High precision X-ray measurements 2021

MDPI condensed matter ONLINE, 8-10/06/2021 INFN Istituto Nazionale di Fisica Nucleare LABORATORI NAZIONALI DI FRASCATI

Dynamical and correlated disorder at nanoscale in complex materials

Gaetano Campi

Institute of Crystallography - CNR

Frascati, 8/06/2021

Complex and inhomogeneous materials

Complex materials are characterized by variations in the atomic and electronic structure on different length scales.

Energy

Atomic scale

↕

Molecular scale

↕

Nanoscale

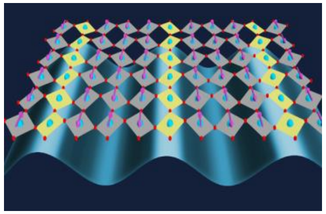
↕

Mesoscale

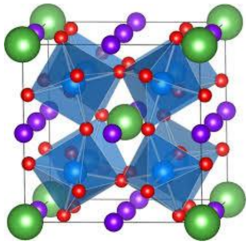
↕

Microscale

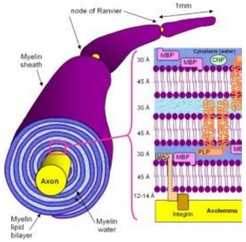
Time



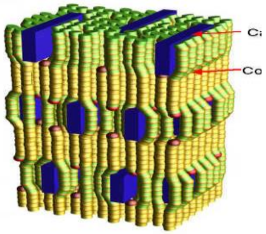
CDW, SDW, orbitals
electronic clumpy patterns



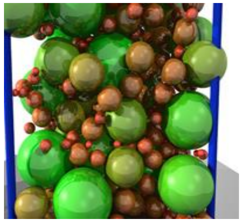
Perovskites



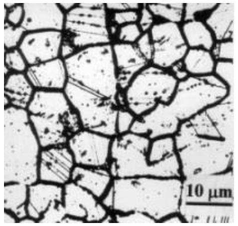
Myelin
Fluctuations at nanoscale



Bone tissue
Mixture at nanoscale



Cements
Packing at nanoscale

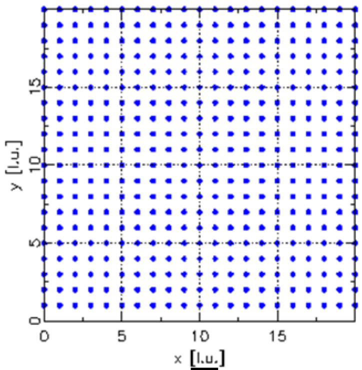


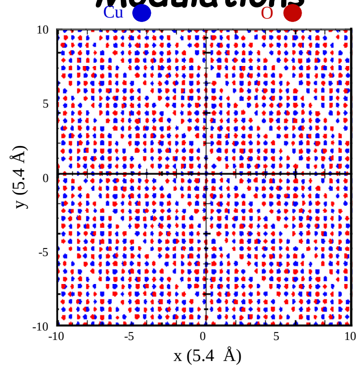
Steel
GB at micron scale

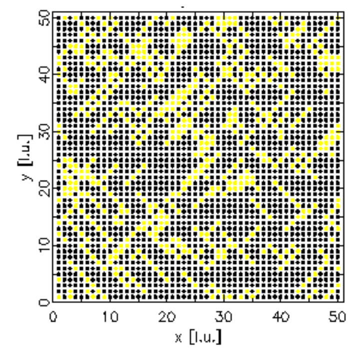
Inhomogeneity at atomic scale:
X-ray *diffuse scattering*

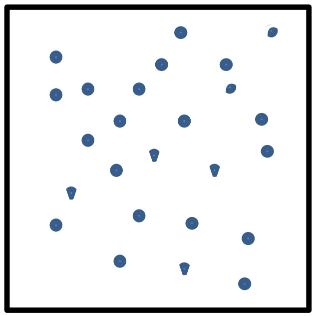
......from point to topological defects: heterogeneous matter

