SCALING LAWS FOR IONIC TRANSPORT IN NANOCHANNELS: BULK, SURFACE AND INTERFACIAL EFFECTS

Antonio Alcaraz[1], María Queralt-Martín[2] and Vicente M. Aguilella[1]

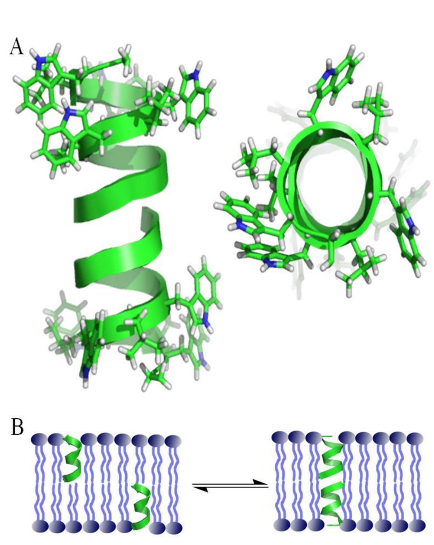
alcaraza@uji.es

[1] Laboratory of Molecular Biophysics, Department of Physics, Universitat Jaume I, Castellón, Spain.

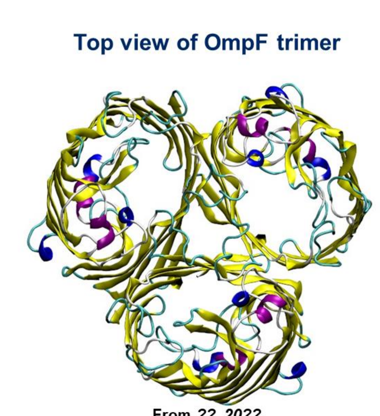
[2] Section on Molecular Transport, Eunice Kennedy Shriver NICHD, National Institutes of Health, Bethesda, MD, USA.

Abstract

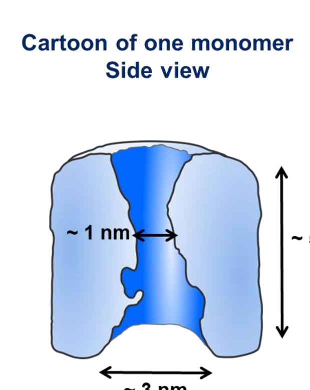
The usual description of ion transport in membrane channels is based on dual model describing the channel conductance as the addition of bulk and surface contributions. This vision constitutes an idealization that it is extremely useful for modelling purposes. However, there are no surface- and bulk-labelled counterions in real solutions, but only ions that due to thermal agitation continuously interchange their role. Furthermore, ion transport in confined geometries may differ significantly from that in bulk conditions. Besides direct electrostatic interactions between the permeating ions and pore charges, other phenomena like interfacial access resistance or entropic effects due to obstacles and irregularities of the boundaries may play a role. We investigate here the limitations of the abovementioned two-state model by assessing experimentally the scaling behavior of channel conductance (G) with salt concentration (c) in structurally different protein and proteolipidic pores, namely **gramicidin A (grA), OmpF of E. Coli, alamethicin (levels L0 and L1) and the CoV-E channel of SARS**. Previous studies in nanochannels have suggested a power law dependence $G \sim c^{\alpha}$, where α is an exponent that has been reported to attain a variety of values depending of the system and the concentration regime. We hypothesize here that scaling exponents found in a specific system arise from a particular interplay between bulk and surface effects, being the distinction between them so subtle that the two-state model faints. In the case of biological pores, we show also that the presence of interfacial effects could give rise to an apparent universal scaling that does not reflect the channel actual characteristics.



