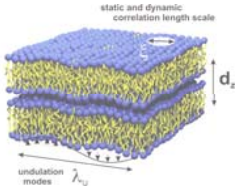
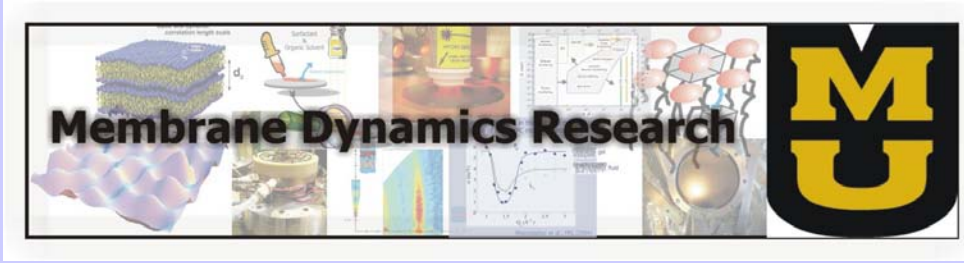


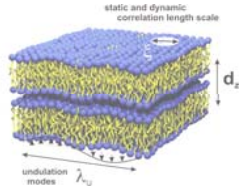


Using Neutron Spectroscopy to Study Collective Dynamics of Biological and Model Membrane Systems

Maikel C. Rheinstädter
Department of Physics and Astronomy
University of Missouri – Columbia

NCNR Summer School,
NIST Gaithersburg,
June 25-29, 2007

Biological Physics is...



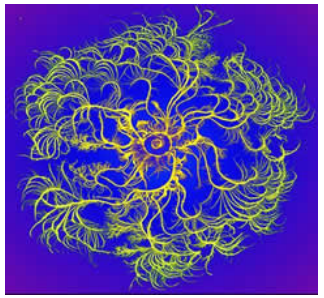
Aims and Scope, European Biophysical Journal:

"the study of biological phenomena using physical methods and concepts … the primary goal … is to advance the understanding of biological structure and function by application of the principles of physical science"

"… a distinctively biophysical approach at all levels of biological organization will be considered, as will both experimental and theoretical studies"

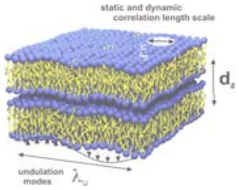
Hierarchy of biological systems:

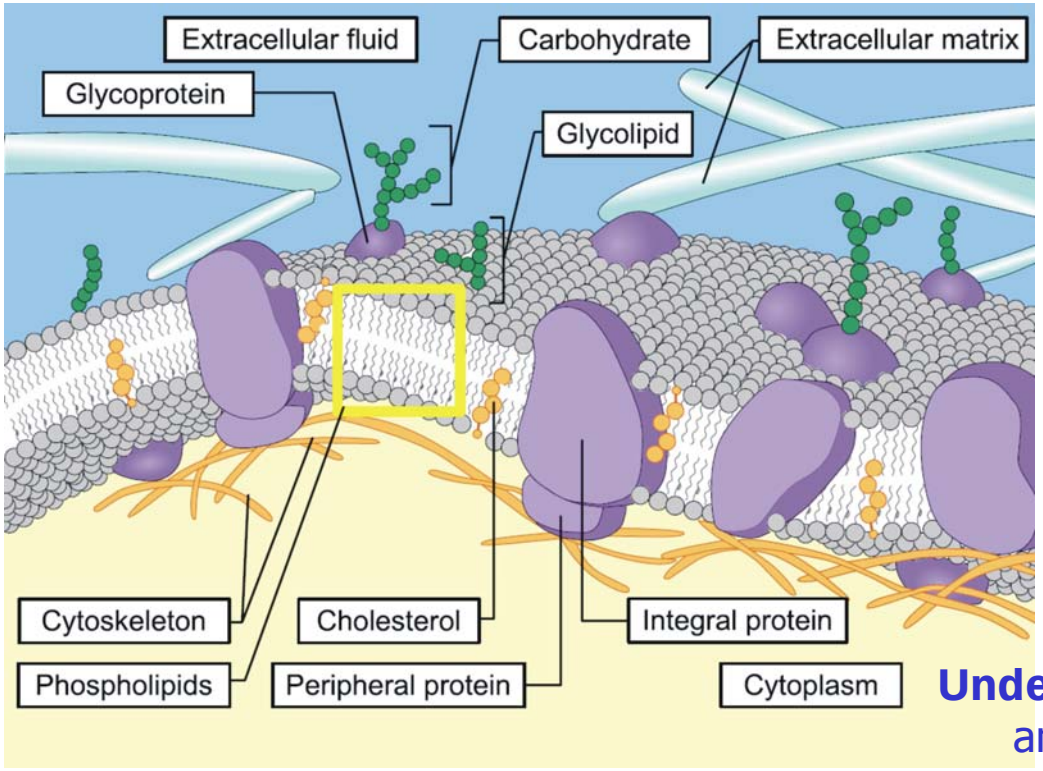
- Organism
- Organ
- Cell
- Organelle
- Cytoskeleton
- Functional Module
- Biological Macromolecule
- Molecule
- Atom



"Although living systems obey the laws of physics and chemistry, the notion of function or purpose differentiates biology from other natural sciences" (*Hartwell et al.*)

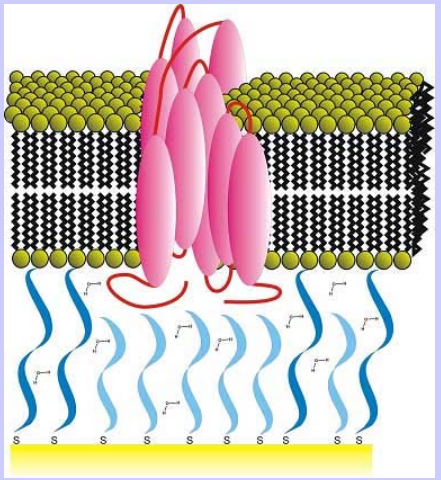
The Cell Membrane



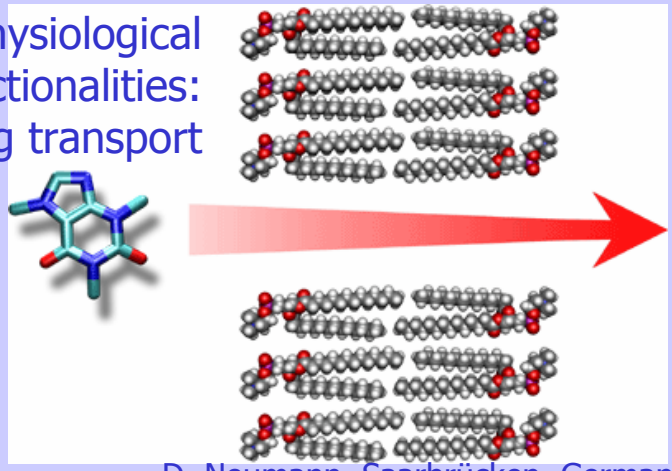


Applications:

Bioengineering:
Biosensors using solid supported membranes



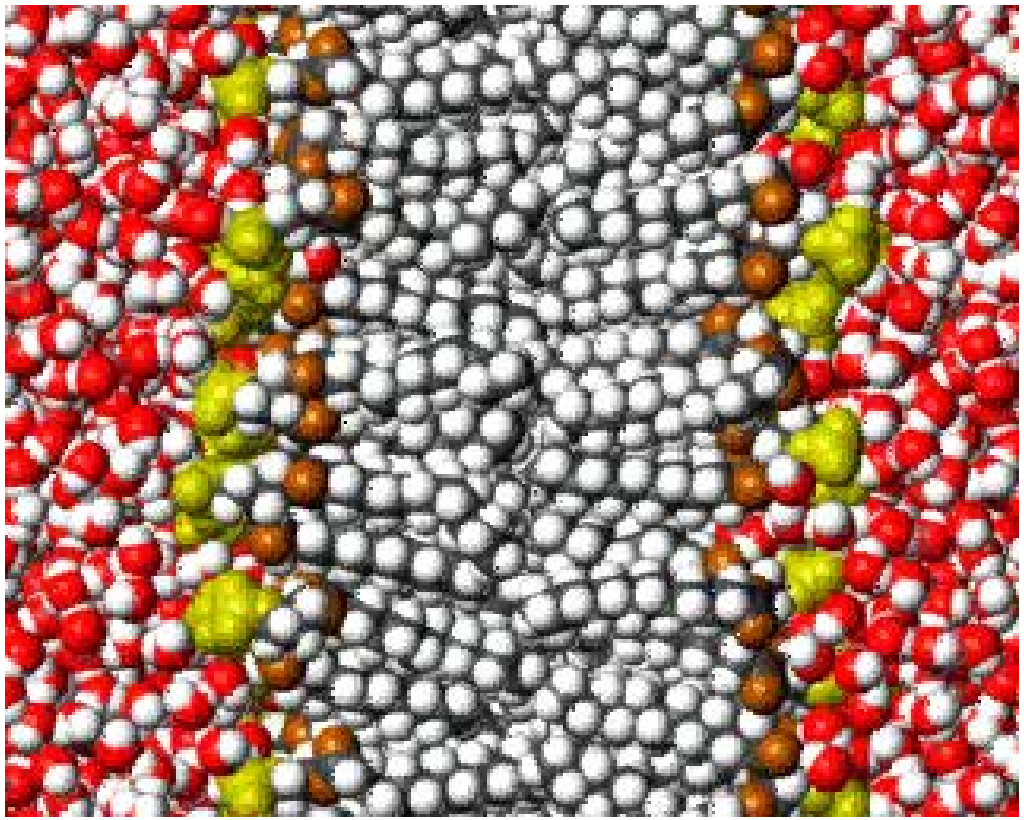
Understanding of physiological and biological functionalities:
Drug transport



D. Neumann, Saarbrücken, Germany

Membrane is the primary site of (inter)action

Membrane Dynamics

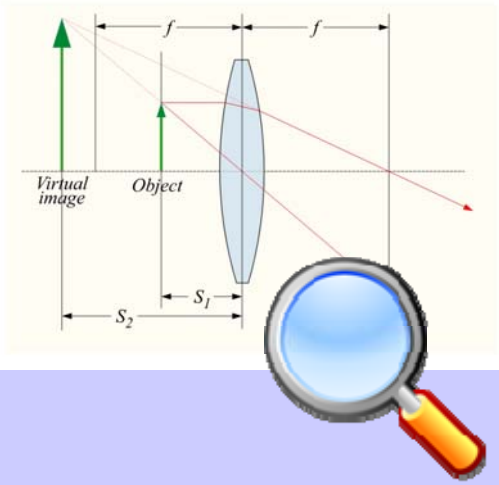


H.Heller, München, Germany

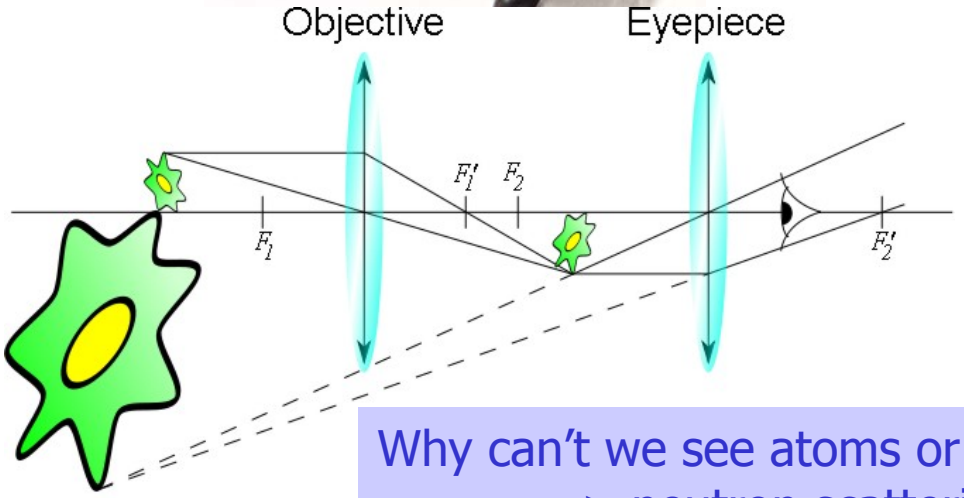
How can we study structure and dynamics on a molecular scale?

Optical Techniques

Magnifying Glass

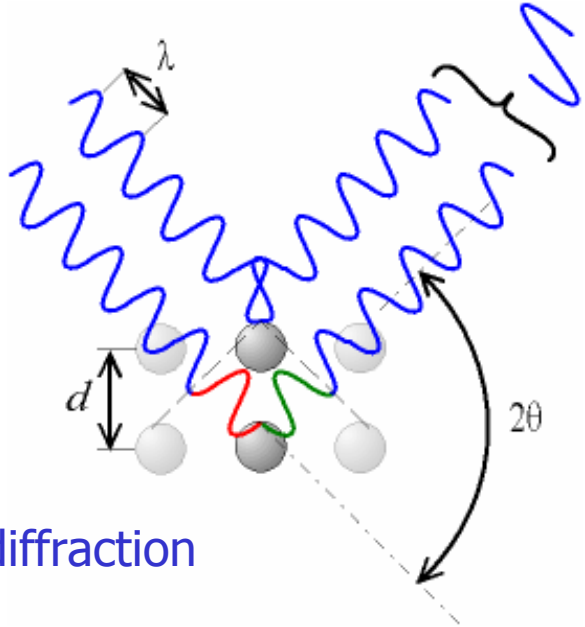


Optical Microscope



Why can't we see atoms or molecules?
-> neutron scattering

Scattering-Reciprocal Space

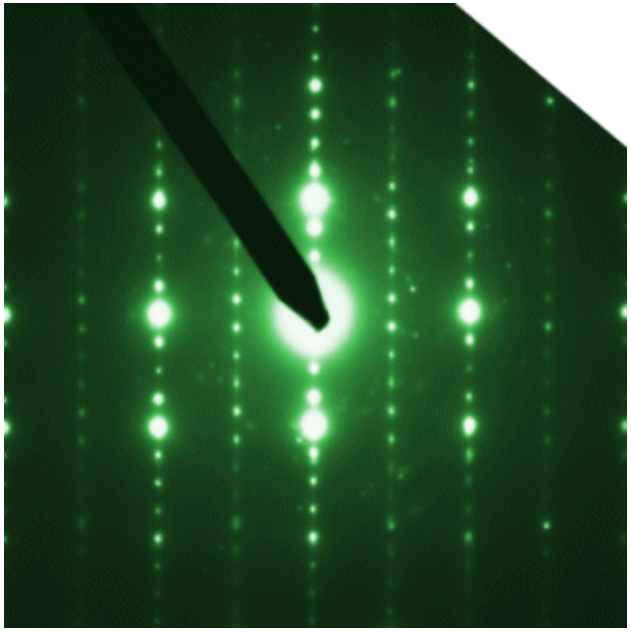


diffraction

"...where the atoms are and how they move."

