for charge balance
- This results in strong vacancy-vacancy correlations



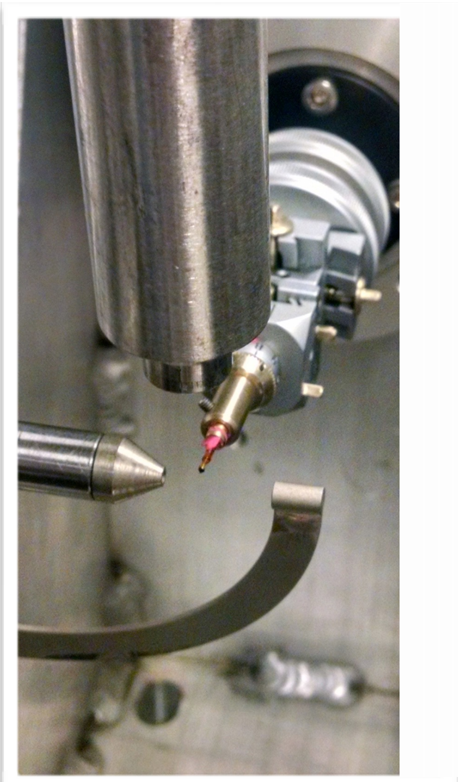

Sillimanite: $Al_2SiO_5$

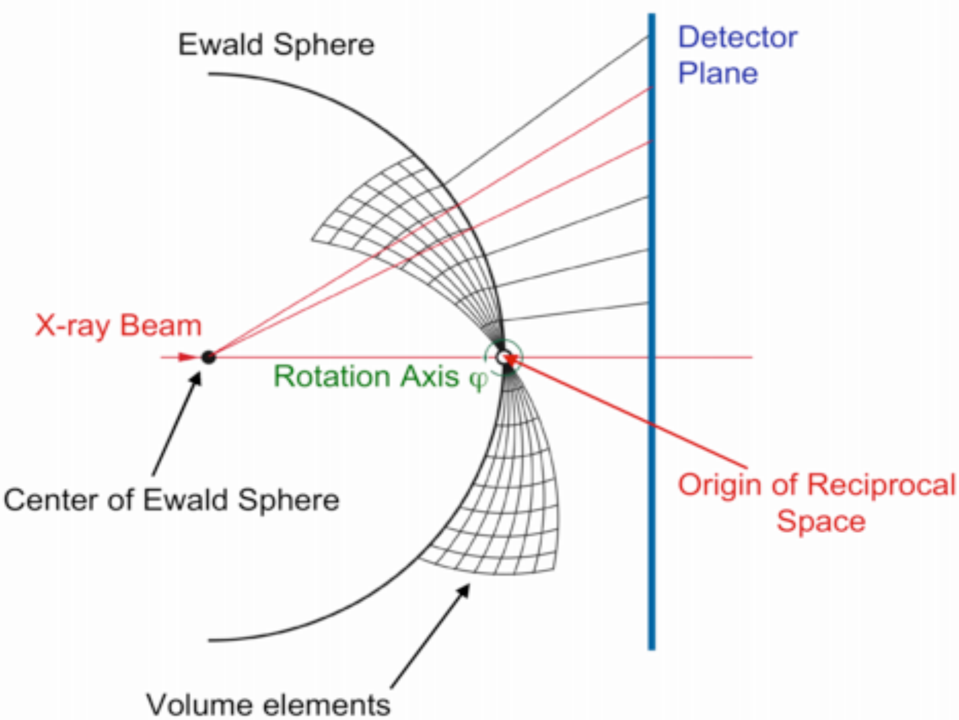


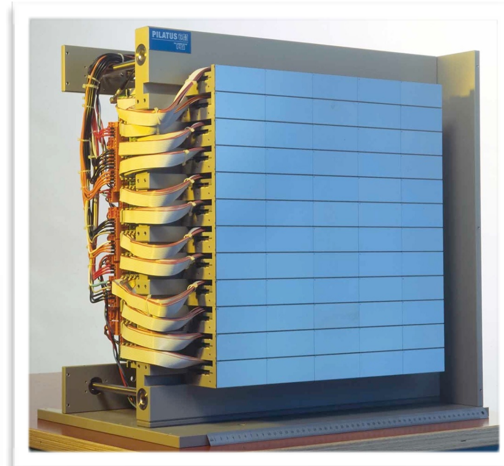

Mullite: $Al_2(Al_{2+2x}Si_{2-2x})O_{10+x}$

B. D. Butler, T. R. Welberry, & R. L. Withers, Phys Chem Minerals **20**, 323 (1993)

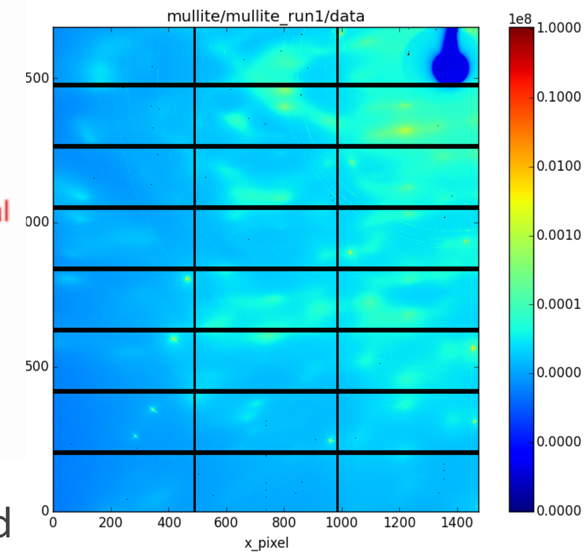
# Measuring X-ray Diffuse Scattering with Continuous Rotation Method





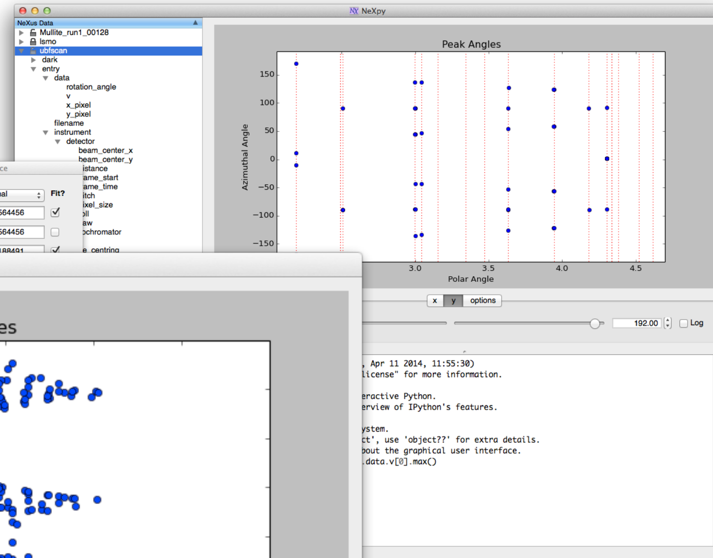



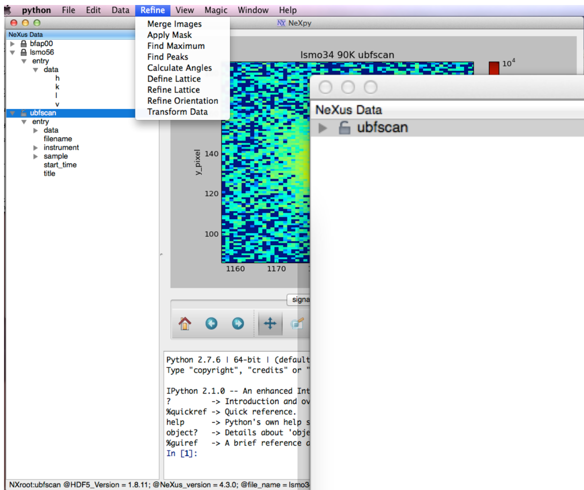
Pilatus 2M Detector

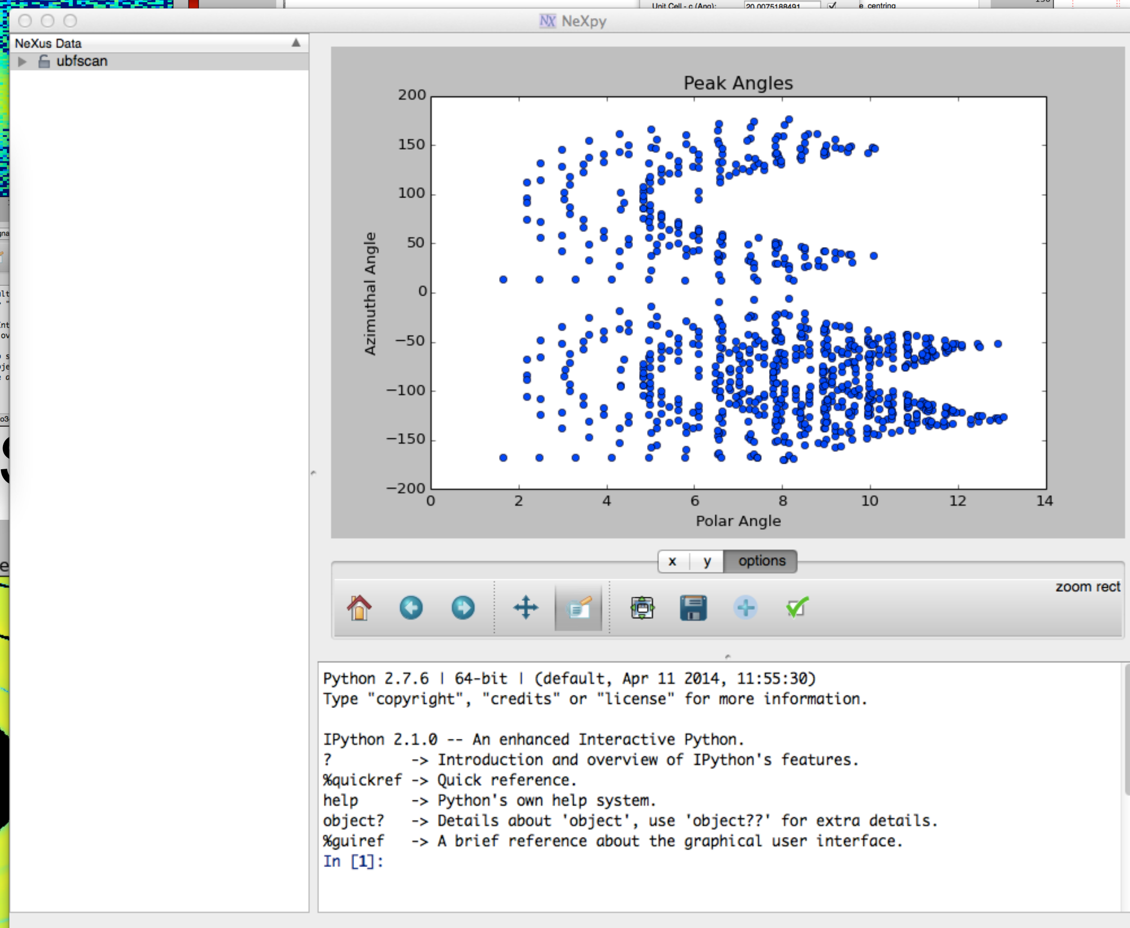



- The sample is continuously rotated in shutterless mode at 1° per second
- A fast area detector (*e.g.*, a Pilatus 2M) acquires images at 10 frames per second
  - *i.e.,* 3600 x 8MB frames ~ 30GB every 6 minutes
- The detector needs low background, high dynamic range, and energy discrimination
  - Ideally, this is performed with high-energy x-rays, *e.g.*, 80 to 100 keV