Gramicidin A

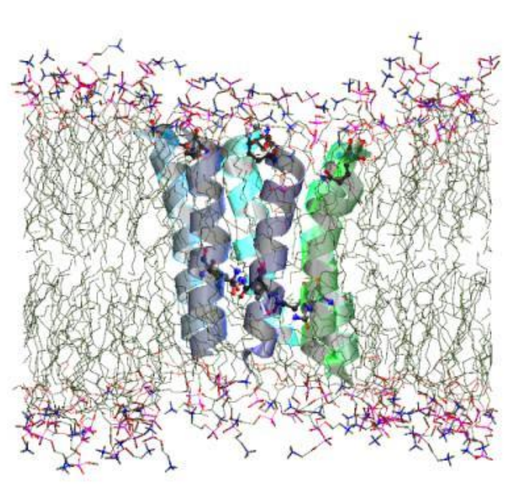


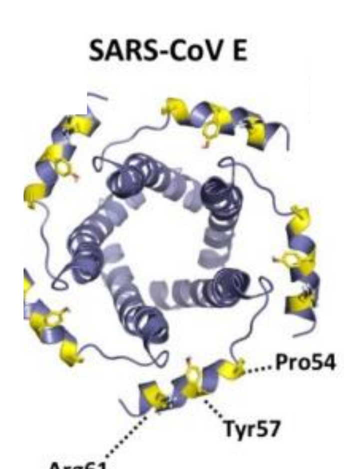
Trimeric protein β-barrel structure



Hour-glass shaped channel

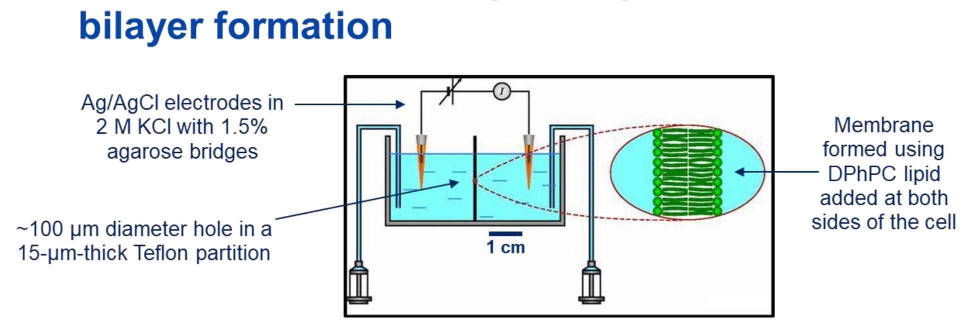
Alamethicin



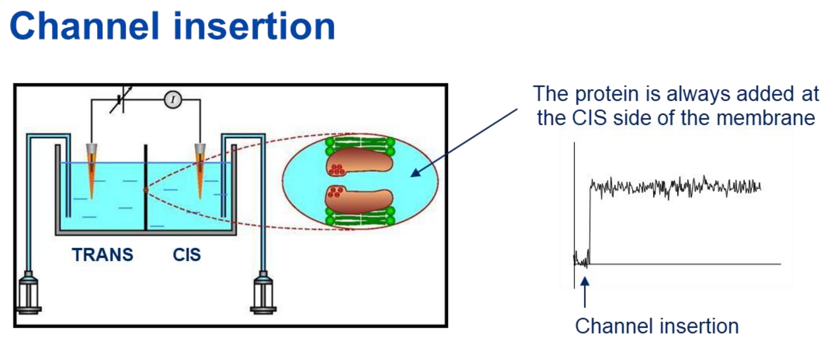


Standard procedure for channel reconstitution and current recording

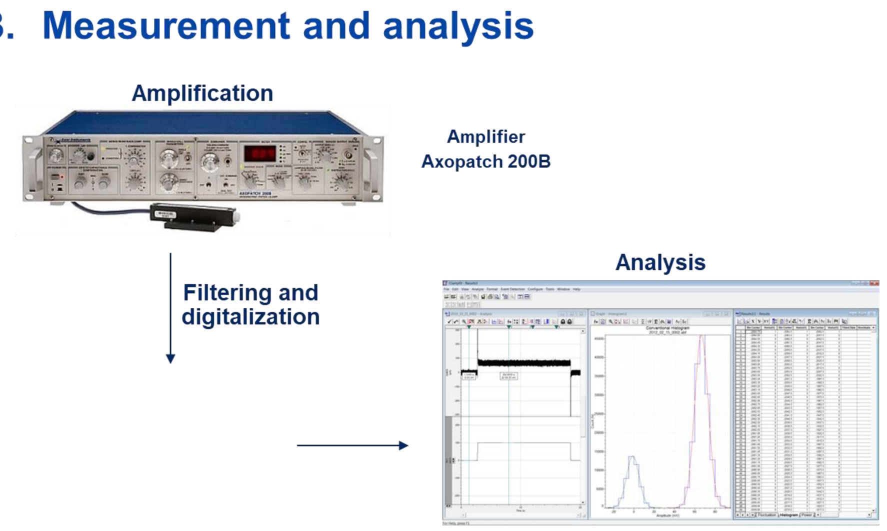
1. Montal-Mueller technique for planar bilayer formation



