Dielectric properties of tissues and cells

Prof. Dr. Alois Loidl

Studies on the issue, if macroscopic dielectric properties of tissues have unlimited validity in both cellular and subcellular dimensions

Part of the German Mobile Telecommunication Research Programme

Participants:

- Dielectric Spectroscopy (A. Loidl, D. Egger, P. Lunkenheimer)
- Patch clamp measurements (A. Wixforth, M. Schneider)
- Theoretical calculations (P. Hänggi, G. Schmidt)

EKM / Institute of Physics, University of Augsburg, Germany

Bundesamt für Strahlenschutz

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Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit

Introduction

Dielectric spectroscopy

Electrolytic solutions

Cell suspensions

Summary

Behaviour of dielectric parameters at cellular and subcellular dimensions

- Permittivity ε and conductivity σ are determining factors in absorption of electromagnetic radiation
- dosimetry essentially relies on the knowledge of dielectric properties of tissue

Specific Absorption Rate

$$SAR = \sigma \frac{|E|^2}{\rho}$$

σ: conductivity (S/m)

E: field strength (V/m)

ρ: mass density (kg/m³)

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Dielectric spectroscopy

complex permittivity: $\varepsilon^* = \varepsilon' - i\,\varepsilon''$ complex conductivity: $\sigma^* = \sigma' + i\,\sigma''$

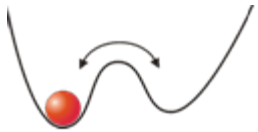
dielectric constant — dielectric loss

$$\sigma^* = i\,\omega\,\varepsilon_0\,\varepsilon^*$$

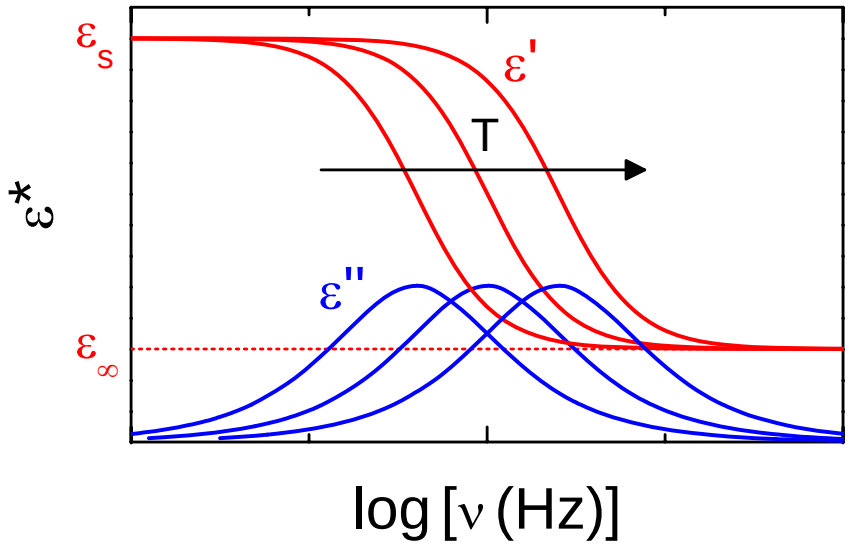
relaxation

reorienting dipolar molecule

charged particle in double-well potential

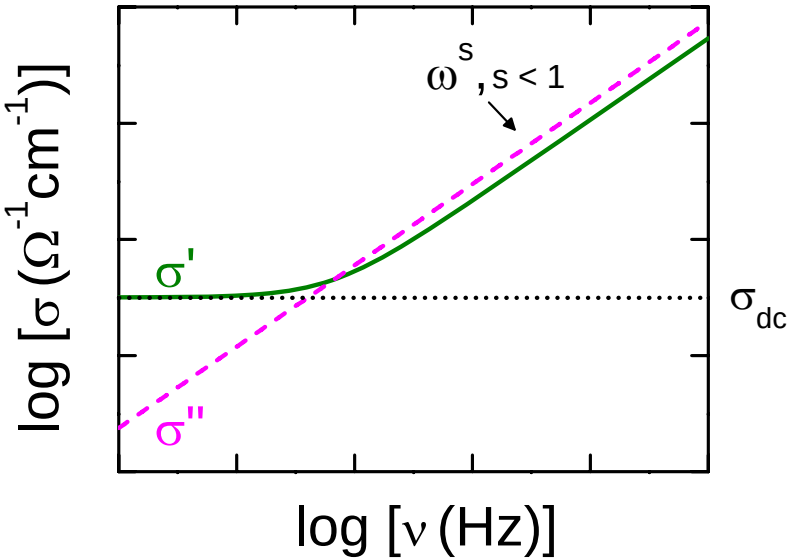


peak in $\varepsilon''(\nu,T)$, step in $\varepsilon'(\nu,T)$ at $\nu = 1/(2\pi\tau)$



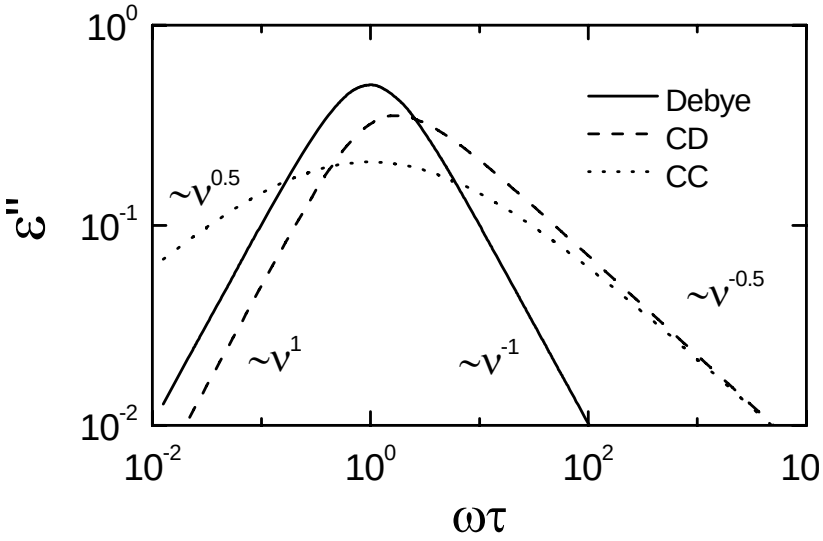
hopping conduction

$\sigma' = \sigma_{dc} + \sigma_0\,\nu^s \quad (s < 1)$



Dielectric spectroscopy

$$\varepsilon^*(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{\left[1 + (i\omega\tau)^{1-\alpha}\right]^\beta} - i\frac{\sigma_{dc}}{\varepsilon_0\omega}$$



$$\tau = \tau_0 \cdot \exp\left(\frac{E_\tau}{k_B(T - T_{VF})}\right)$$

or

$$\tau = \frac{1}{2D_R}$$

Rotational diffusion coefficient

$$D_R = \frac{k_B T}{8\pi\eta r_H^3}$$

η viscosity

r_H hydrodyn. radius

$$\sigma_{dc} = \sigma_0 \cdot \exp\left(-\frac{E_\sigma}{k_B T}\right)$$

$$\sigma_0 = \frac{n_0 q^2 a^2 \nu_0}{6k_B T}$$

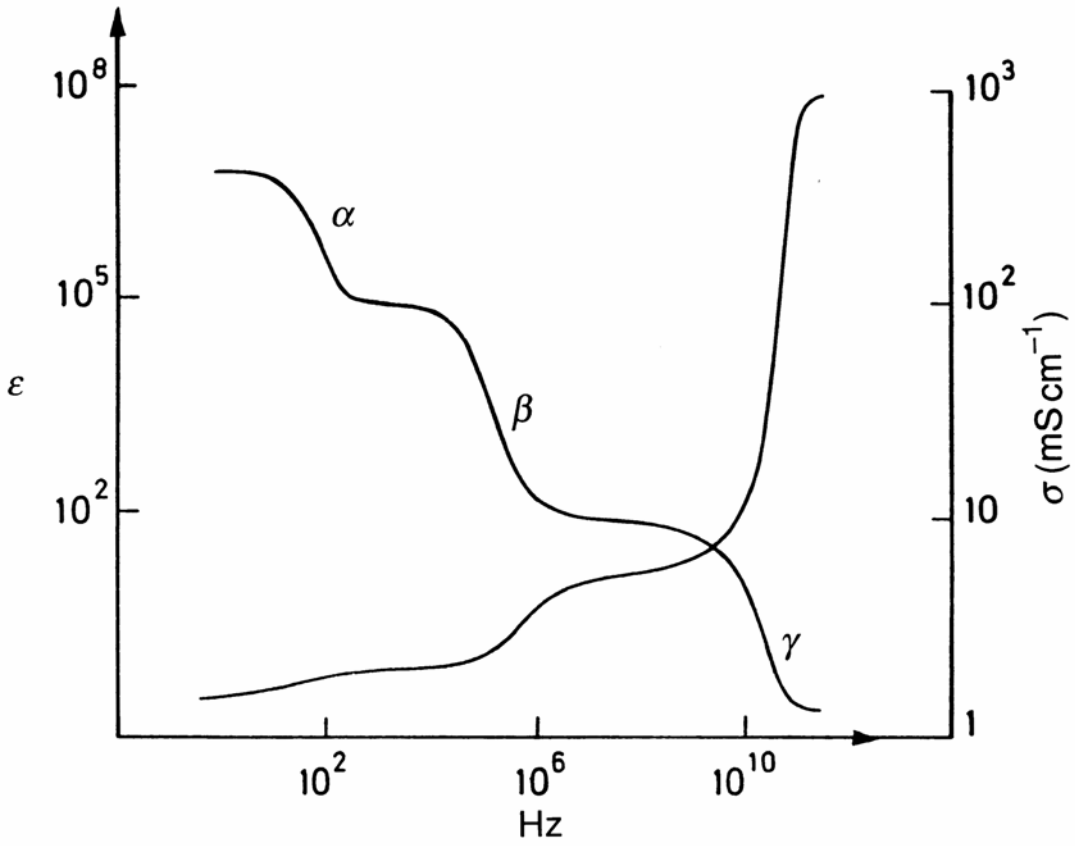
$$D_\sigma = \frac{k_B T \sigma_{dc}}{(ne)^2}$$

Conductivity diffusion

(Nernst-Einstein)

Dielectric spectroscopy

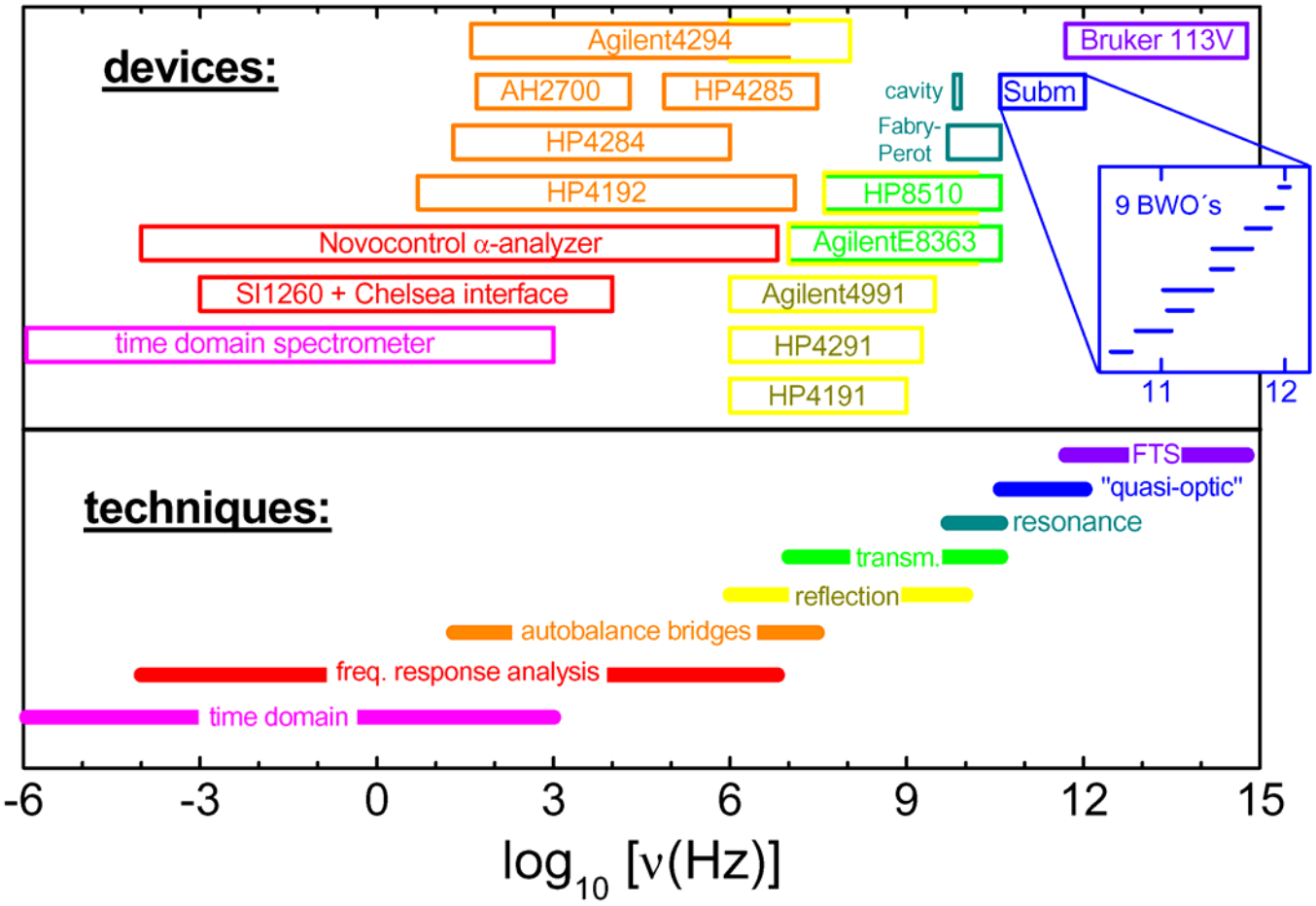
Major dispersion regimes in biological matter



- α-dispersion
  counter-ion relaxation?
  membrane structure/channels?
- β-dispersion
  1 kHz...100 MHz
  charging of cell membranes
- γ-dispersion
  > 100 MHz
  rotation of water molecule
- δ-dispersion
  bound water
  relaxation of macromolecules

Broadband dielectric spectroscopy

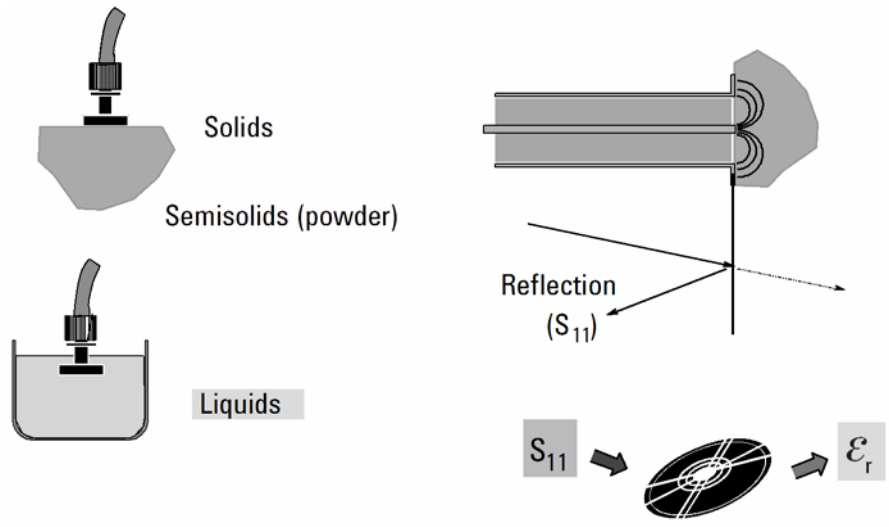
- Measurement of dielectric constant and complex conductivity
- Parameters: frequency, temperature (0.1 K < T < 1000 K), doping, magnetic field
- Extremely **broad frequency range:** 10^{-6} Hz < ν < 10^{15} Hz

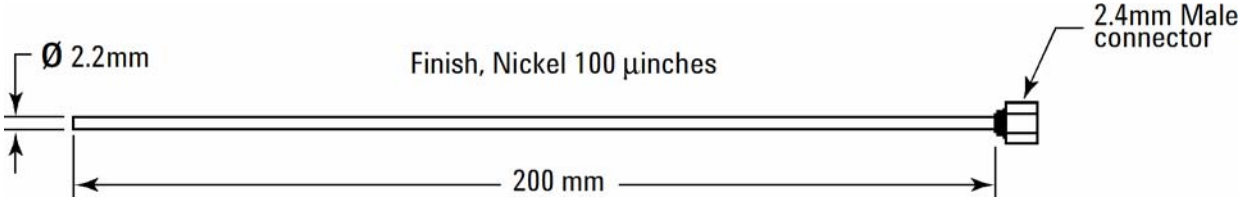


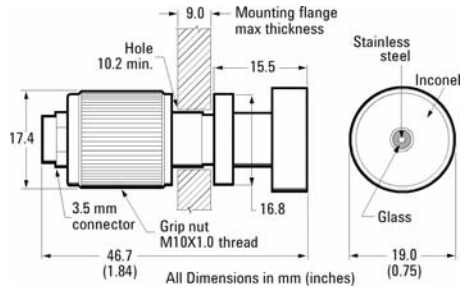
for details, see U. Schneider, P. Lunkenheimer, A. Pimenov, R. Brand, and A. Loidl, Ferroelectrics **249**, 89 (2001).