# Data Reduction Workflows

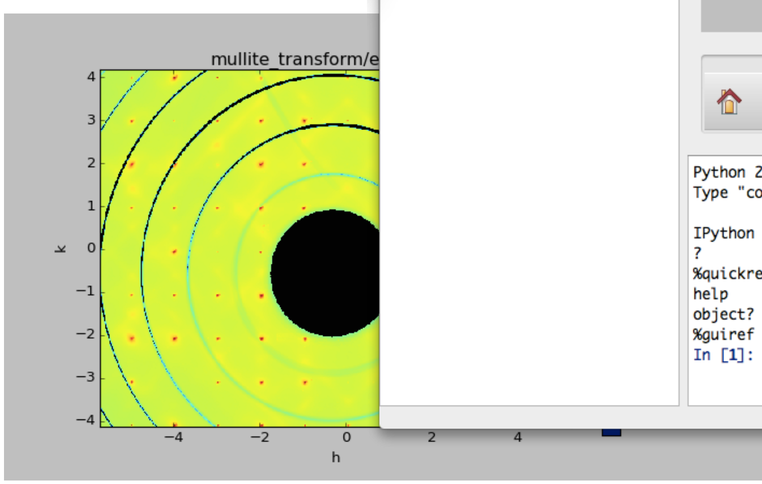


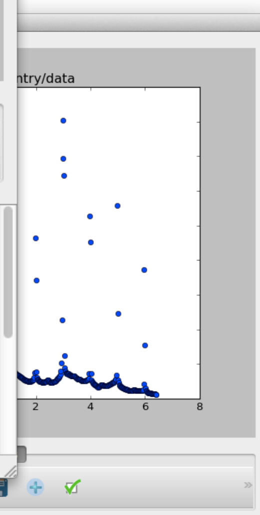




Peak

d Orientation



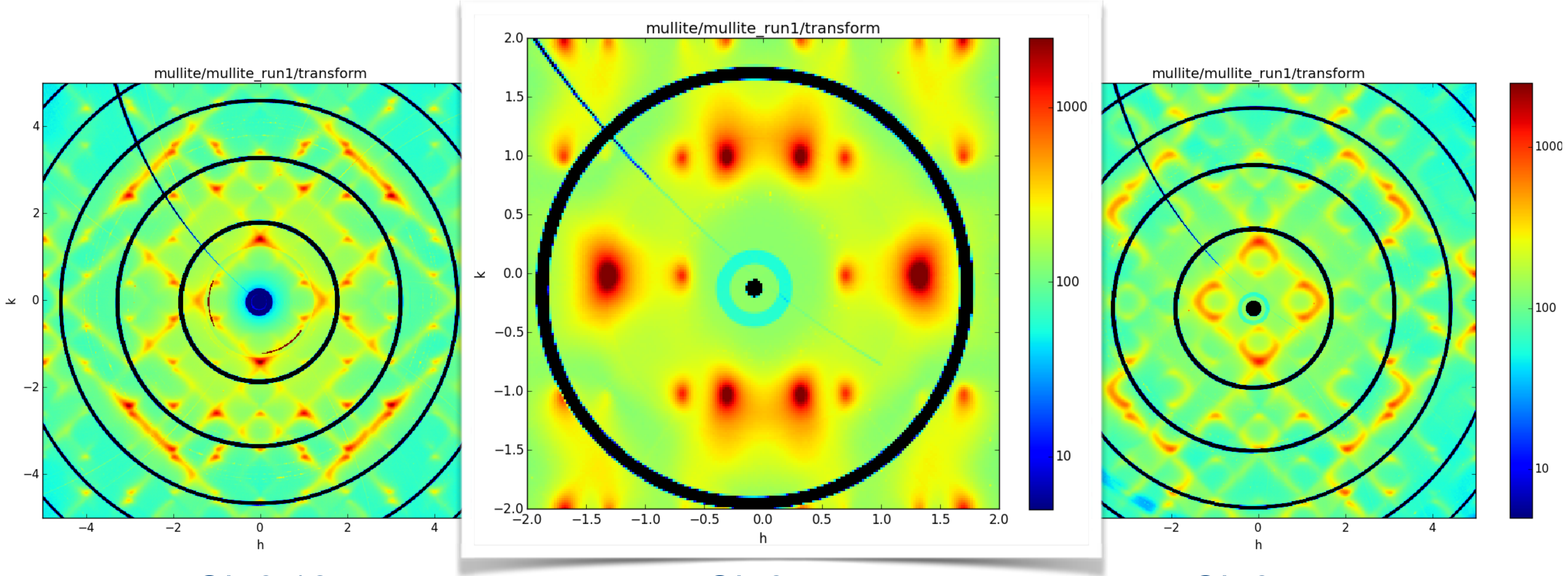



Coordinate Transformation

Data Projections

# 3D Diffuse Scattering in Mullite

- There is strong diffuse scattering throughout reciprocal space
- The shape of the diffuse scattering is strongly dependent on the value of Ql
- There are incipient superlattice peaks at **Q** = 0.5 *c** + 0.31 *a**




Ql=0.16 Ql=0.5 Ql=0.75

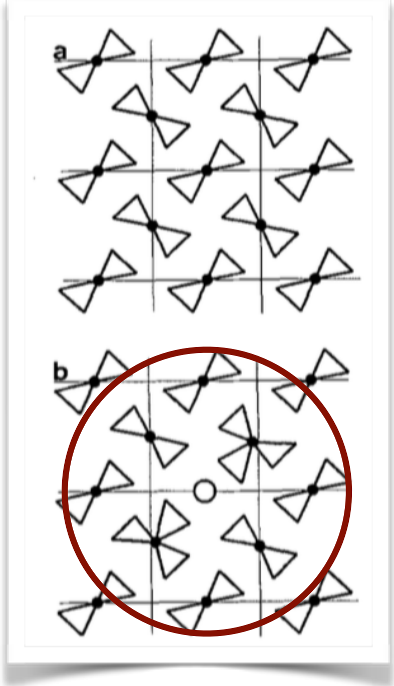
# Monte Carlo Analysis

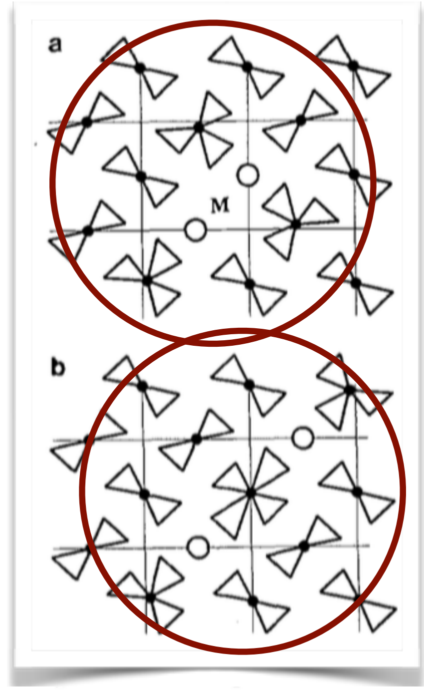
- In a classic analysis, Richard Welberry and colleagues developed a set of interaction energies to model mullite disorder
- Interaction energies were initialized:
  - insights from chemical intuition
  - insights from the measured diffuse scattering
- The diffuse scattering was calculated using a Monte Carlo algorithm to generate vacancy distributions first in 2D slices and then in 3D

$$P_i = \frac{e^{-V_i}}{1+e^{-V_i}},$$

where,

$$V_i = \frac{\sum_j E_{ij}}{kT} + \frac{(N_v - N_v^o)^2}{N_v^o}\,\mathrm{sgn}\,(N_v - N_v^o).$$

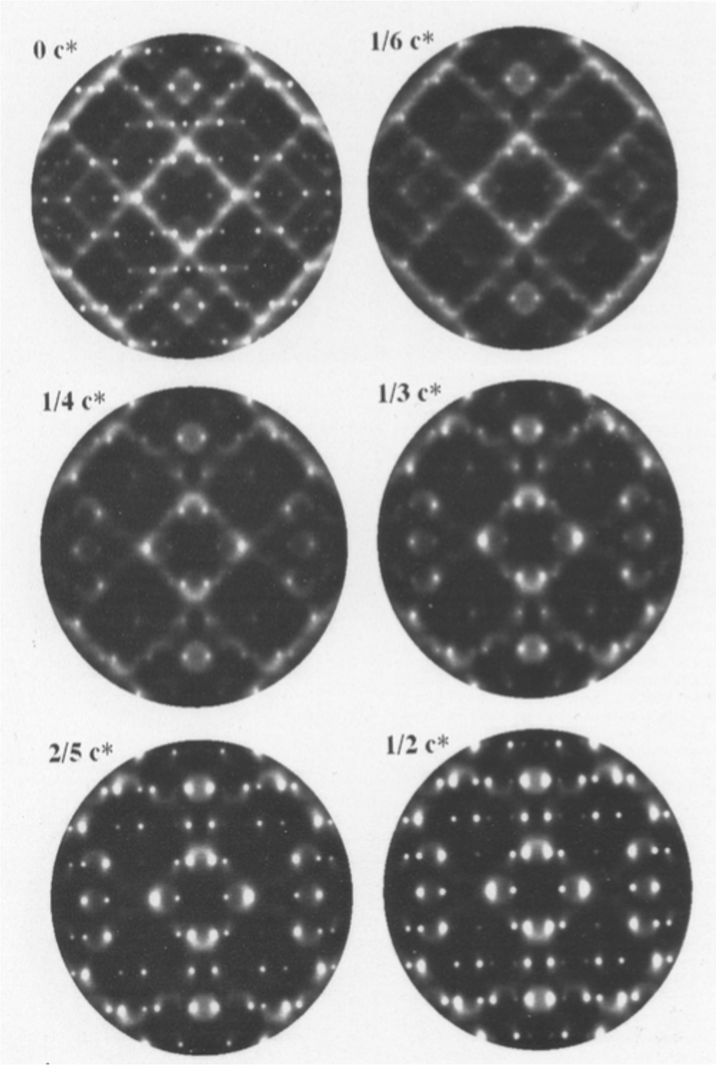


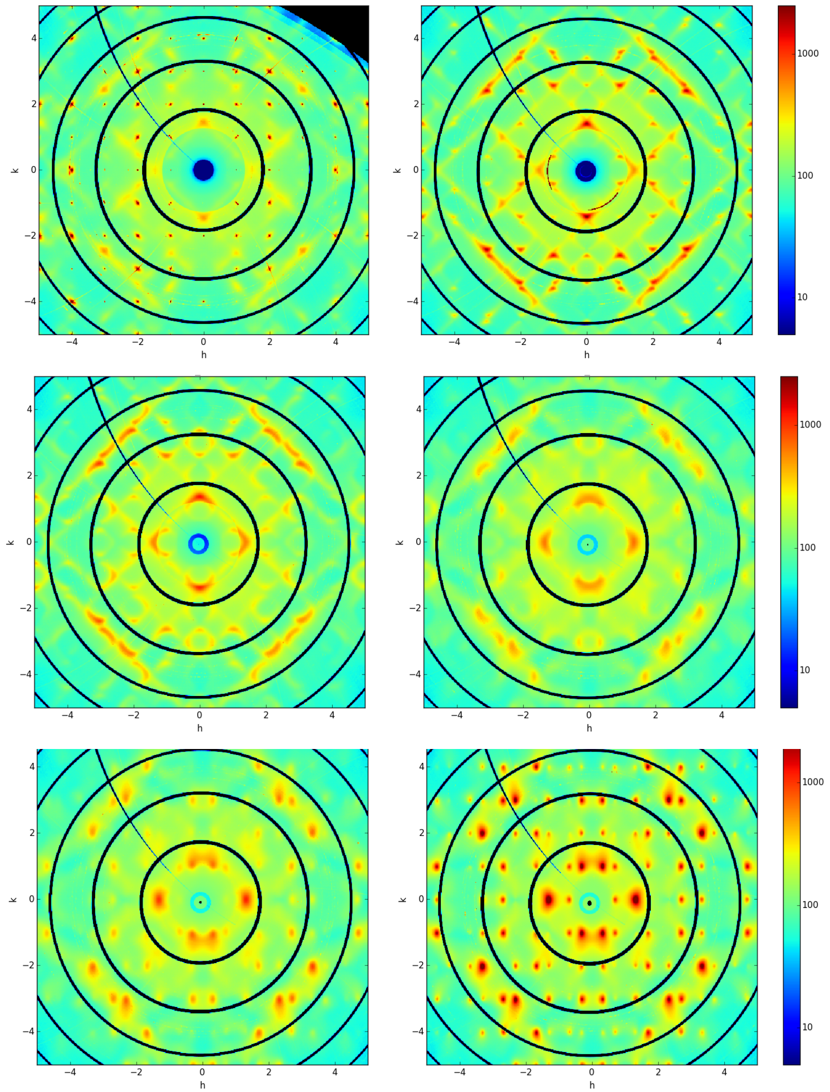




| Interatomic vector | $\alpha_{lmn}$ | Interatomic vector | $\alpha_{lmn}$ |
|---|---|---|---|
| $\frac{1}{2}\langle 1\,1\,0\rangle$ | −0.24 | $\langle 0\,2\,0\rangle$ | +0.13 |
| $[1\,1\,0]$ | −0.23 | $\frac{1}{2}\langle 3\,1\,0\rangle$ | +0.22 |
| $[1\,-1\,0]$ | −0.05 | $\frac{1}{2}\langle 1\,3\,0\rangle$ | −0.01 |
| $\langle 1\,0\,0\rangle$ | −0.06 | $\langle 1\,0\,1\rangle$ | +0.07 |
| $\langle 0\,1\,0\rangle$ | +0.22 | $\langle 0\,1\,1\rangle$ | −0.12 |
| $\langle 0\,0\,1\rangle$ | −0.03 | $\frac{1}{2}\langle 3\,3\,0\rangle$ | +0.17 |
| $\frac{1}{2}[1\,-1\,2]$ | +0.12 | $\langle 1\,1\,1\rangle$ | −0.01 |
| $\frac{1}{2}[1\,1\,2]$ | +0.12 | $\frac{1}{2}\langle 3\,1\,2\rangle$ | −0.11 |
| $\langle 2\,0\,0\rangle$ | −0.12 | $\frac{1}{2}\langle 3\,3\,2\rangle$ | −0.07 |