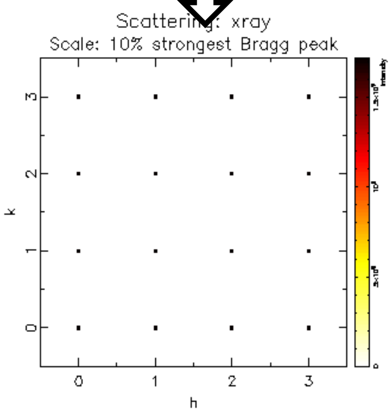
Modulations *Striped atomic G and GB*

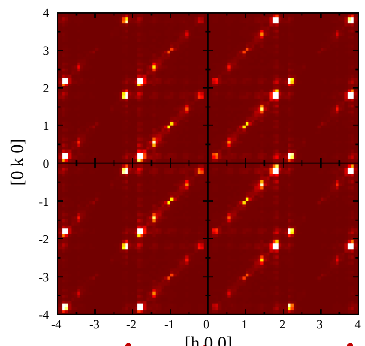




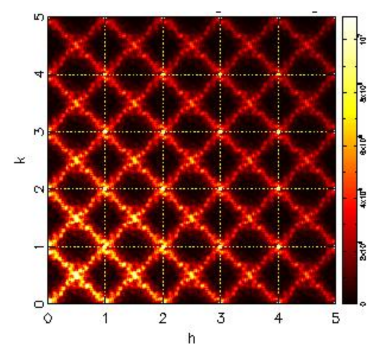




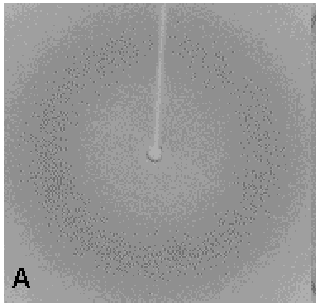




superlattice peaks



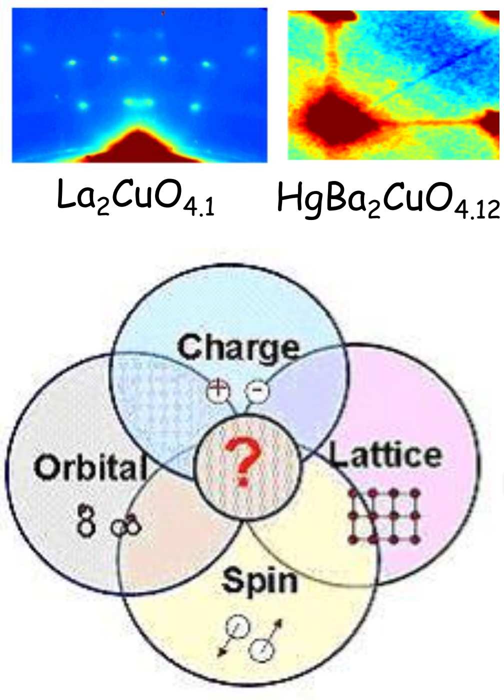
streaks



Order ⟺ **Correlated disorder** ⟺ **Disorder**

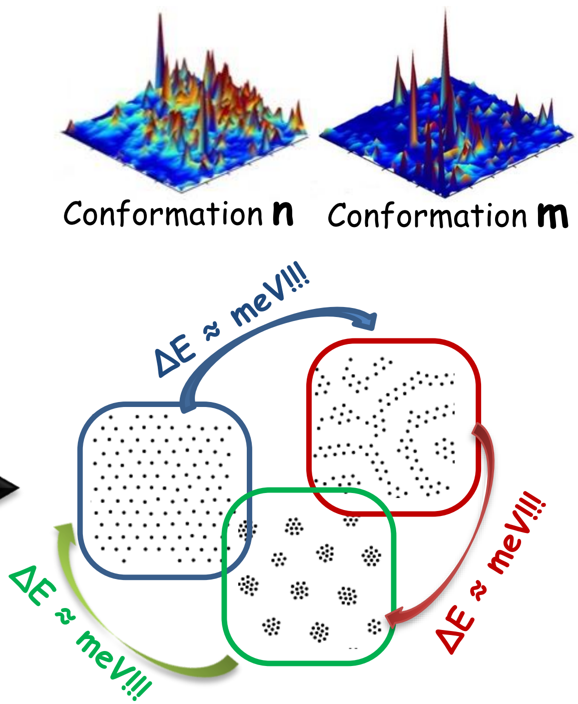
Disorder and complexity in matter

Correlated disorder



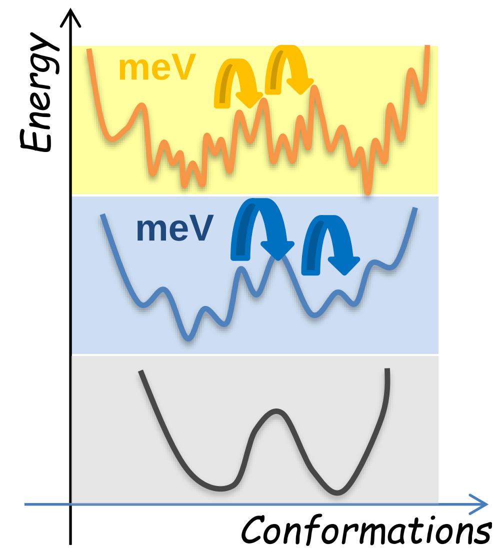
Several materials have inhomogeneous phases. This occurs when several physical interactions such as spin, charge, strain, orbital are simultaneously active.

Pattern formation



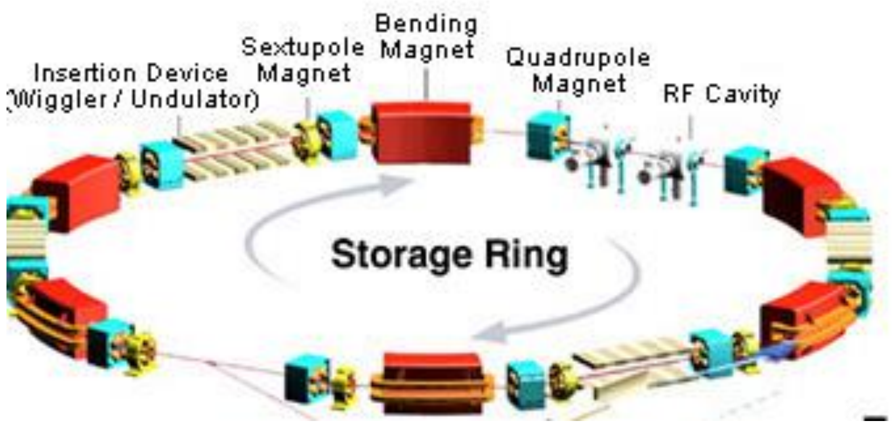
The spontaneous emergence of spatial patterns and correlated disorder is due to many competing states, as in soft materials and biological systems.

Complexity

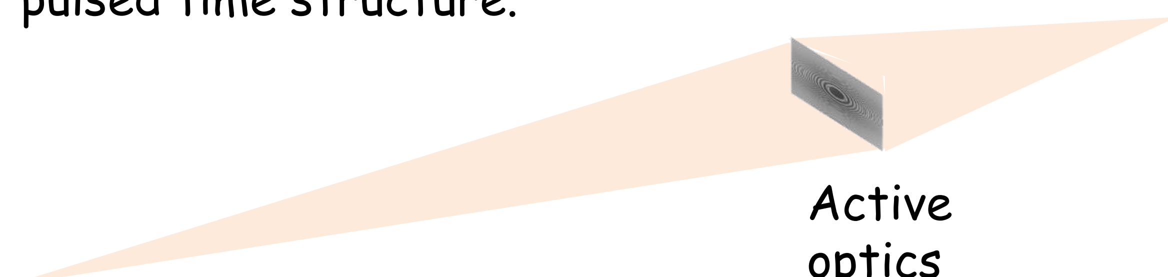


Different spatial patterns produce an energy landscape where transitions between different conformations involve similar energy values down to few meV.

METHODS



(i) high intensity and brilliance (20 orders of magnitude higher);
(ii) broad and continuous spectral range from the infrared to the X-ray;
(iii) narrow angular divergence;
(iv) high degree of polarization;
(v) pulsed time structure.