Scattering vector

$$q = \frac{4\pi \sin\theta}{\lambda} = \frac{2\pi}{d}$$



Fourier Transformation

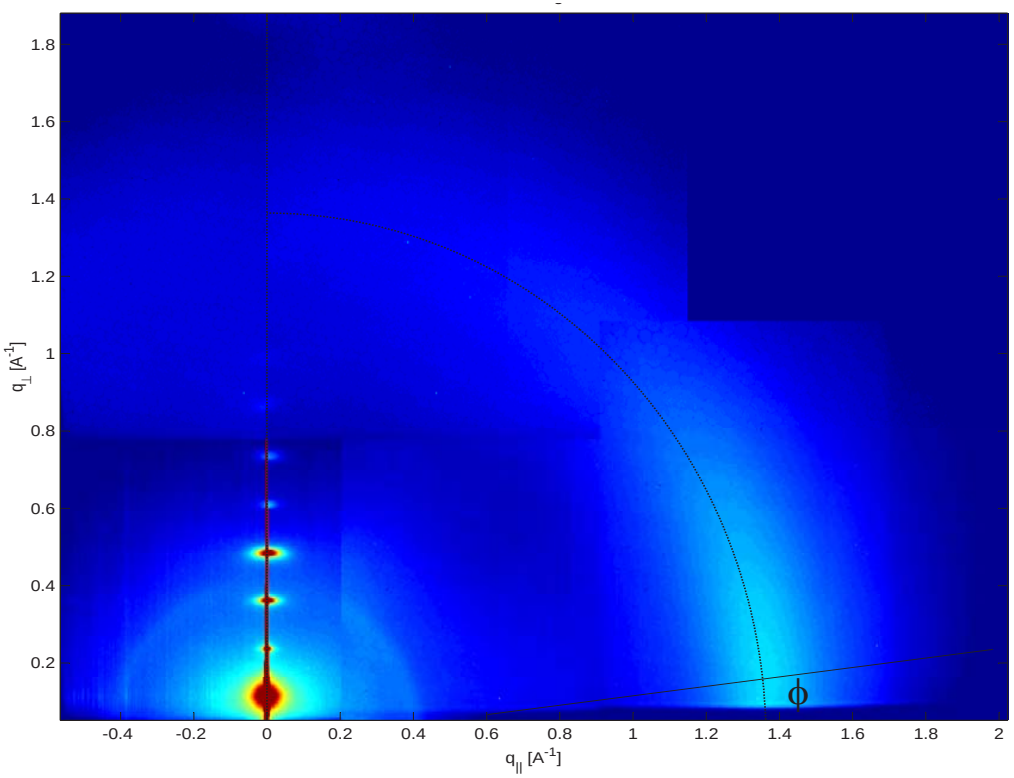
'real space' ⟷ *'reciprocal space'*

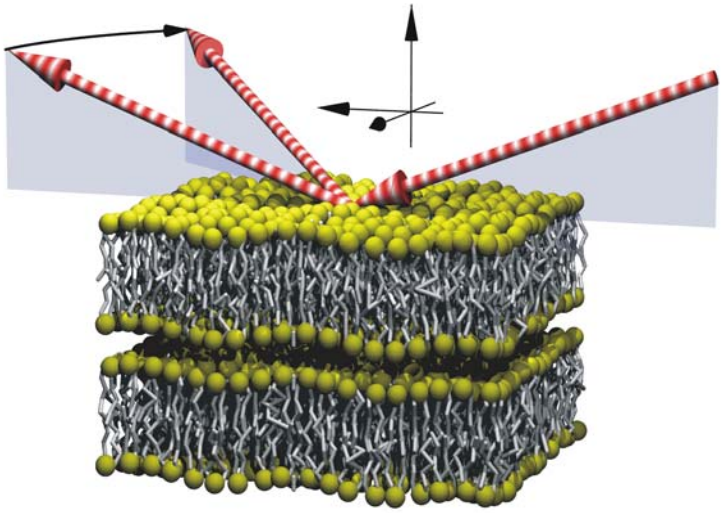
Scattering laws

momentum $\vec{q} = \frac{m}{\hbar}(\vec{v}_1 - \vec{v}_2)$

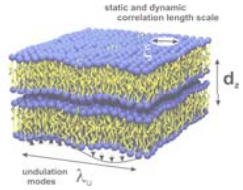
energy $\hbar\omega = \frac{1}{2}m\left(v_2^2 - v_1^2\right)$

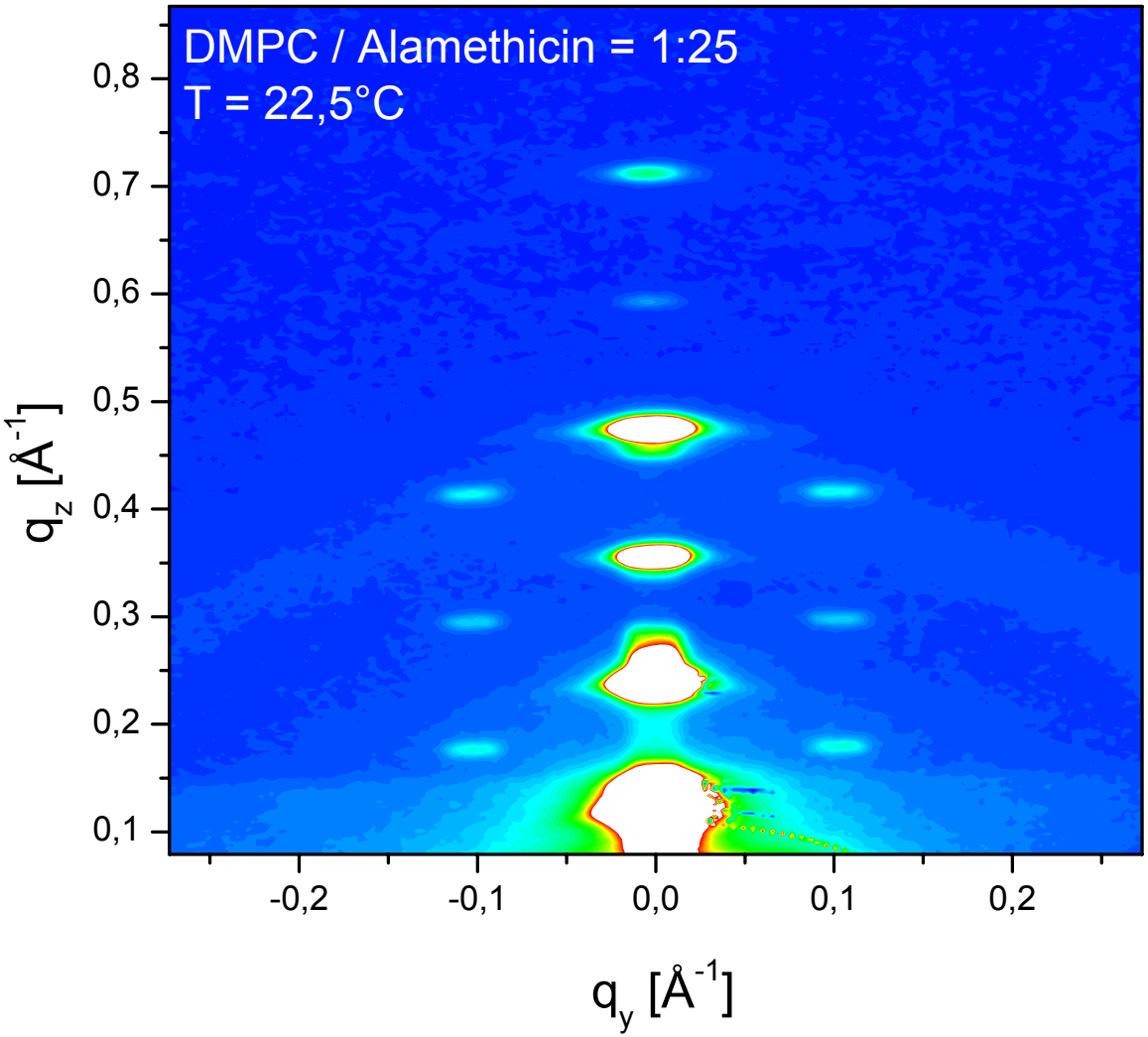
Reciprocal Space of a Membrane

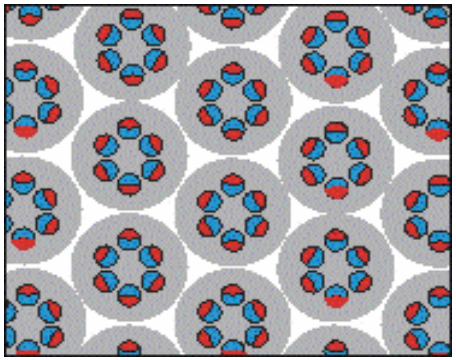


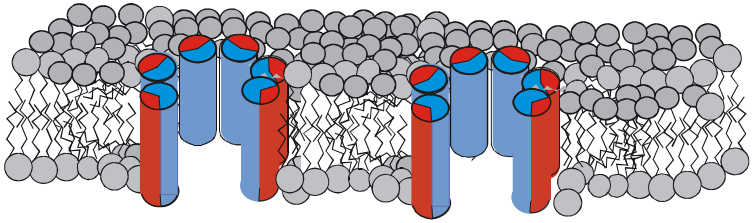


Complex Membrane

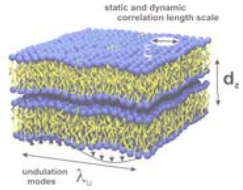




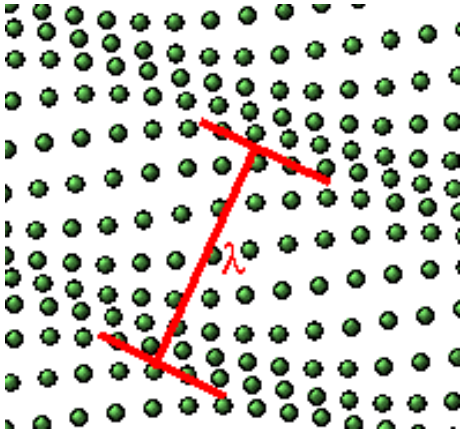


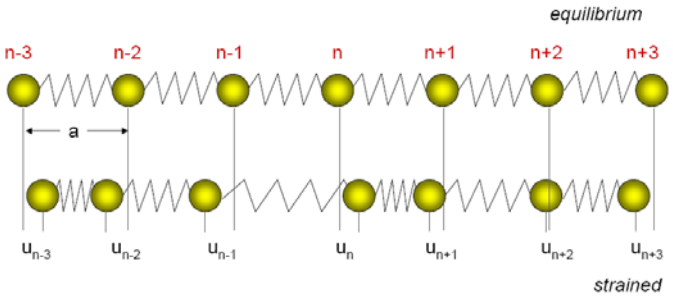


Collective Dynamics - Phonons

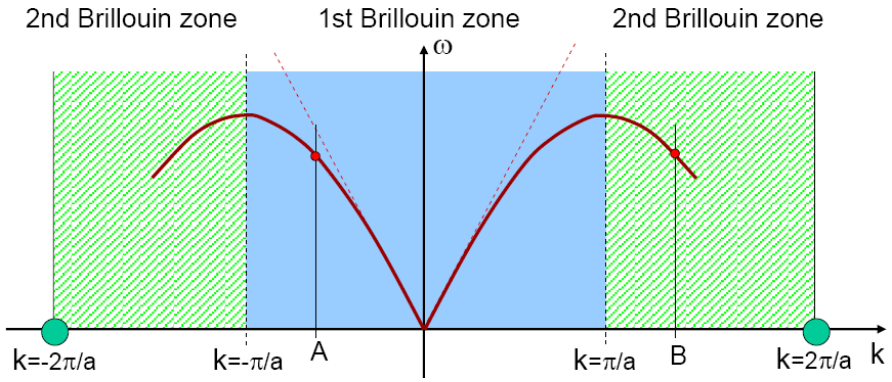


"...where the atoms are and how they move."