B. D. Butler, T. R. Welberry, & R. L. Withers, Phys Chem Minerals **20**, 323 (1993)

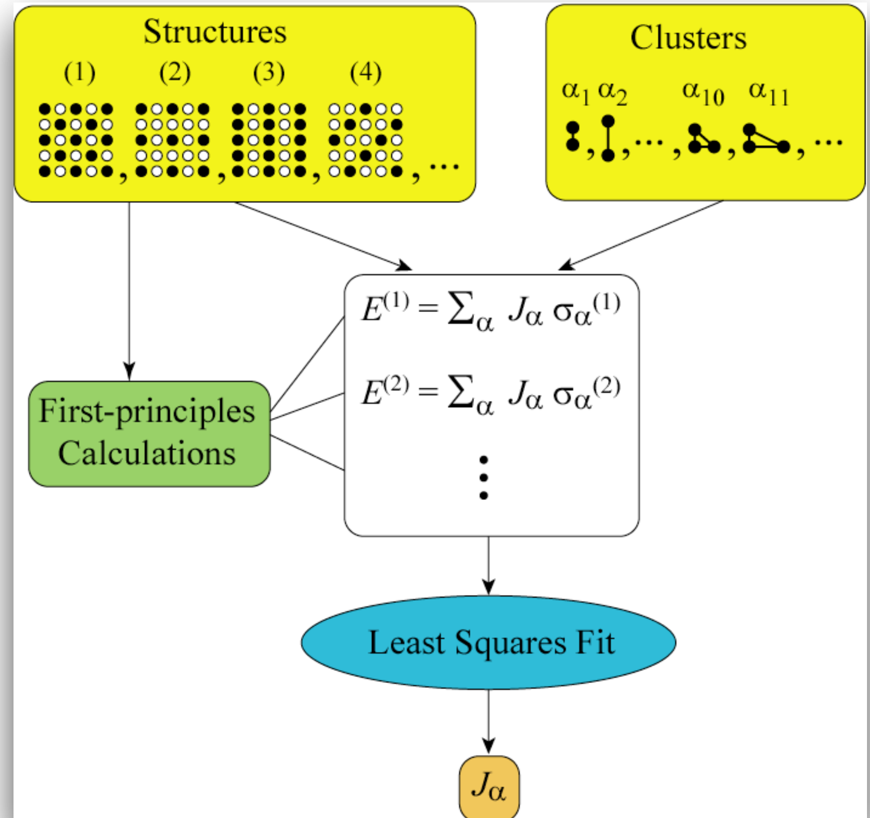
# Monte Carlo Analysis Results

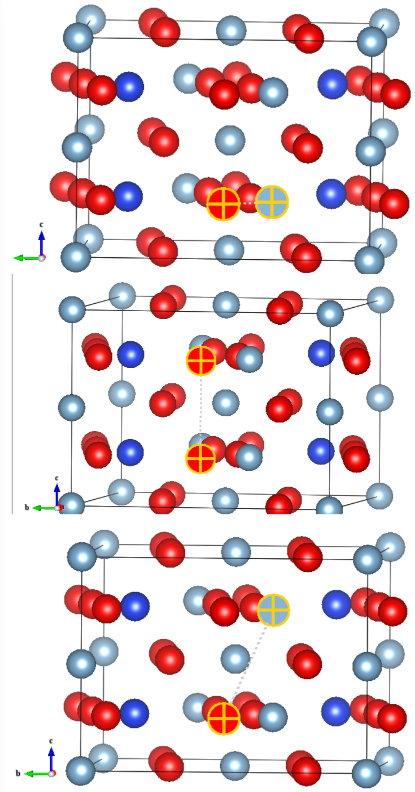


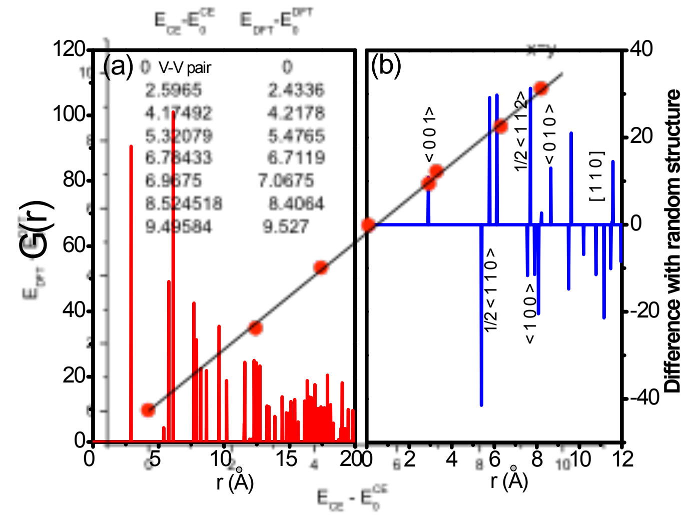



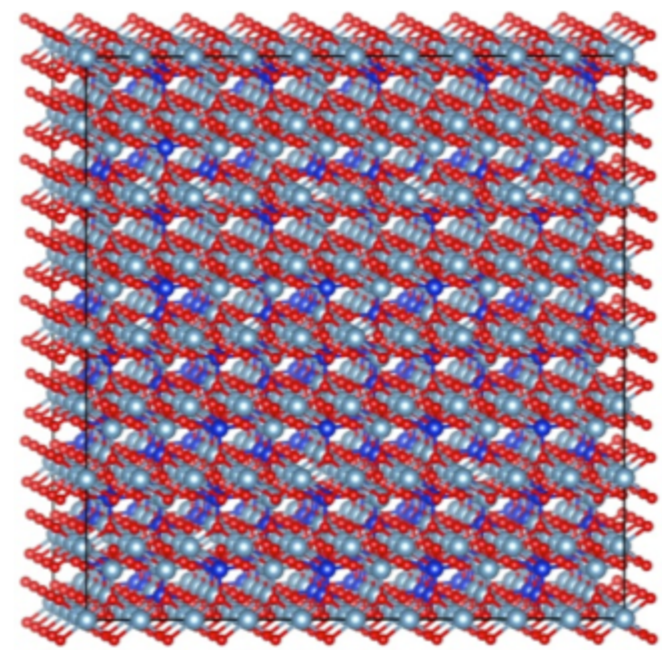
# Vacancy Short-Range Order in Mullite

## A First-Principles Approach





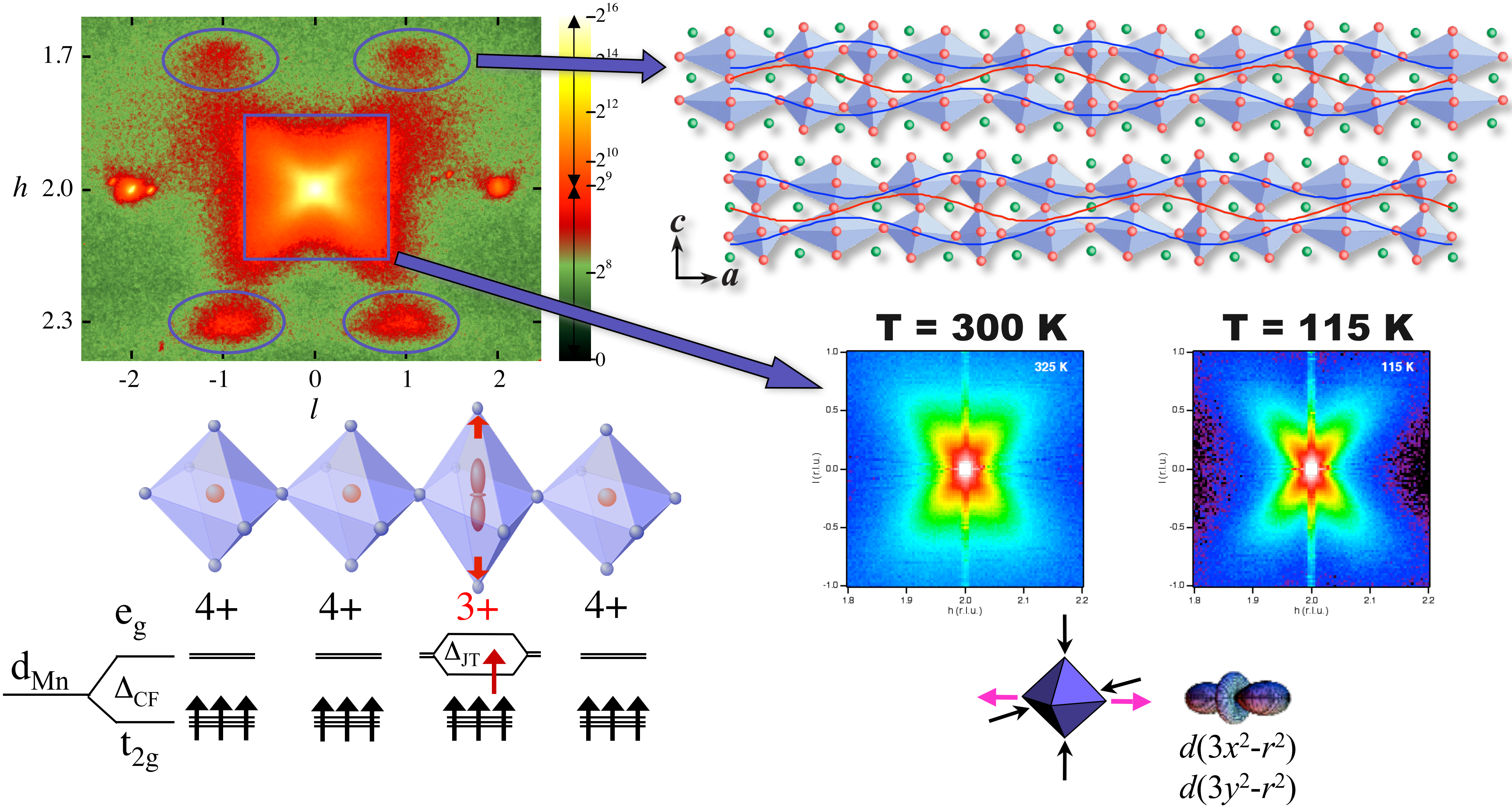
$$E(\sigma) = J_0 + \sum_i \sigma_i J_i + \sum_{i,j} J_{ij}\sigma_i\sigma_j + \sum_{ijk} J_{ijk}\sigma_i\sigma_j\sigma_k + \ldots$$

Peter Zapol & Anh Ngo

Lowest Energy 3:2 Mullite Structure from Kinetic Monte Carlo Calculation

# Case Study 1: Bilayer Manganites

# Diffuse Scattering from Jahn-Teller Polarons



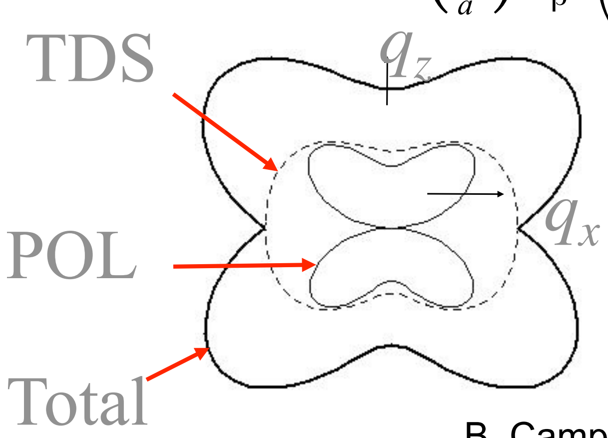
# Huang Scattering

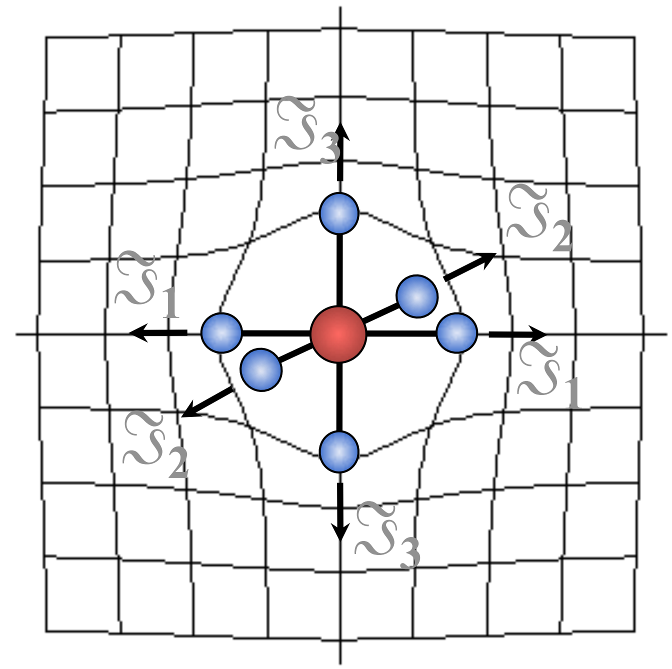
$$I(\mathbf{Q}) = \sum_{m,n} e^{i\mathbf{Q}\cdot(\mathbf{R}_m - \mathbf{R}_n)} f_m f_n e^{-W_m} e^{-W_n} \left\langle (\mathbf{Q}\cdot\mathbf{u}_m)(\mathbf{Q}\cdot\mathbf{u}_n) \right\rangle$$

$$I_{POL}(\mathbf{Q}) = N\left|F_{\mathbf{G}}\right|^2 \sum_{\alpha,\beta,\gamma,\delta} Q_\beta Q_\delta \left( \sum_{j,j'} \frac{\varepsilon_{\alpha,\mathbf{q},j}\,\varepsilon^*_{\beta,\mathbf{q},j}\,\varepsilon^*_{\gamma,\mathbf{q},j'}\,\varepsilon_{\delta,\mathbf{q},j'}}{\omega^2_{\mathbf{q},j}\,\omega^2_{\mathbf{q},j'}} \right) \sum_{m,n} \Im_{m,\alpha} \Im_{n,\gamma}\, e^{i\mathbf{q}\cdot(\mathbf{R}_m - \mathbf{R}_n)}$$

$$I_{TDS}(\mathbf{Q}) = N\left|F_{\mathbf{G}}\right|^2 \left(\frac{kT}{2M}\right) \sum_{\beta,\delta} Q_\beta Q_\delta \left( \sum_{j} \frac{\varepsilon^*_{\beta,\mathbf{q},j}\,\varepsilon_{\delta,\mathbf{q},j}}{\omega^2_{\mathbf{q},j}} \right)$$

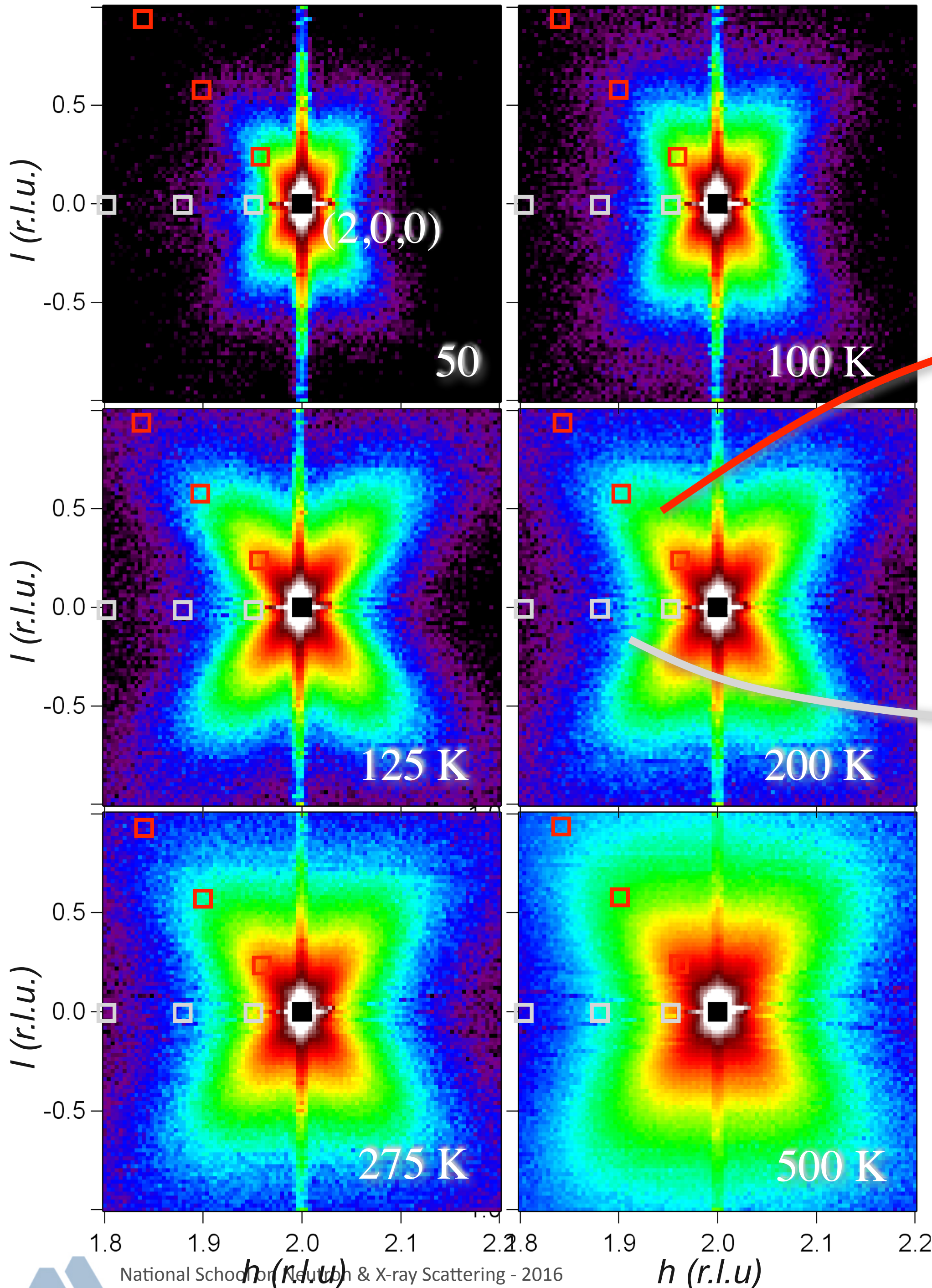
$$u_{m,\delta} = \int \frac{d^3q}{\left(\frac{2\pi}{a}\right)^3} \sum_{\beta} \left( \sum_{j} \frac{\varepsilon^*_{\beta,\mathbf{q},j}\,\varepsilon_{\delta,\mathbf{q},j}}{\omega^2_{\mathbf{q},j}} \right) \sum_{n} \Im_{n,\beta}\, e^{i\mathbf{q}\cdot(\mathbf{R}_m - \mathbf{R}_n)}$$