Open-ended coaxial probe (100 MHz - 40 GHz)

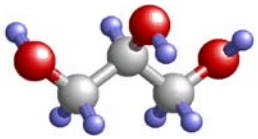
- Ideal for liquids or semisolids
- measurements with network analyzer (Agilent E8363B PNA Series)



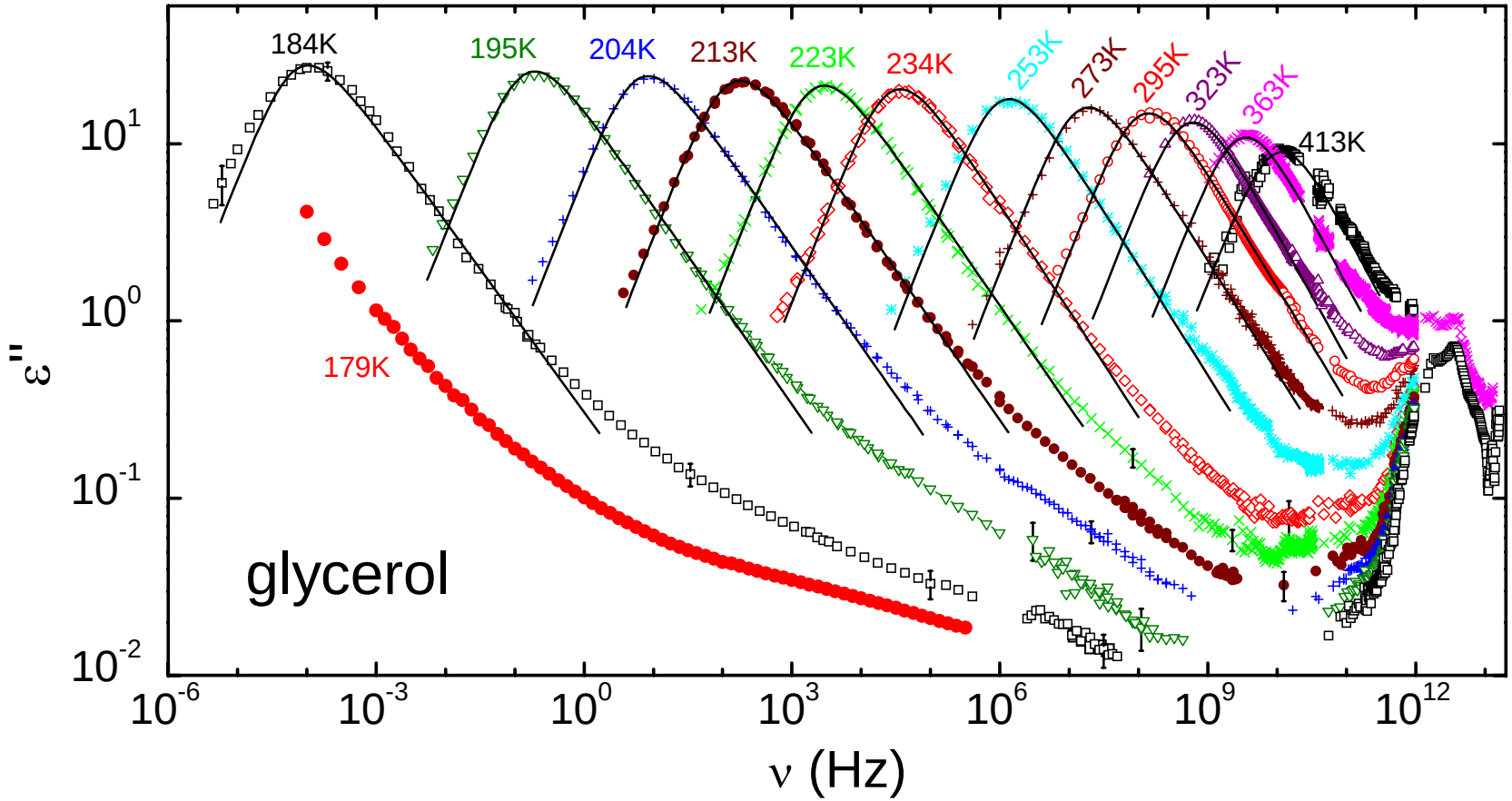




Example: glycerol

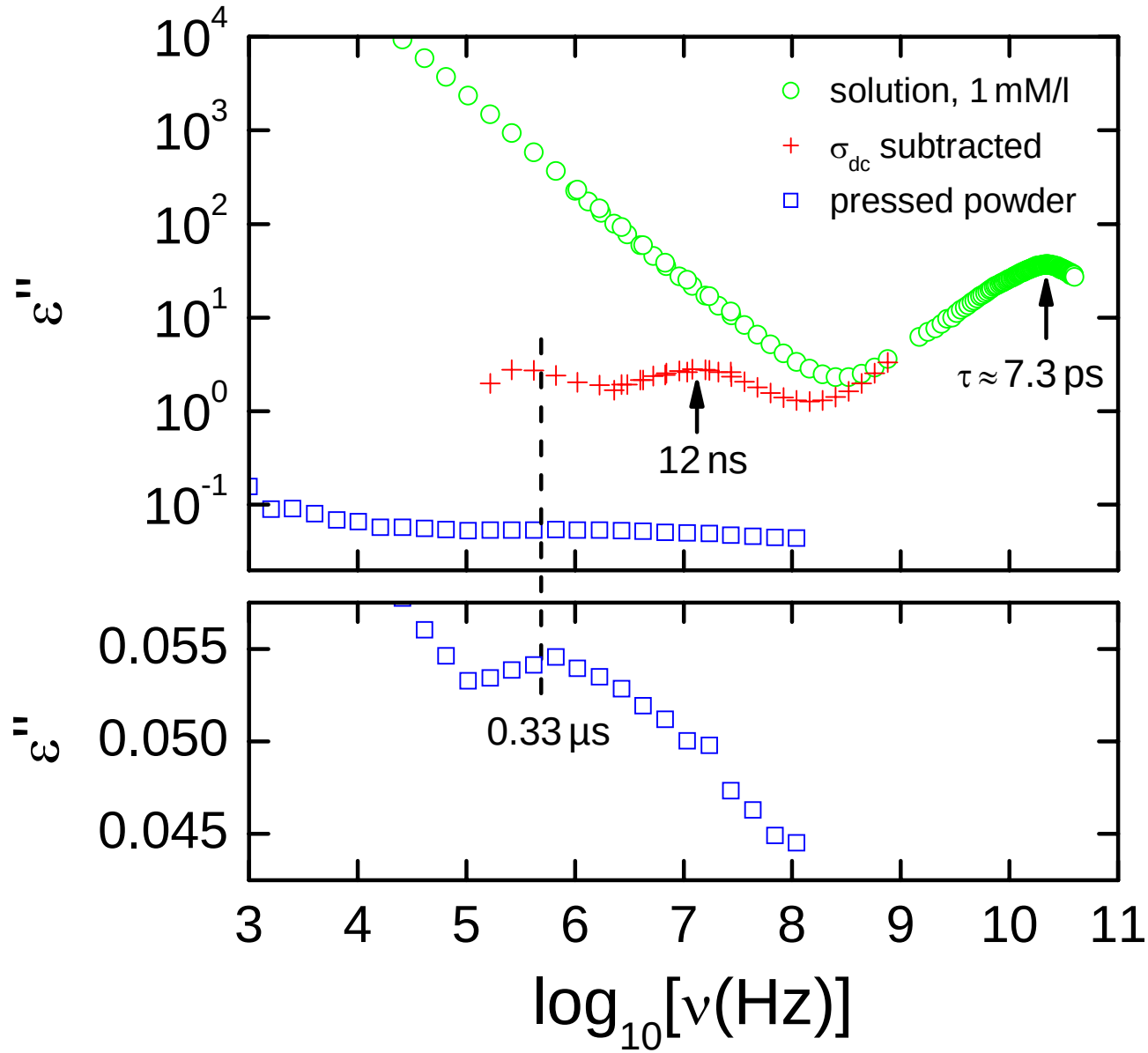


$C_3H_8O_3$
network glass former (hydrogen bonded)
T_m=291 K; $T_g \approx$185 K

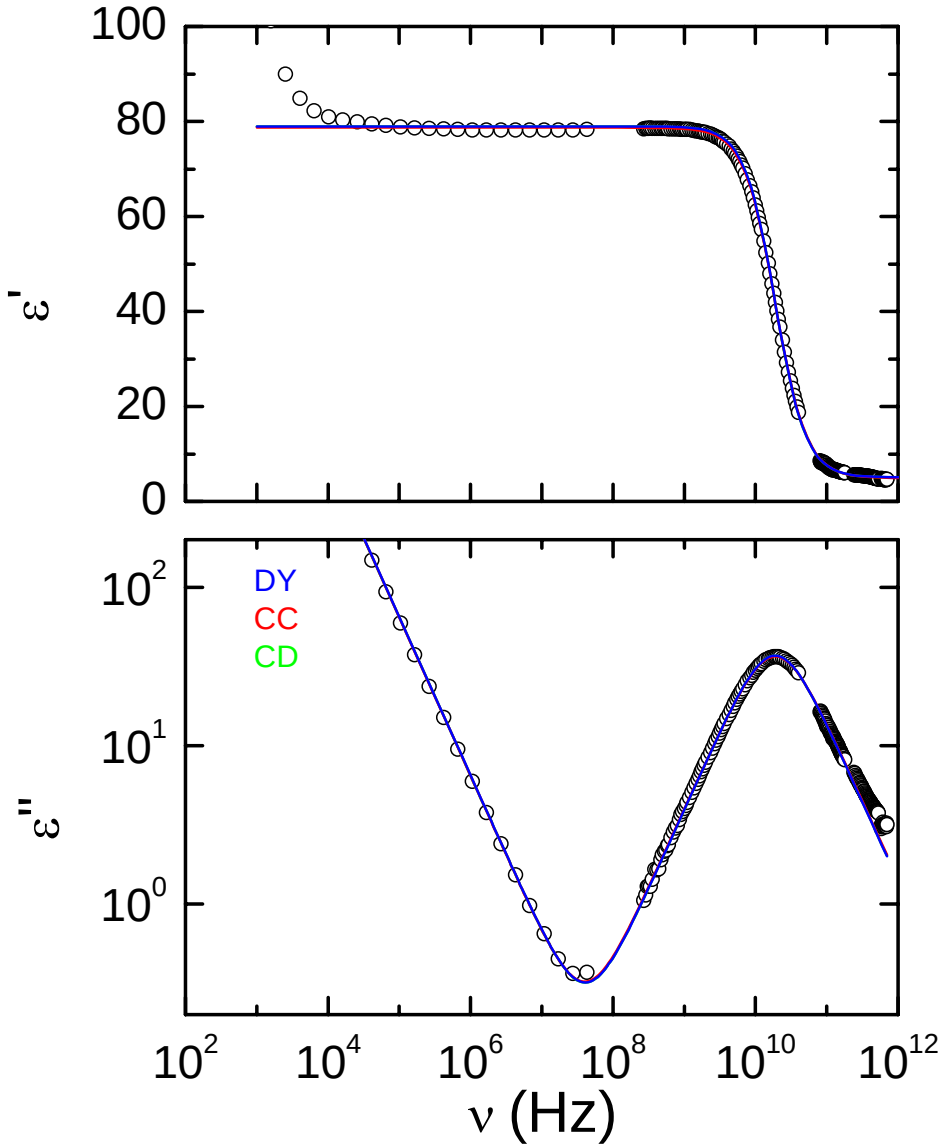


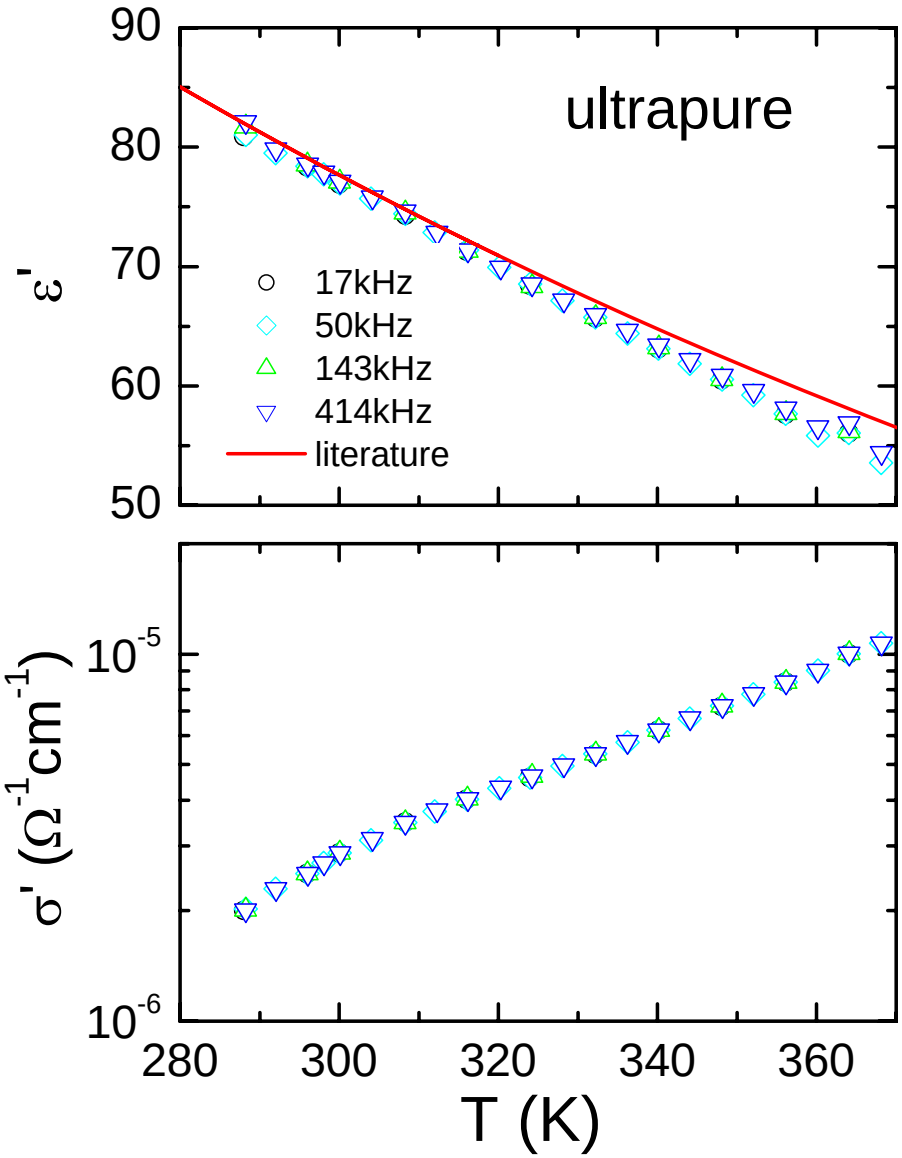
P. Lunkenheimer *et al.*, PRL **77**, 318 (1996); P. Lunkenheimer *et al.*, Contemp. Phys. **41**, 15 (2000); U. Schneider *et al.*, PRL **84**, 5560 (2000).