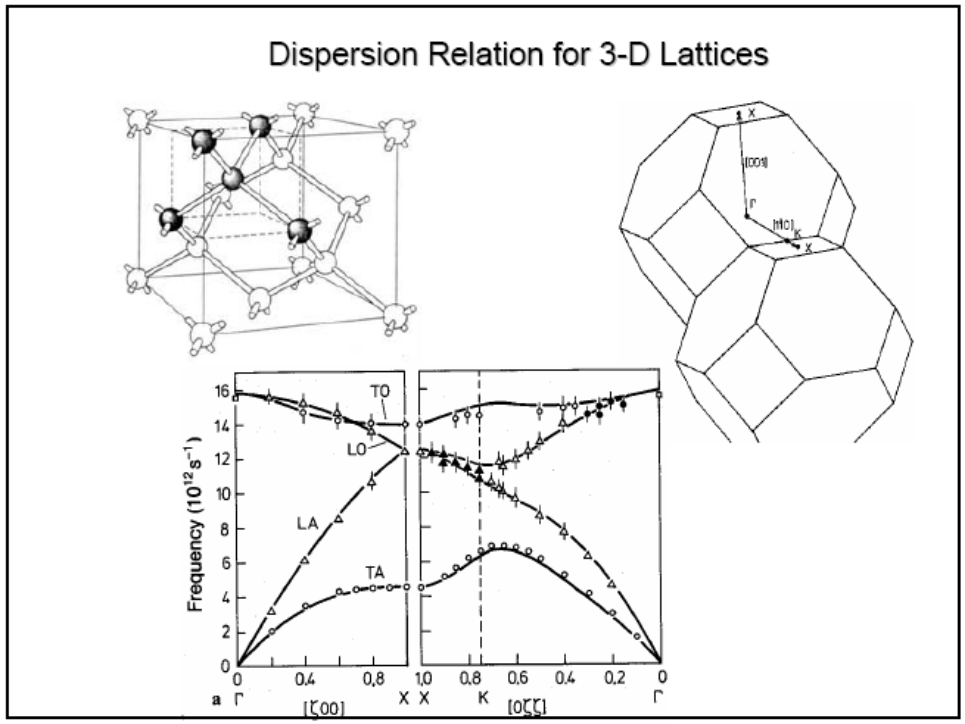




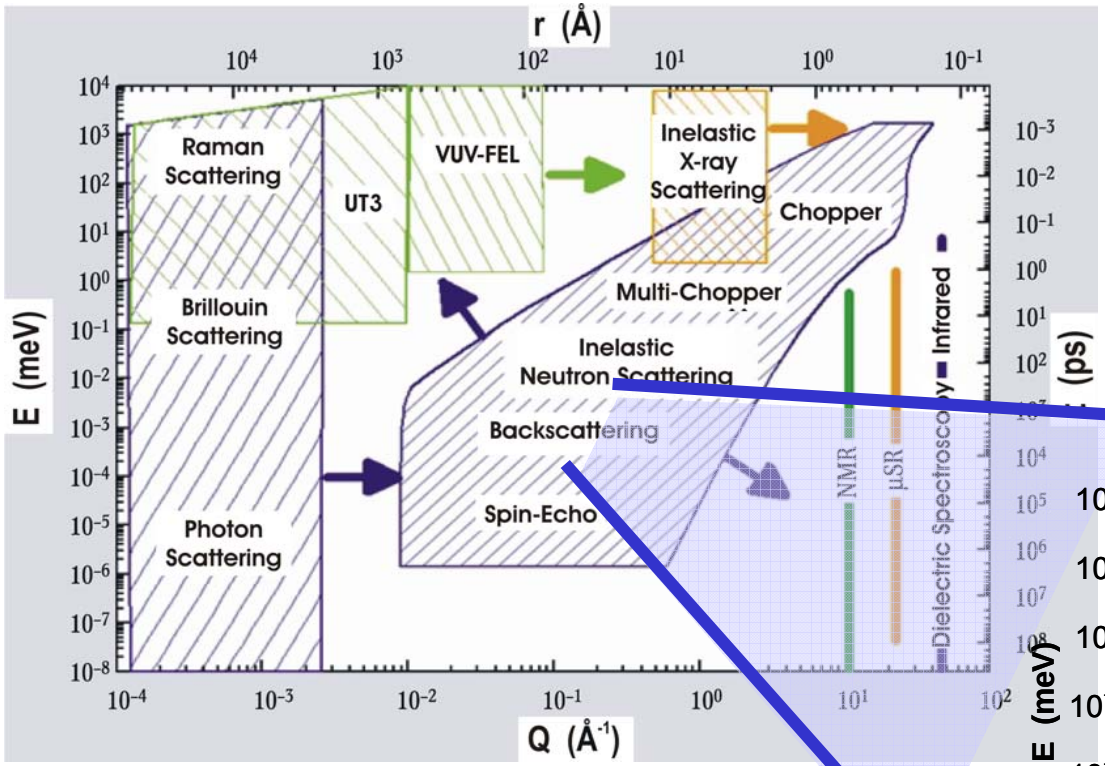
Terry P. Orlando, MIT



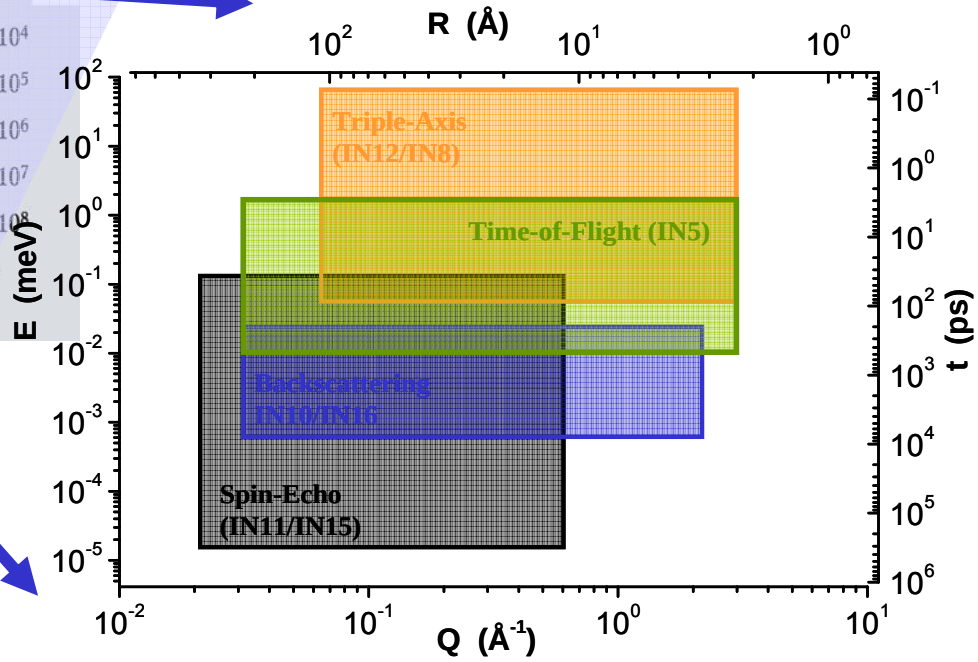
Dispersion Relation ω(k)



"Broadband" Neutron Spectroscopy

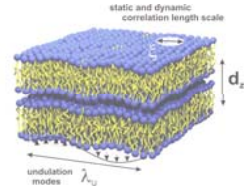


Inelastic neutron scattering gives wave vector resolved access to dynamics

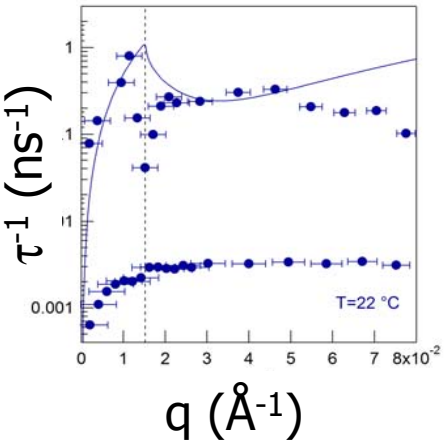


excitations relaxations ⟷ specific motions

Mesoscopic Membrane Fluctuations



Dispersion relation

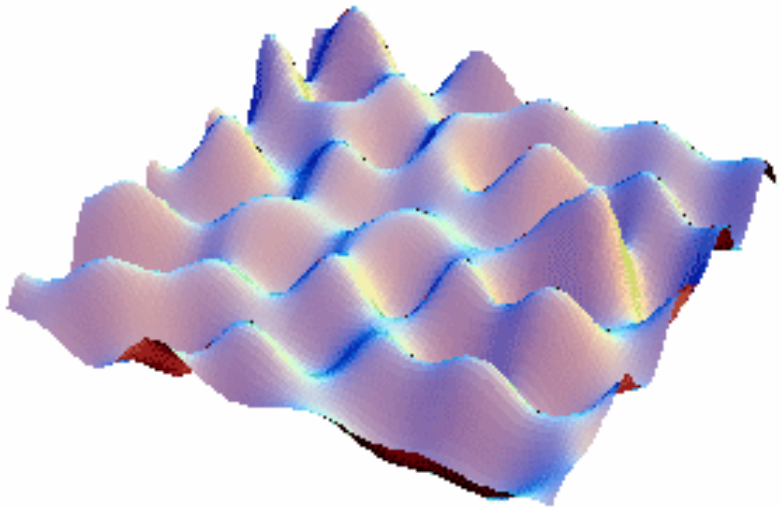


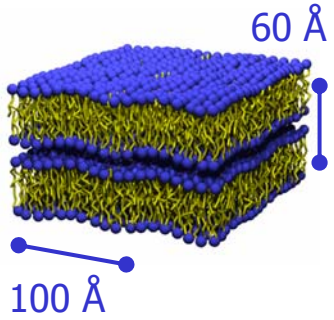
Contains 'dynamic' information

'Phonons in membranes'

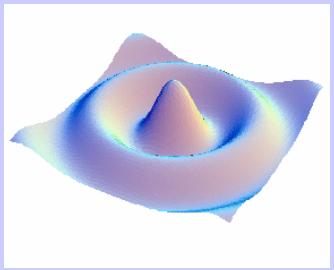
q-dependence of excitation frequencies and relaxation rates

Thermal membrane fluctuations

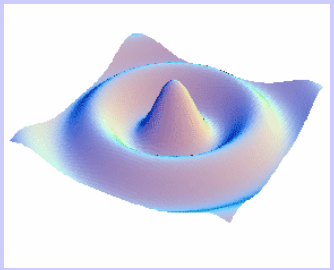




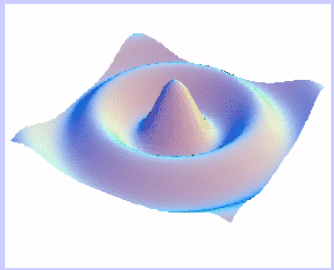
Elementary excitations


Propagating

+


Oscillating

+


Relaxating

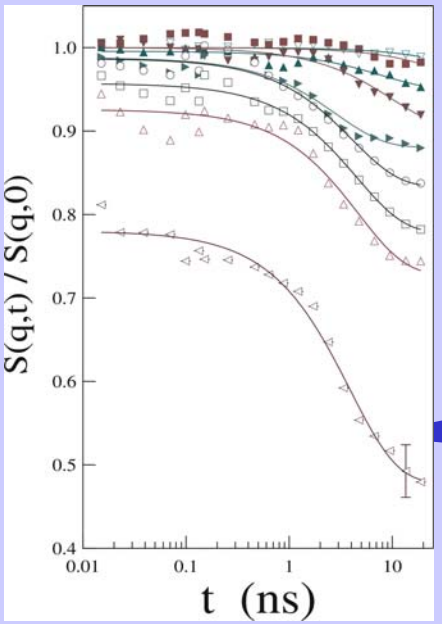
Mode

Collective Excitations in model membranes

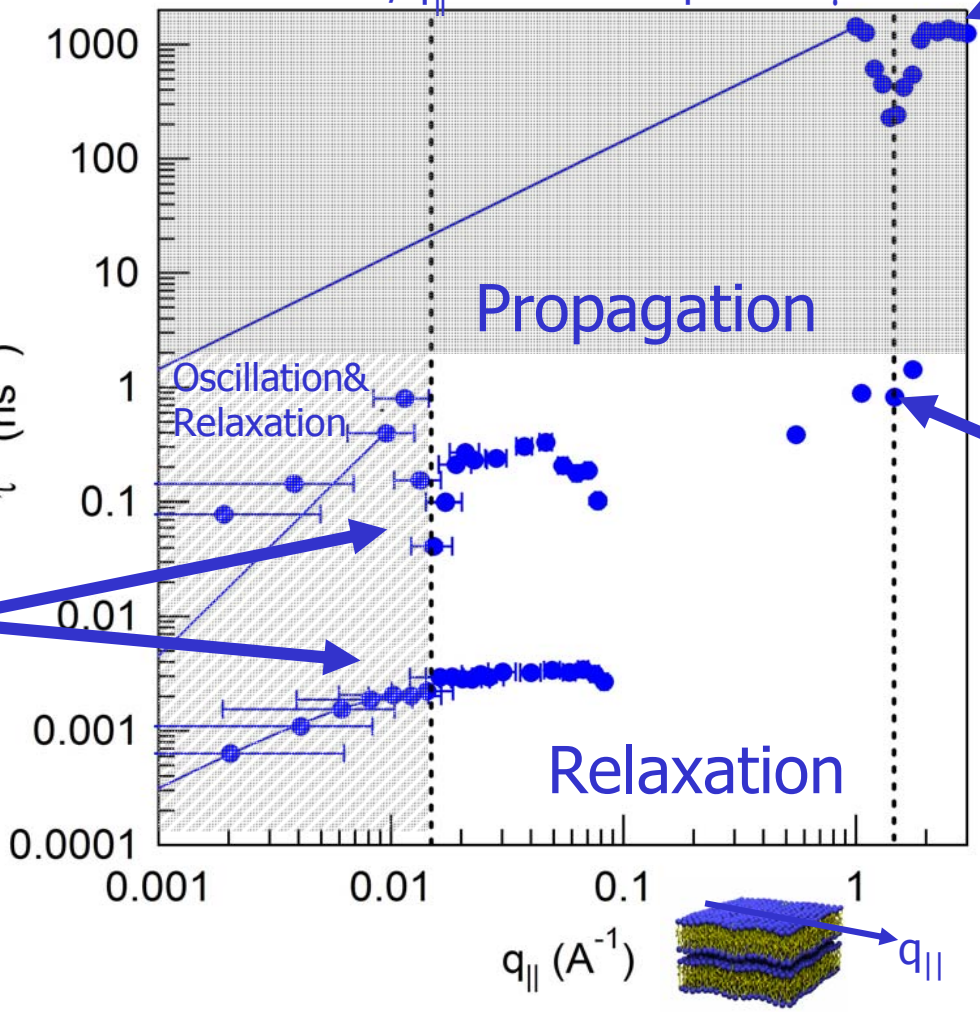
The 'Neutron Window'