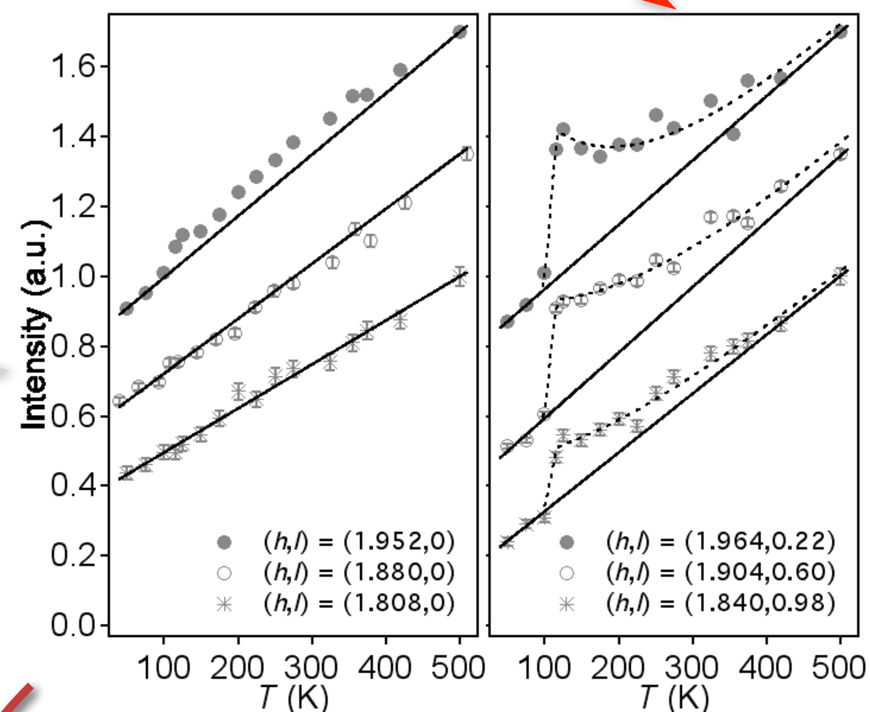



B. Campbell *et al* Phys. Rev. B. **67**, 020409 (2003)

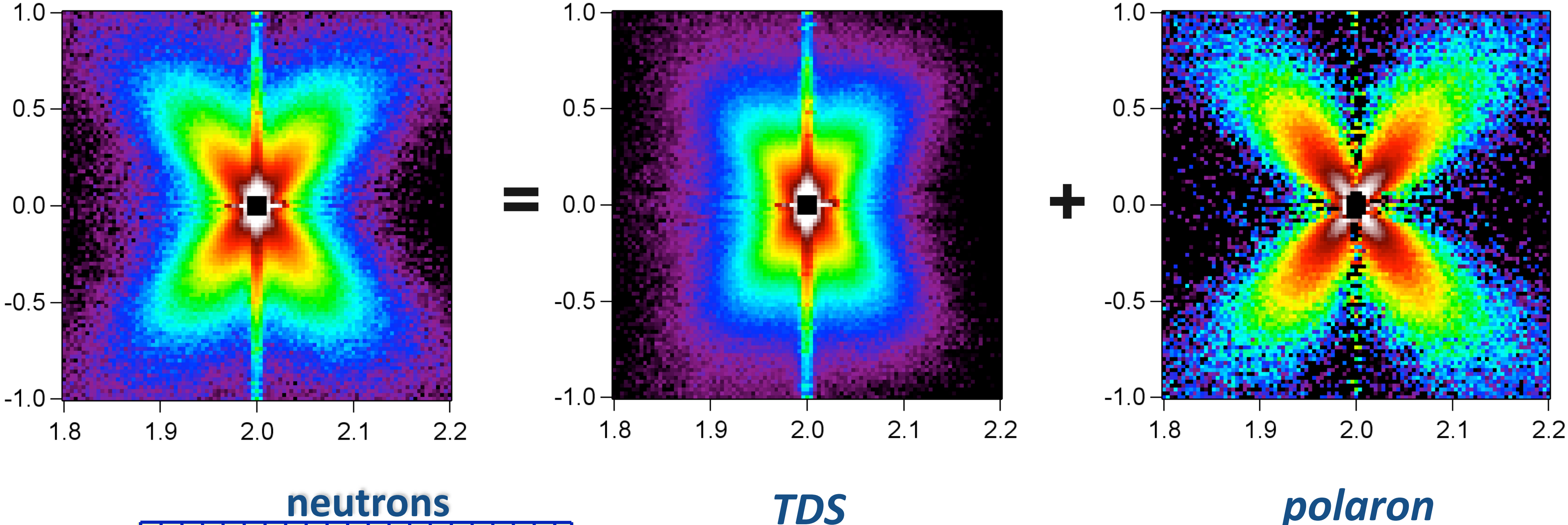
single crystal synchrotron x-ray scattering
11-ID-D, APS@Argonne