Ubiquitin

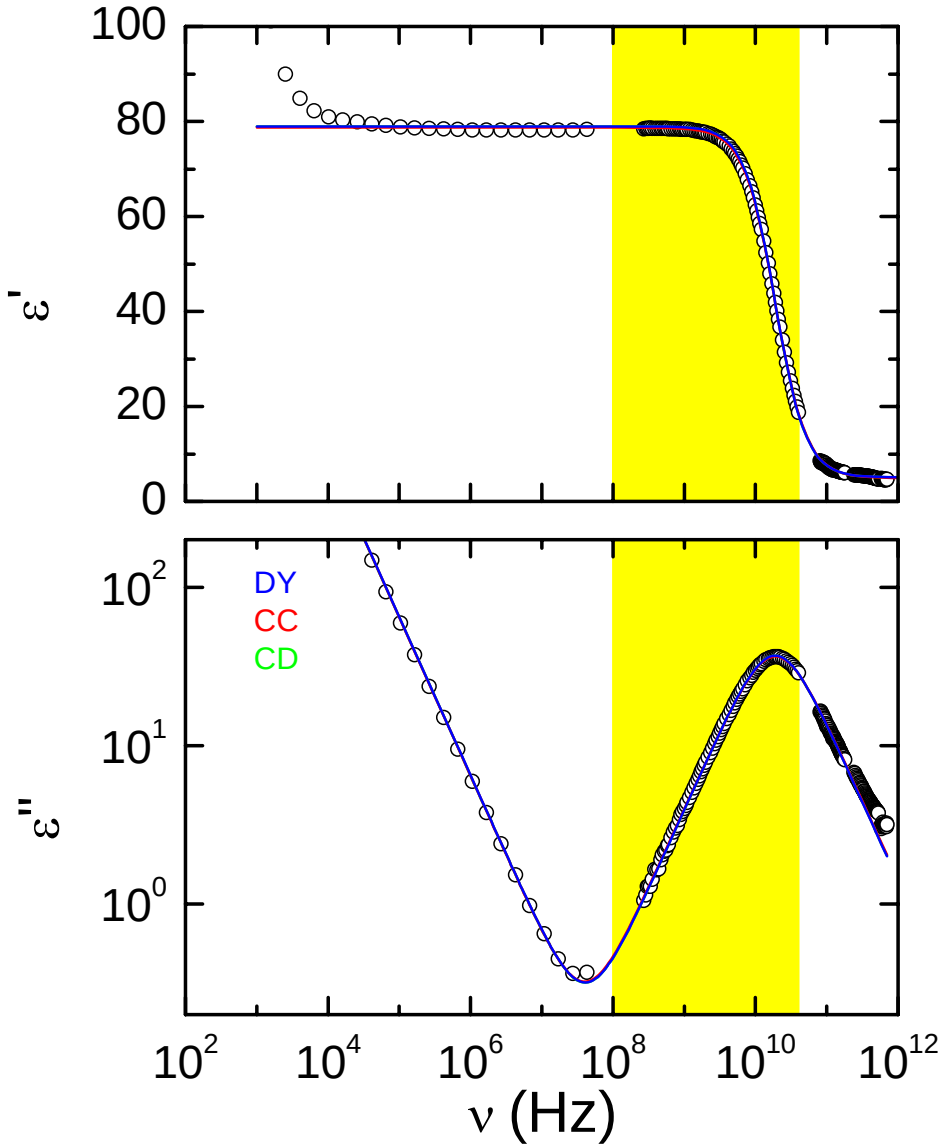

solution, 1 mM/l
σdc subtracted
pressed powder
τ ≈ 7.3 ps
12 ns
0.33 µs
ε''
ε''
log10[ν(Hz)]

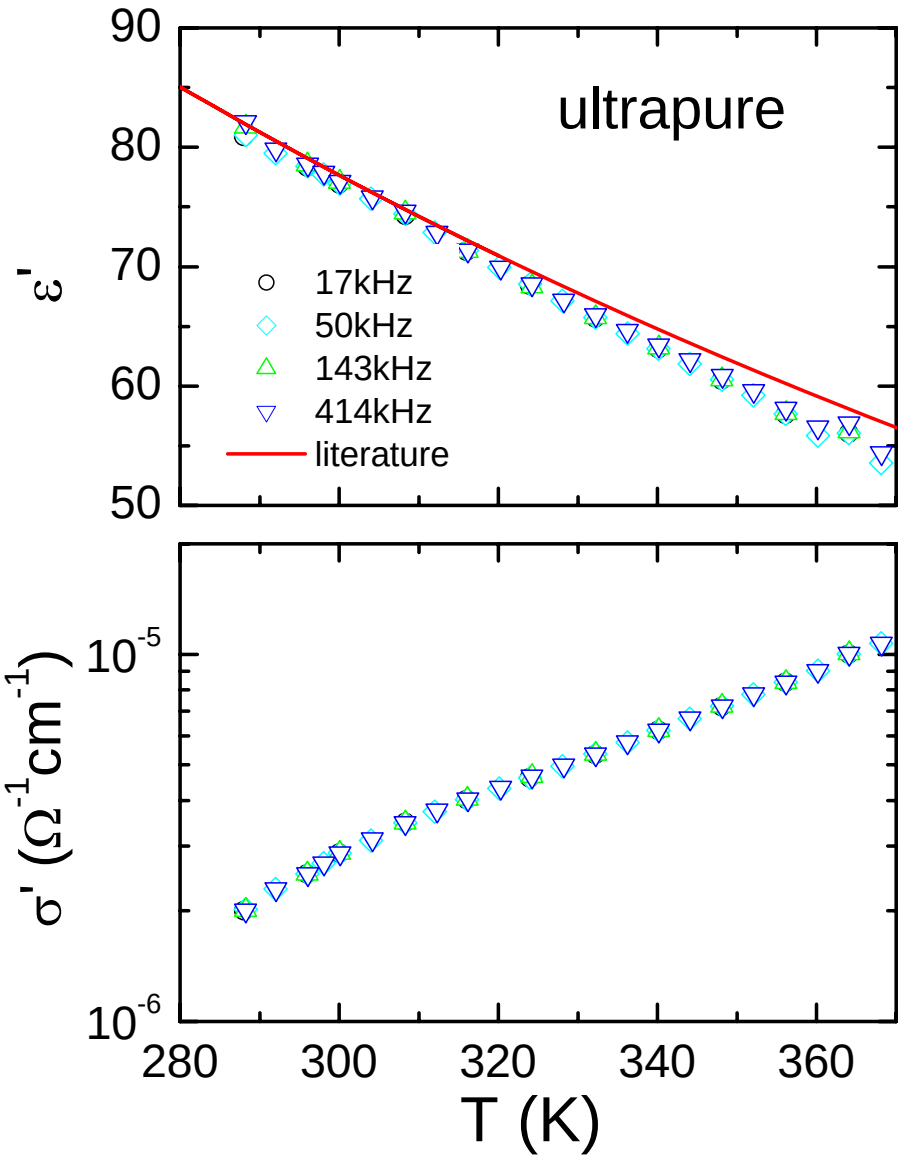
Dielectric properties of pure water





Dielectric properties of pure water





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Summary

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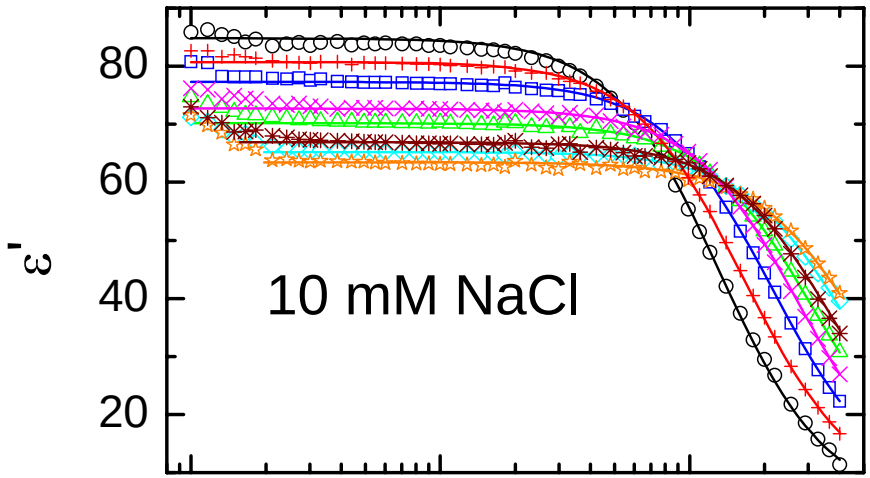
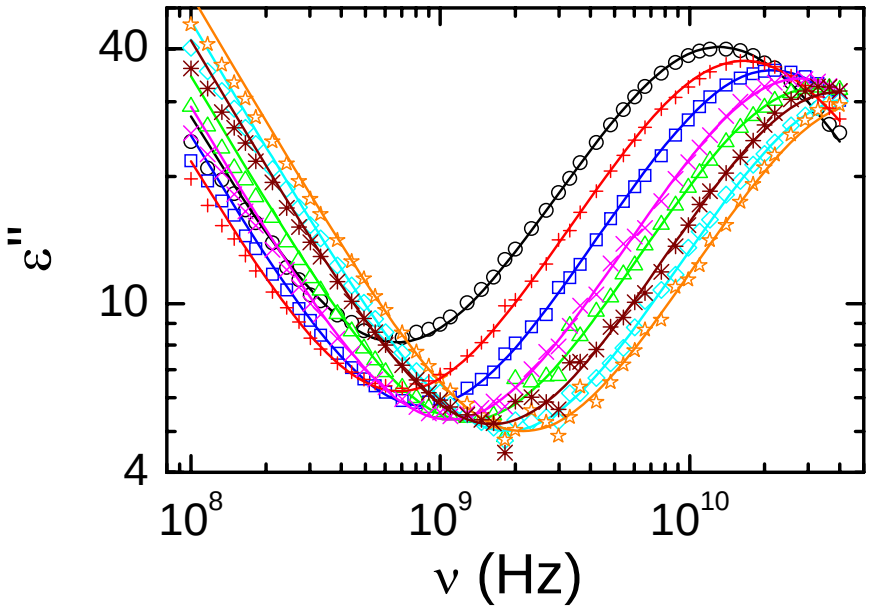
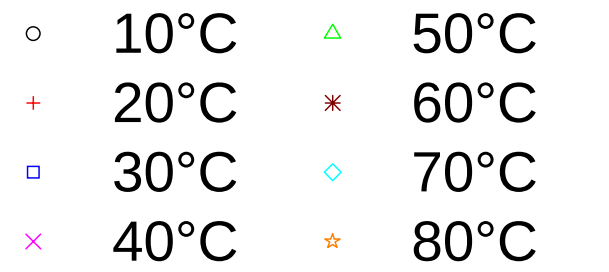
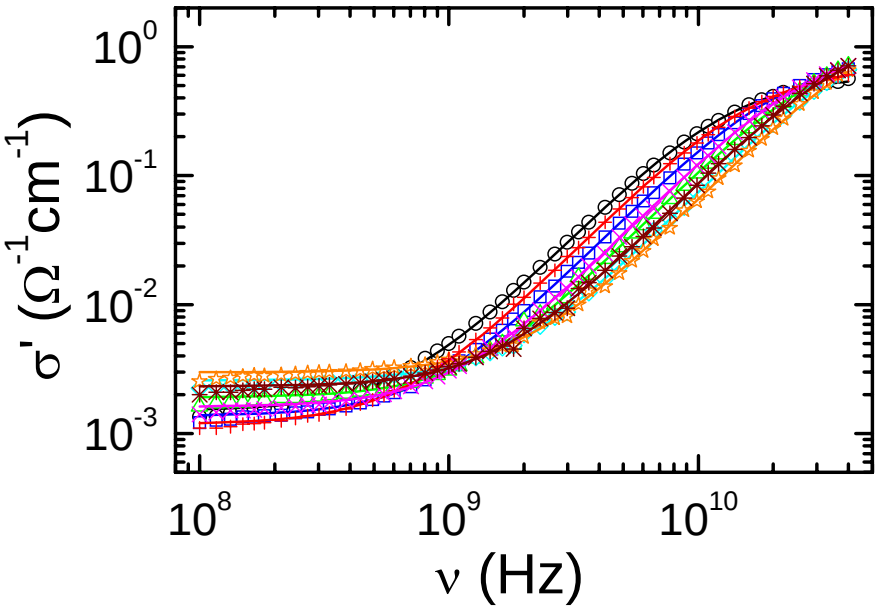
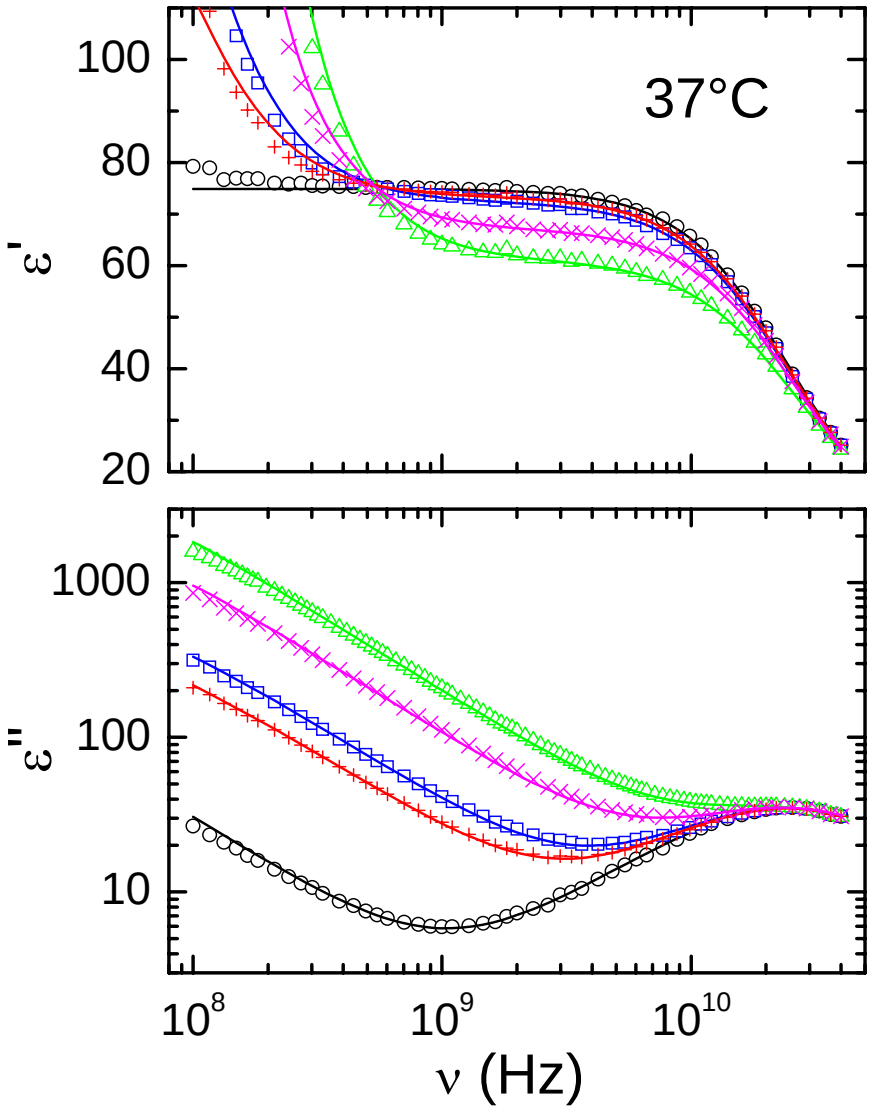