DMPC –d54

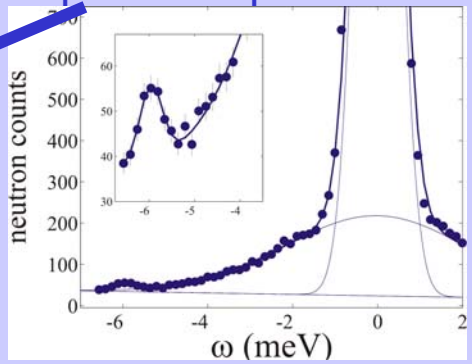
Neutron-Spin-Echo-Spectrometer



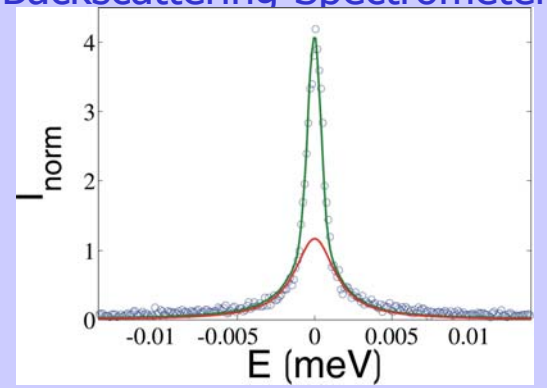
2Å<2π/q$_{||}$<5000Å & 1ps<τ<1μs



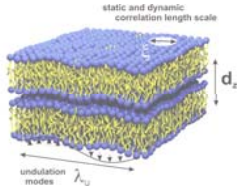
Triple-Axis-Spectrometer

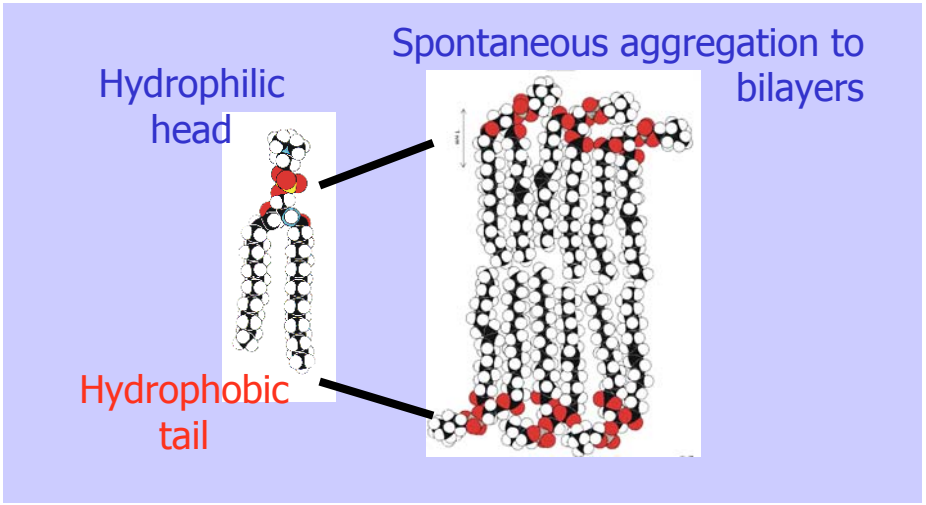


Backscattering-Spectrometer



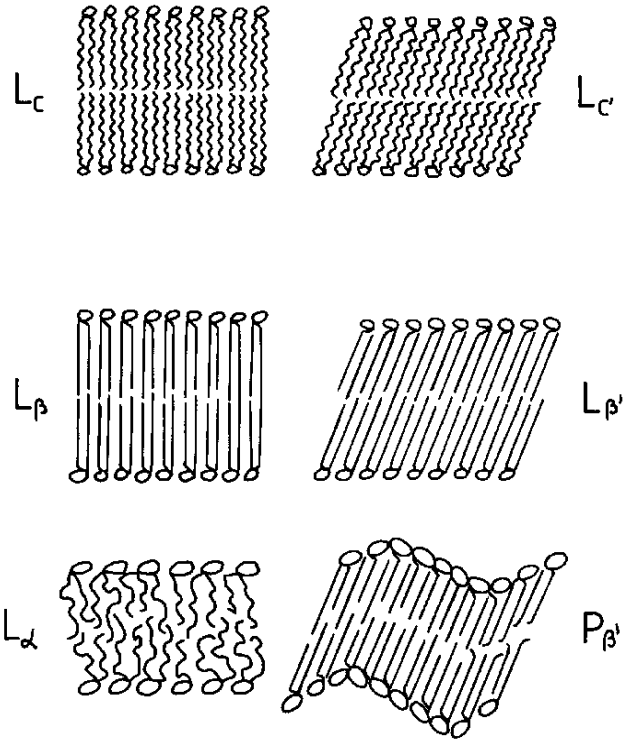
(Phospho-)Lipids and Membranes



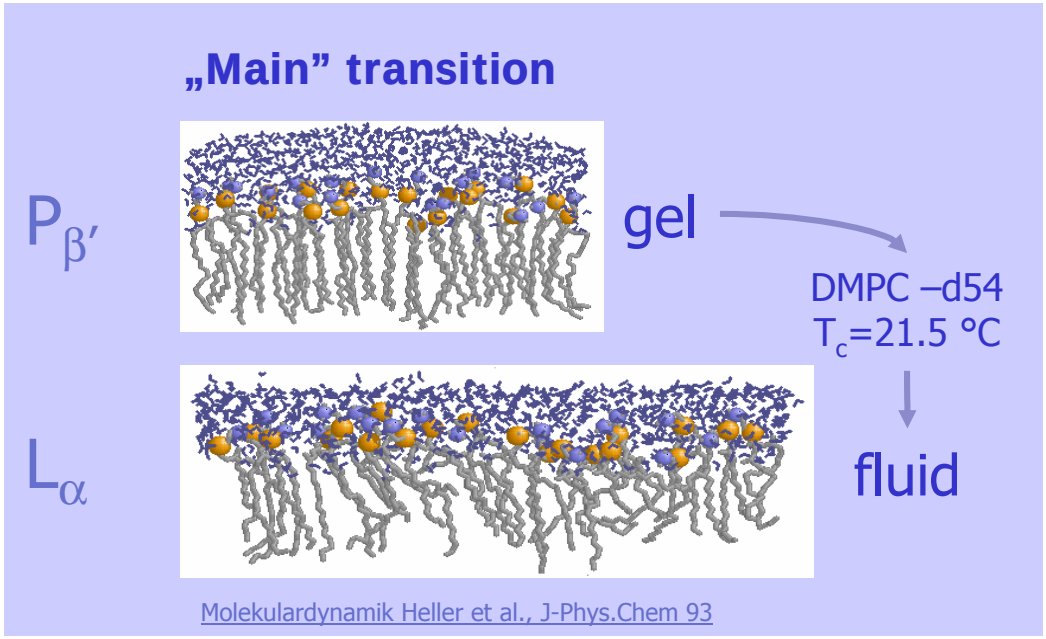


Lipid/Water **Lamellar** Phases

Parameters: temperature + hydration



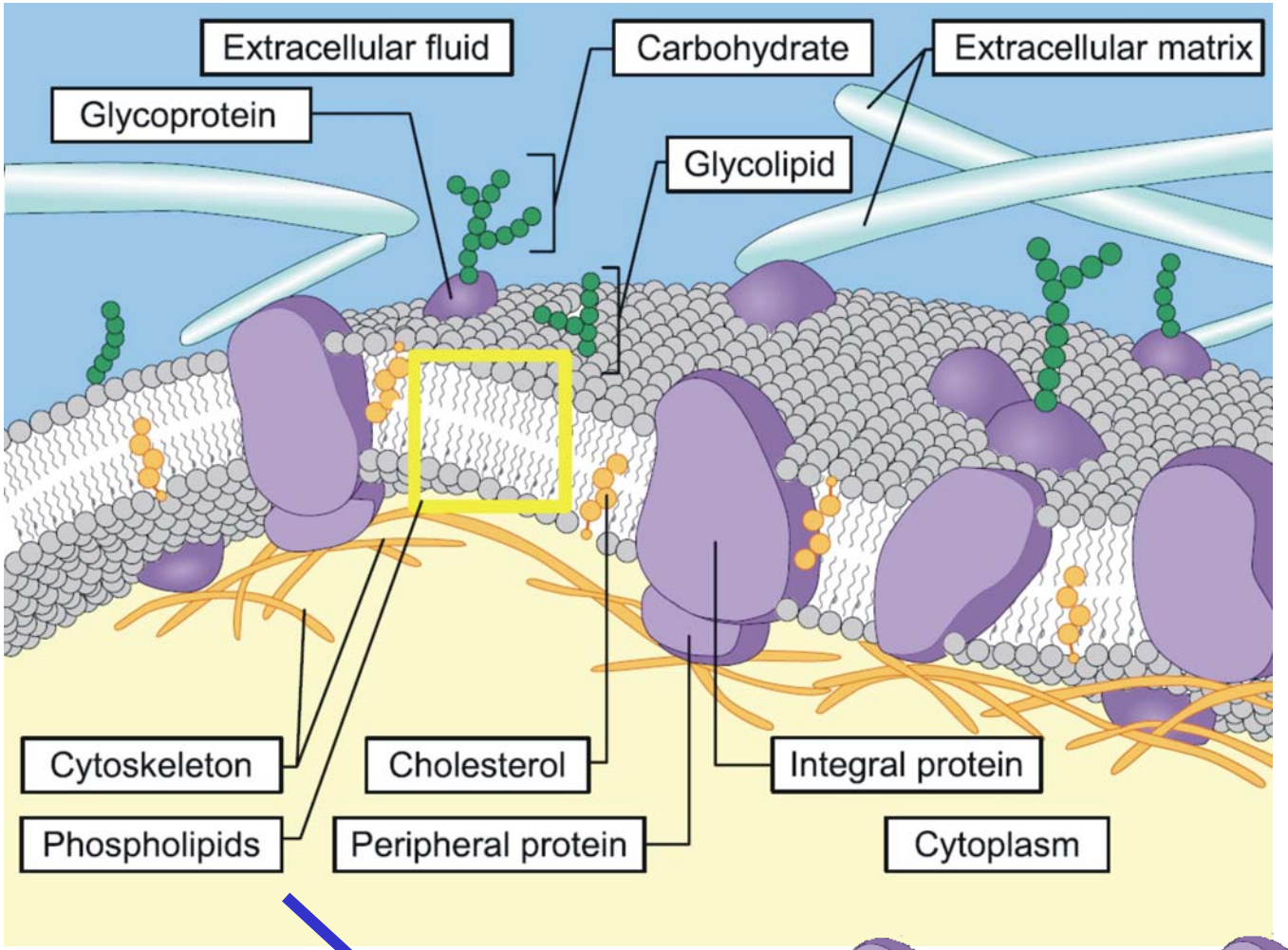
Handbook of Biological Physics



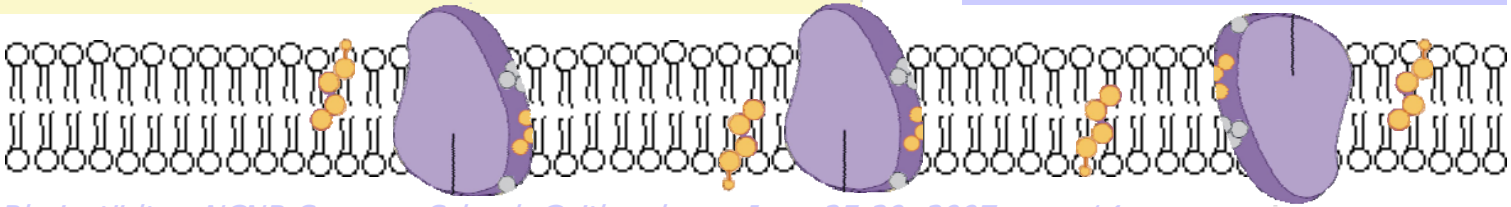
Molekulardynamik Heller et al., J-Phys.Chem 93