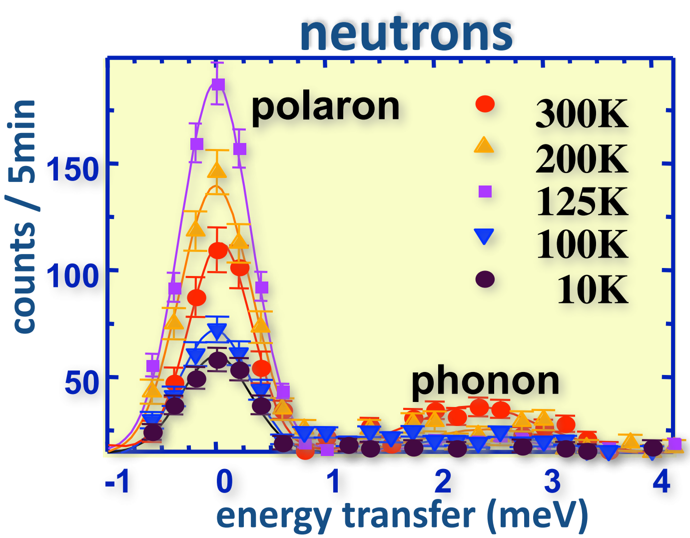


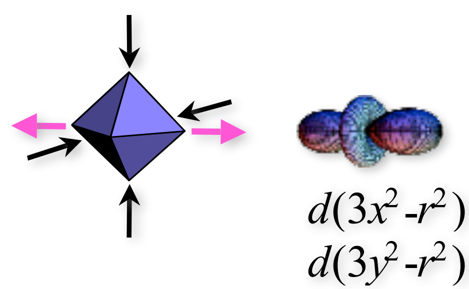




**this allows us to subtract background from thermal diffuse scattering!**

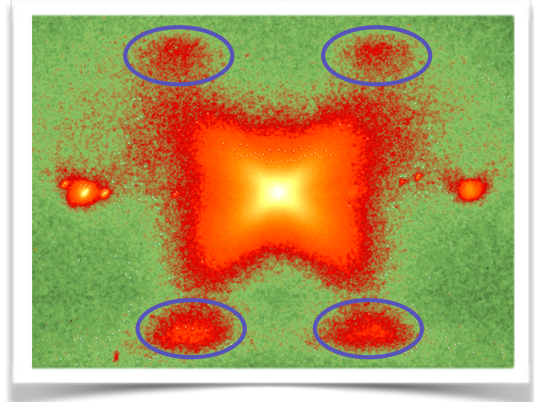
# TDS + Huang scattering

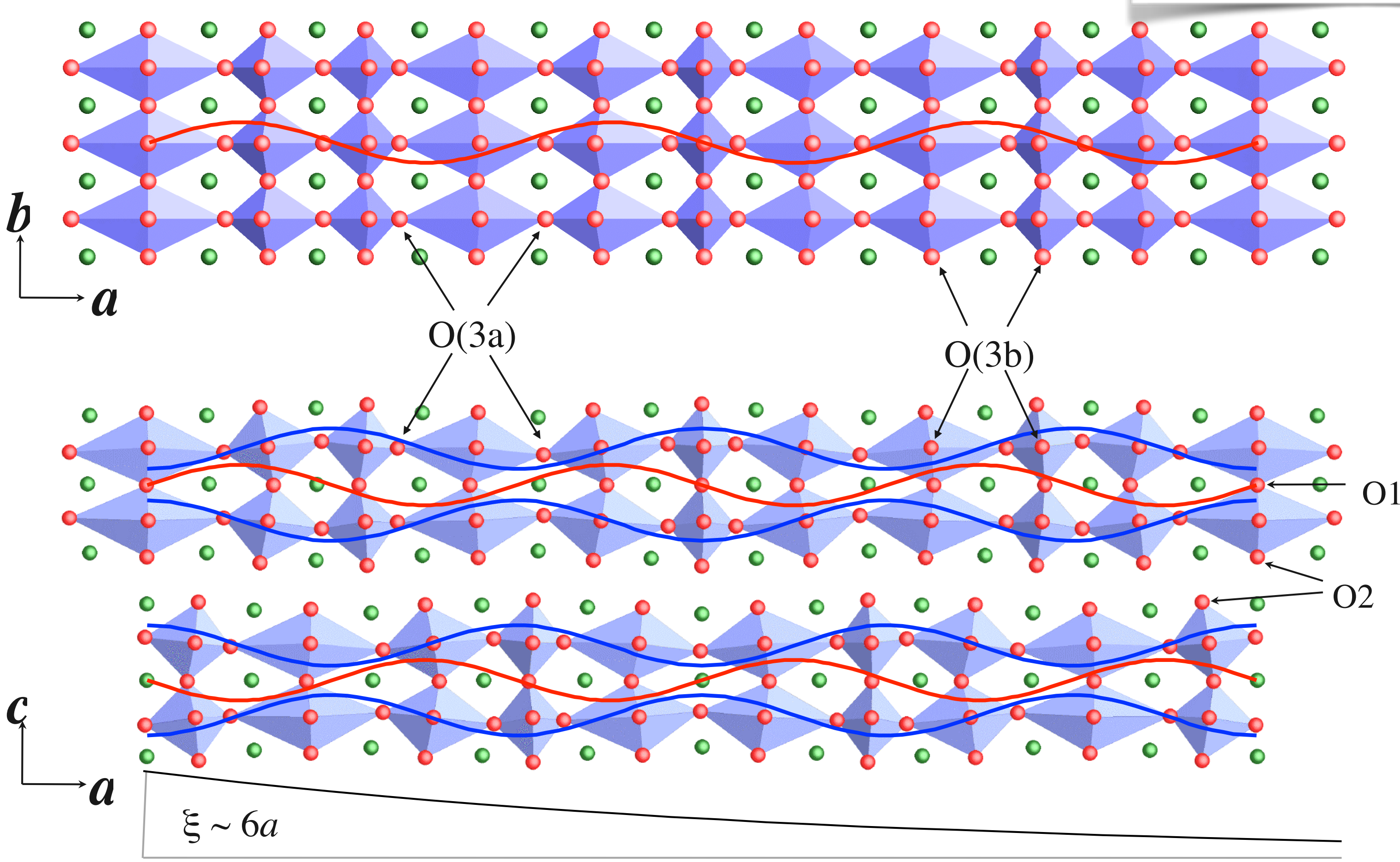


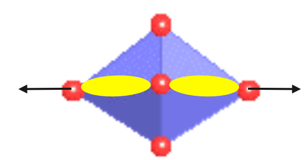



# Cooperative Jahn-Teller Distortions



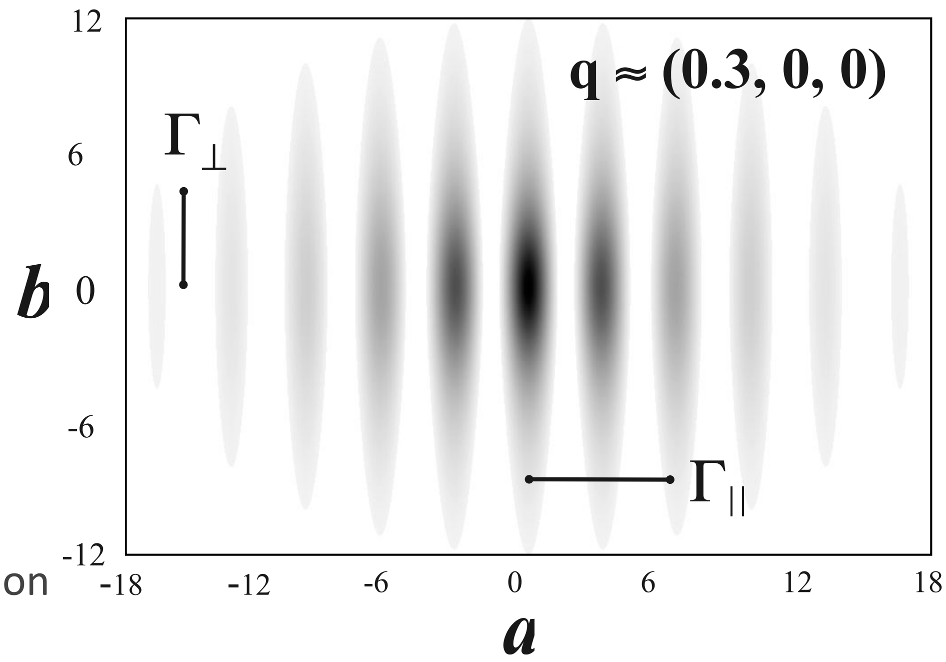


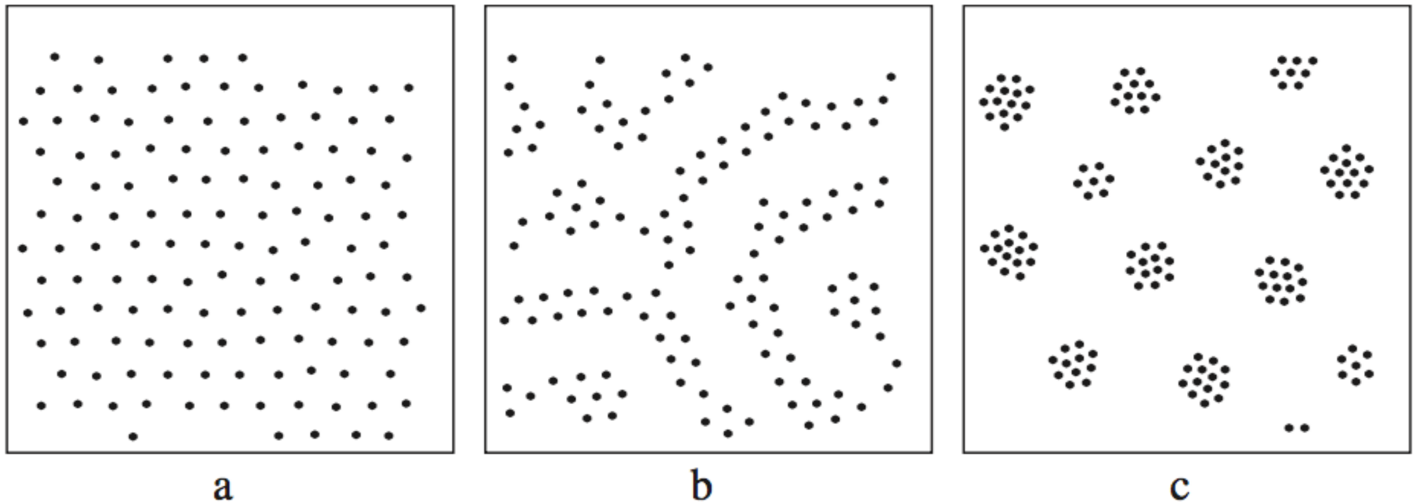



B. J. Campbell, R. Osborn, D. N. Argyriou, L. Vasiliu-Doloc, J. F. Mitchell, S. K. Sinha, U. Ruett, C. D. Ling, Z. Islam, and J. W. Lynn, Physical Review B **65**, 014427 (2001)

# Origins of Stripe Formation

- Stripe formation is a very common motif of disordered systems
- It is the response of a system with interactions that compete on different length scales
  - *e.g.*, long-range repulsion *vs* short-range attraction

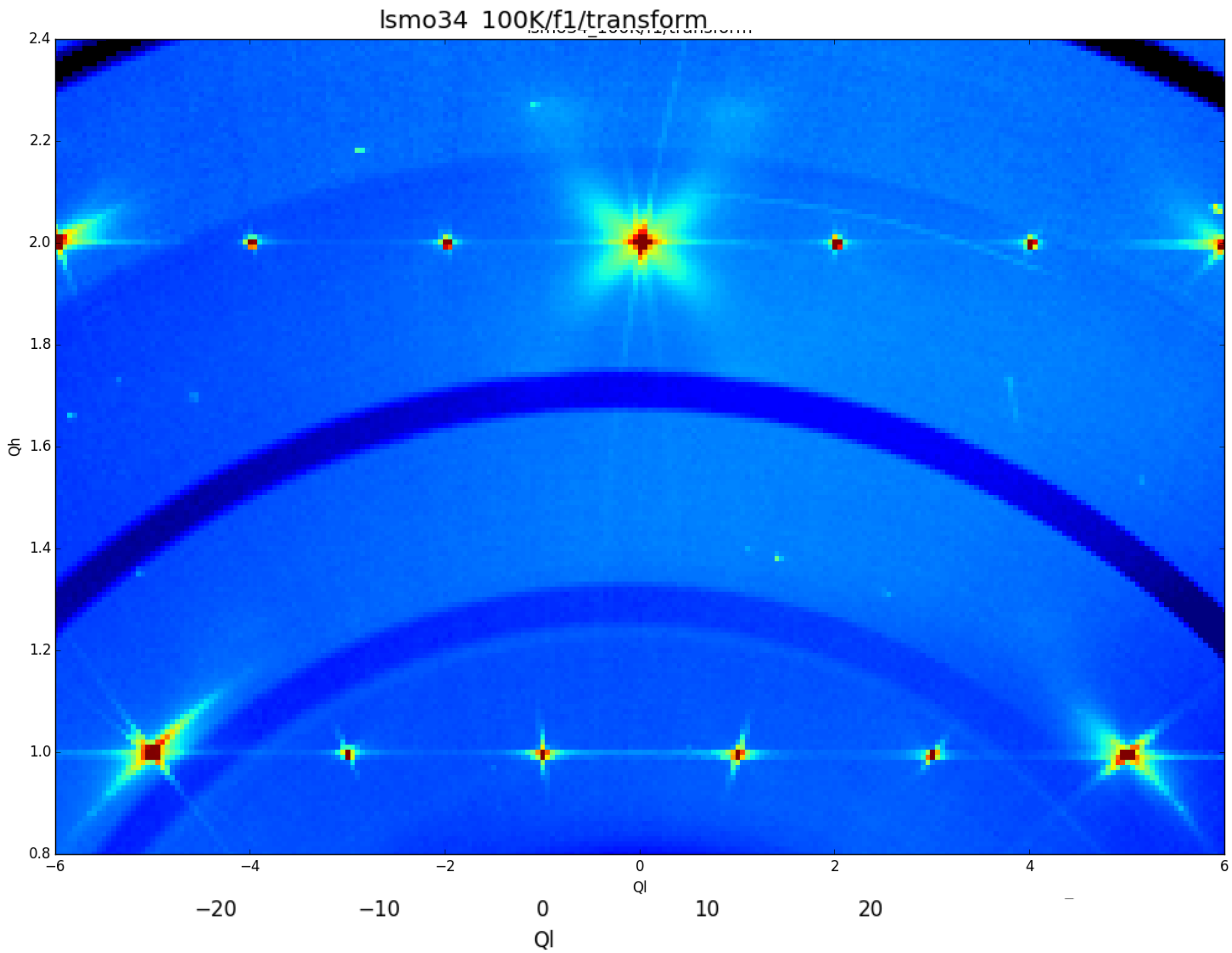


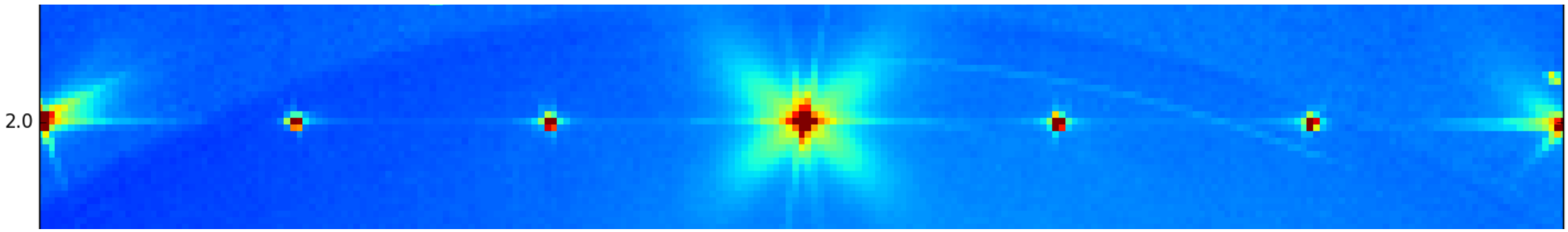

Wigner Lattice | Stripes | Phase Separation

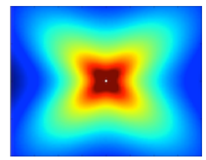
C. Reichhardt, C. J. Olsen, I. Martin & A. Bishop, EPL **61**, 221–227 (2003).

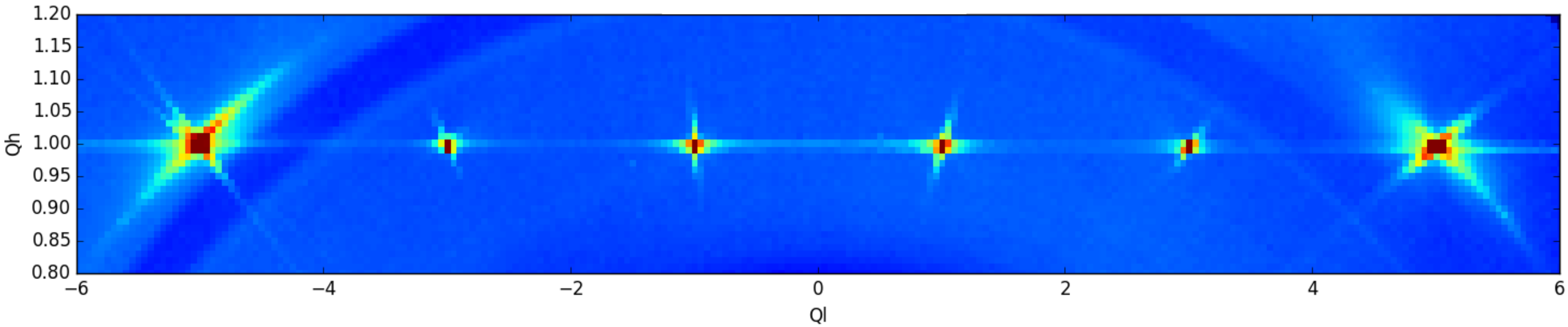
# Bilayer Manganites Revisited

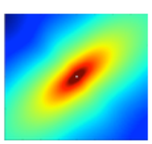
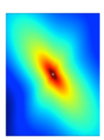
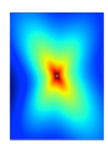
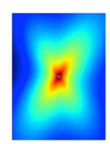
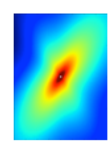
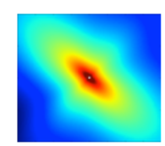