2. Channel insertion

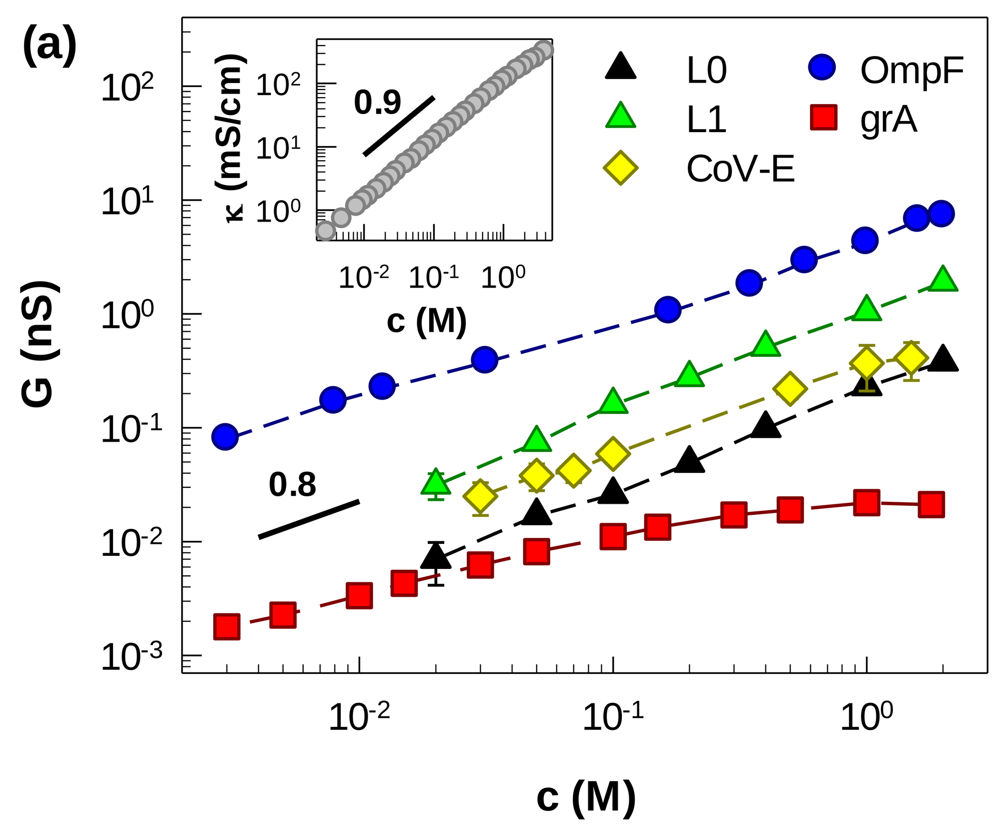


3. Measurement and analysis



1 Apparent universal scaling in neutral membranes

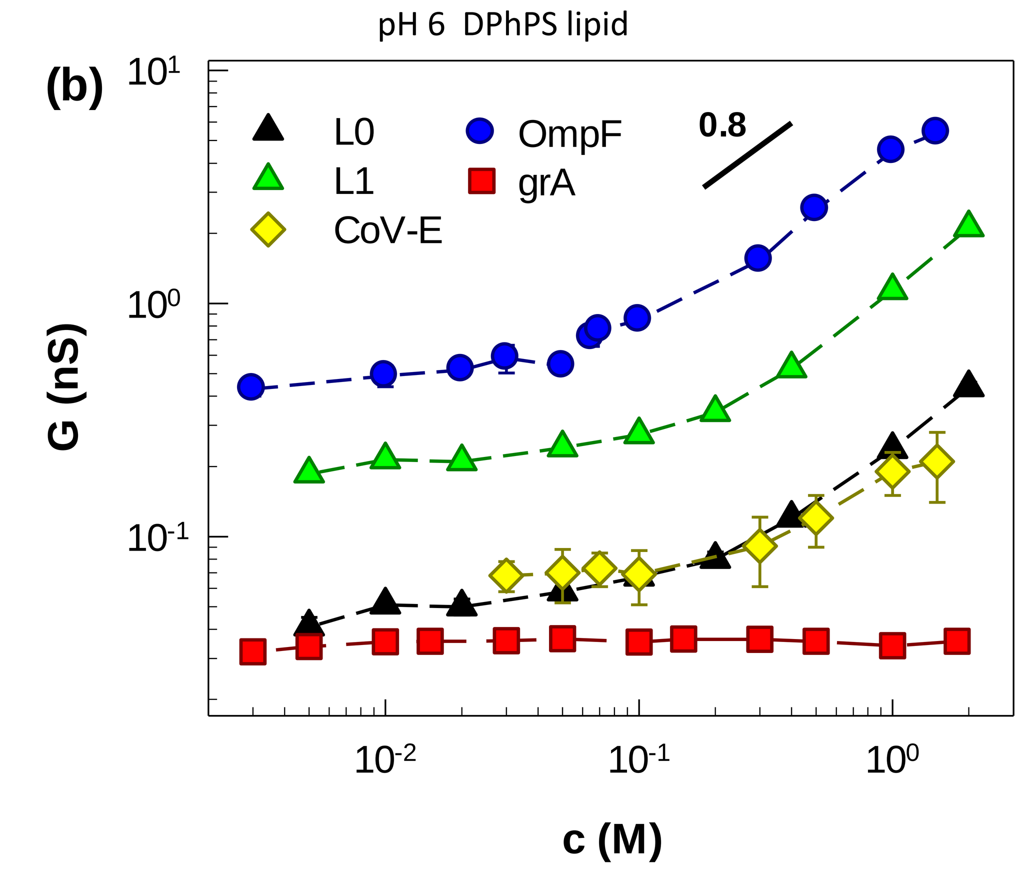