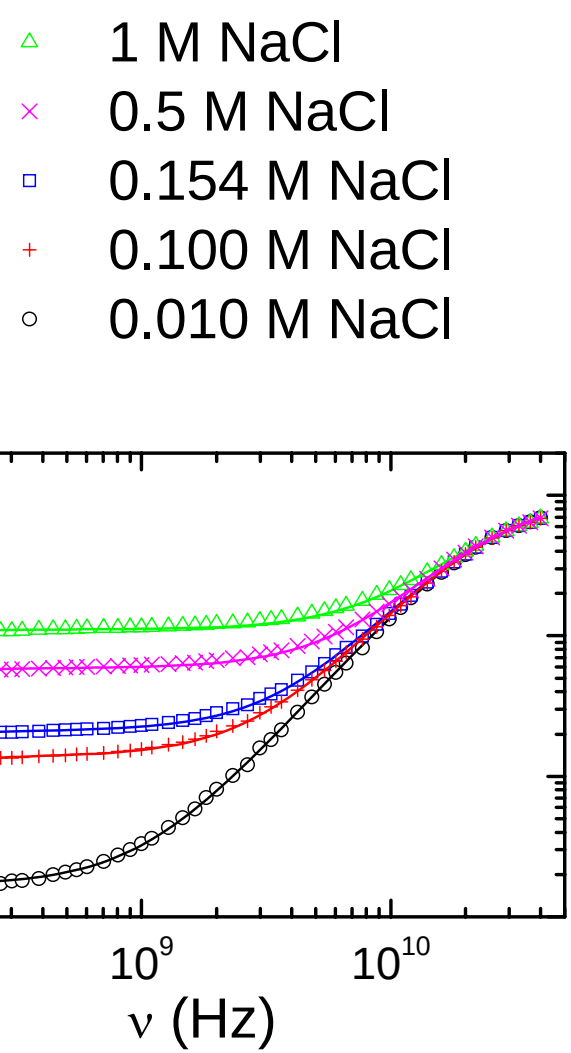




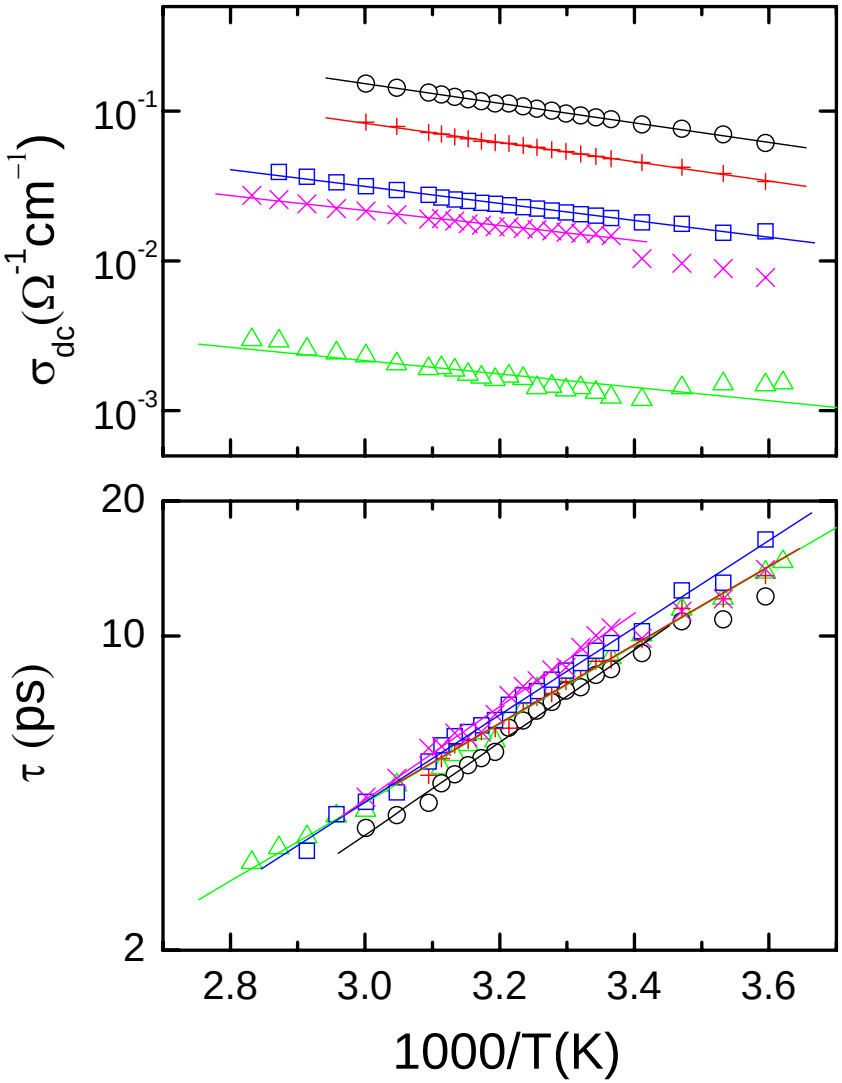


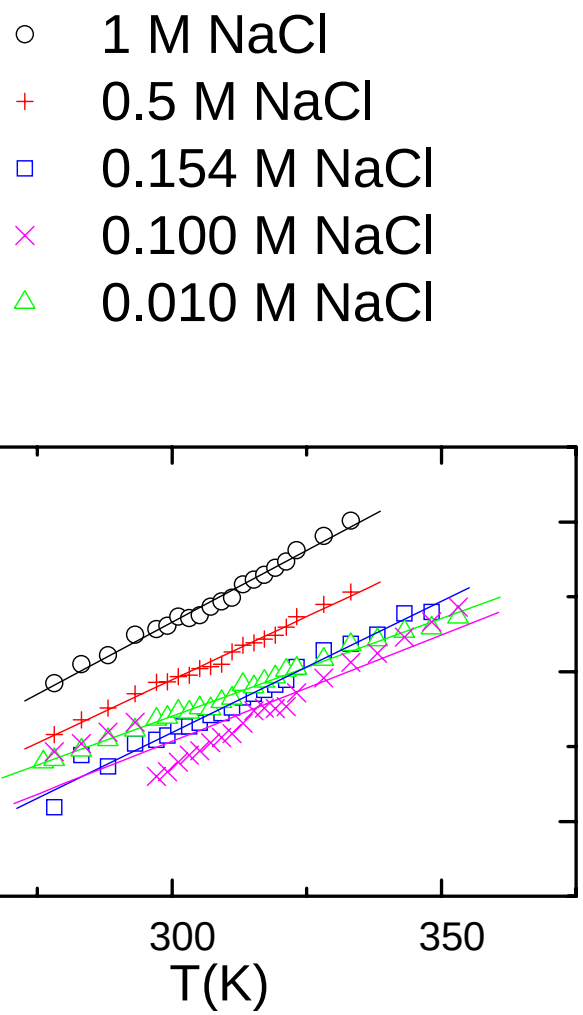
Electrolytic solutions



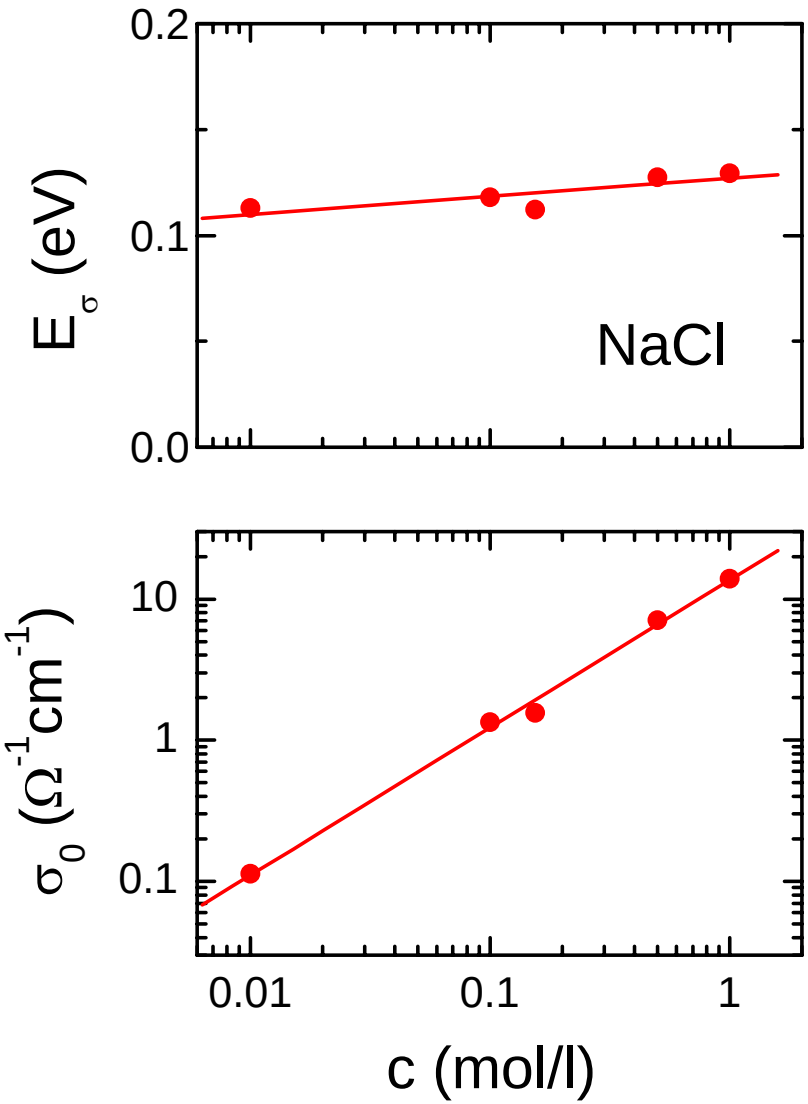


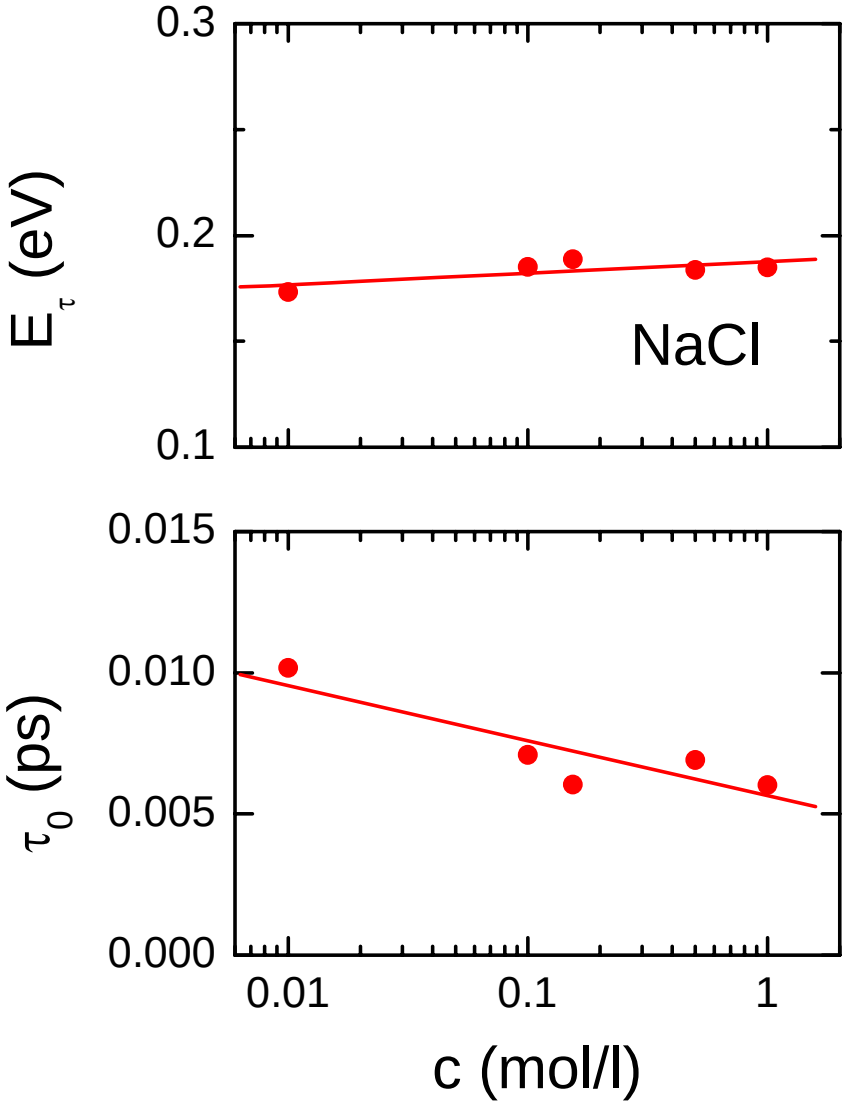
Fitparameters: NaCl electrolytes



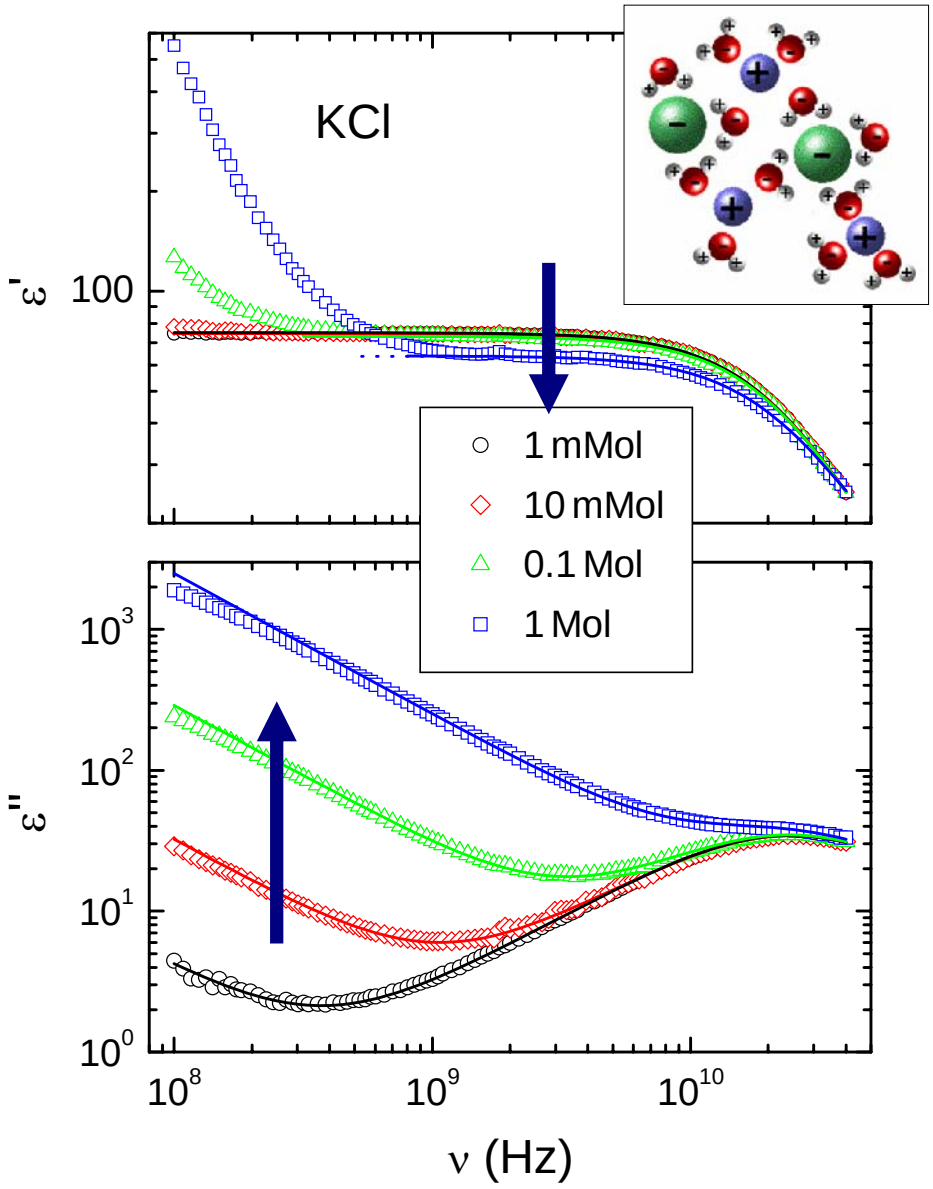


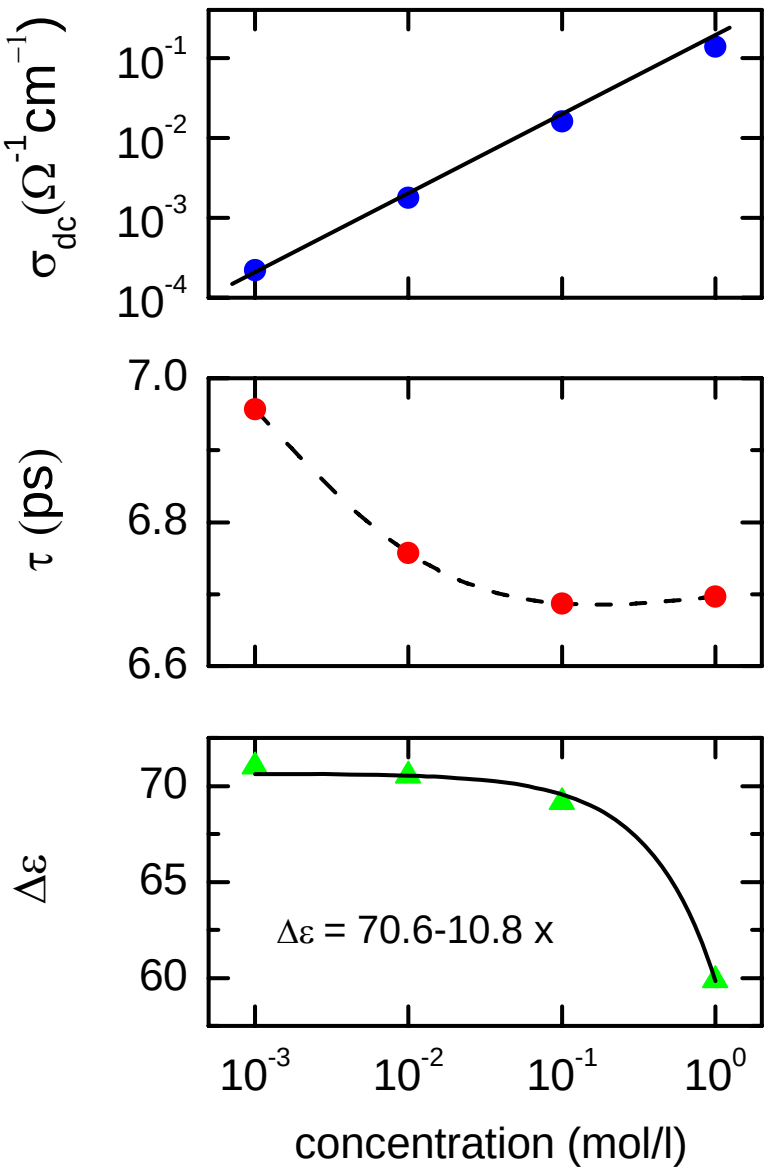
Hindering barriers and prefactors of electrolytic solutions



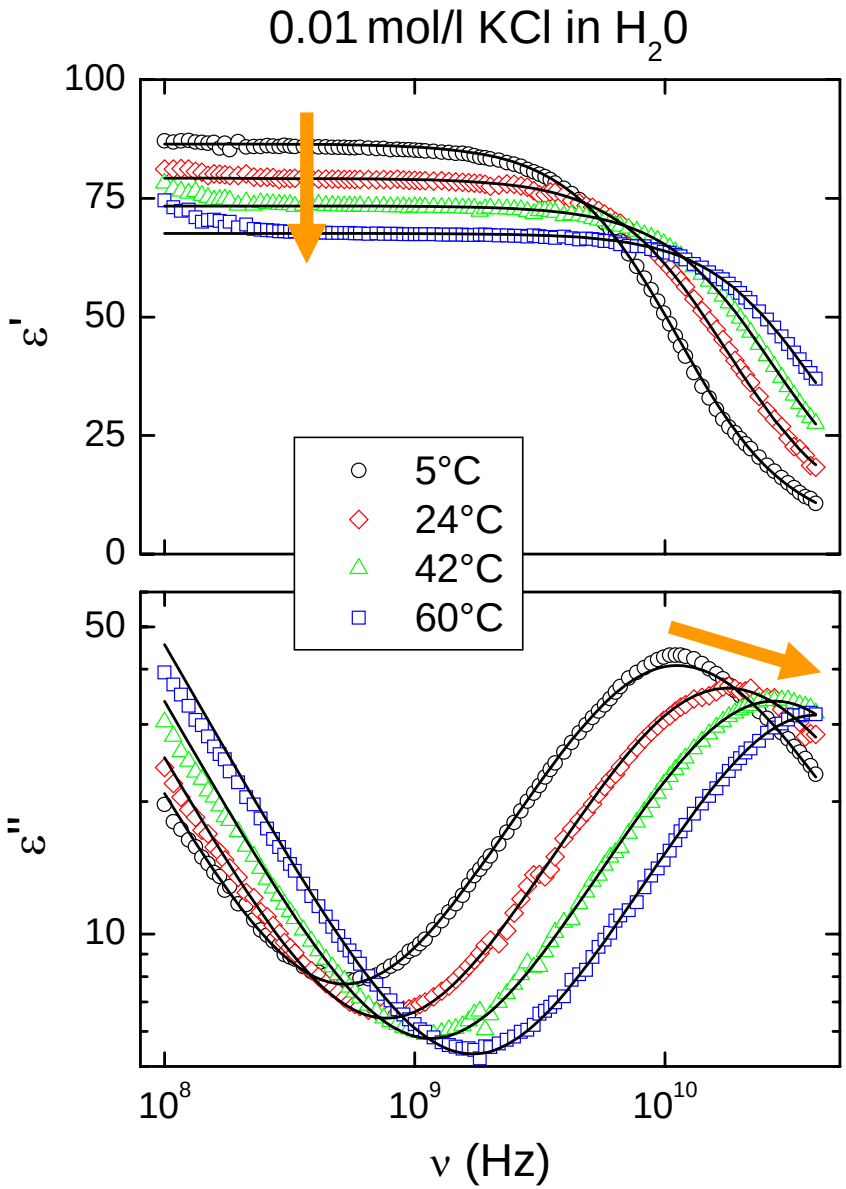


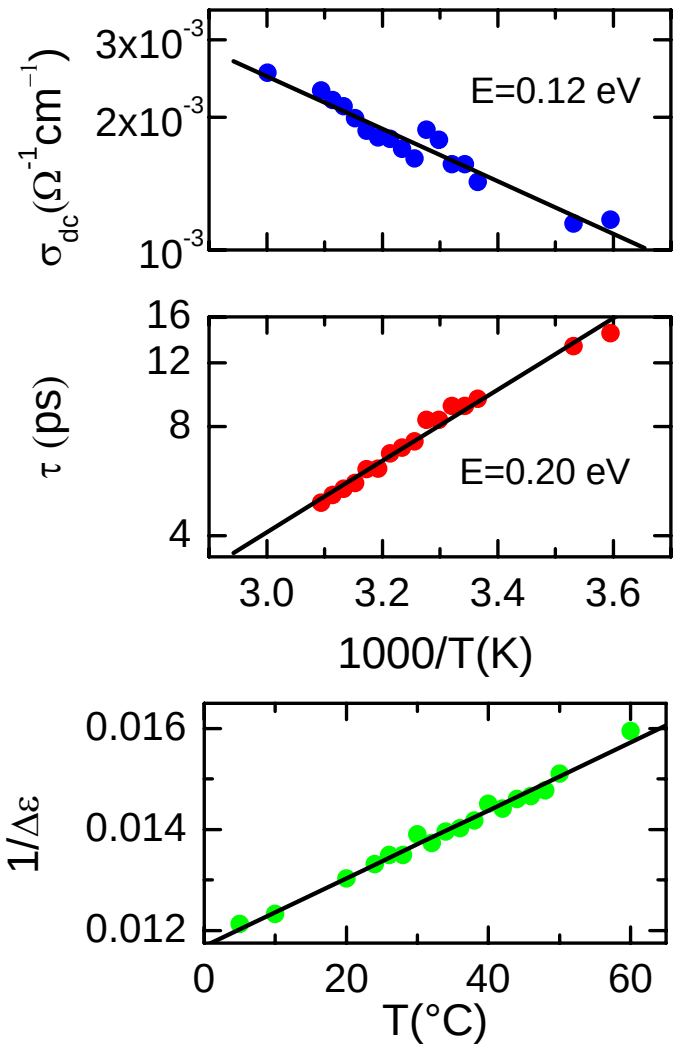