# Huang Scattering as a Function of (Qh, Qk, Ql)

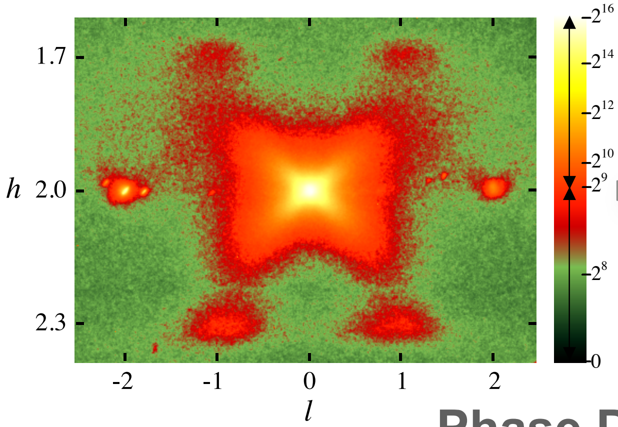


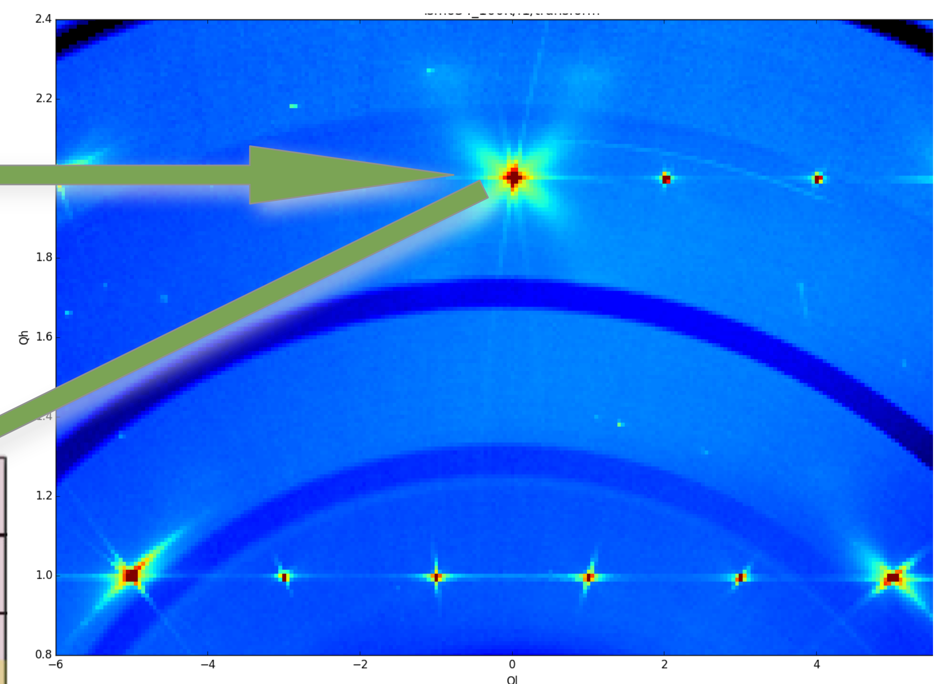





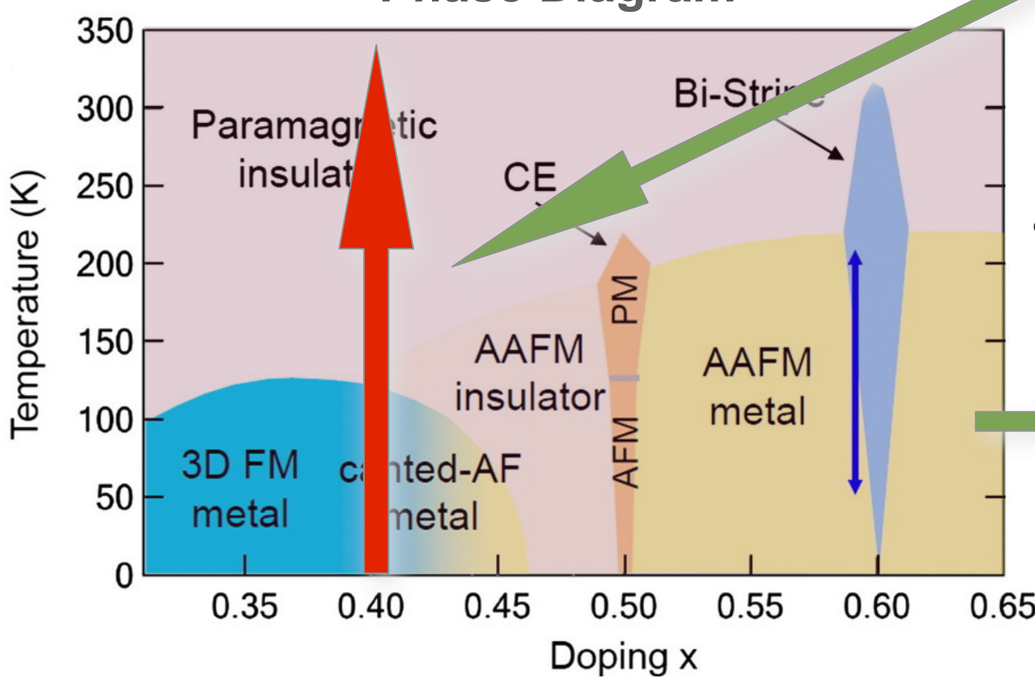








# Expanding the Concept of a Data Set




Phase Diagram

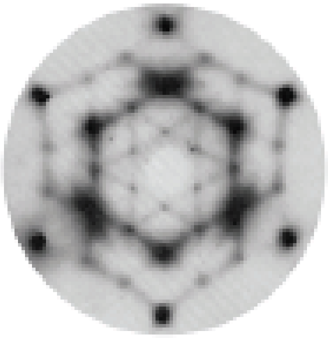



Correlated Data Analysis/
Machine Learning

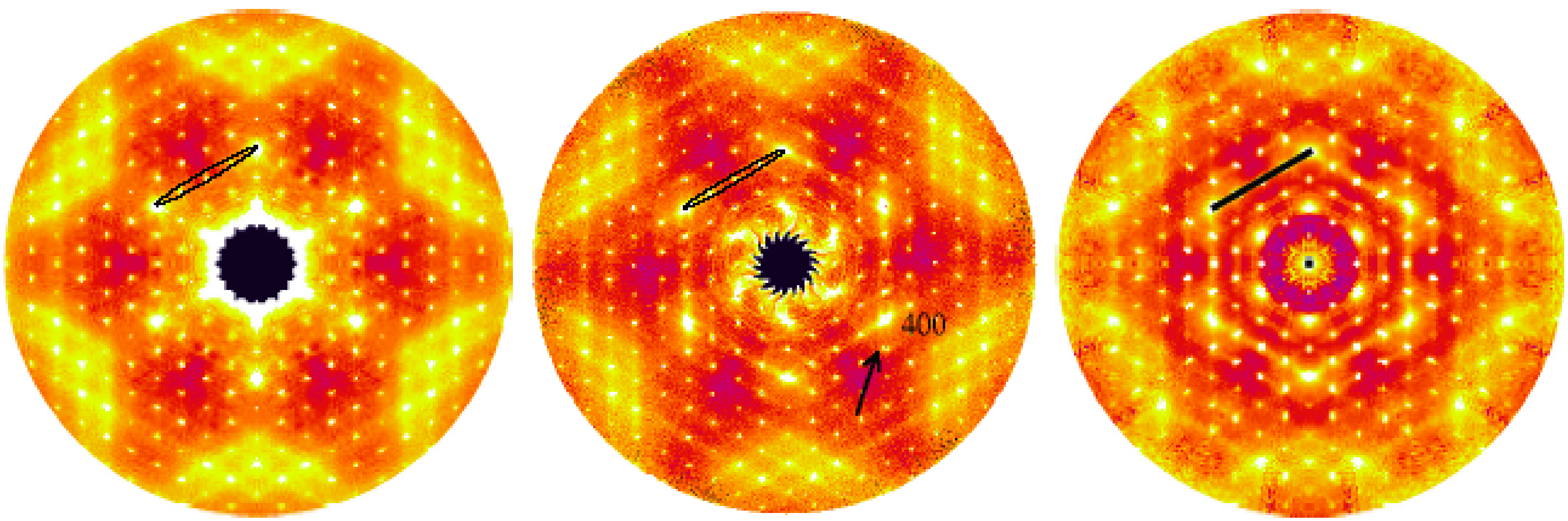
**Total Data: $S(\mathbf{Q}, T, x)$**

# How do I look at static disorder?

# Importance of Elastic Discrimination



BENZIL




Detector 1
2θ~142.5°

Detector 2
2θ~90.0°

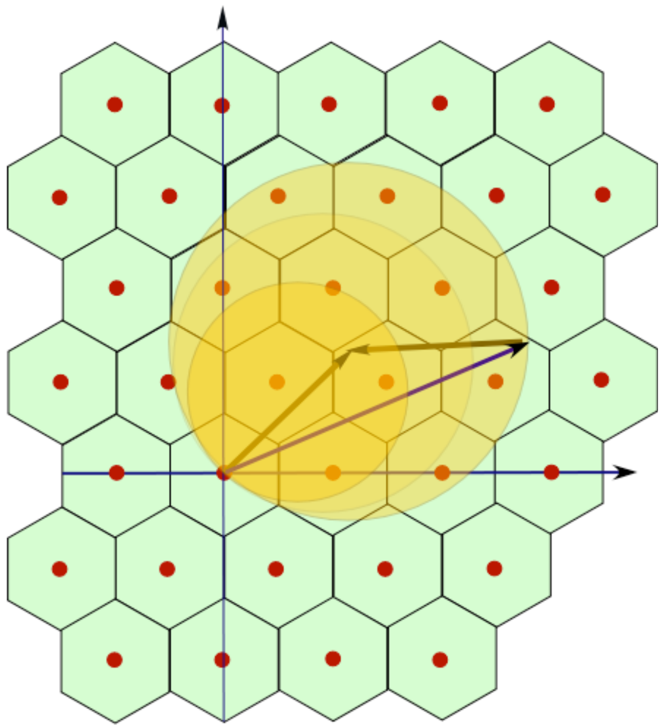
Detector 3
2θ~37.5°

T. R. Welberry *et al* J. Appl. Cryst. **36**, 1400 (2003)

# Measuring Large Volumes of Reciprocal Space

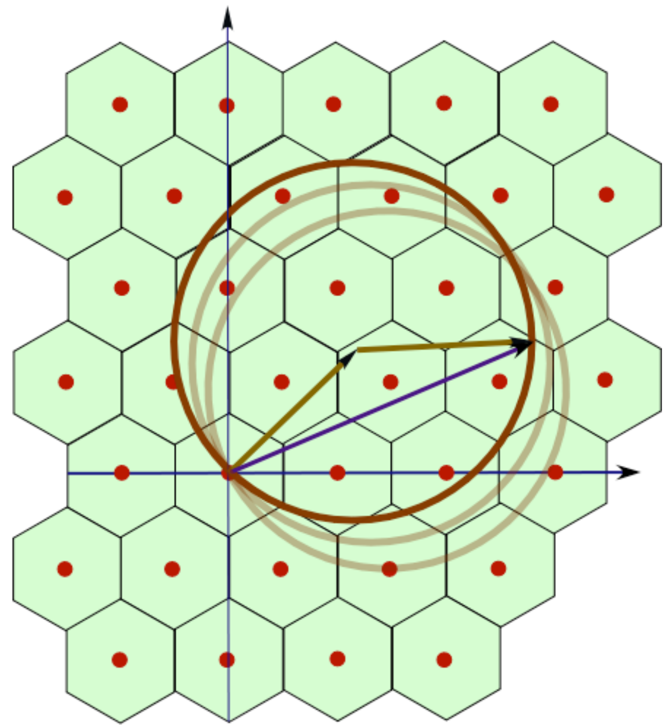
## Conventional Time-of-Flight Neutron Methods