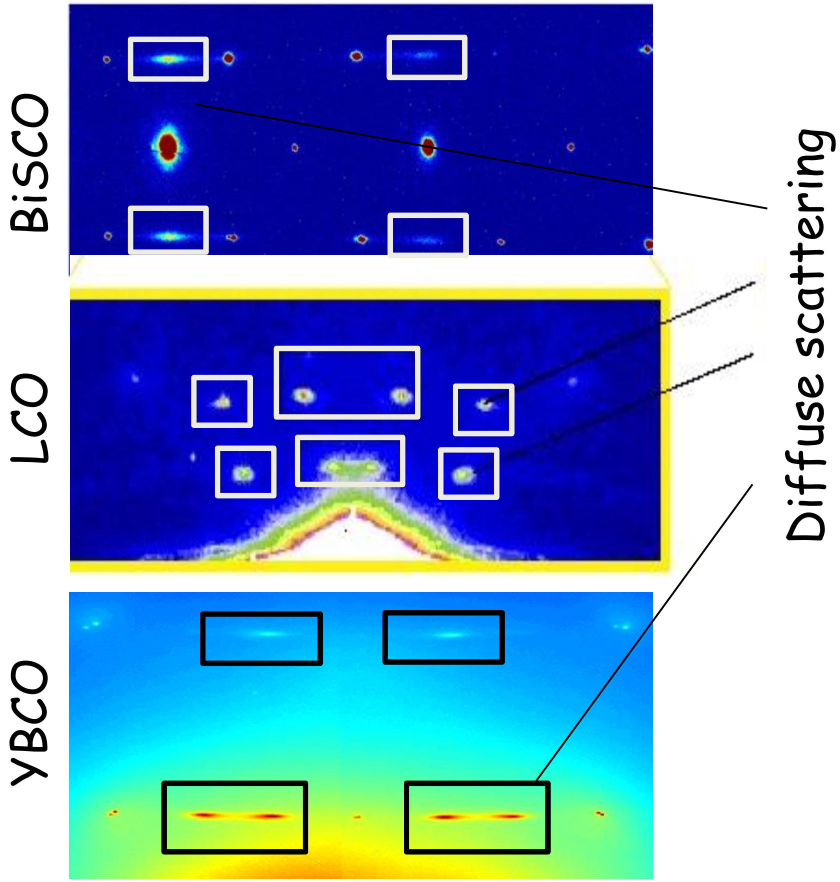


Active optics

High Precision X ray Measurements
1. Crystal orientation and peaks indexing

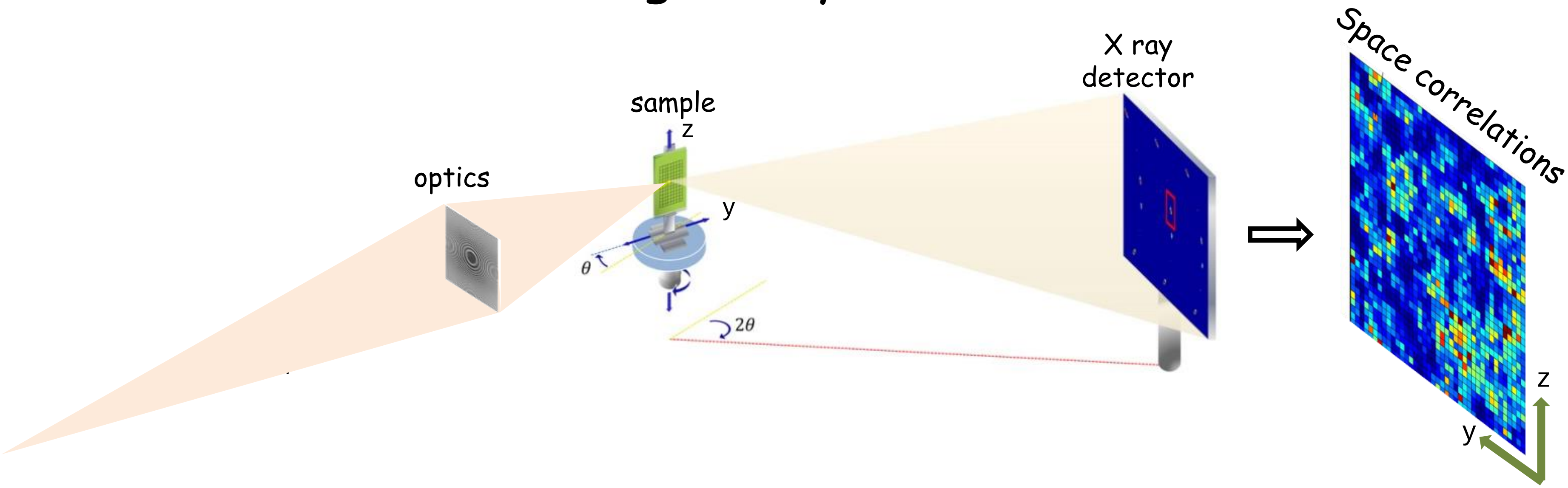
Correlated disorder in atomic structure

4 circle K-diffractometer

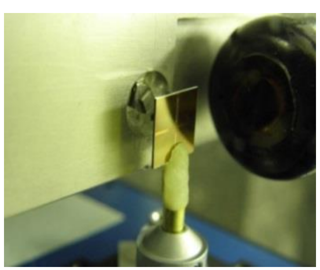
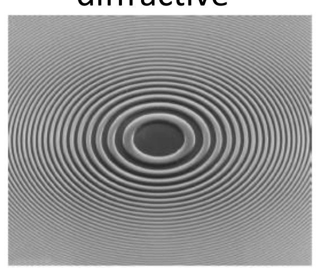


High Precision X ray Measurements
2. Scanning micro/nano XRD

Scanning X-Ray Diffraction



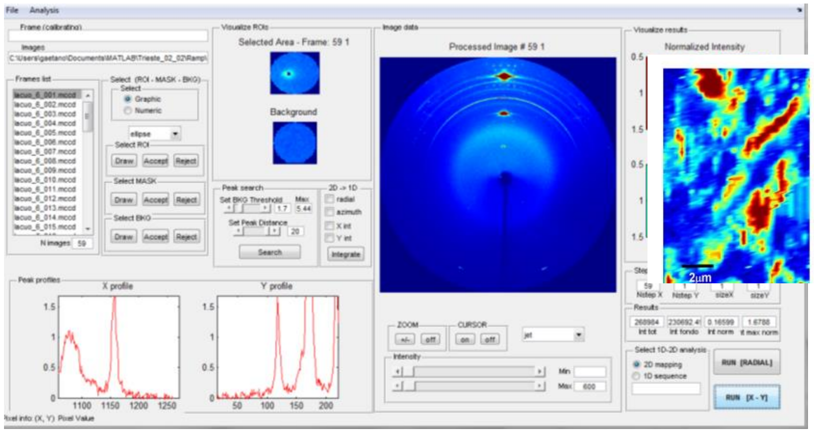
FOCUSING OPTICS

NFL refractive	K-B reflective	ZONE PLATES: diffractive
		

Mesh:
100x100 μm

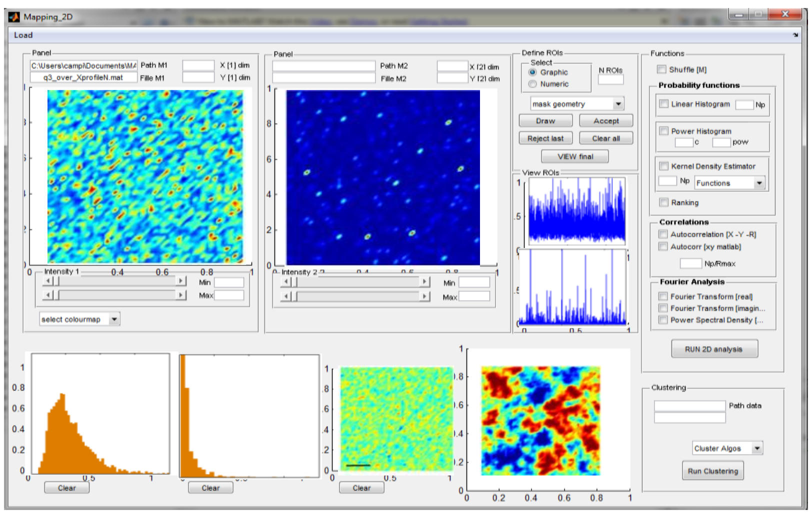
- Step: 1μm; **10000** frames
- Step: 100 nm; **1000000** frames

Methods
3. Big datasets analysis: Statistical Physics



X ray microdiffraction analysis

Mapping
(domain size, population of coexisting *soft-like* phases)



Spatial Statistical analysis
Spatial Probability Distributions

Correlations in space and time
Continuous/Discrete patterns

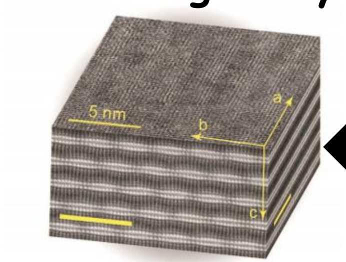
Clustering
Aggregation/dispersion
Spatial tessellation