Electrolytic solutions (concentration dependence)





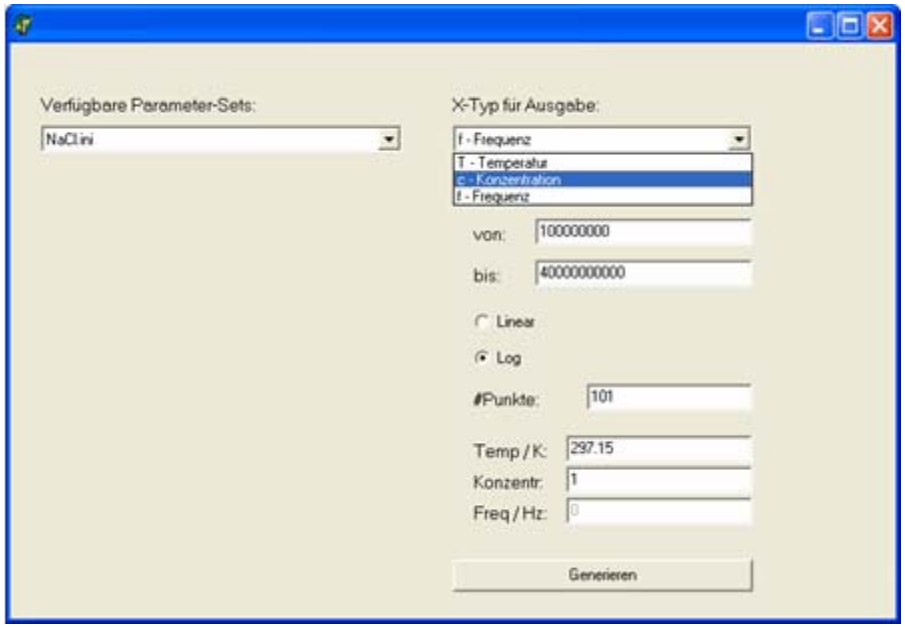
Electrolytic solutions (temperature dependence)





Universal description of electrolytic solutions

$$\varepsilon^*(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{\left[1 + (i\omega\tau)^{1-\alpha}\right]^\beta} - i\frac{\sigma_{dc}}{\varepsilon_0 \omega}$$



$$\Delta\varepsilon = \varepsilon_s - \varepsilon_\infty = \frac{C}{T - T_C}$$

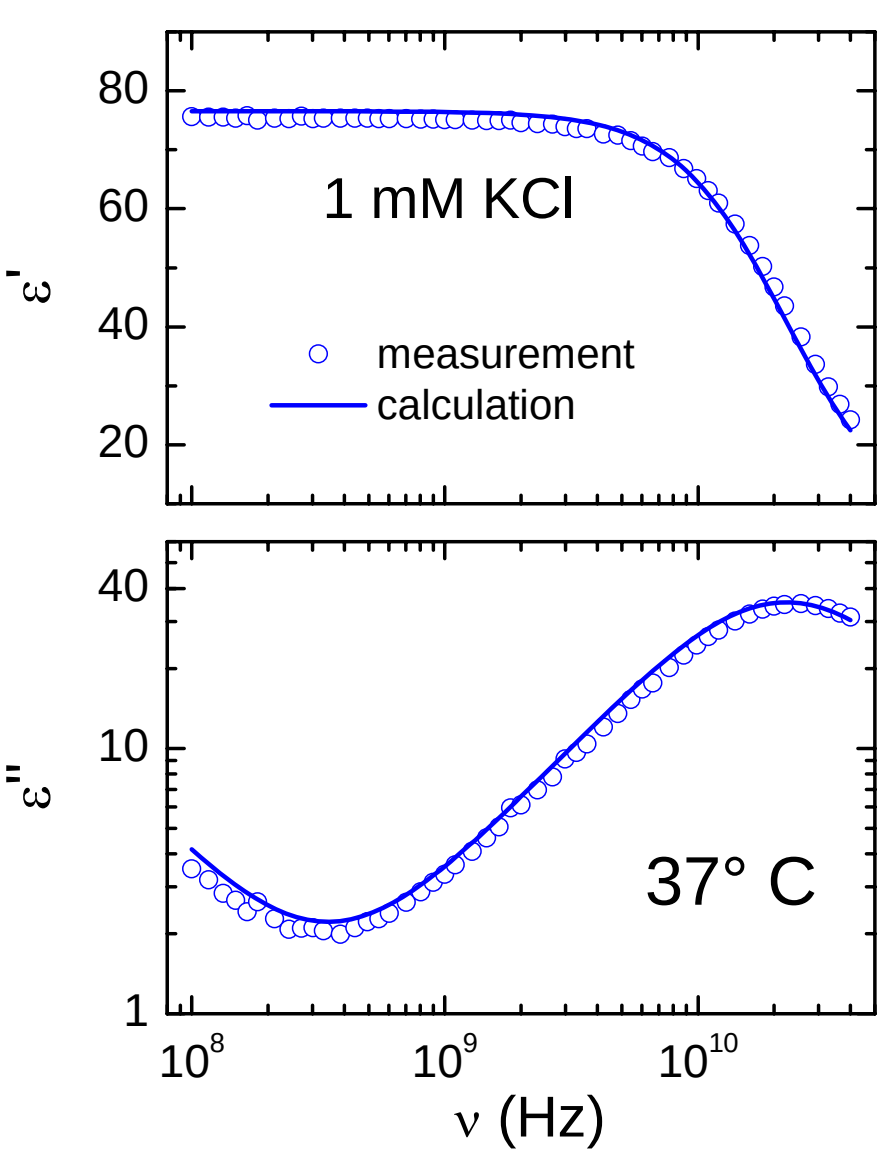
$$\tau = \tau_0 \cdot \exp\left(\frac{E_\tau}{k_B T}\right)$$