pH 6 DPhPC lipid



Bulk-like conduction for all channels

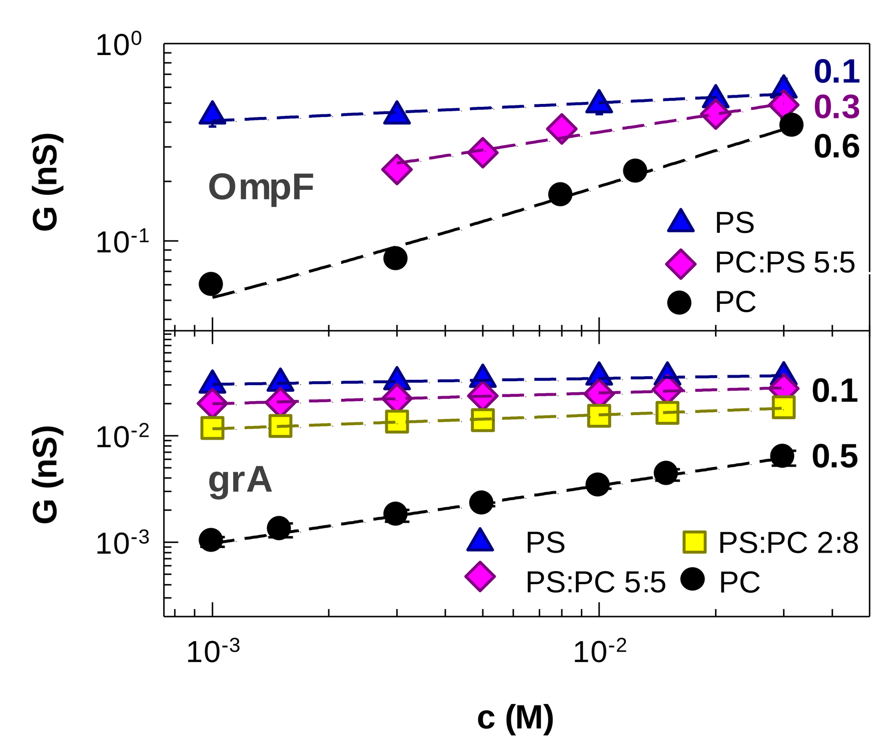
Lipid charge reveals channel intrinsic properties