Connectivity
Percolation

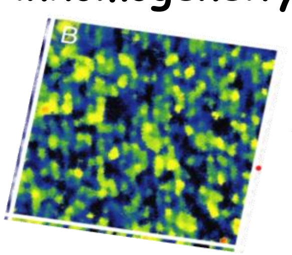
APPLICATIONS

1. HTCS cuprates

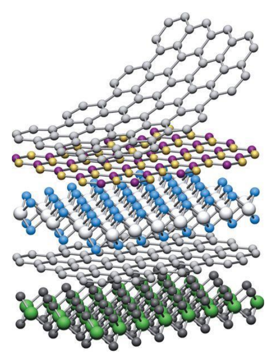
Lattice inhomogeneity



Electronic inhomogeneity

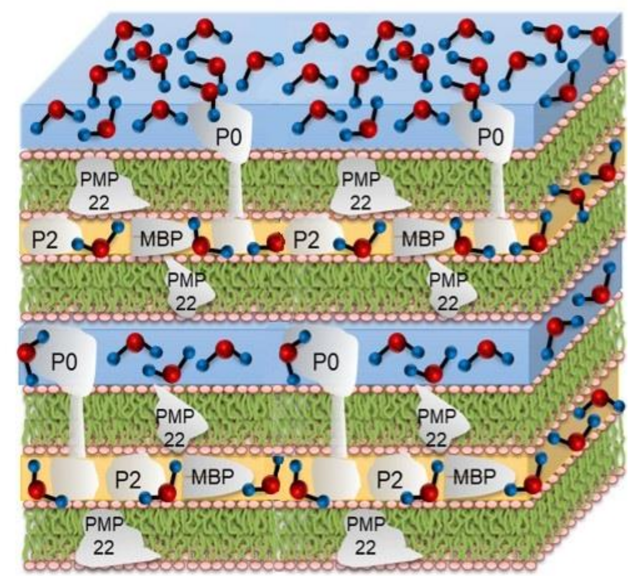


Layers at atomic scale



2. Myelin

Layers at nanometric scale



DEFECTS and CDW SELF-ORGANIZATION in La_2CuO_{4+y}

Vol 466 | 12 August 2010 | doi:10.1038/nature09260 nature

LETTERS

Scale-free structural organization of oxygen interstitials in La_2CuO_{4+y}

Michela Fratini[1]†, Nicola Poccia[1], Alessandro Ricci[1], Gaetano Campi[1,2], Manfred Burghammer[3], Gabriel Aeppli[4] & Antonio Bianconi[1]

nature materials

LETTERS

PUBLISHED ONLINE: 21 AUGUST 2011 | DOI: 10.1038/NMAT3088

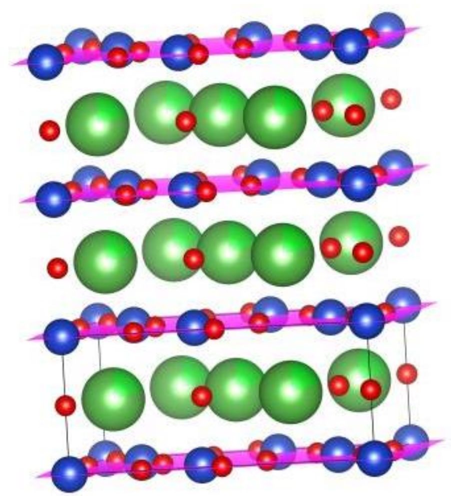
Evolution and control of oxygen order in a cuprate superconductor

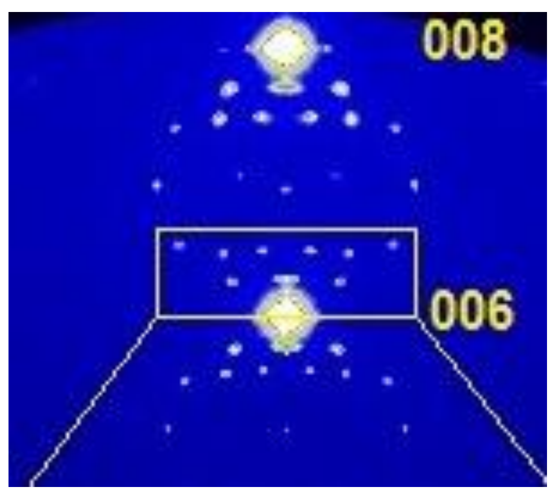
Nicola Poccia[1], Michela Fratini[1], Alessandro Ricci[1], Gaetano Campi[2], Luisa Barba[3], Alessandra Vittorini-Orgeas[1], Ginestra Bianconi[4], Gabriel Aeppli[5] and Antonio Bianconi[1]*