Functionality determined by structure and dynamics

Towards biological membranes

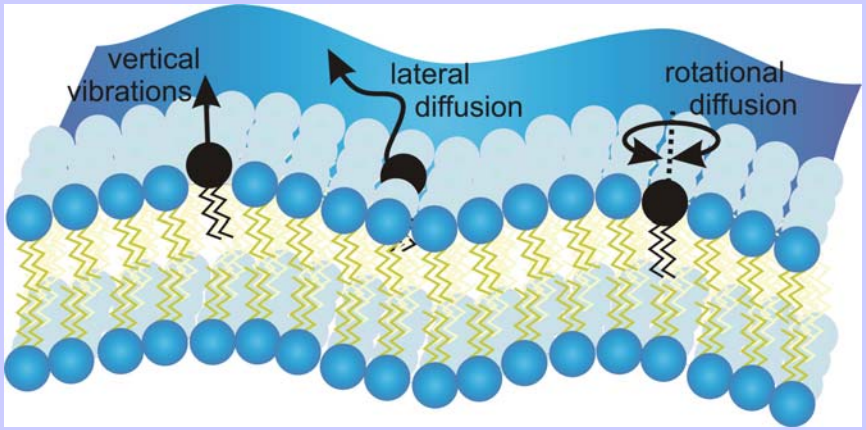


Simple model system



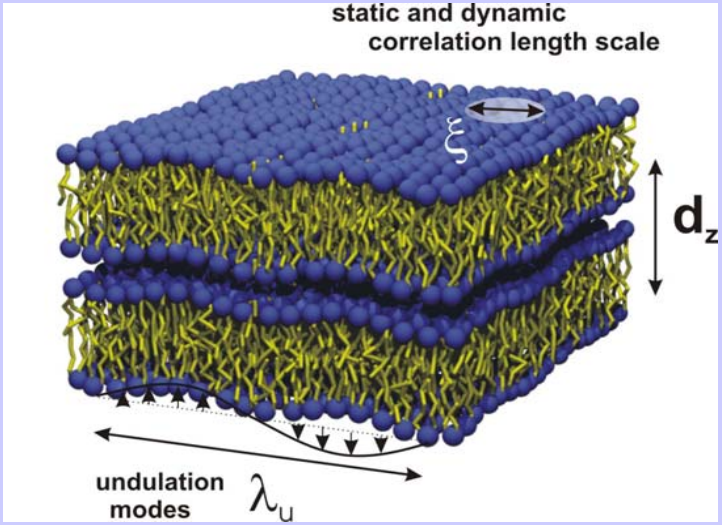
Membrane Dynamics

Local modes in bilayers



- Incoherent inelastic neutron scattering
- NMR
- Dielectric spectroscopy

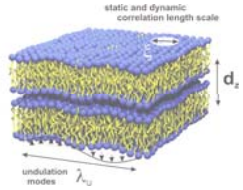
- Coherent in- and quasielastic neutron scattering
- Inelastic X-ray scattering



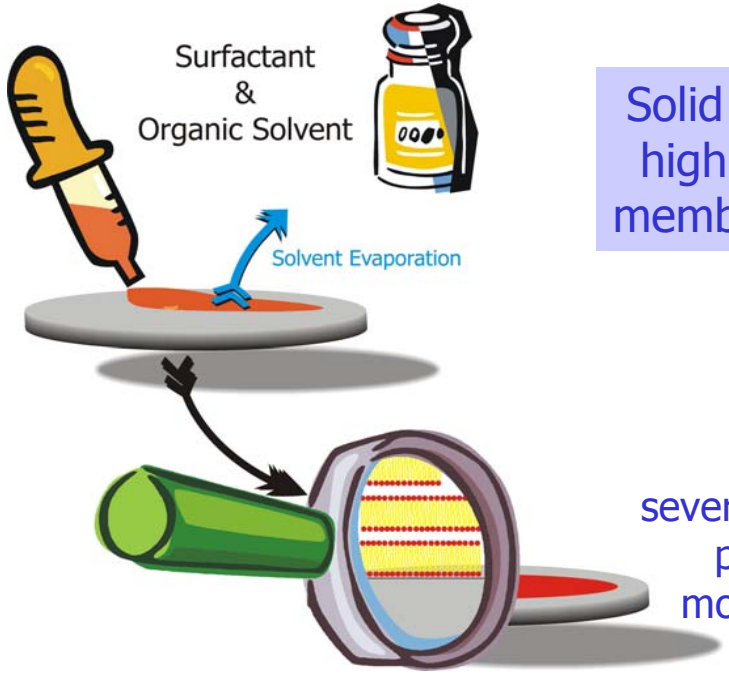
Collective excitations

Correlated molecular motions might be responsible for 'functionalities' of the membrane and structural changes

Stacked Planar Membranes



Sample Preparation

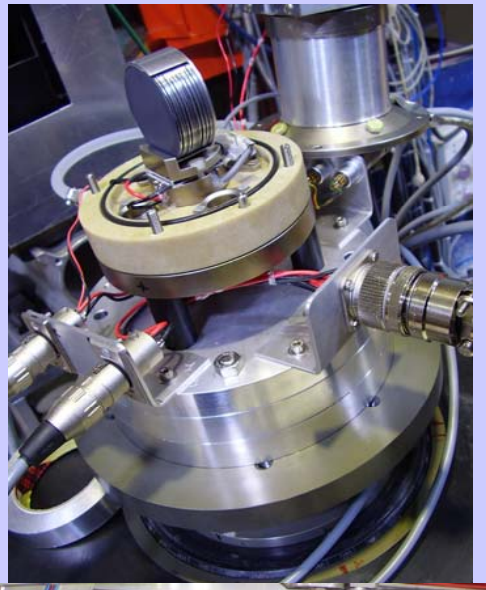


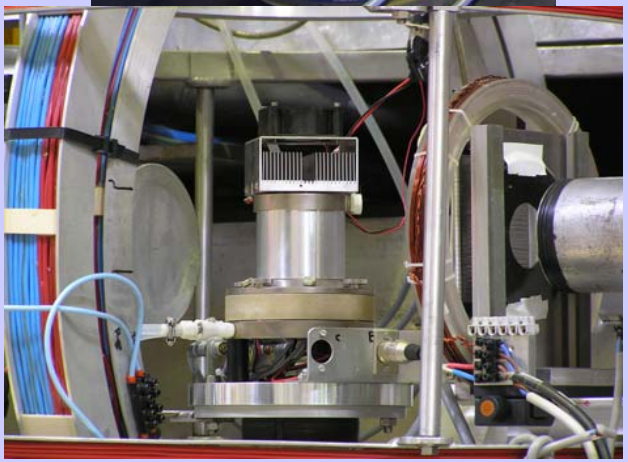
Solid supported, highly oriented membrane stacks

several 1000 bilayers per Si-wafer, mosaicity ~ 0.5°

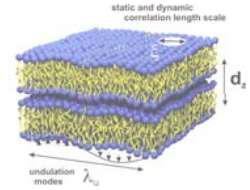
„Sandwich-sample" with 500 mg of deuterated DMPC

"Humidity Chamber"

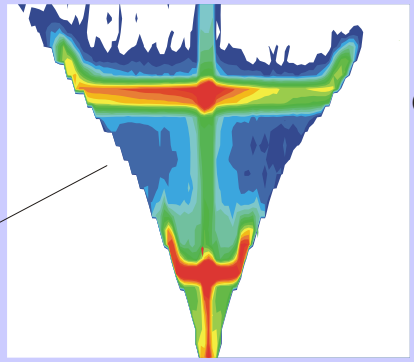


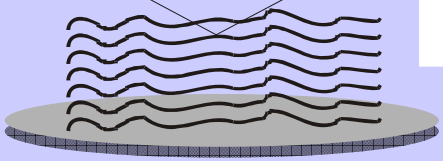


Scattering from aligned phases

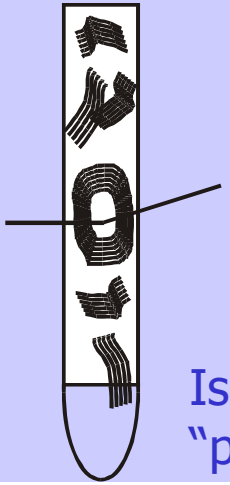


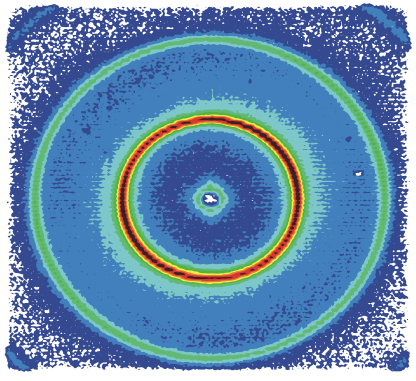
Highly oriented solid supported membranes



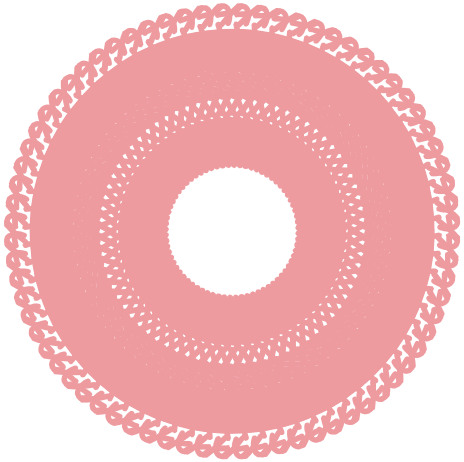


Si-wafer



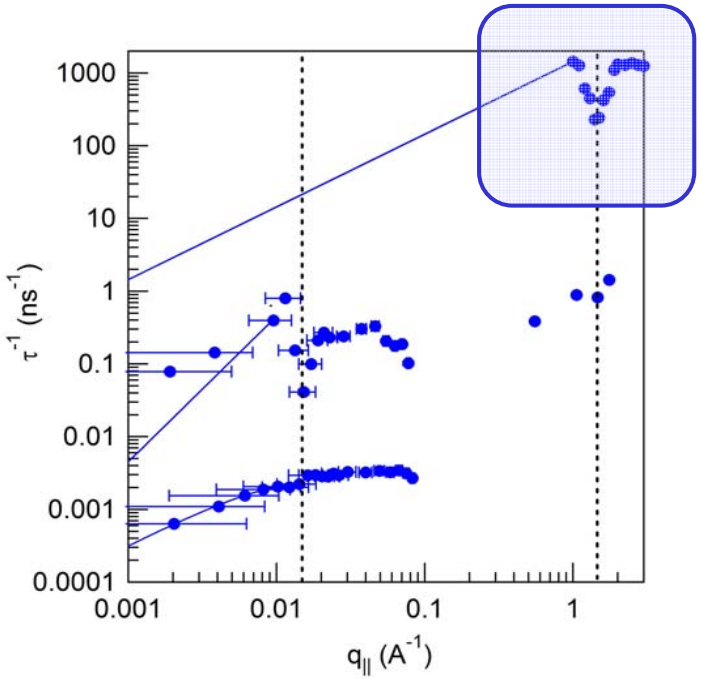


Isotropic solution
"powder"



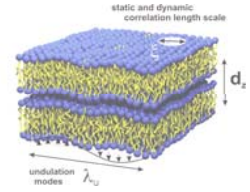
TAS

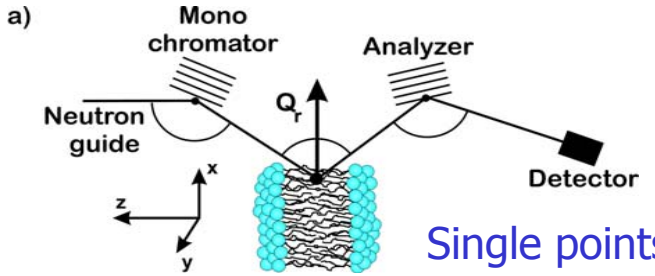
Neutron Three-Axes to measure the short wavelength fluctuations



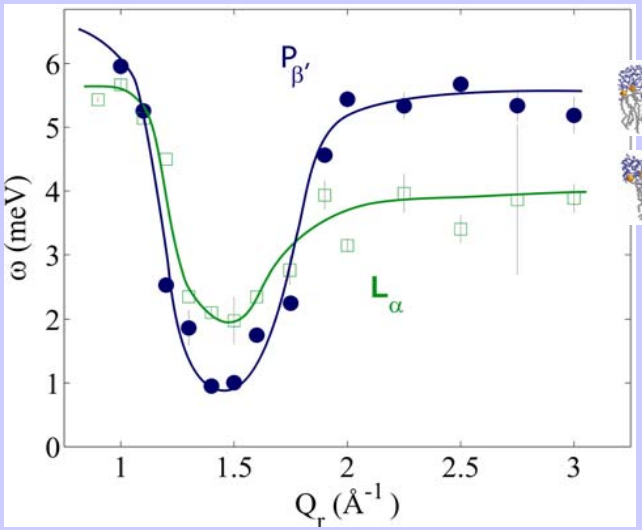
Rheinstädter, Ollinger, Fragneto, Demmel, Salditt, PRL **93**, 108107 (2004).