pH 6 DPhPS lipid



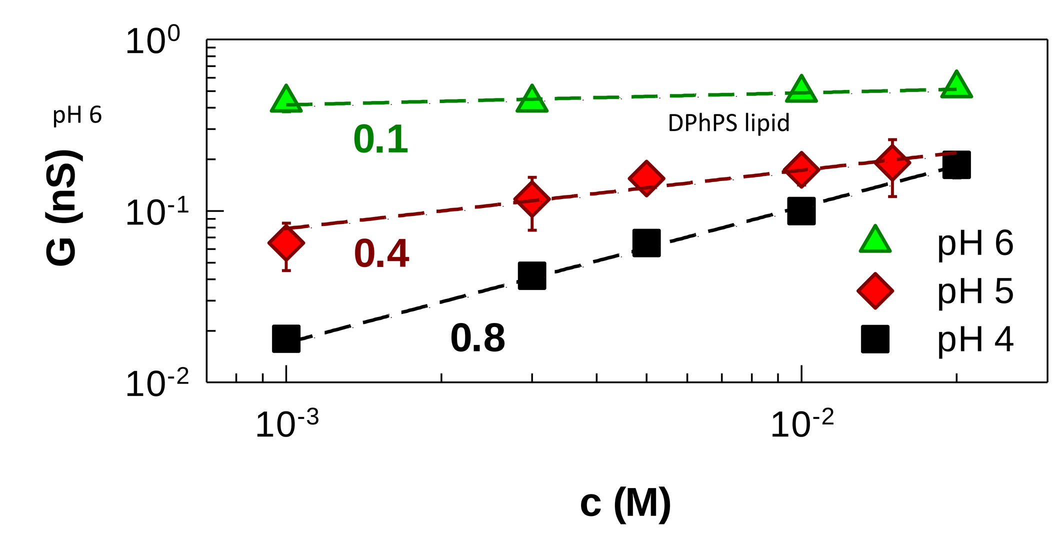
Surface conduction at low c that varies with each channel

2 Lipid charge determines actual G scaling



Lipid mixtures

Channel charge controls ion transport



Bulk and surface conduction are tightly interconnected through interfacial effects

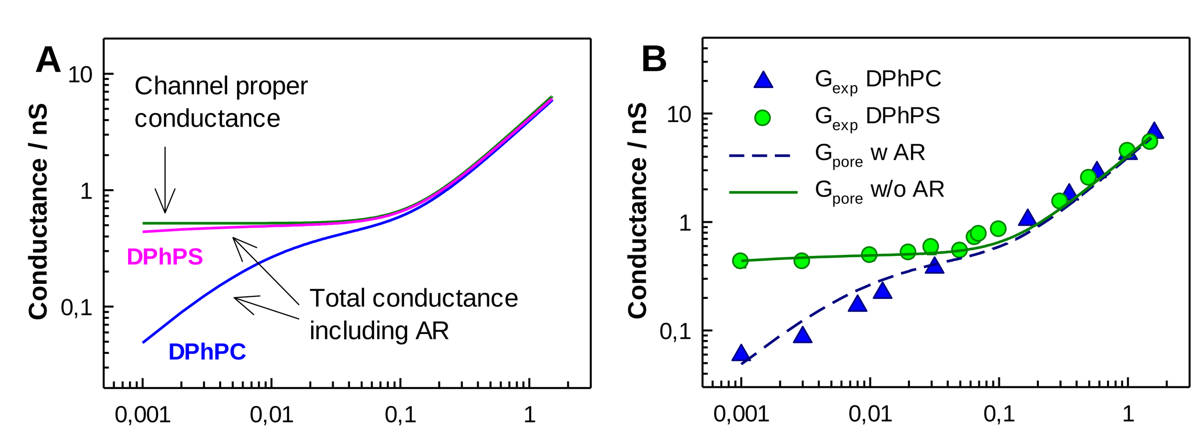
3 Theoretical analysis of scaling arguments

$$G = \left(\pi D^2 \kappa / 4L\right)\sqrt{\left(\rho_p / 2c\right)^2 + 1}$$

2 limiting cases, $c \gg \rho_p$ (bulk conduction) $G \sim c$ and $c \ll \rho_p$ (surface conduction) $G \sim c^0$

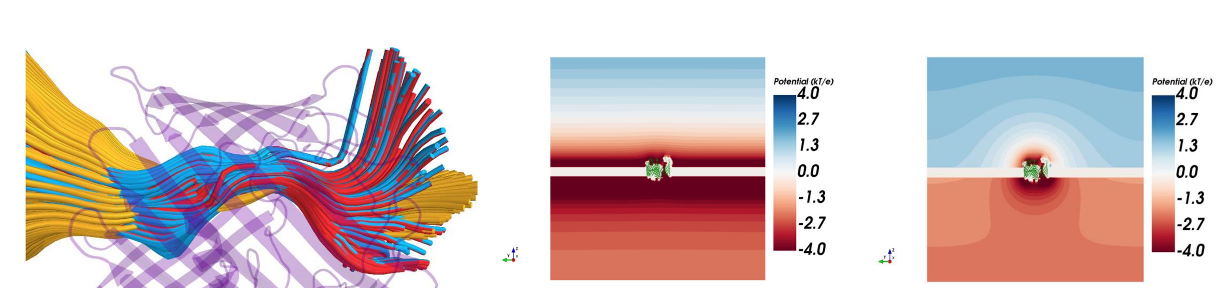
$$1/G = \left(\left(\pi D^2 \kappa / 4L\right)\sqrt{\left(\rho_p / 2c\right)^2 + 1}\right)^{-1} + \left(2D\kappa\sqrt{\left(\rho_i / 2c\right)^2 + 1}\right)^{-1}$$