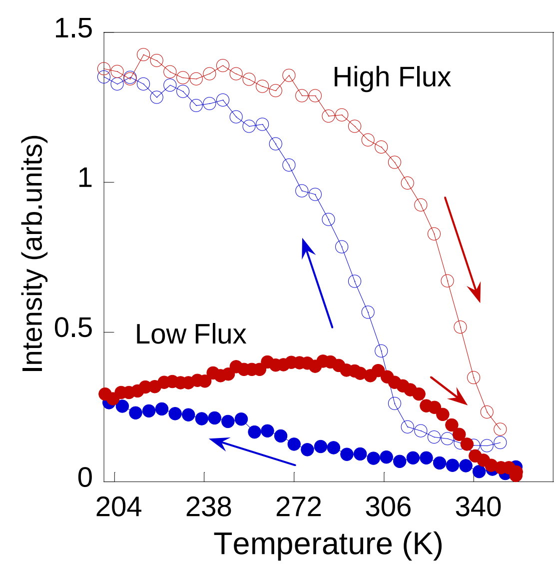
Layered structure + i-O dopants

i-O ordering + CDW ordering

Thermal cycling + X ray illumination

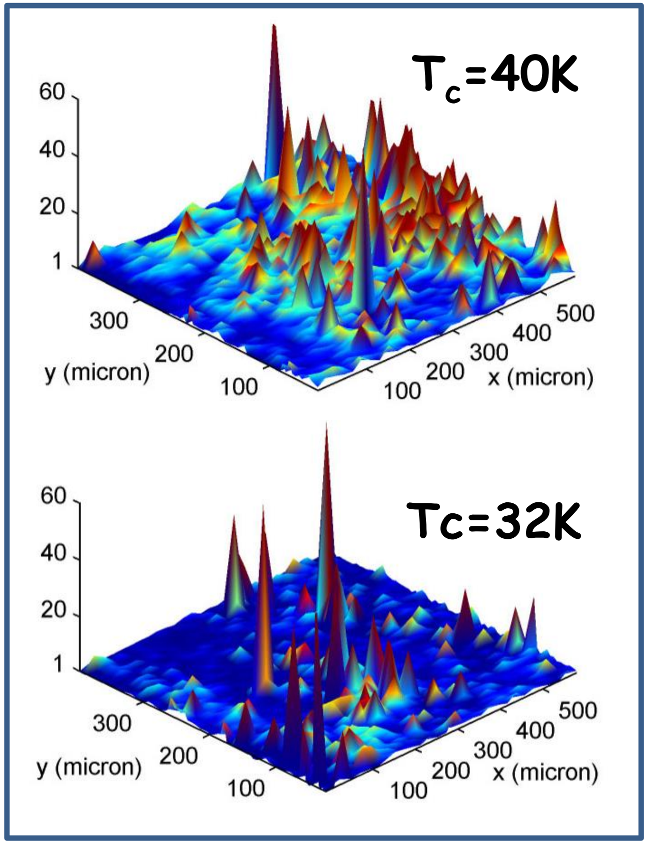




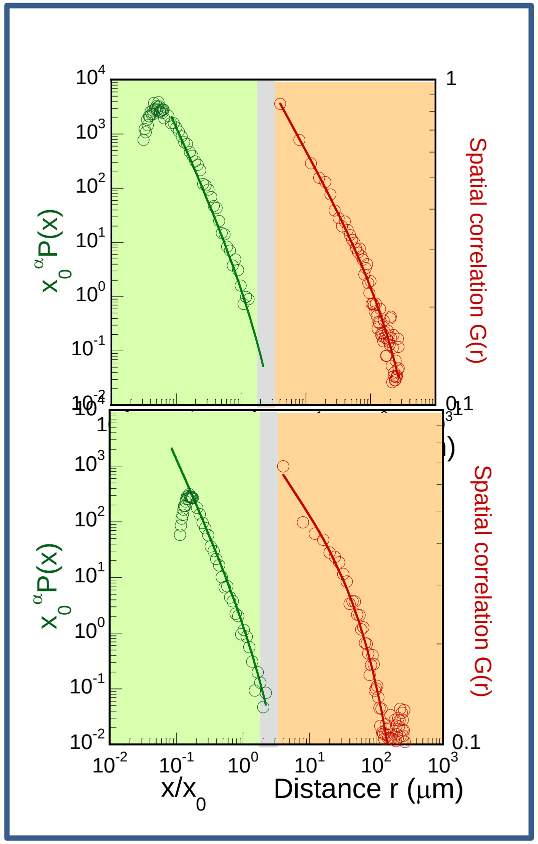


Scale free order

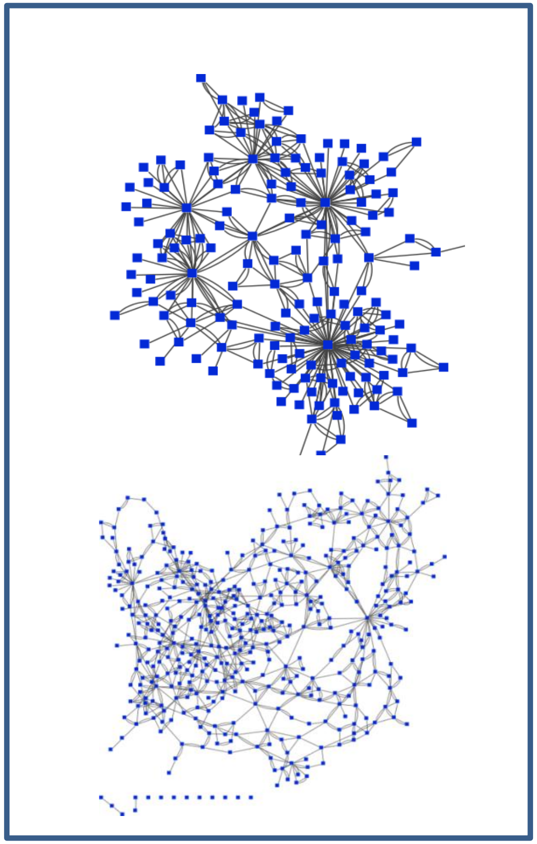
Spatial patterns: conformation **n, m**



Spatial distributions and correlations



Connectivity



Two different sample preparation with the same oxygen content but different Tc and configurations due to oxygen distribution.

Non-euclidean electronic space

LETTER

doi:10.1038/nature14987

Inhomogeneity of charge-density-wave order and quenched disorder in a high-T_c superconductor

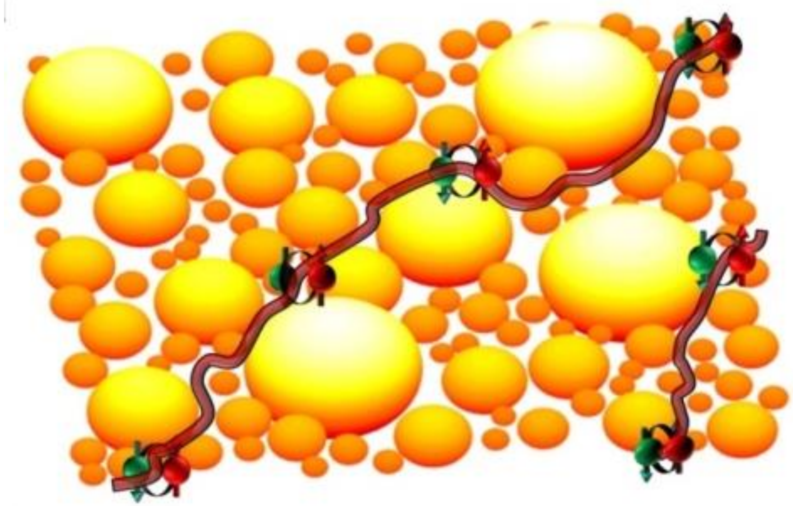
G. Campi[1,2*], A. Bianconi[1,2*], N. Poccia[2,3], G. Bianconi[4], L. Barba[5], G. Arrighetti[5], D. Innocenti[2,6], J. Karpinski[6,7], N. D. Zhigadlo[7], S. M. Kazakov[7,8], M. Burghammer[9,10], M. v. Zimmermann[11], M. Sprung[11] & A. Ricci[2,11*]

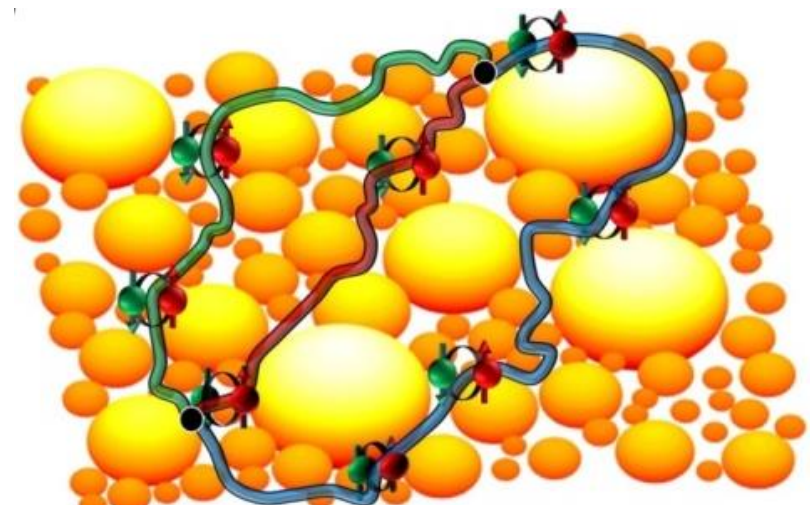
J Supercond Nov Magn
DOI 10.1007/s10948-015-3326-9