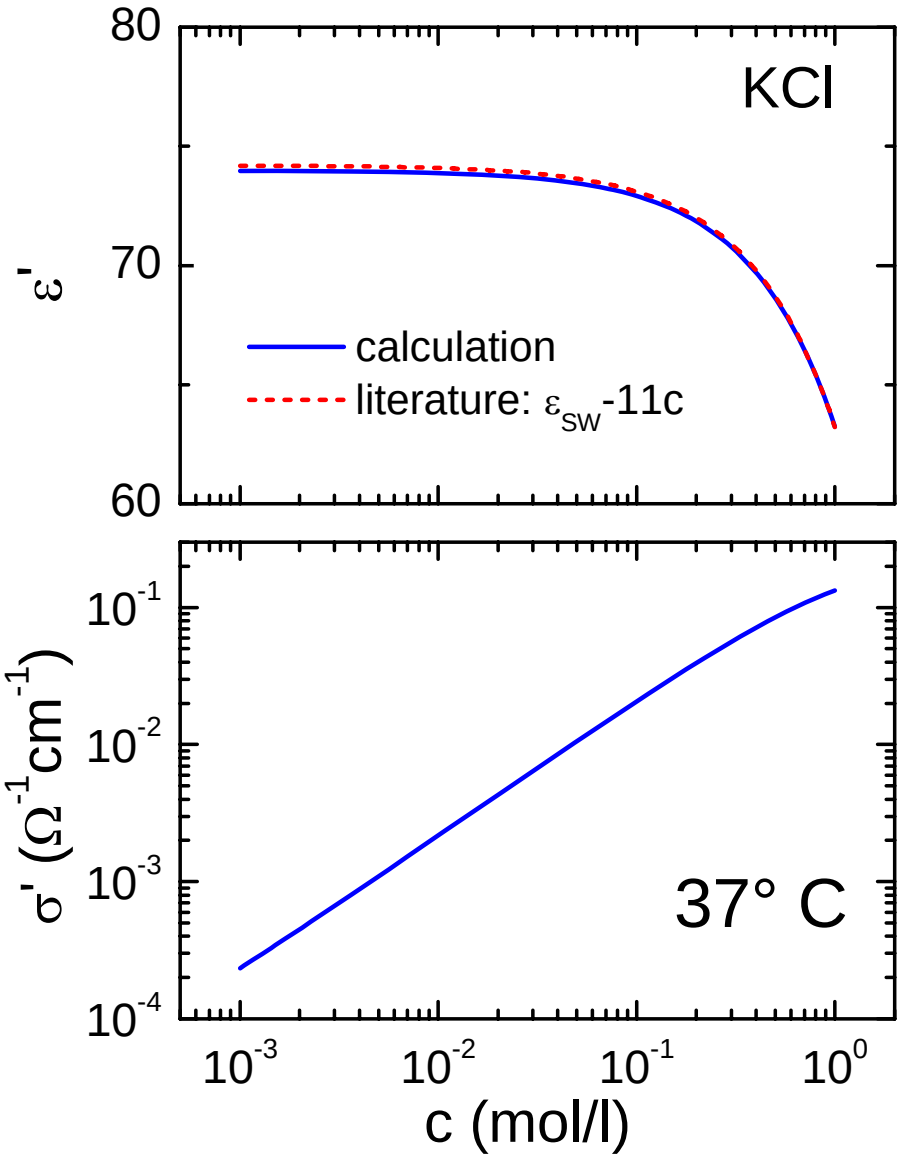
$$\sigma_{dc} = \sigma_0 \cdot \exp\left(-\frac{E_\sigma}{k_B T}\right)$$

Max. 14 Parameter:

ε_∞, α, β, A_{curie}, B_{curie}, AT_{curie}, BT_{curie},
$A\sigma_0$, AE_σ, BE_σ, $A\tau_0$, $B\tau_0$, AE_τ, BE_τ,

ε and σ as function of ν, c, T





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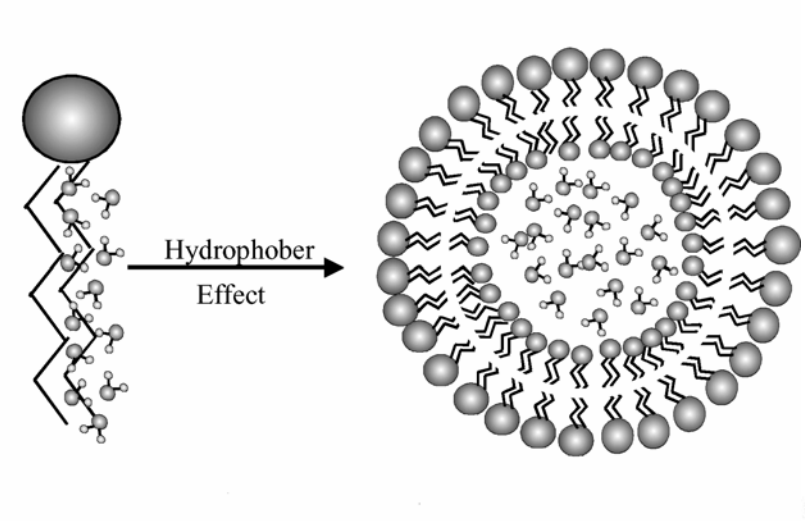
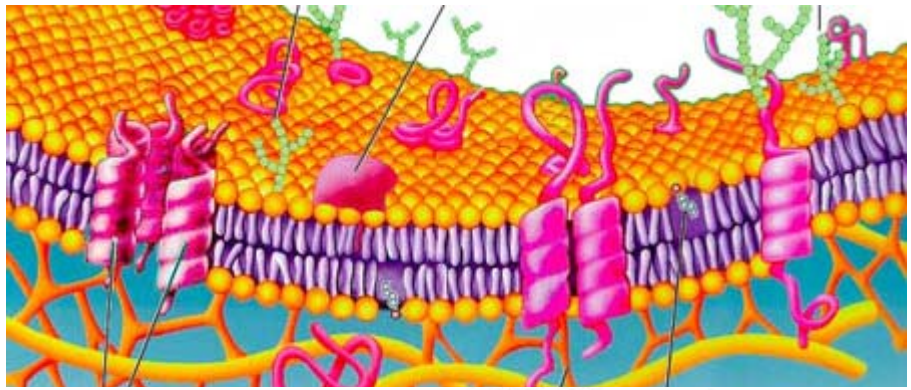
Cell suspensions

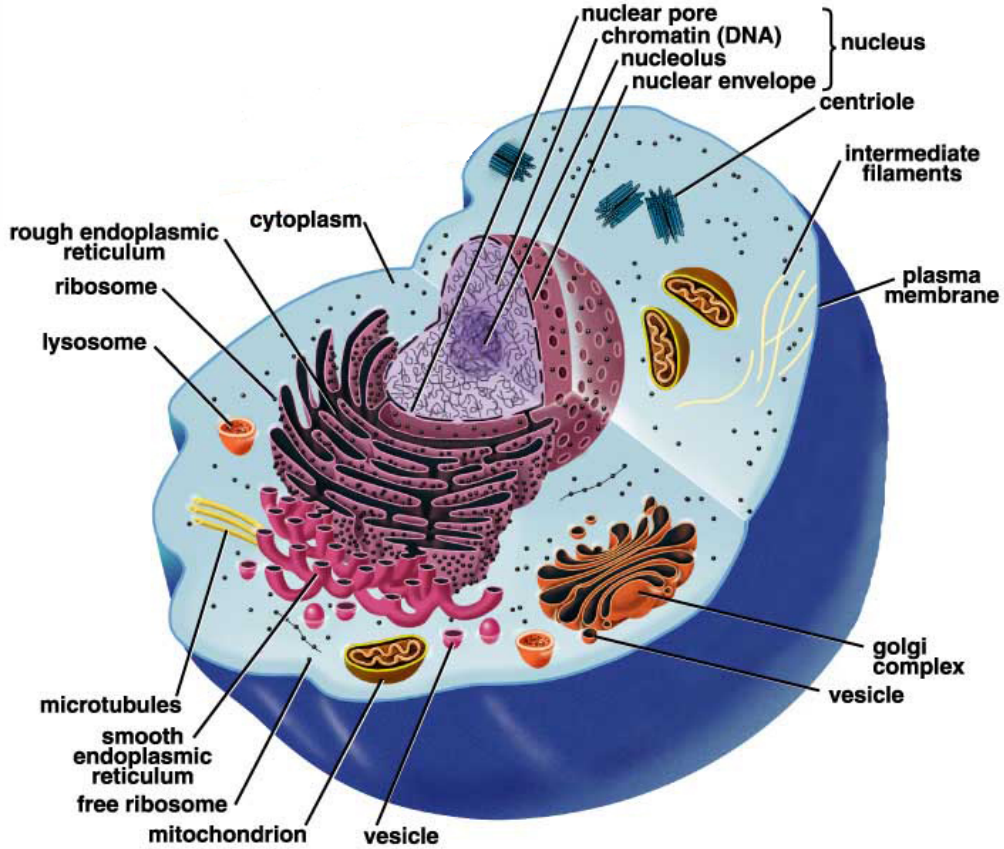
Summary

Dielectric properties of cell suspensions

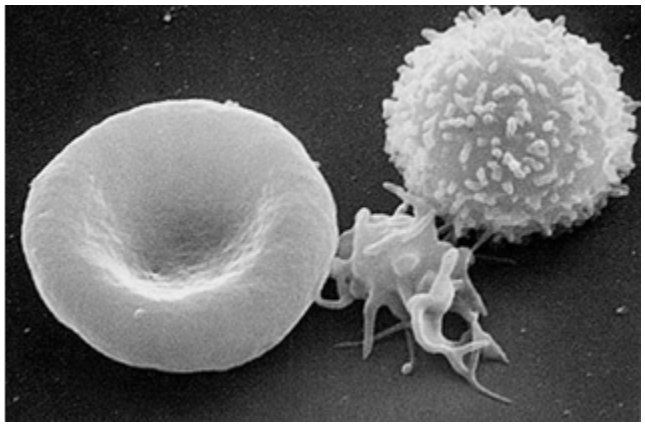


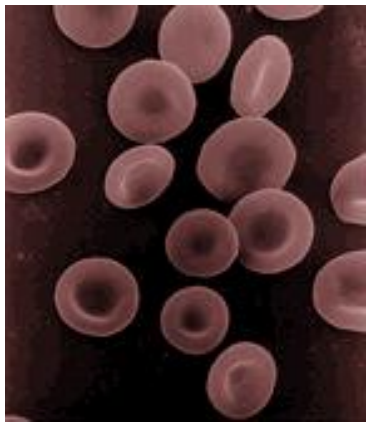


Unilamellar vesicels as cellular model systems



Dielectric properties of cell suspensions

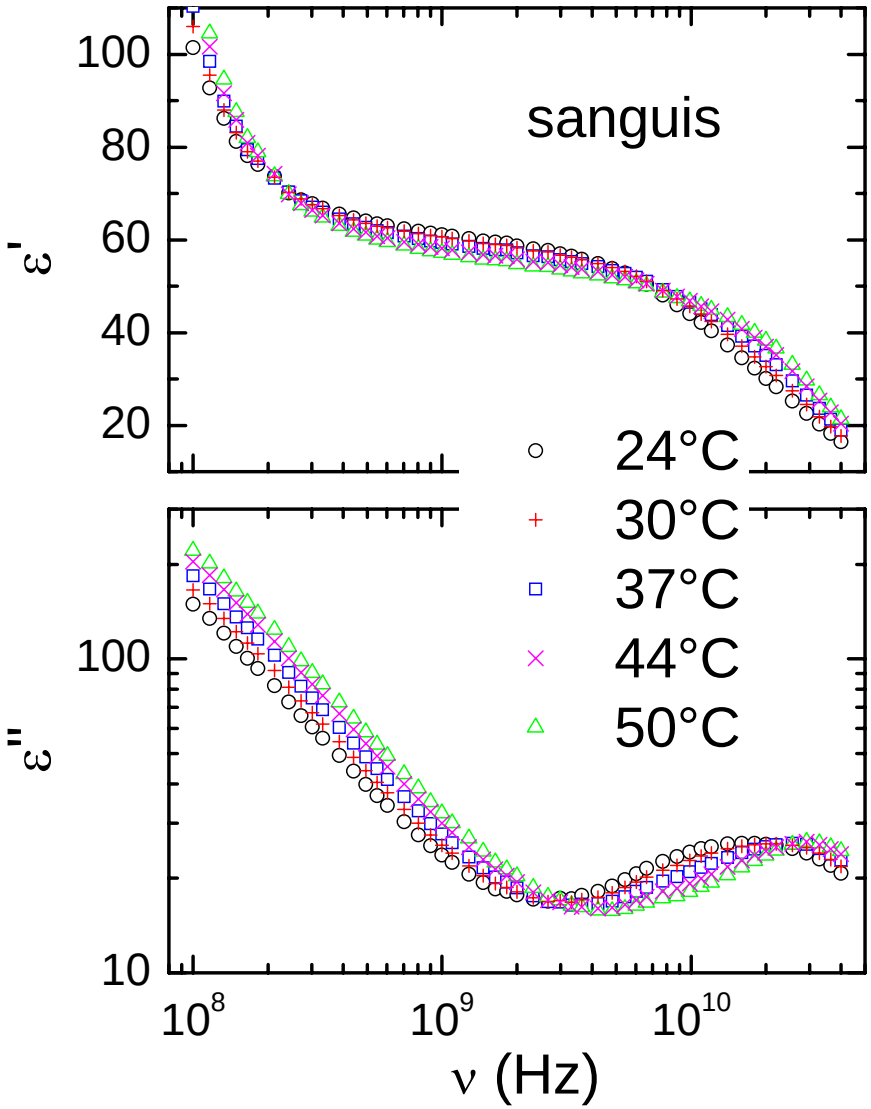




Red cell isolation:

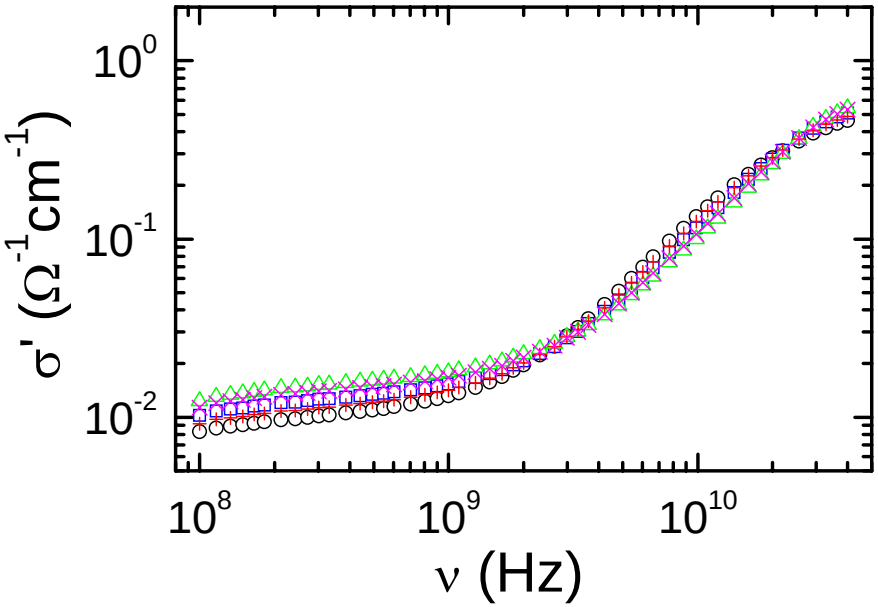
- Addition of isotonic buffer to the whole blood
- Centrifugation at 600 x g
- Removing the supernatant and resuspending in isotonic buffer

Dielectric properties of cell suspensions

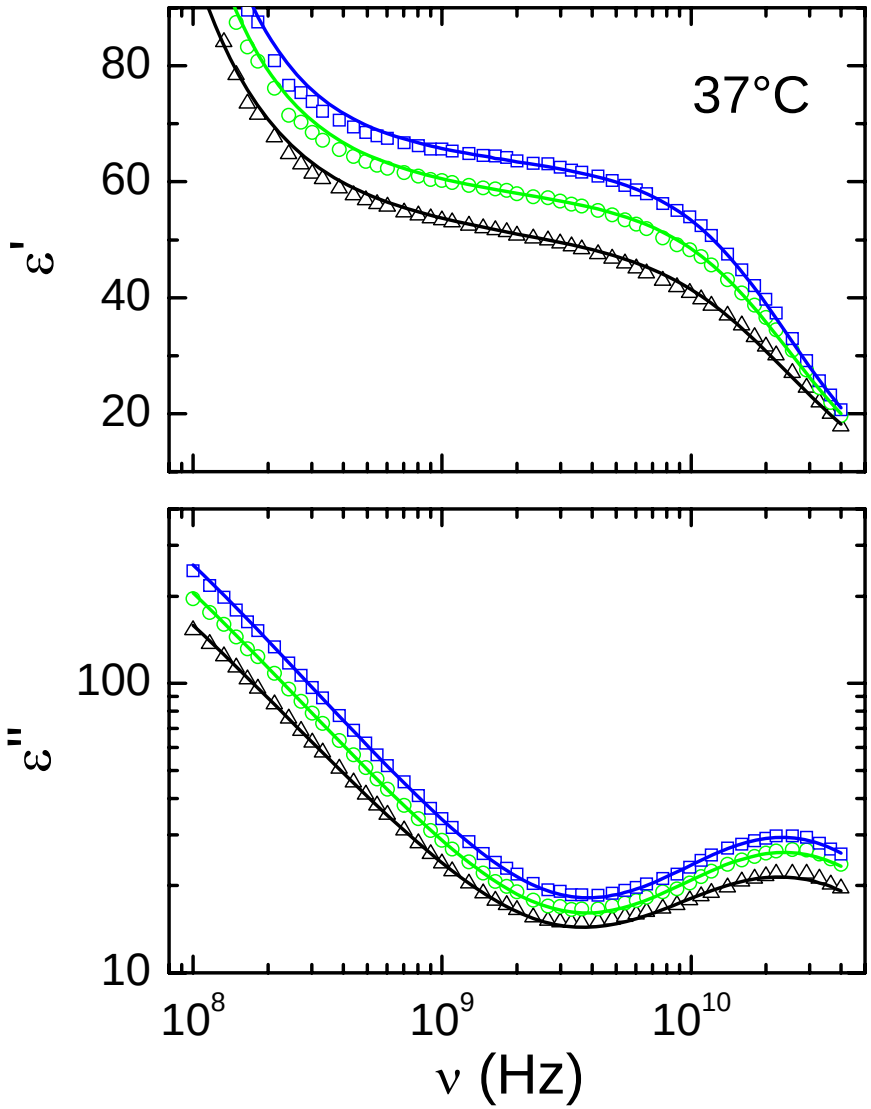


Measurements of whole blood:

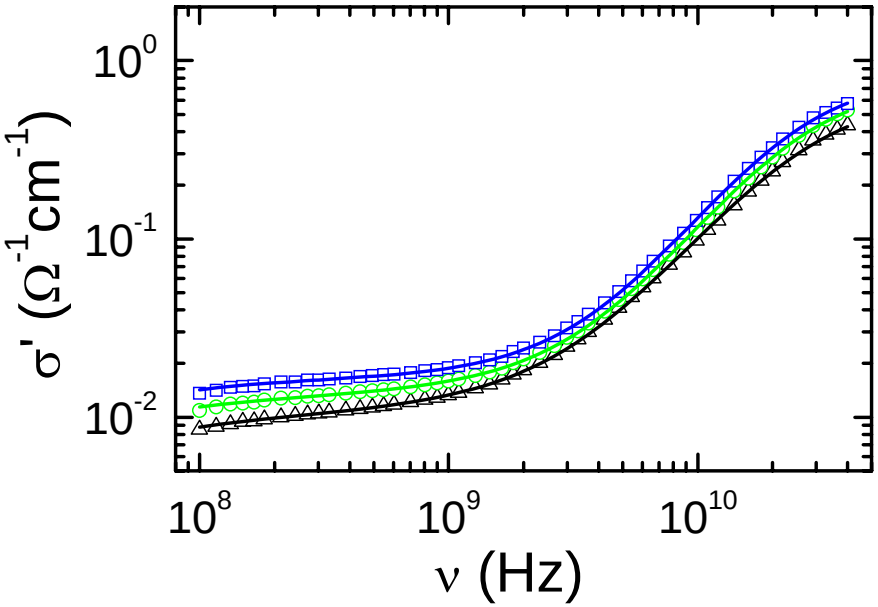
Indications of a δ-relaxation?



Dielectric properties of cell suspensions



Red blood cells (Ht 90%)
Red blood cells (Ht 60%)
Red blood cells (Ht 30%)

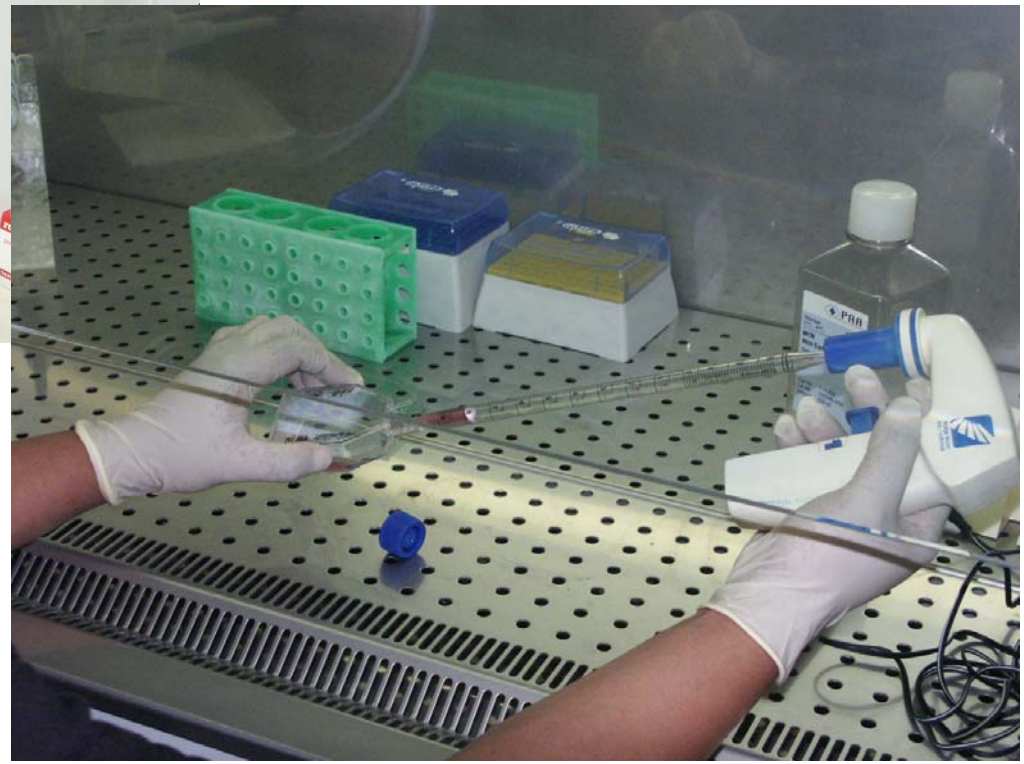


Dielectric properties of cell suspensions

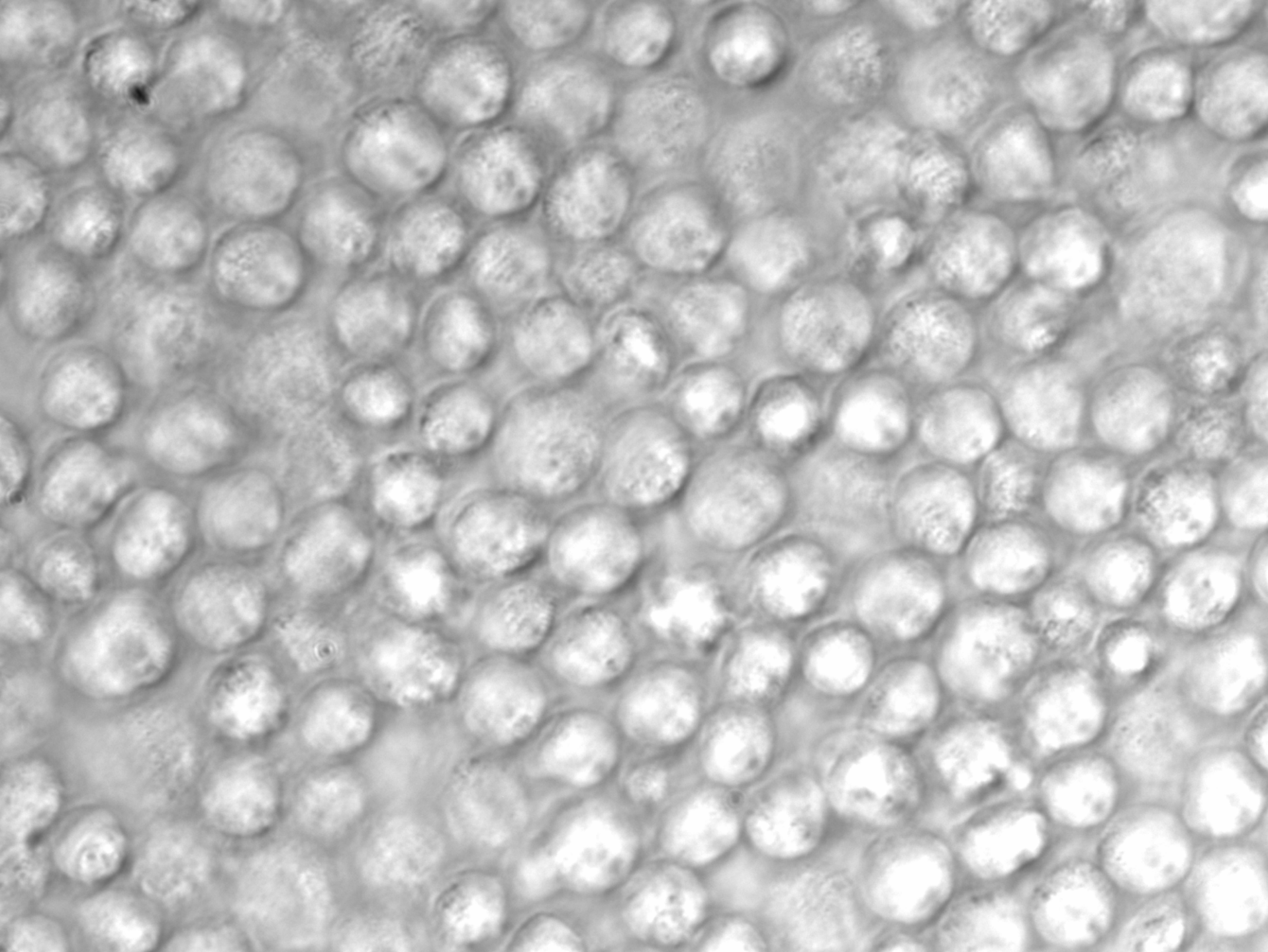
Incubator for cell cultivation:

37° C

5 % CO_2



- fibroblasts
- melanoma cells
- PC12 nerve cells
- hepatocytes



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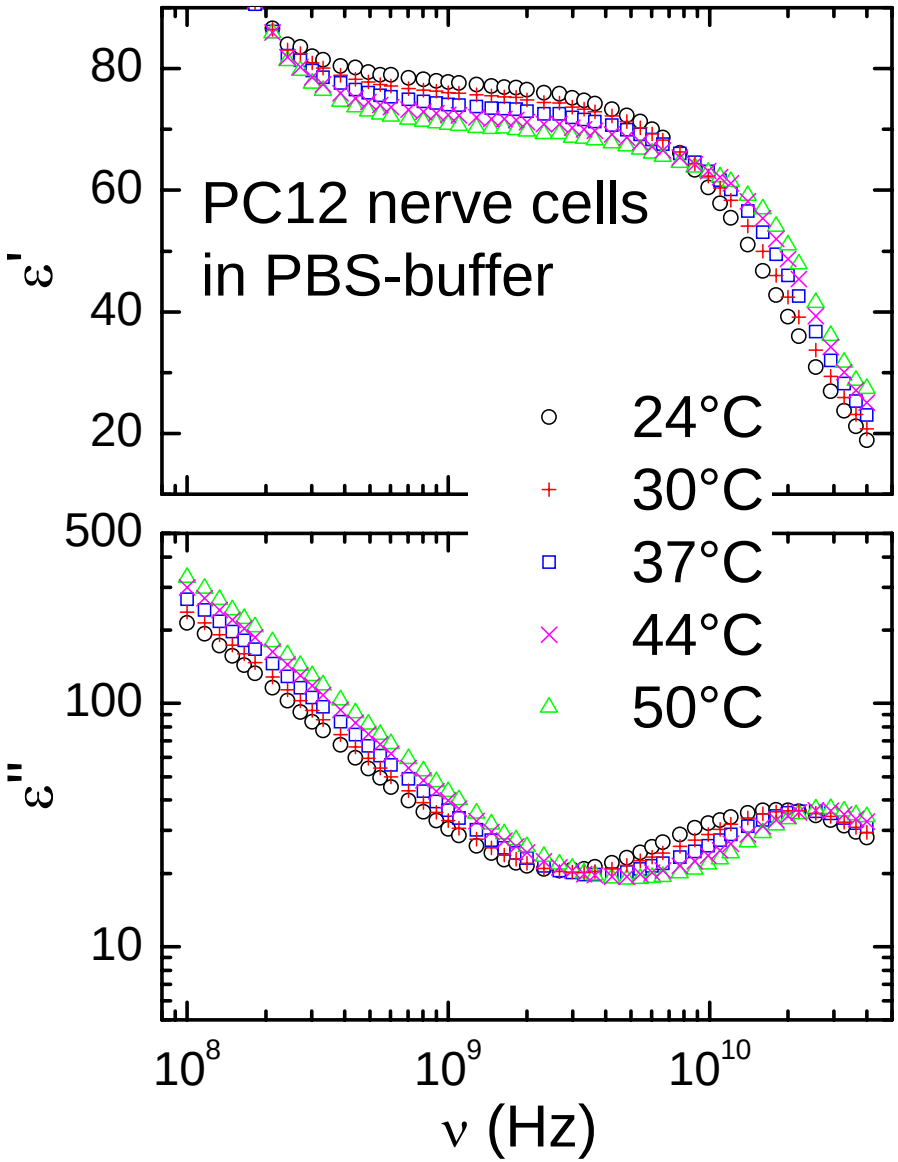