**White Beam:**
***efficient***



***NO energy discrimination***

**Fixed $k_i$ :**
***energy resolved***



***NOT efficient***

# Cross Correlation Chopper

**TOF Laue Diffractometer**

- highly efficient data collection
- wide dynamic range in Q

**Statistical Chopper**

- elastic energy discrimination
- optimum use of white beam

**Sample with :**

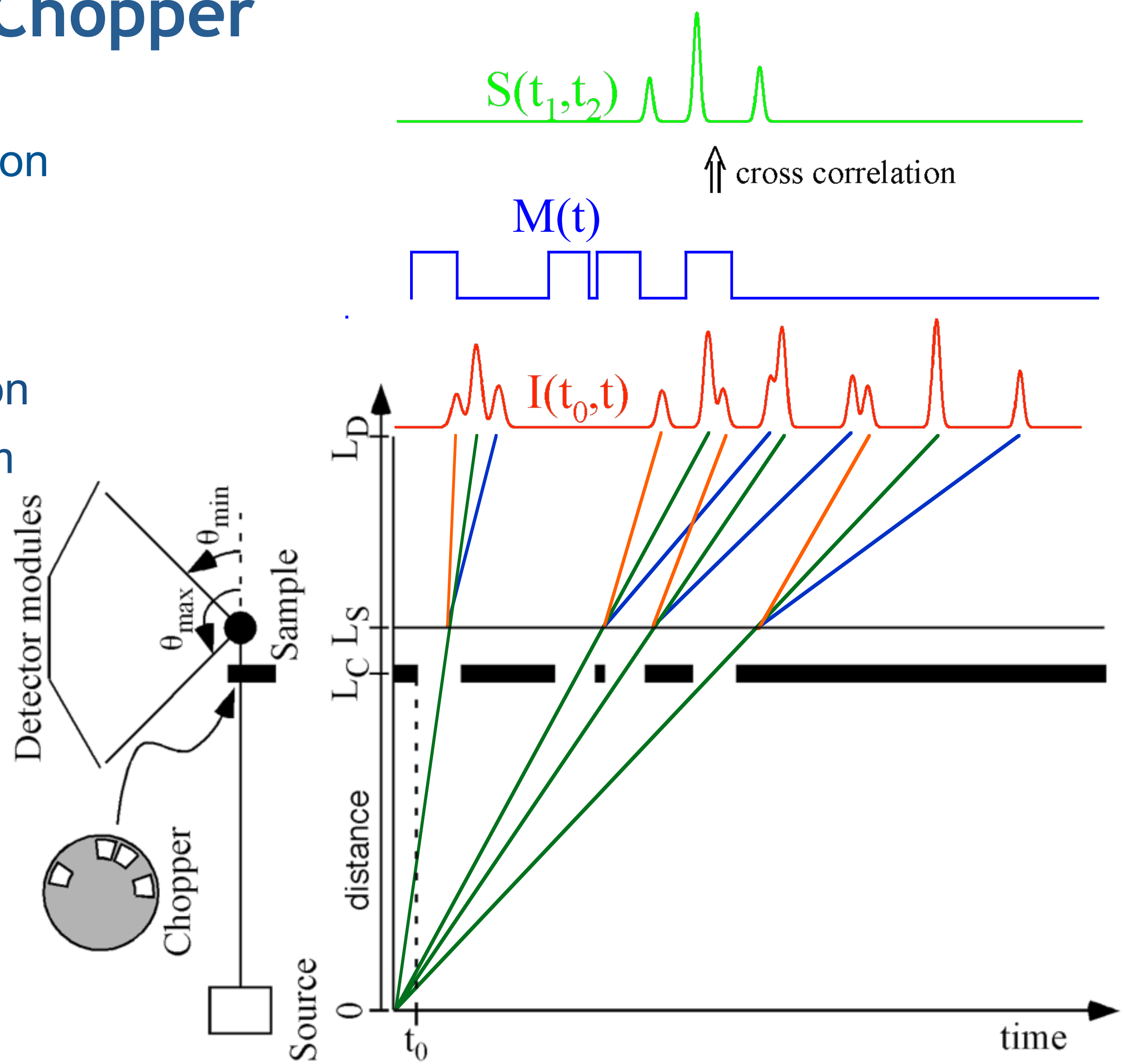
**elastic scattering**

$$\hbar\omega = 0$$

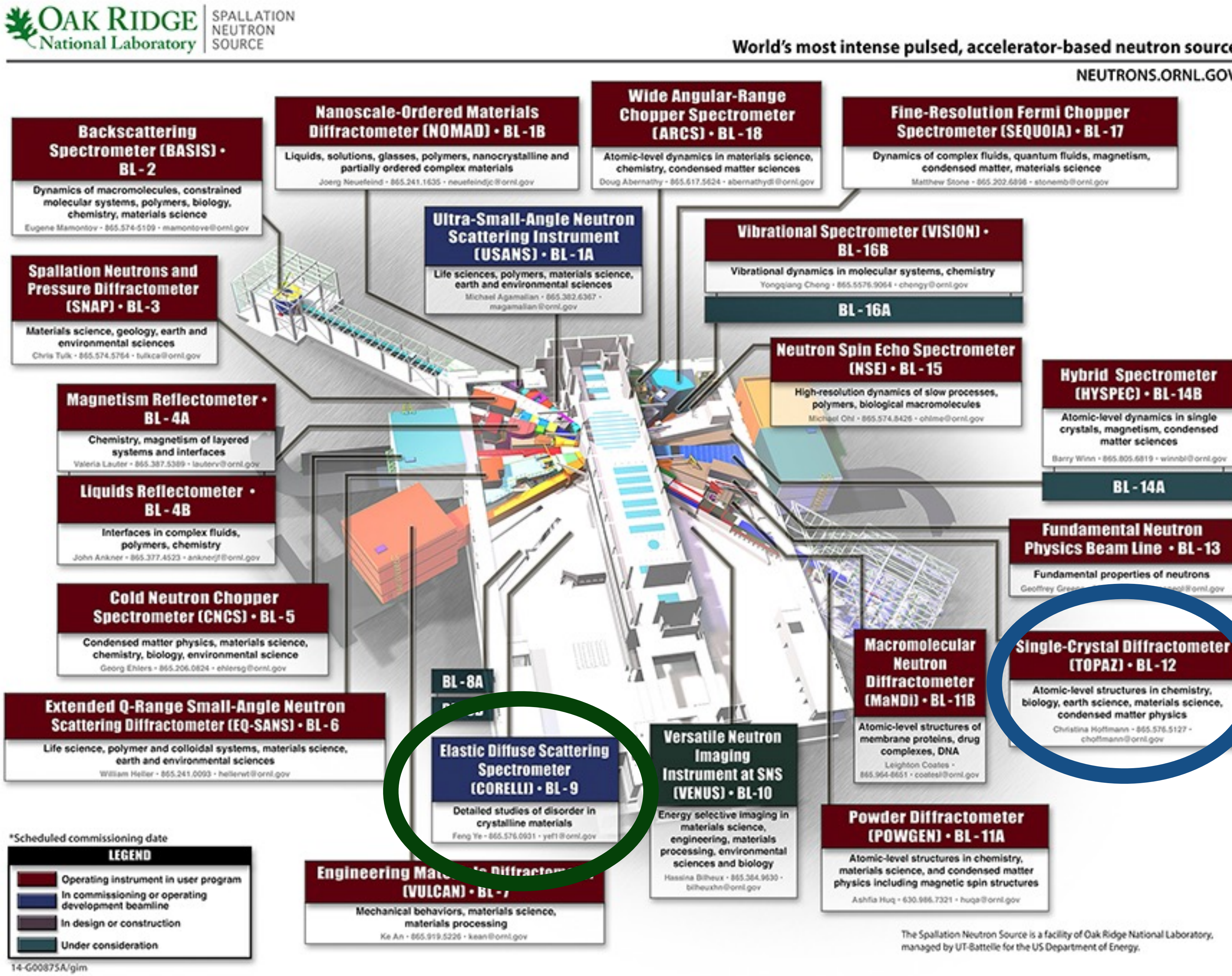
**inelastic excitations**

$$\hbar\omega = +E_0$$

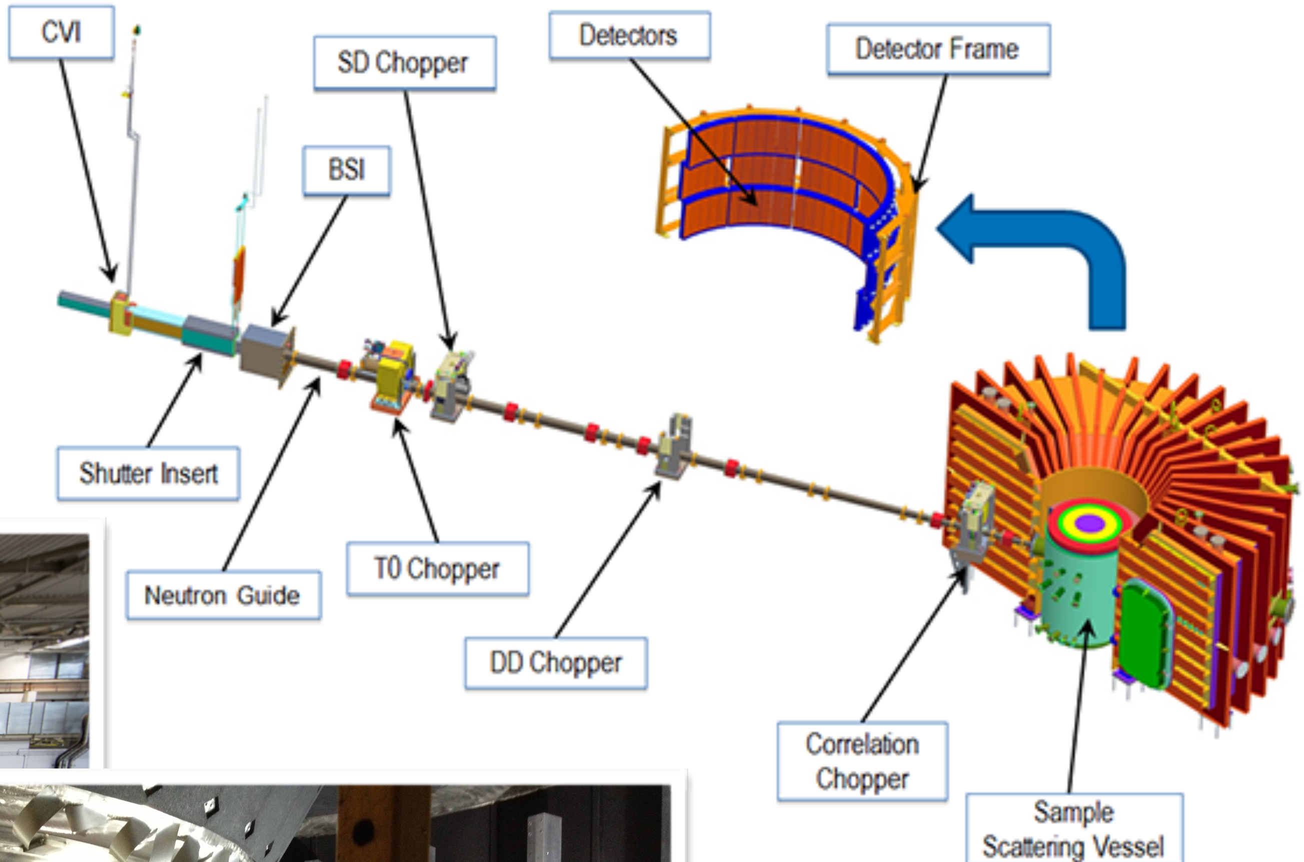
$$\hbar\omega = -E_0$$



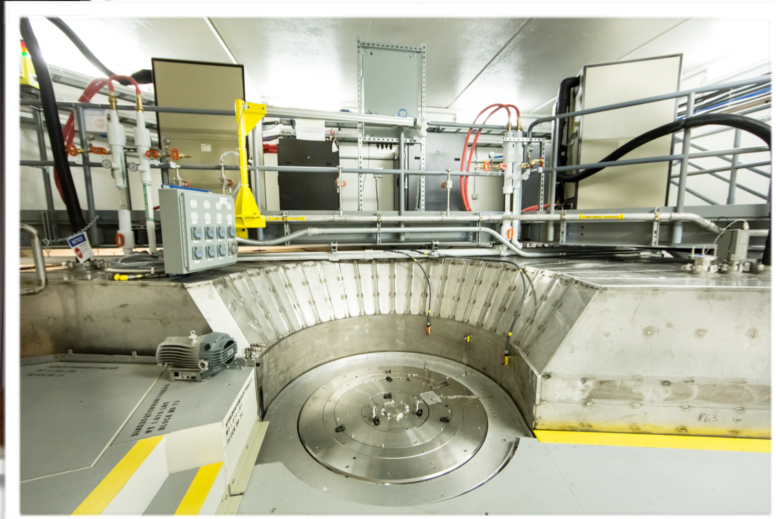

16


OAK RIDGE National Laboratory
SPALLATION NEUTRON SOURCE
World's most intense pulsed, accelerator-based neutron source
NEUTRONS.ORNL.GOV
Backscattering Spectrometer (BASIS) • BL-2
Dynamics of macromolecules, constrained molecular systems, polymers, biology, chemistry, materials science
Nanoscale-Ordered Materials Diffractometer (NOMAD) • BL-1B
Liquids, solutions, glasses, polymers, nanocrystalline and partially ordered complex materials
Wide Angular-Range Chopper Spectrometer (ARCS) • BL-18
Atomic-level dynamics in materials science, chemistry, condensed matter sciences
Fine-Resolution Fermi Chopper Spectrometer (SEQUOIA) • BL-17
Dynamics of complex fluids, quantum fluids, magnetism, condensed matter, materials science
Ultra-Small-Angle Neutron Scattering Instrument (USANS) • BL-1A
Life sciences, polymers, materials science, earth and environmental sciences
Vibrational Spectrometer (VISION) • BL-16B
Vibrational dynamics in molecular systems, chemistry
BL-16A
Spallation Neutrons and Pressure Diffractometer (SNAP) • BL-3
Materials science, geology, earth and environmental sciences
Neutron Spin Echo Spectrometer (NSE) • BL-15
High-resolution dynamics of slow processes, polymers, biological macromolecules
Hybrid Spectrometer (HYSPEC) • BL-14B
Atomic-level dynamics in single crystals, magnetism, condensed matter sciences
BL-14A
Magnetism Reflectometer • BL-4A
Chemistry, magnetism of layered systems and interfaces
Liquids Reflectometer • BL-4B
Interfaces in complex fluids, polymers, chemistry
Fundamental Neutron Physics Beam Line • BL-13
Fundamental properties of neutrons
Cold Neutron Chopper Spectrometer (CNCS) • BL-5
Condensed matter physics, materials science, chemistry, biology, environmental science
Macromolecular Neutron Diffractometer (MaNDi) • BL-11B
Atomic-level structures of membrane proteins, drug complexes, DNA
Single-Crystal Diffractometer (TOPAZ) • BL-12
Atomic-level structures in chemistry, biology, earth science, materials science, condensed matter physics
BL-8A
Extended Q-Range Small-Angle Neutron Scattering Diffractometer (EQ-SANS) • BL-6
Life science, polymer and colloidal systems, materials science, earth and environmental sciences
Elastic Diffuse Scattering Spectrometer (CORELLI) • BL-9
Detailed studies of disorder in crystalline materials
Versatile Neutron Imaging Instrument at SNS (VENUS) • BL-10
Energy selective imaging in materials science, engineering, materials processing, environmental sciences and biology
Powder Diffractometer (POWGEN) • BL-11A
Atomic-level structures in chemistry, materials science, and condensed matter physics including magnetic spin structures
Mechanical behaviors, materials science, materials processing
*Scheduled commissioning date
LEGEND
Operating instrument in user program
In commissioning or operating development beamline
In design or construction
Under consideration
14-G00875A/gim
The Spallation Neutron Source is a facility of Oak Ridge National Laboratory, managed by UT-Battelle for the US Department of Energy.

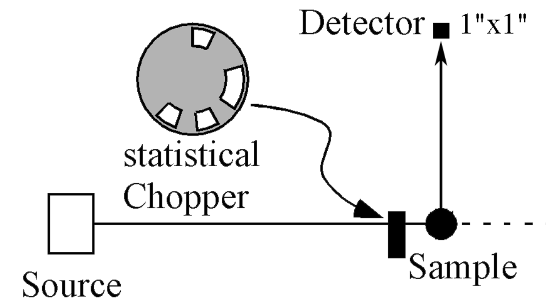
# Corelli



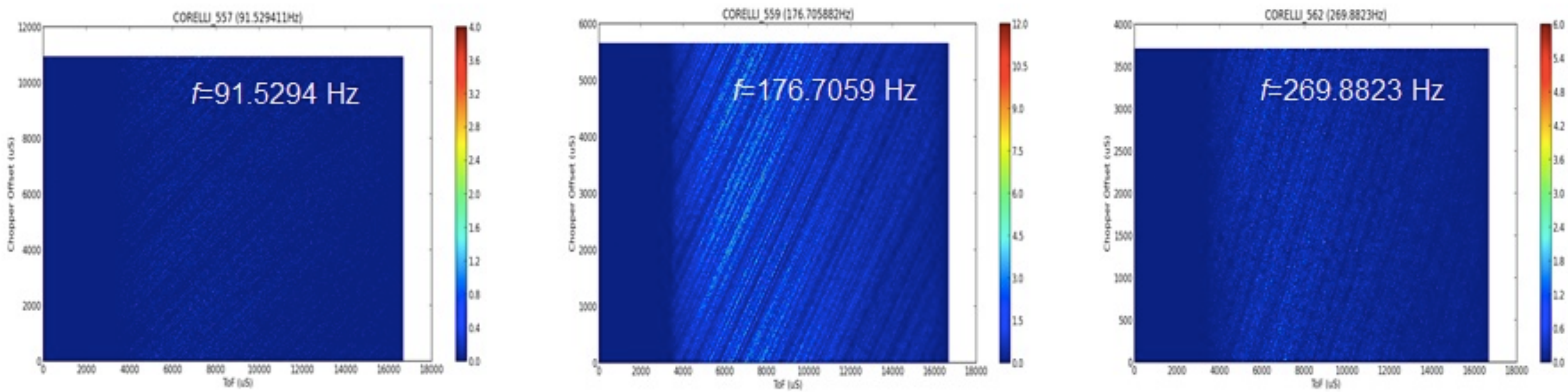
CVI
SD Chopper
Detectors
Detector Frame
BSI
Shutter Insert
Neutron Guide
T0 Chopper
DD Chopper
Correlation Chopper
Sample Scattering Vessel