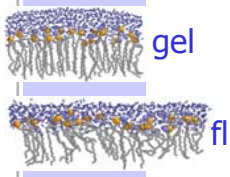
Short-Range Dispersion Relation on TAS





Single points in S(Q,ω)





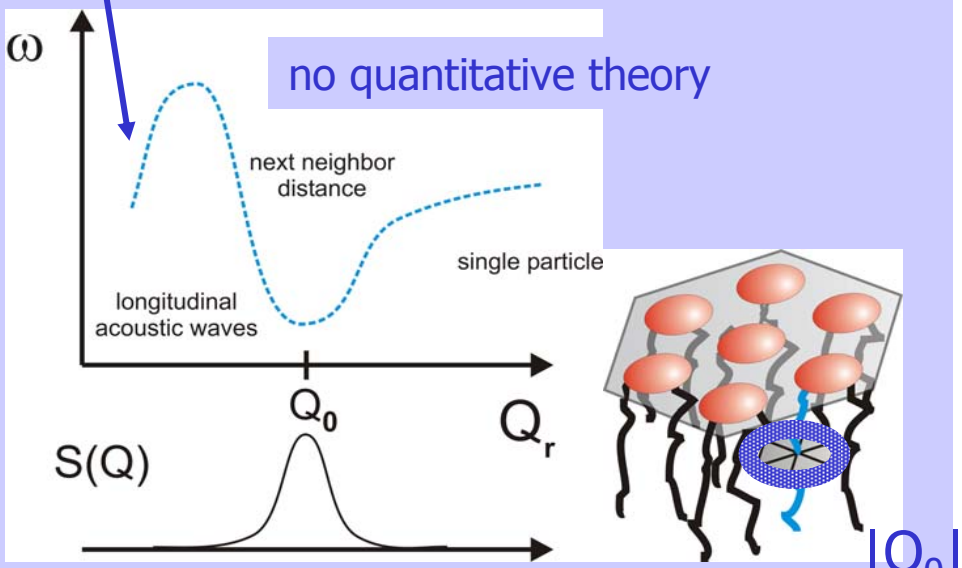
gel

fluid

Rheinstädter *et al.*, PRL (2004)

Dispersion relation as found in ideal liquids as liquid argon or liquid helium
→ c-atoms of the acyl-chains behave "quasi liquid"

Low-Q range difficult to access for neutrons (and X-rays)

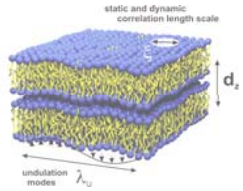


$2\pi/Q_0$ defines quasi „Brillouin-zone"

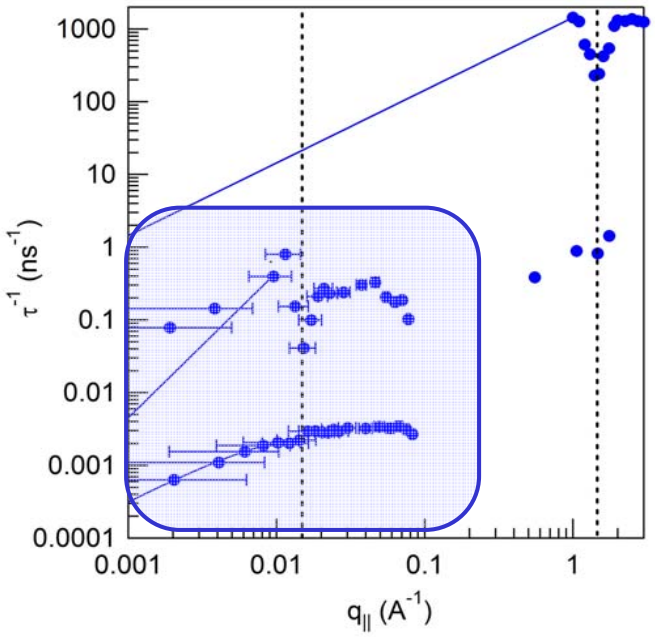
Directed transport?

Experiment: Drug Enhancer

NSE

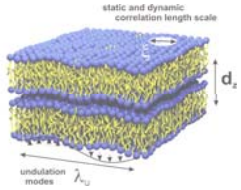


Neutron Spin-Echo to measure long wavelength undulations

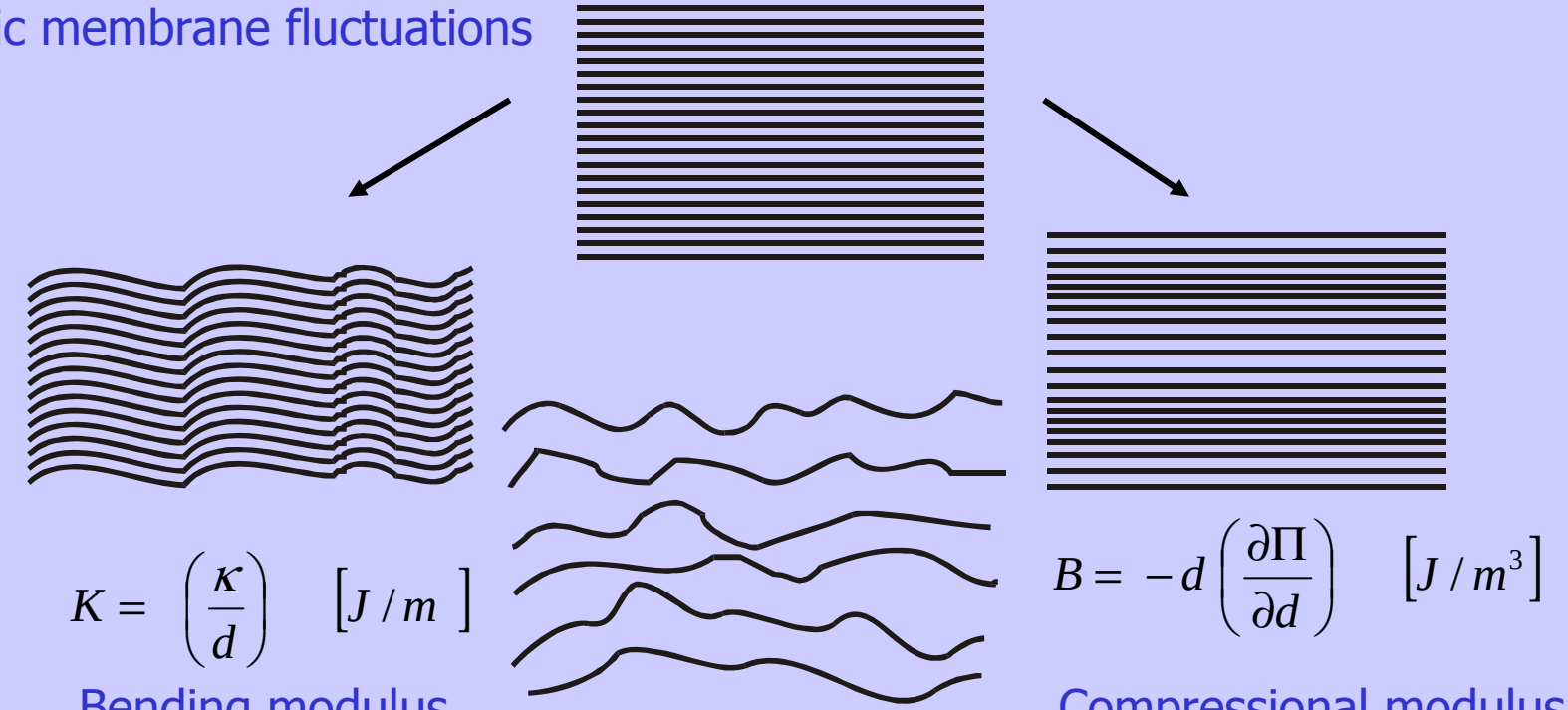


Rheinstädter, Häussler, Salditt, PRL **97**, 048103 (2006).

Membrane Elasticity



Mesoscopic membrane fluctuations



$$K = \left(\frac{\kappa}{d}\right) \quad [J/m]$$

Bending modulus

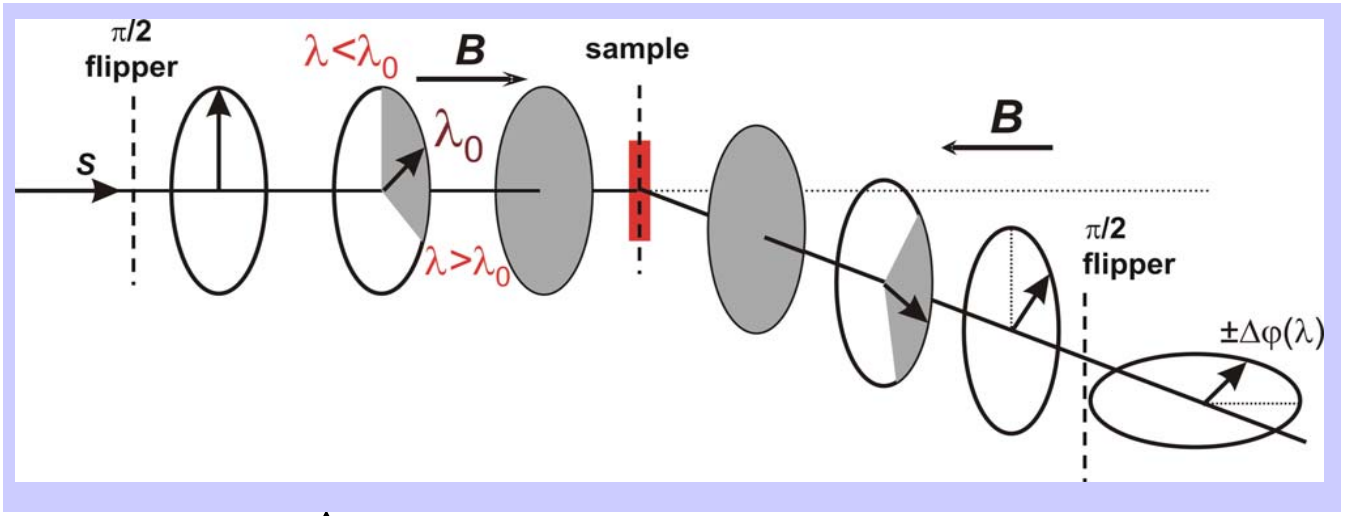
$$B = -d\left(\frac{\partial \Pi}{\partial d}\right) \quad [J/m^3]$$

Compressional modulus

$$H = \int dV \left\{ B\left[\frac{\partial u}{\partial z}\right]^2 + K[\nabla^2 u]^2 \right\}$$

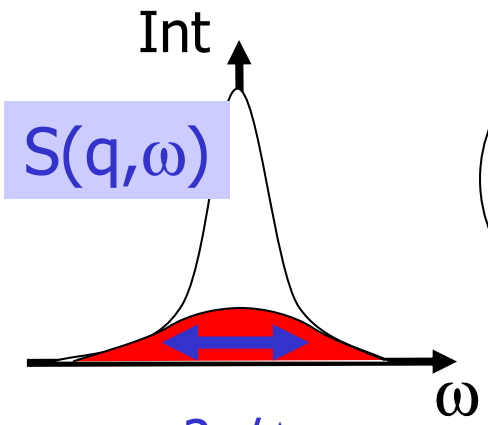
timescales $1ns = \dfrac{4.14}{1\mu eV}$

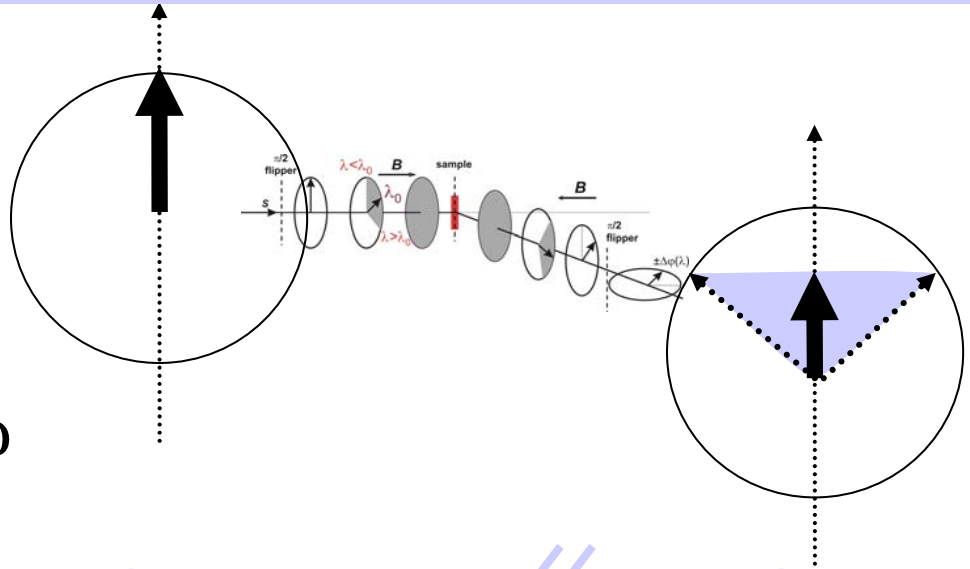
Spin-Echo Technique

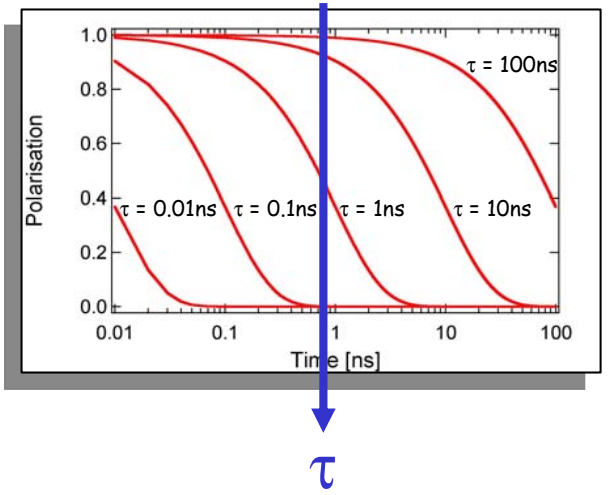


$\Delta\lambda/\lambda \cong 15\%$

S(q,t)