ORIGINAL PAPER

High-Temperature Superconductivity in a Hyperbolic Geometry of Complex Matter from Nanoscale to Mesoscopic Scale

G. Campi[1,2] · A. Bianconi[1,2,3]

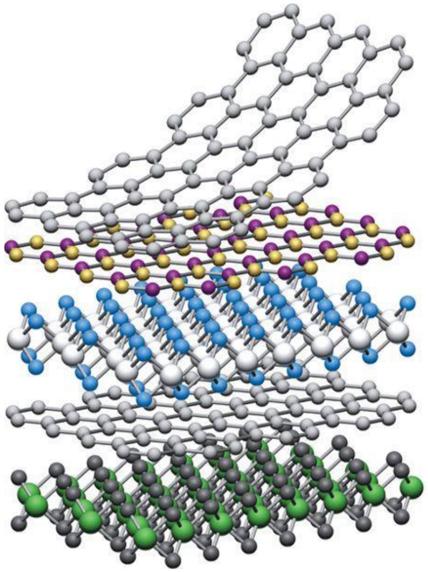




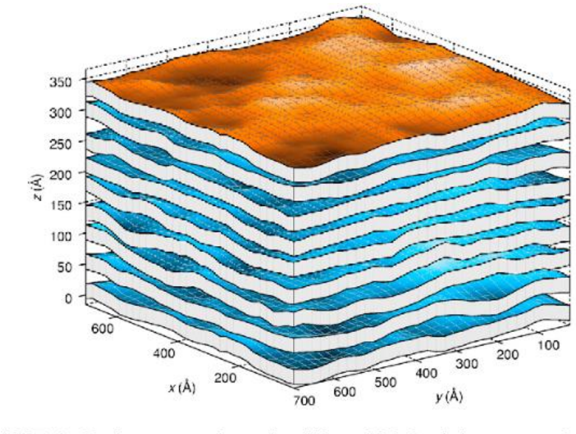
The CDW crystalline puddles form inhomogeneous spatial patterns giving rise to a new non-Euclidean geometry in the **interstitial space** left by the crystals of electrons. The free electrons, which do not crystallize, form Cooper pairs flowing along paths in the interstitial space at low temperatures.

Order and correlated disorder in biology

Structural Fluctuations at nano/mesoscale



Membranes



Fibers

Myelin
X ray Diffraction and E-D profiles

SCIENTIFIC REPORTS

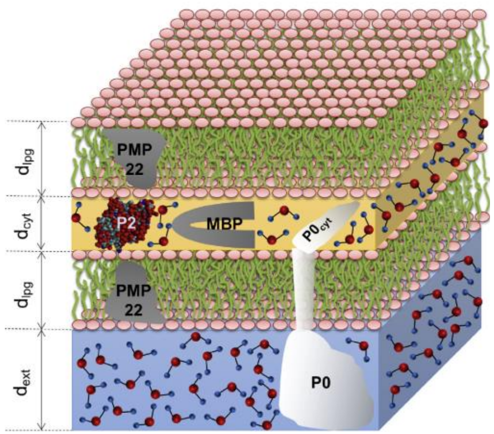
OPEN

SUBJECT AREAS:
MEMBRANE BIOPHYSICS
SELF-ASSEMBLY

Received
19 May 2014

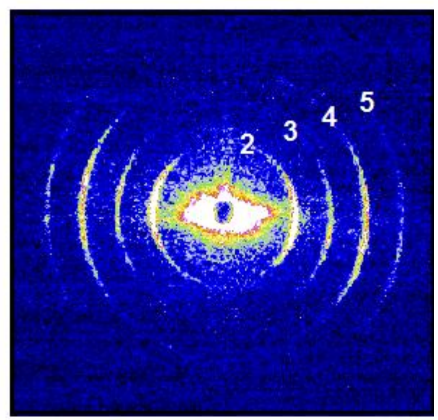
Changes of statistical structural fluctuations unveils an early compacted degraded stage of PNS myelin

Nicola Poccia[1,2*], Gaetano Campi[3*], Alessandro Ricci[1,4], Alessandra S. Caporale[1], Emanuela Di Cola[5], Thomas A. Hawkins[6] & Antonio Bianconi[1,3]



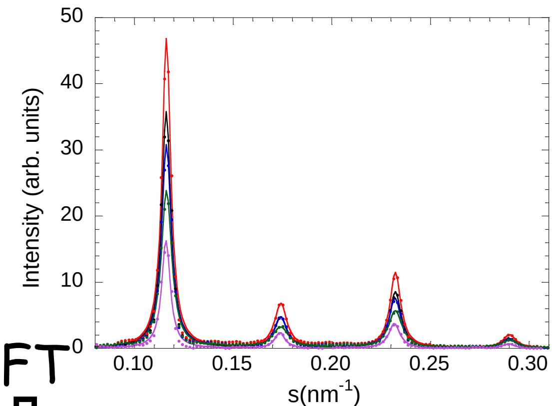
Myelin structural unit with the four principal myelin protein. The PMP22 protein is located in the lpg membrane. The P0 protein helps to build the myelin layers stacking. The cytoplasmic layer, *cyt*, (yellow), is the location of the structured protein P2 and the intrinsically disordered protein MBP.

Myelin XRD

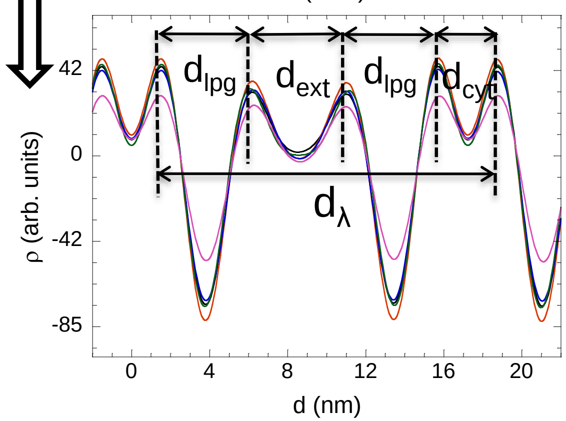


2-D diffraction pattern of myelin shows the expected arc-rings corresponding to the Bragg diffraction orders h = 2, 3, 4, 5. The exposure time was 300ms