If interfacial effects are included it is not possible to separate limiting cases

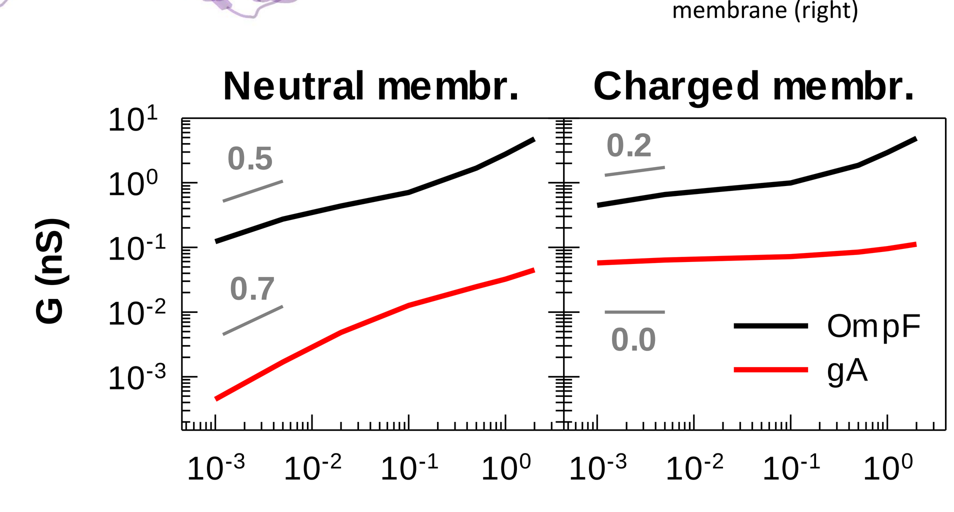


Results published in Alcaraz et al. *ACS Nano* 11, 10392 (2017)

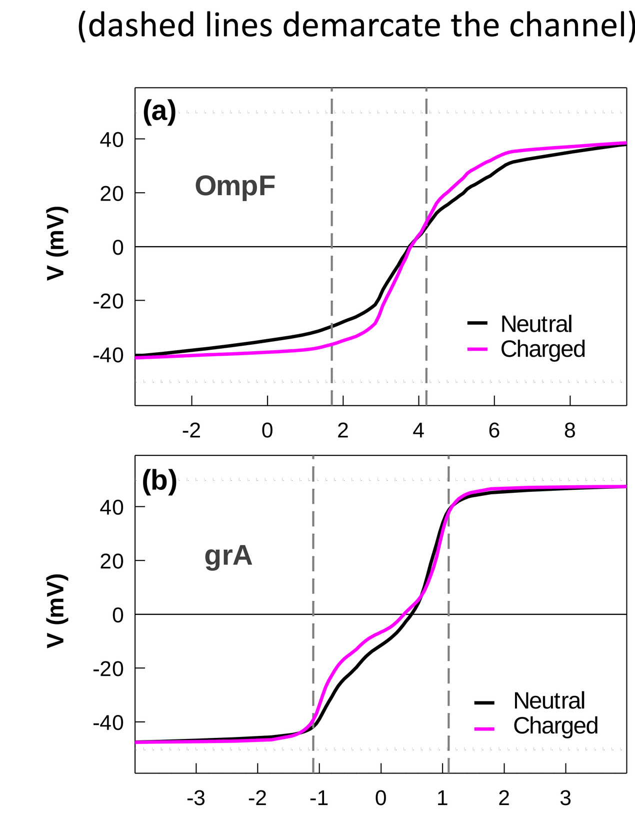
4 Numerical calculations: 3D Poisson-Nernst-Planck



Electric potential map in charged (left) and neutral membrane (right)



Calculated potential profiles at 100 mV in neutral and charged membranes (dashed lines demarcate the channel)



Conclusions

- ✓ **Scaling laws are not characteristic of the channel, but they are a strong function of solution concentration, pH and membrane charge.**
- ✓ **Interfacial effects linking bulk and surface effects are necessary to account for some experimental findings.**
- ✓ **When interfacial effects dominate an apparent universal scaling can be found in channels with dissimilar characteristics.**
- ✓ **3D structure-based PNP equation provides calculations in good agreement with experiments.**