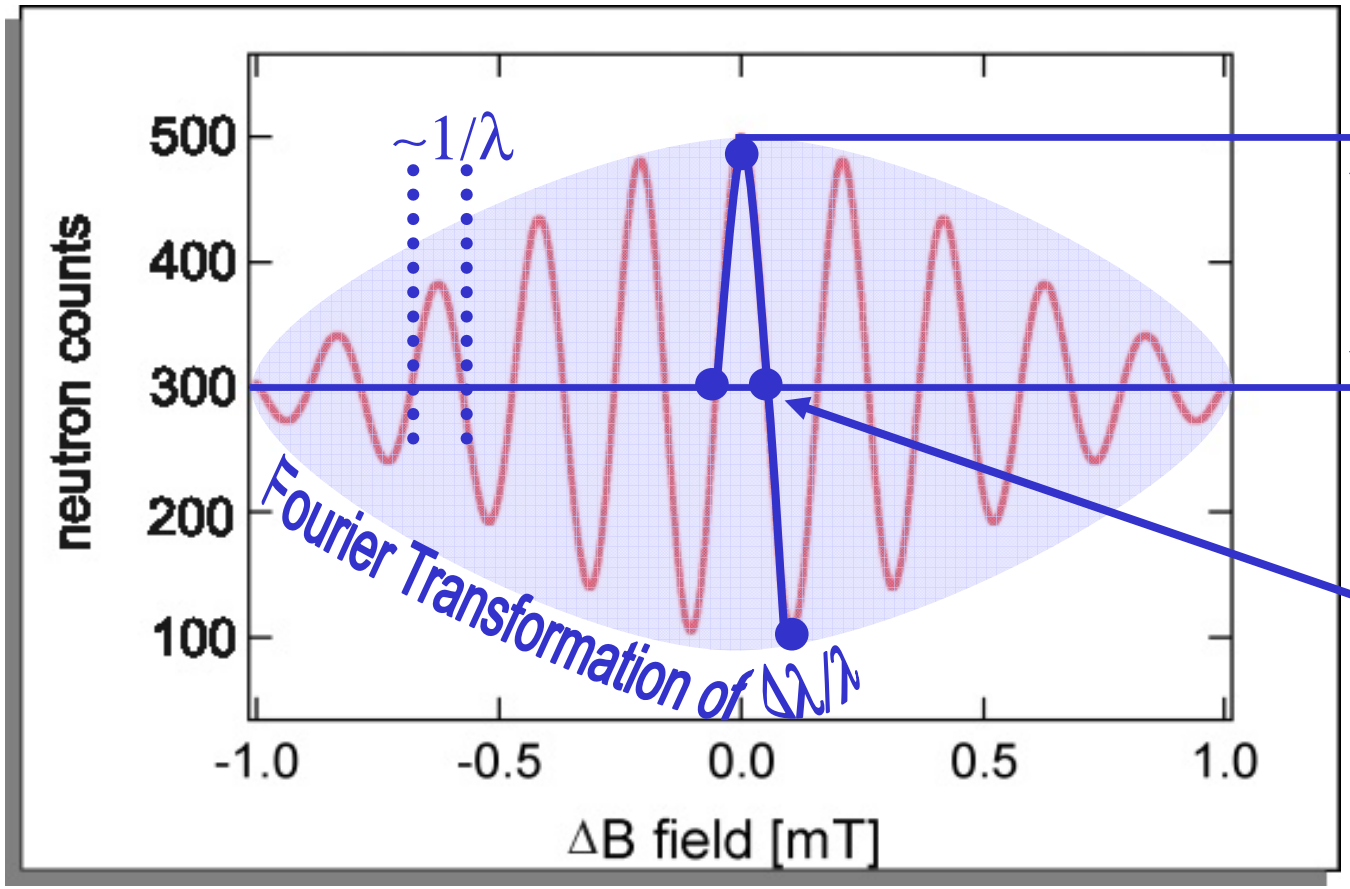






good monochromatization ⇏ good energy resolution

Echo Signals: Characteristics



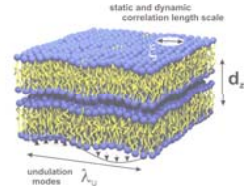
Amplitude

S(q,t)=P(t)=Amp/Aver=0.67

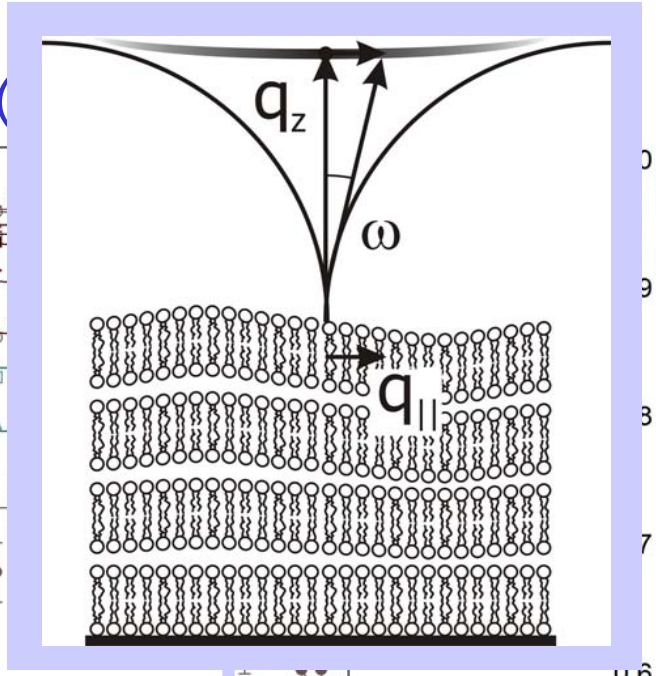
Average

4 point measurement

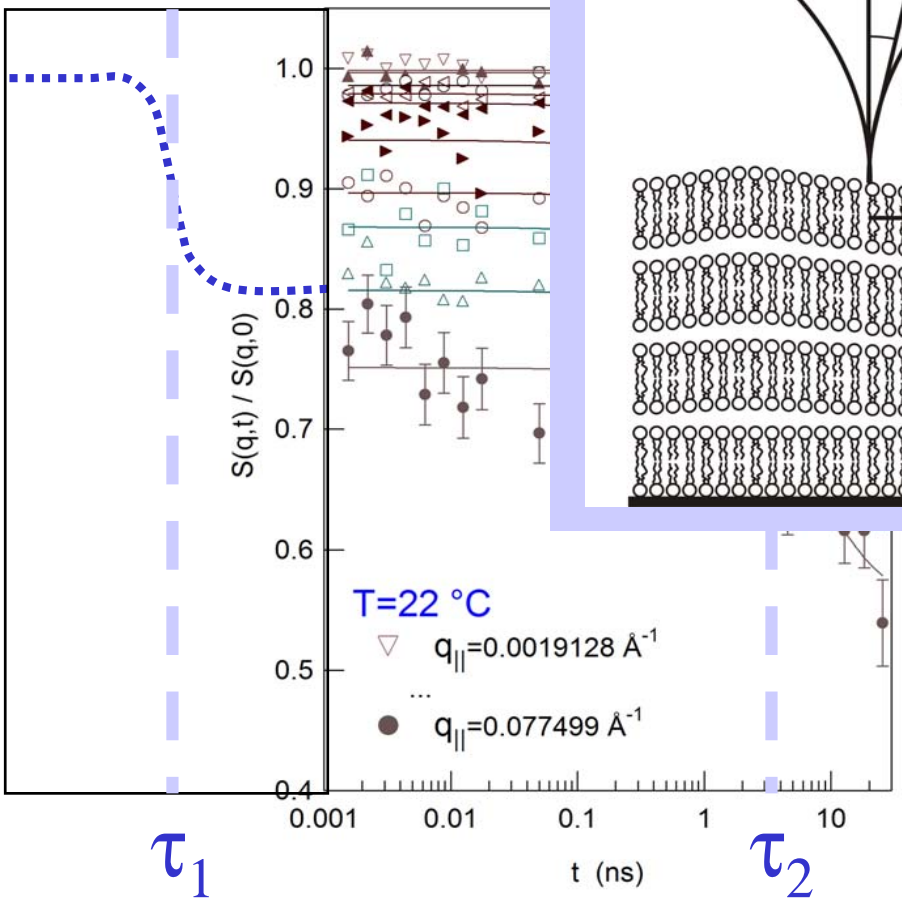
Spin-Echo Measurements

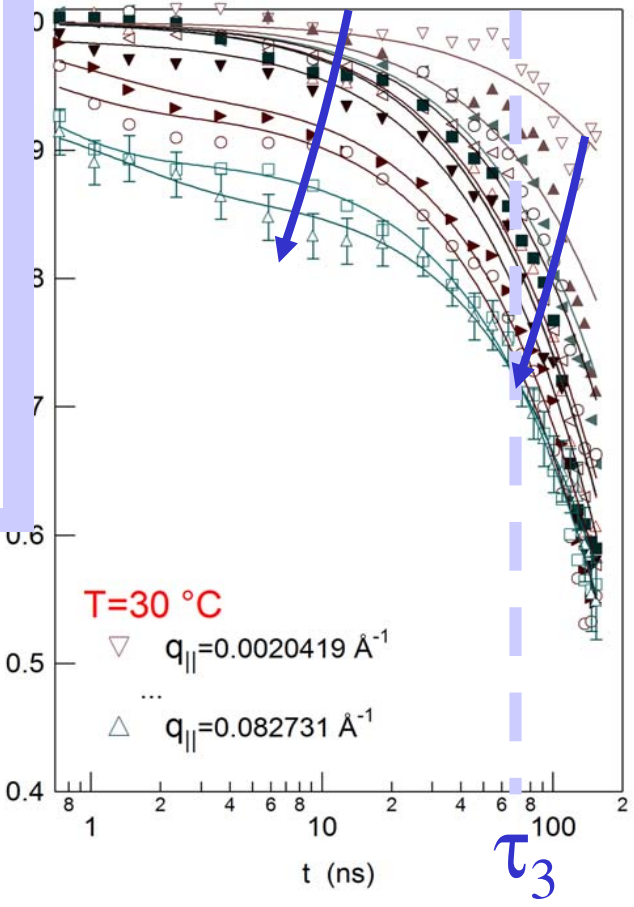


IN11 (

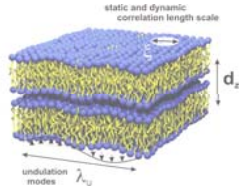


IN15 (slow relaxations)





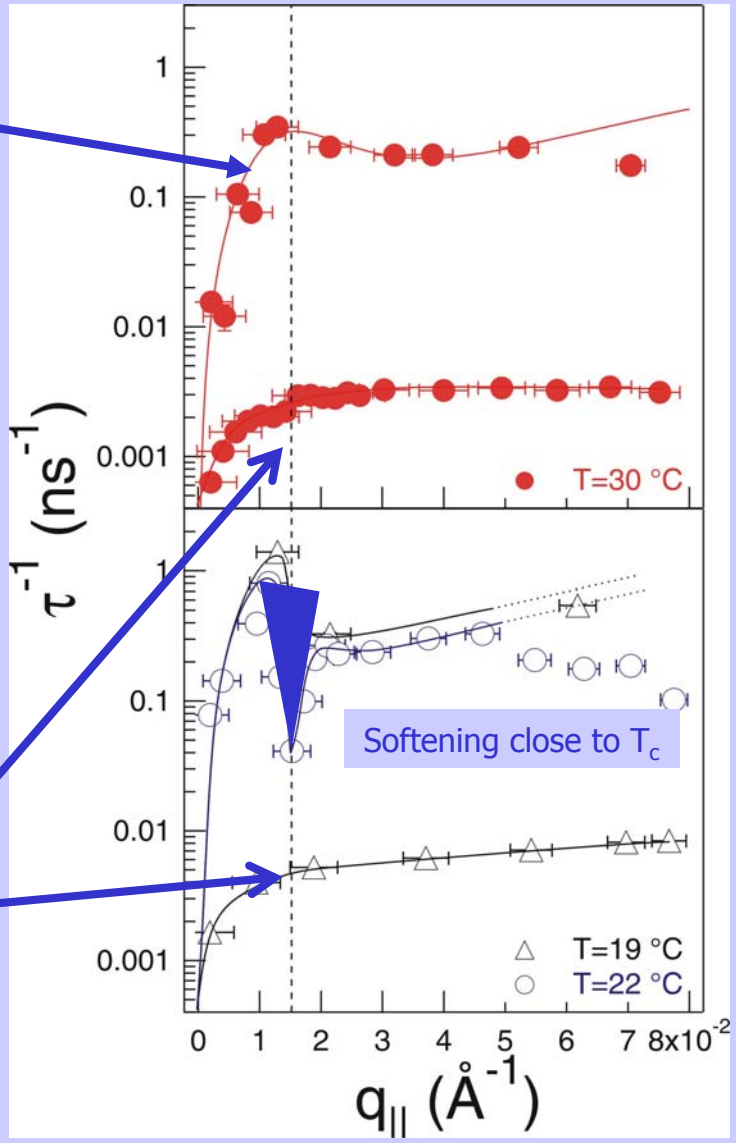
Undulation Dispersion Relations



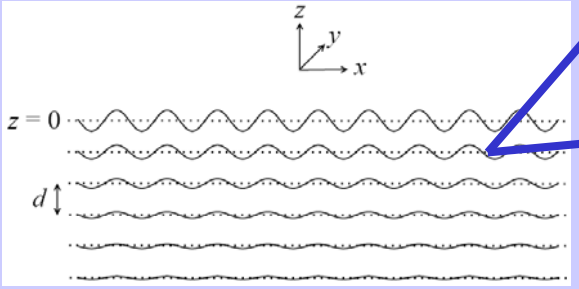
Fit to smectic hydrodynamic theory
Ribotta, PRL 32, 6, (1974).

$$\tau^{-1}(q_{\|}) = \frac{\kappa / d}{\eta_3} q_{\|}^2 \frac{q_{\|}^4 + (\pi/(\Lambda D))^2}{q_{\|}^4 + \frac{1}{\mu\eta_3}(\pi D)^2}$$

κ=14.5 k_BT
η_3=0.016 Pa·s
Λ=10.3 Å
B=1.08 107 J/m3



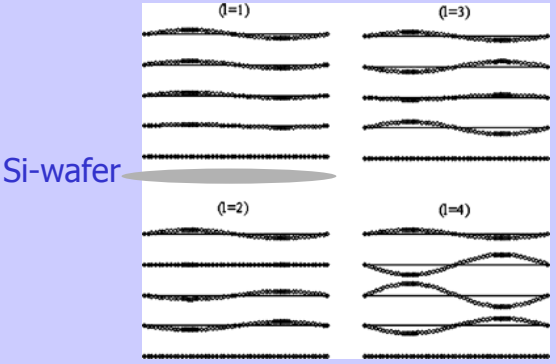
Surface mode ?