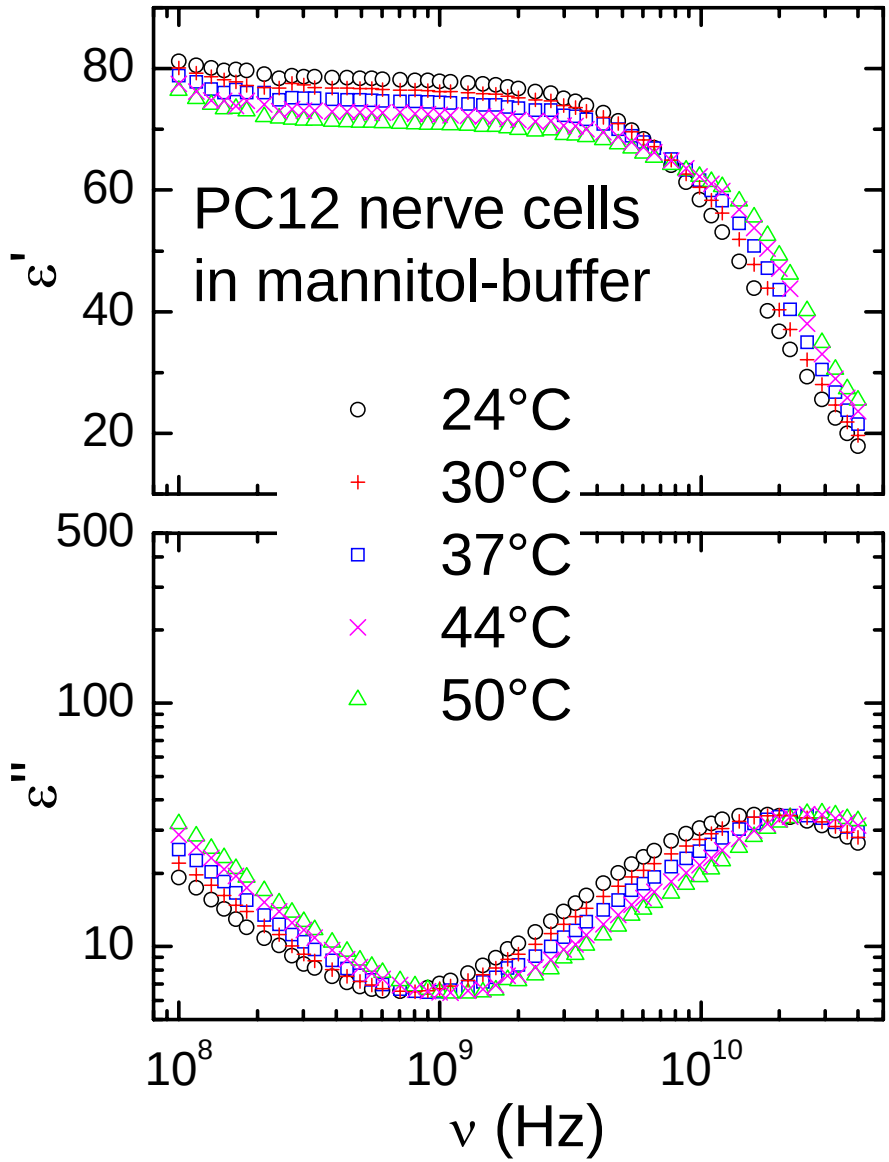

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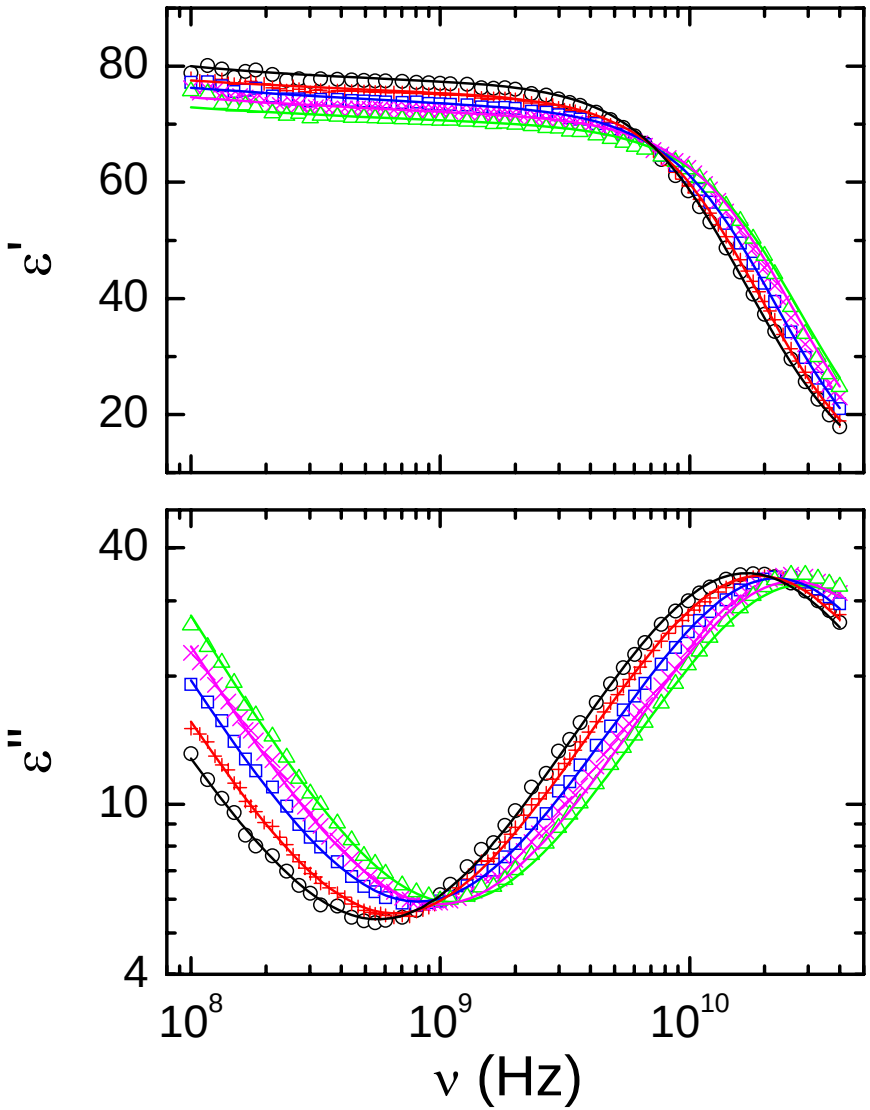
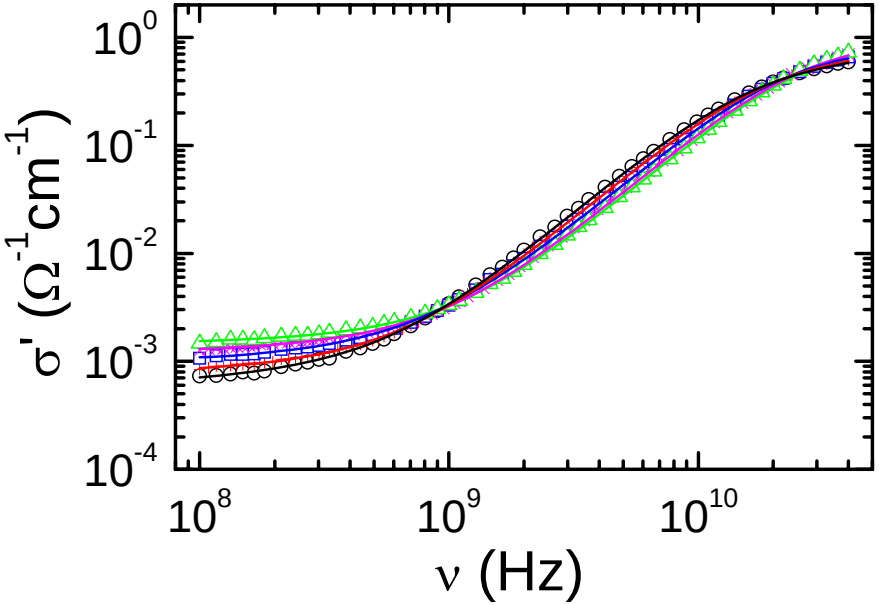


fibroblasts
in mannitol-buffer

80 million cells
per ml

24°C
30°C
37°C
44°C
50°C



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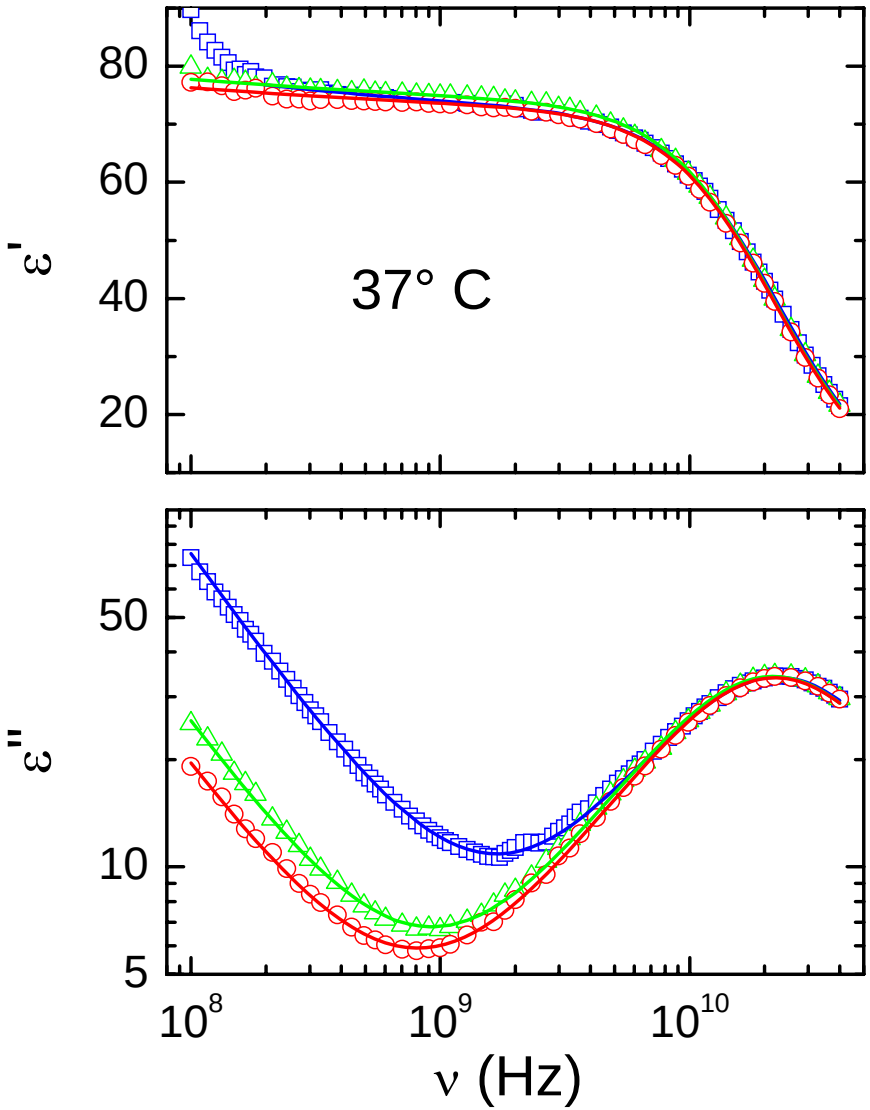
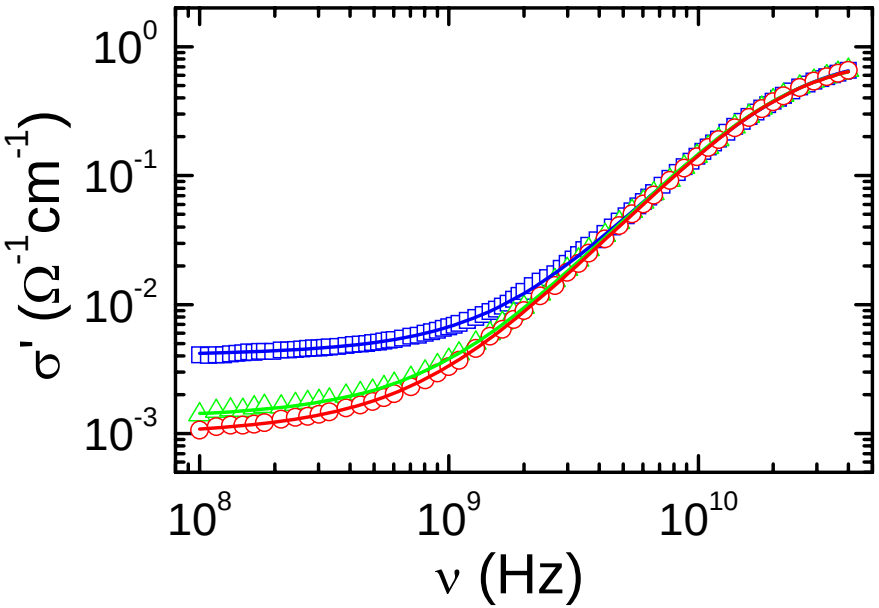


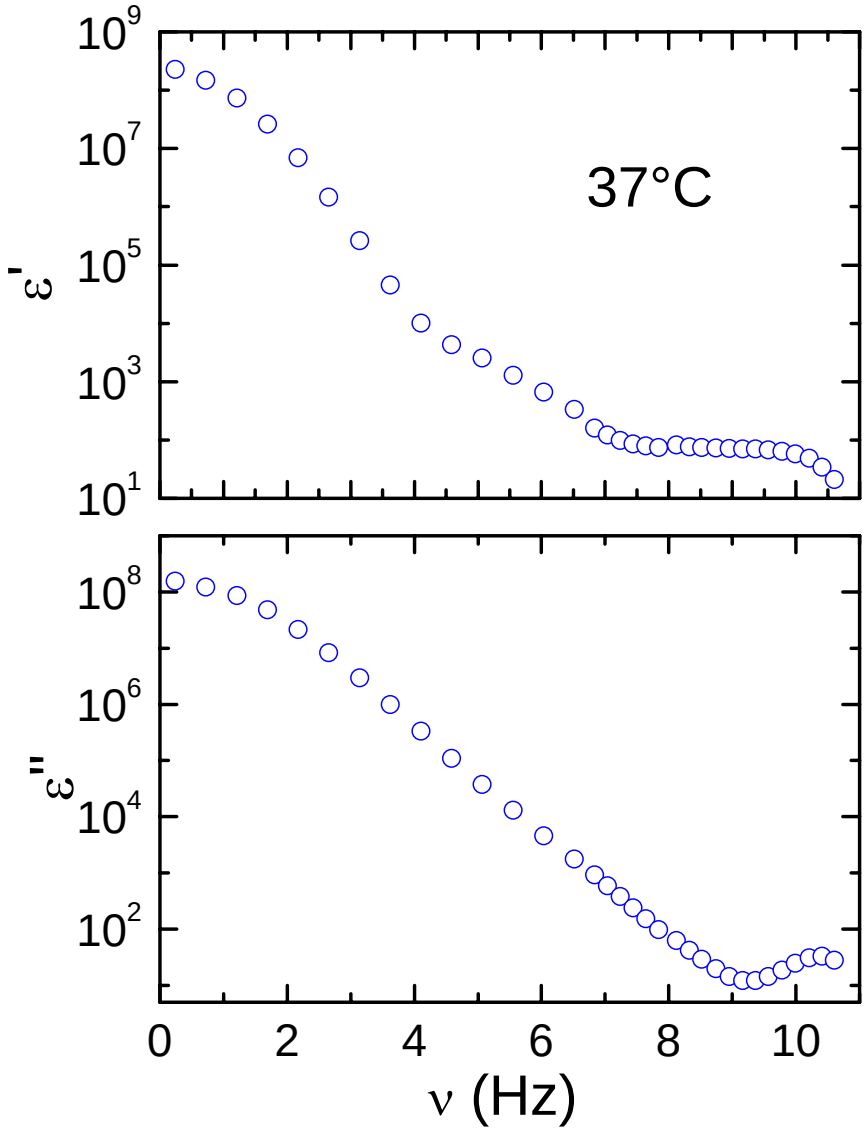
fibroblasts

in mannitol-buffer

- 10 million cells per ml
- 50 million cells per ml
- 80 million cells per ml

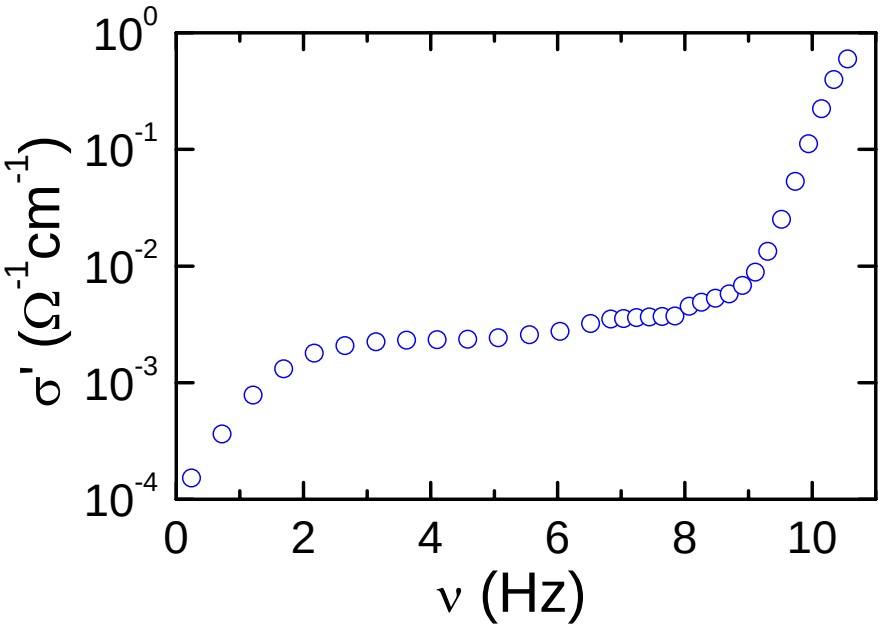


Dielectric properties of cell suspensions



fibroblasts
in mannitol-buffer

200 million cells
per ml



Summary and outlook

- Dielectric properties of electrolytes and cell suspensions in the relevant frequency regime are dominated by γ dispersion: Smooth functions of temperature, frequency and concentration. In whole blood indications of additional processes. No indications of resonant processes beyond experimental uncertainties.
- When compared to pure water, ε' decreases while σ' strongly increases due to dc conductivity. However, with increasing cell concentrations the conductivity becomes suppressed again.
- So far all investigations were perfomed with SAR values close to 0.1 W/kg (with respect to the external electric field). Field dependent and non-linear experiments are planned in the near future.