Myelin ED

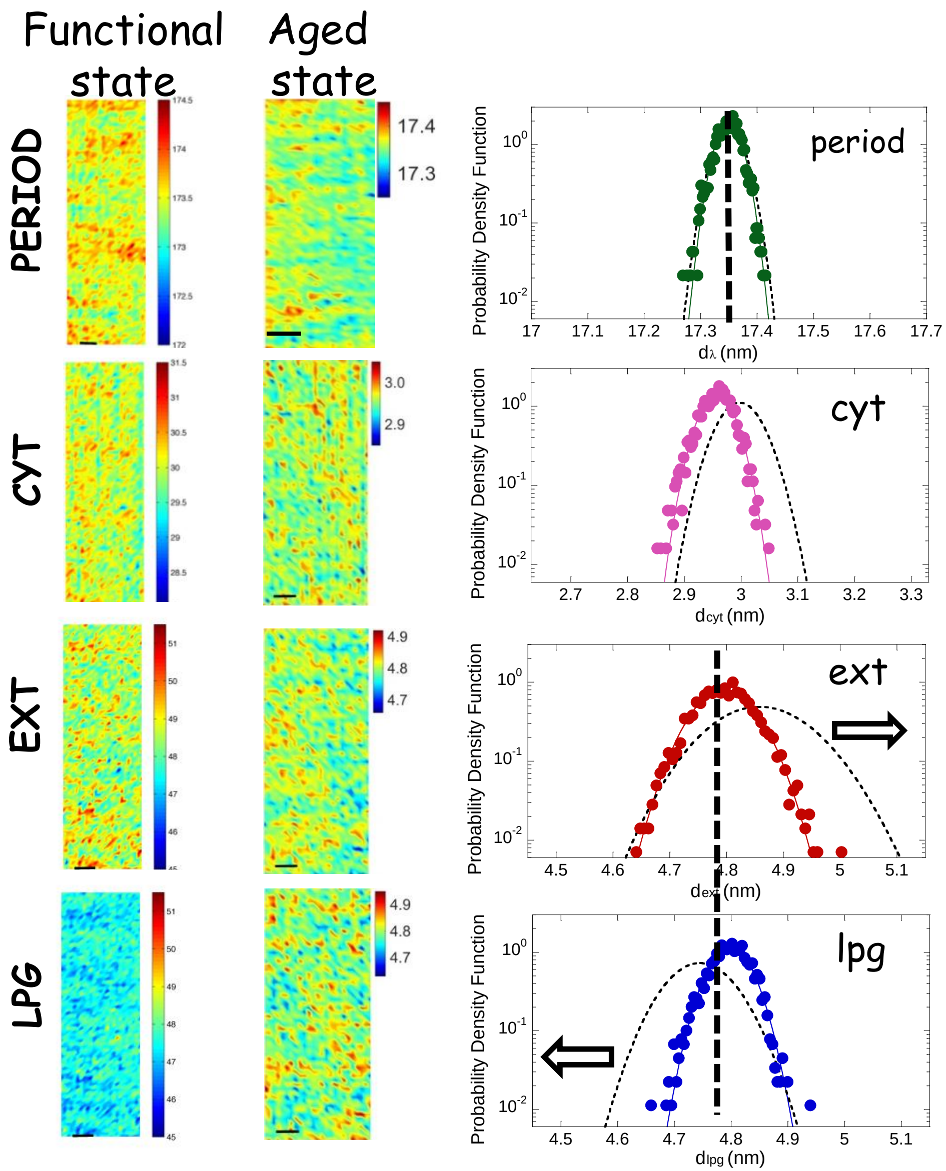


FT



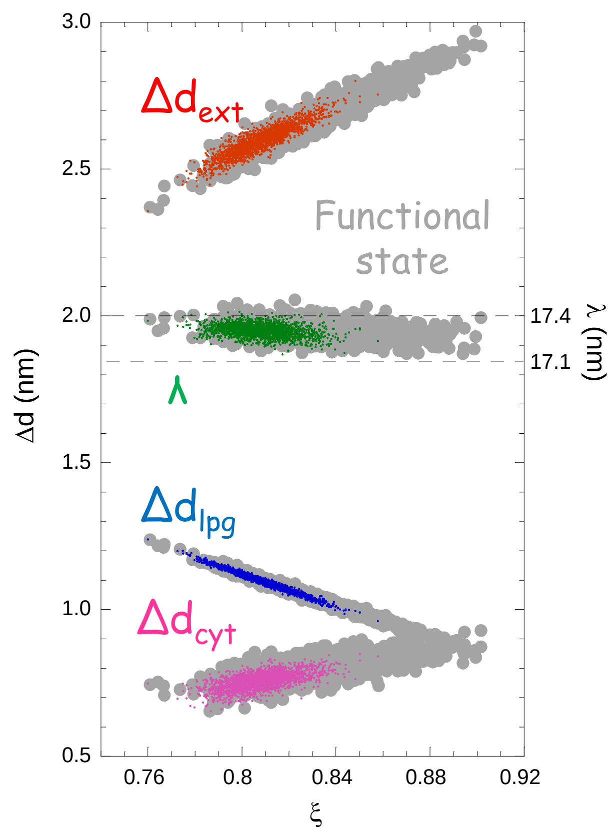
From the differences between two adjacent maxima d_{cyt} d_{ex} d_{lpg} and $d_\lambda=2d_{lpg}+d_{ext}+d_{cyt}$ were obtained.

Myelin
Spatial statistics of fluctuations



$\xi = (d_{ext} + d_{cyt})/2d_{lpg}$

Larger correlated fluctuations in the functional state



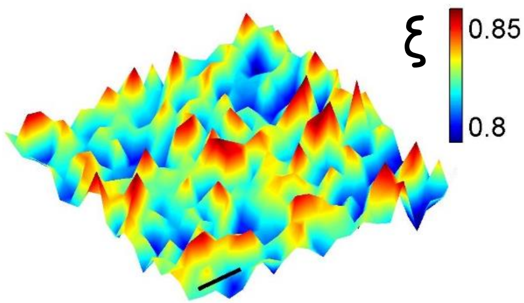
Levi correlated disorder in functional state

ACSNANO
Cite This: ACS Nano 2018, 12, 729–739
www.acsnano.org
ARTICLE

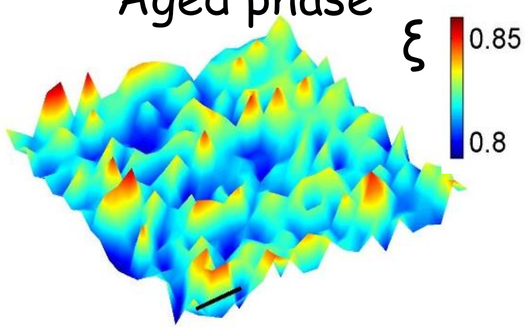
Nanoscale Correlated Disorder in Out-of-Equilibrium Myelin Ultrastructure