Bary-Soroker and Diamant,
Europhys. Lett., 73, 871 (2006), March 15, 2006

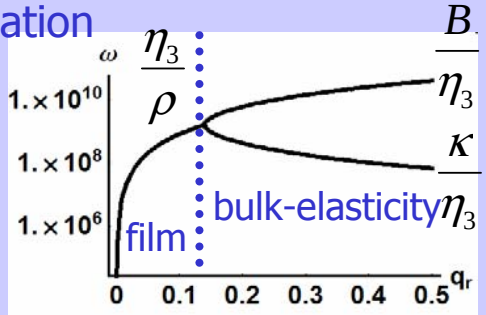
Dynamics of solid supported bilayers

Undulations



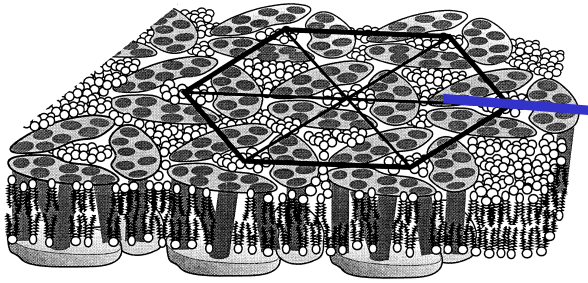
Romanov and Ul'yanov, PRE 66, 061701 (2002)

Relaxation

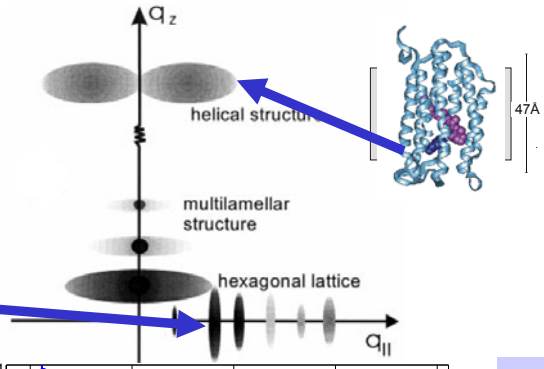


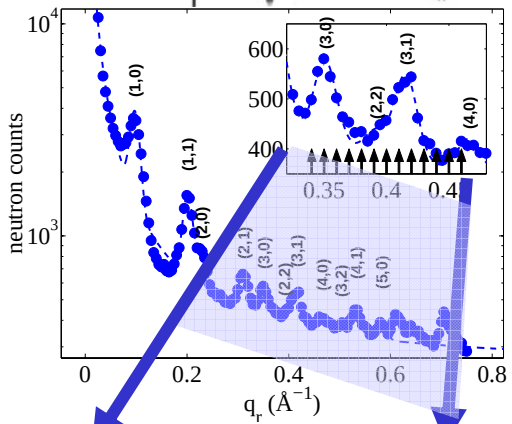
Outlook: Protein Dynamics

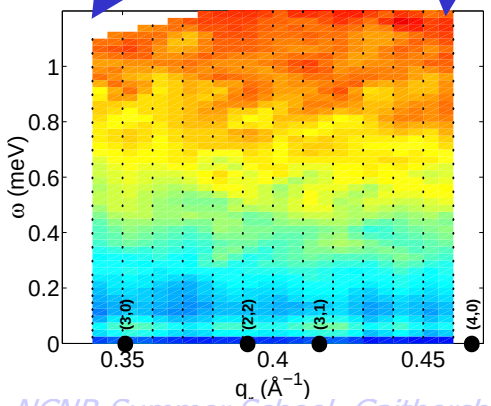
Bacteriorhodopsin in Purple Membrane



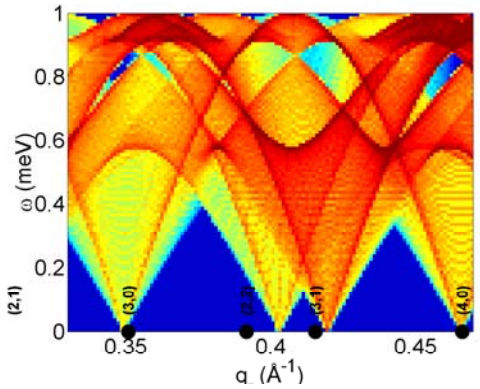
Sample: Dieter Oesterhelt, MPI Munich







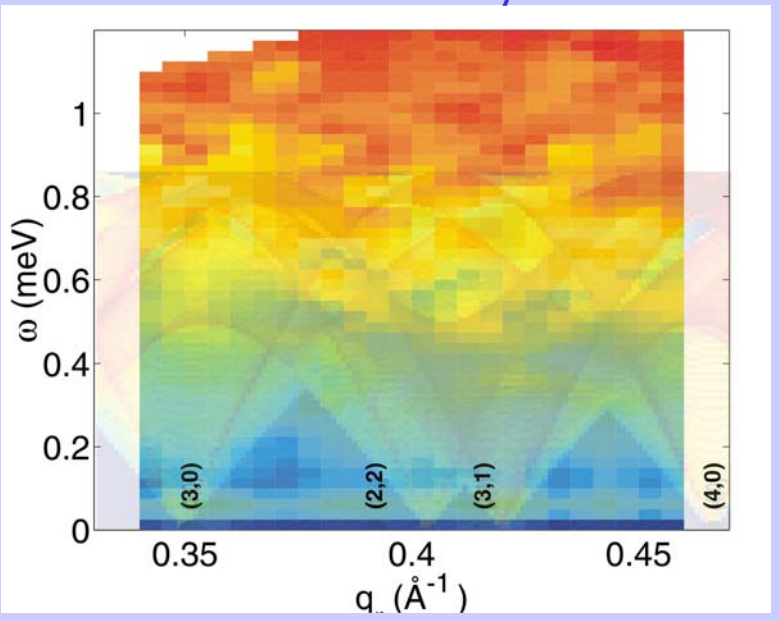
Acoustic phonon spectrum



Karin Schmalzl, Dieter Strauch, ILL+U Regensburg

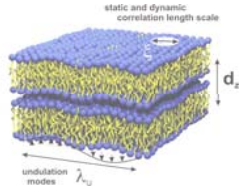
3-axis (IN12)

Data+Theory



Challenge: Study Dynamics of Proteins embedded in Membranes

Thanks to

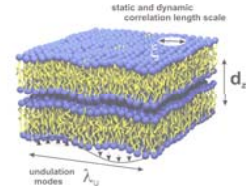


- Tim Salditt, Institut für Röntgenphysik

- Wolfgang Häußler, FRMII, TUM
- Christoph Ollinger, IRP
- Giovanna Fragneto, ILL, D17
- Wolfgang Schmidt, FZ-Jülich, IN12
- Franz Demmel, ILL, IN3
- Arno Hiess, ILL, IN8
- Tilo Seydel, IN10/IN16
- Fanni Juranyi, FOCUS, PSI
- Klaus Habicht, HMI
- Klaus Kiefer, HMI
- Thomas Hauss, HMI
- Dieter Richter, FZ-Jülich
- Dieter Strauch, Regensburg
- Karin Schmalzl, FZ-Jülich
- Dieter Oesterhelt, MPI for Biochemistry

- Institut Laue-Langevin
- DFG, Grant SA 772/8-2

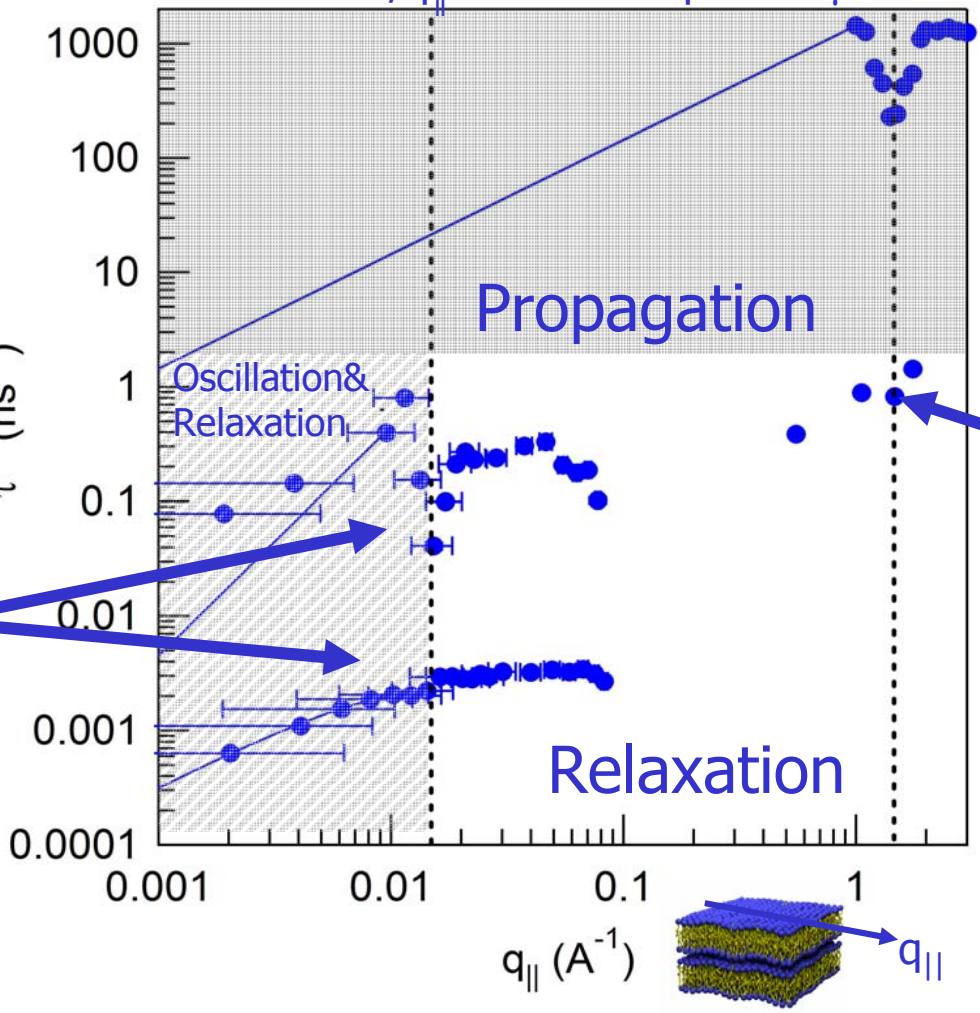
Collective Excitations in model membranes



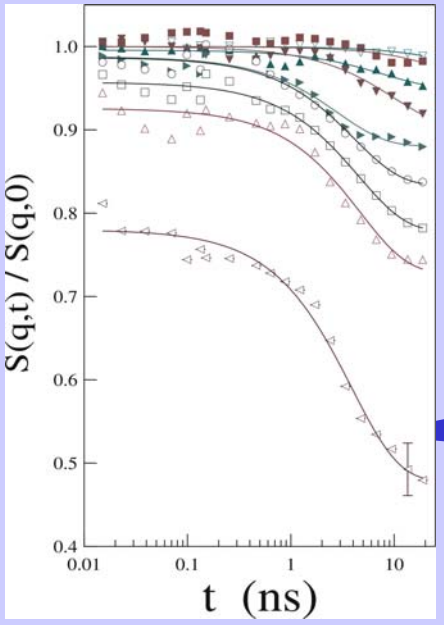
The 'Neutron Window'

DMPC –d54

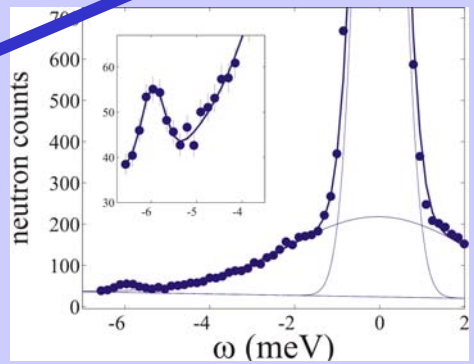
2Å<2π/q$_{||}$<5000Å & 1ps<τ<1μs



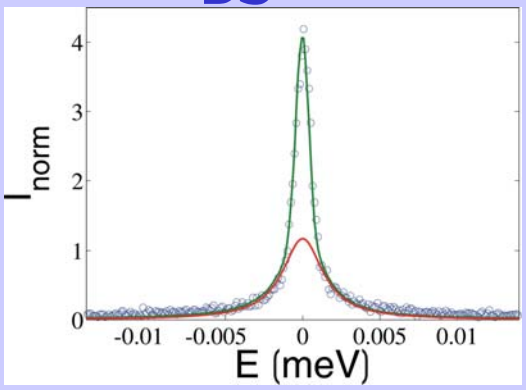
NSE



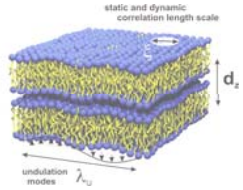
TAS



BS



Rheinstädter et al., PRL **93**, 108107 (2004).
Rheinstädter et al., PRL **97**, 048103 (2006).
Rheinstädter et al., PRE **71**, 061908 (2005).
Rheinstädter et al., PRE **75**, 011907 (2007).


static and dynamic
correlation length scale
undulation
modes