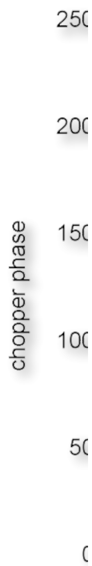



# Cross Correlation in Action

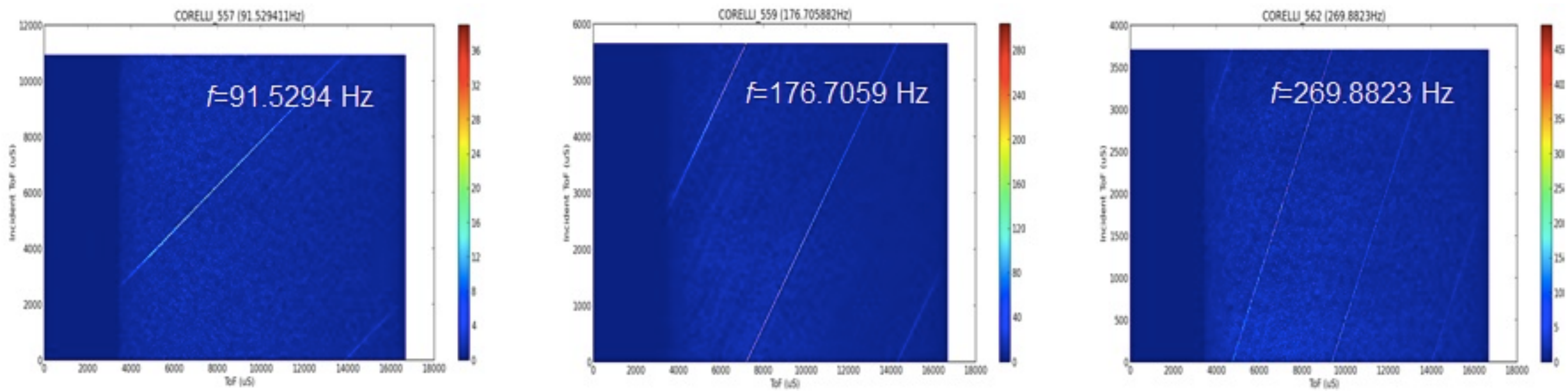



Before cross-correlation



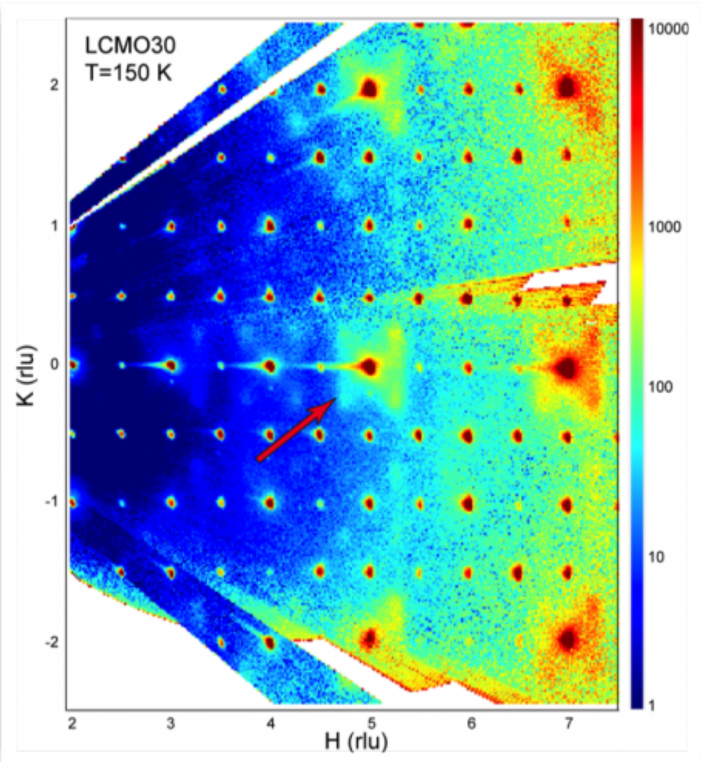




After cross-correlation

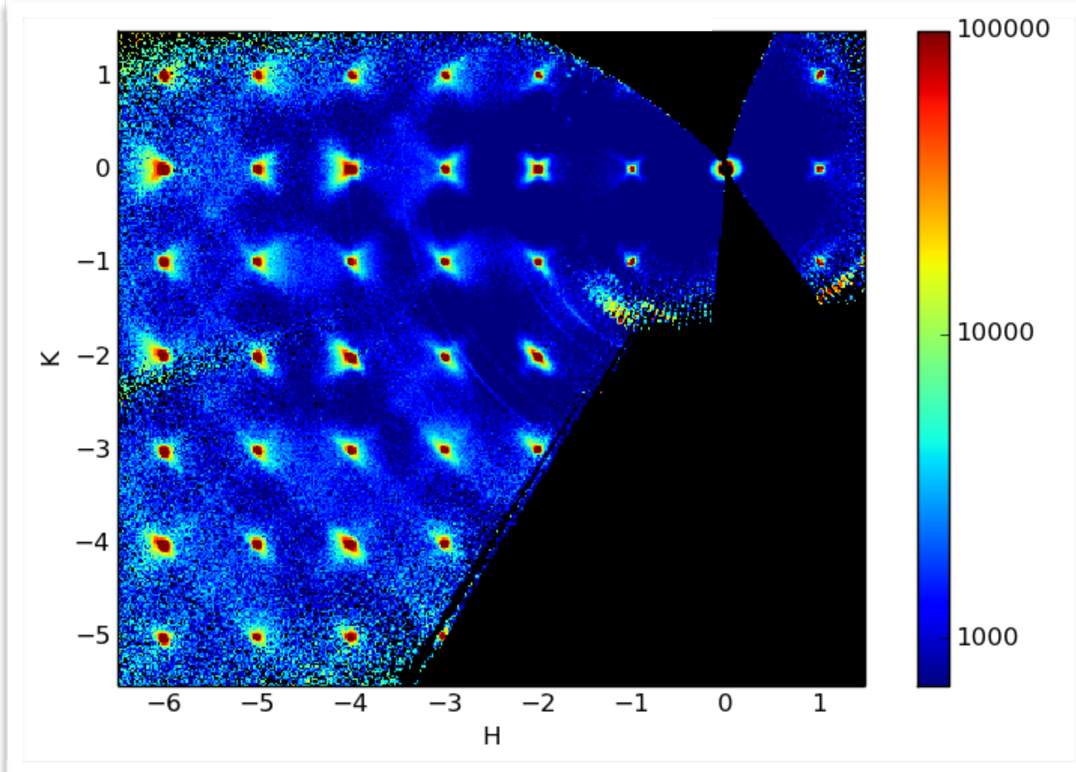


# First Results

- $La_{0.7}Ca_{0.3}MnO_3$

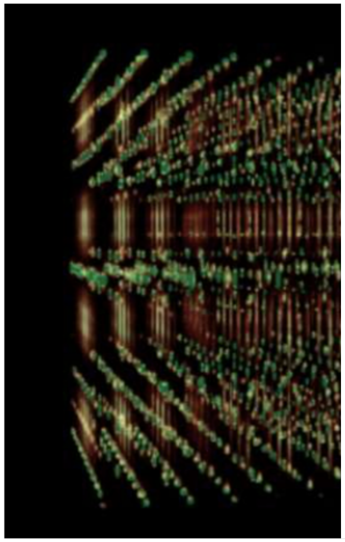


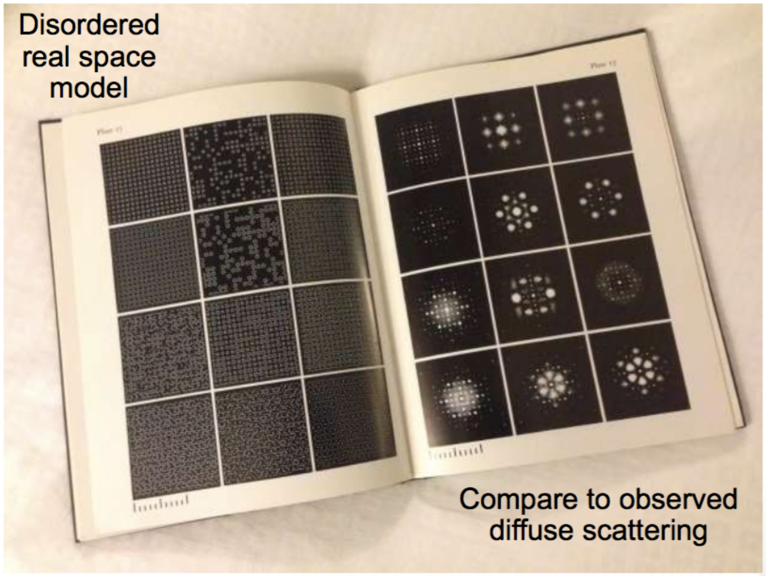

- $PbMn_{1/3}Nb_{2/3}O_3$-30%$PbTiO_3$



# The Future

- High-Energy X-rays
  - Absorption lengths similar to neutrons
  - Most existing detectors have low efficiency but alternatives exist, *e.g.* CdTe
- Micro-diffuse scattering
  - Benefiting from increased brightness of, *e.g.,* APS Upgrade
- Increasing use of *ab initio* computational modeling
  - Allowing more complex systems to be investigated
  - Less dependence on intuition in modeling
- Enhanced analysis tools
  - Machine learning
  - Correlated data analysis
  - Easier co-refinement of neutrons and x-rays






Atlas of Optical Transforms, Harburn, Taylor and Welberry (1975)

# A Few References

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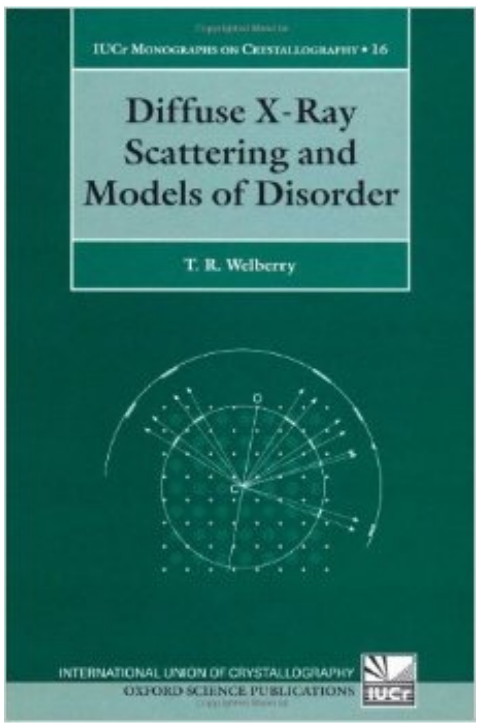
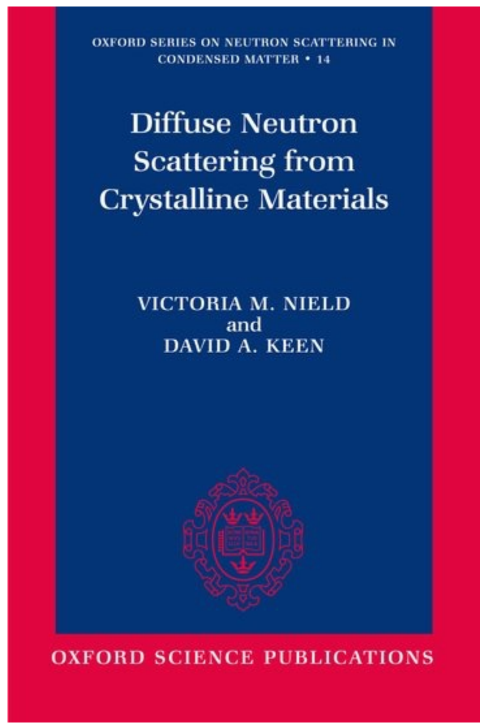
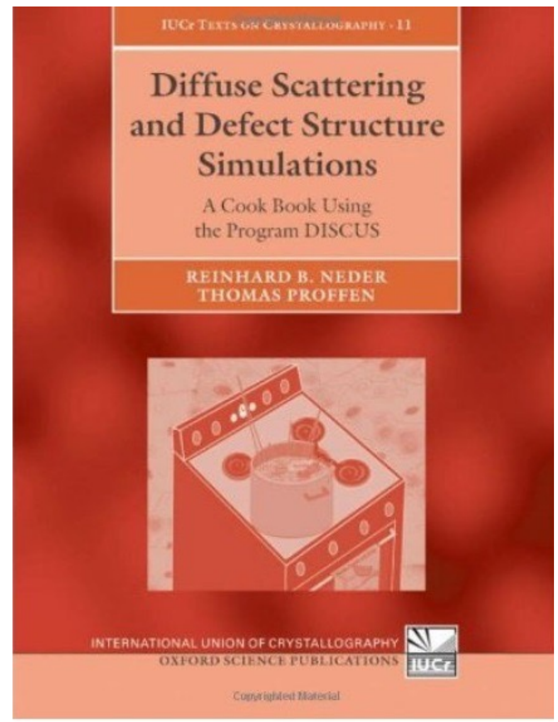
- F. Frey, Acta Cryst B **51**, 592–603 (1995).
- T. R. Welberry & D. J. Goossens, Acta Cryst A **64**, 23–32 (2007).
- D. A. Keen & A. L. Goodwin, Nature News **521**, 303–309 (2015).



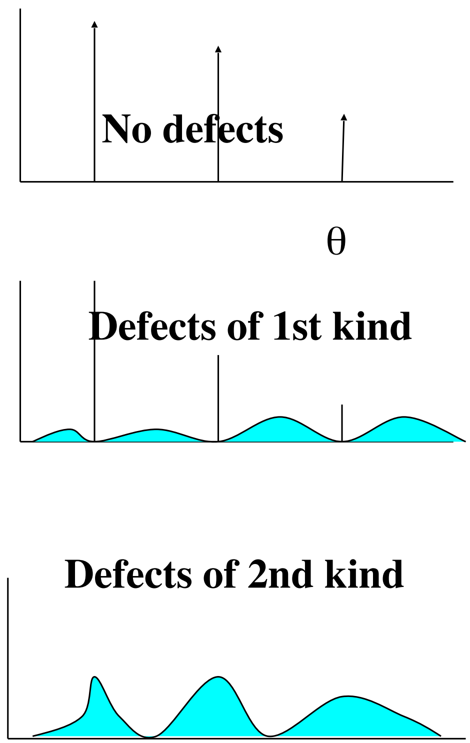



# Diffuse Scattering Song

- Come eager young scholars - so tender and new
  I'll teach you diffraction - what I says mostly true
  Between the Bragg Peaks lies a world where you see
  Fluctuations and defects- they stand out plane-ly
- *Chorus*
  For its dark as a dungeon between the Bragg peaks
  But here in the darkness - each defect speaks
  It gathers- from throughout- reciprocal space
  And re-distributes all over the place.
- Between the Bragg peaks - one thing that we see
  Is TDS on our CCD
  Intensity totals are conserved- you can't win
  It steals from the Bragg peaks that stay very thin
- Substitutional alloys can cause quite a stir
  The shorter the length scale the greater the blur
  With care you can find out the bond length between
  Each atom pair type-the measurements clean
- Dislocations and other- type 2 defects
  Destroy the Bragg peaks -they turn them to wrecks
  But near the Bragg peaks- you still can see
  Intense diffraction continuously
- Many -are- the defects you find
  Between the Bragg peaks where others are blind
  So go tell your friends and impress your boss
  You've new understanding -with one hours loss

Gene Ice




Krivoglaz Classifications