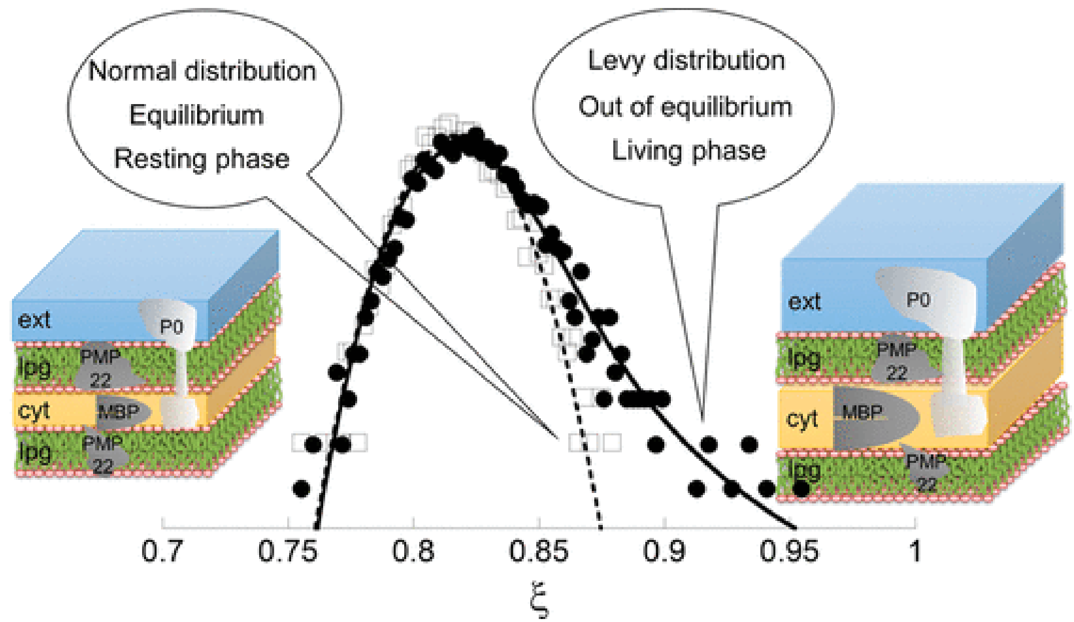
Gaetano Campi,[†] Michael Di Gioacchino,[†,‡,§] Nicola Poccia,[∥] Alessandro Ricci,[‡] Manfred Burghammer,[⊥] Gabriele Ciasca,[#] and Antonio Bianconi[*,†,‡,∇]

Functional phase



Aged phase





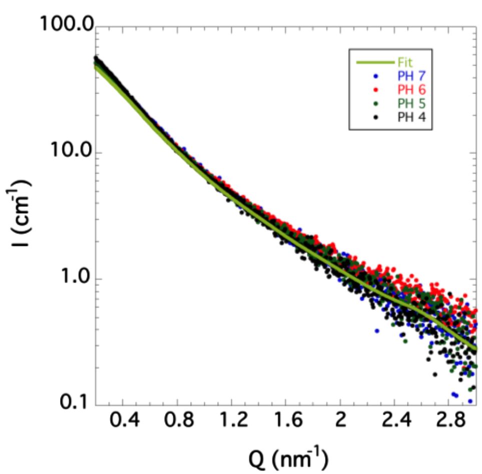
The PDF of ξ shows a skewed Levy distribution in the functional state. The Levy distributions provide a statistical description of complex systems out of thermodynamic equilibrium

Correlated disorder and IDP

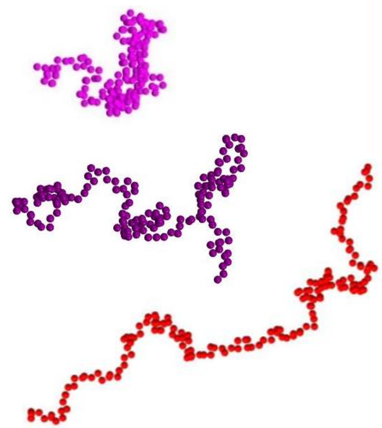
Contents lists available at ScienceDirect
BBA - Biomembranes
journal homepage: www.elsevier.com/locate/bbamem

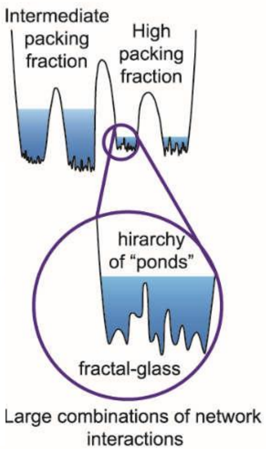
Myelin basic protein dynamics from out-of-equilibrium functional state to degraded state in myelin

Michael Di Gioacchino[a,b,c,*], Antonio Bianconi[b,c,d], Manfred Burghammer[e], Gabriele Ciasca[f], Fabio Bruni[a], Gaetano Campi[b]

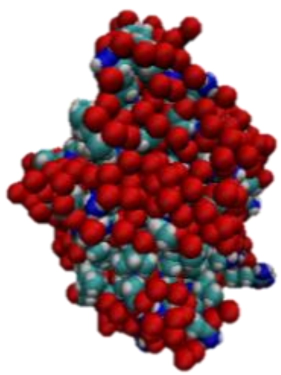


SAXS profiles measured at room temperature of the MBP in aqueous solution alongside the curve fit (green line) obtained by Ensemble Optimization Method (EOM)





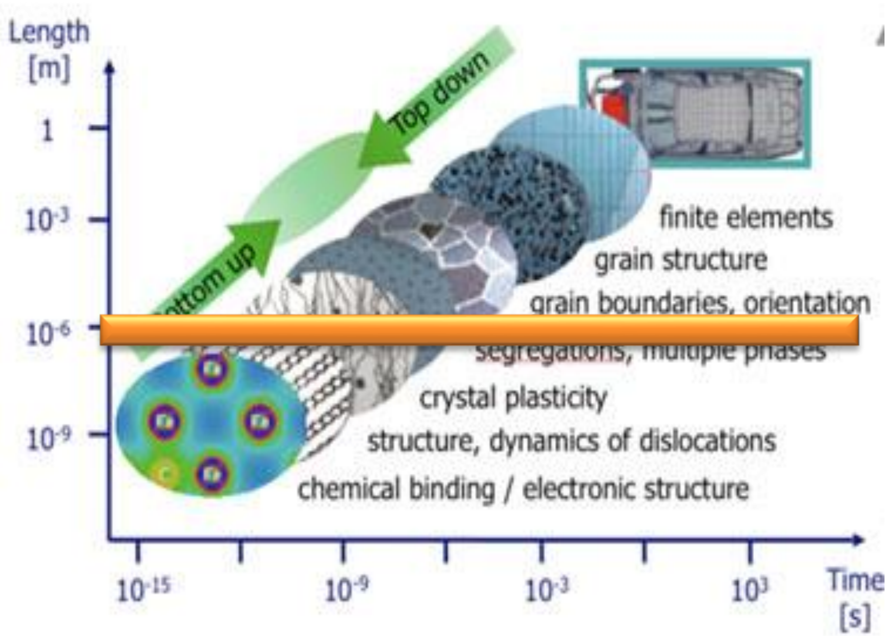
A 3D representation of some possible conformations of MBP extracted by EOM, used to fit the SAXS data. Large combinations of network interactions allow to **organize the disorder**



A 3D representation of P2 folded structure

Conclusions

Functional disorder control
for
Multiscale Material Engineering



above 10 microns are a classical issue of Material Engineering to optimize material properties.

from 10 microns to 0.1 nm structural fluctuations represent a **new field** of fundamental science for developing innovative material functionality.

Alessandro Ricci
Nicola Poccia

Michela Fratini
Gabriele Ciasca

Luisa Barba
Manfred Burghammer

LorenzaSuber

Naurang Saini
Antonio Bianconi

Thanks