Directional transport through nanopores

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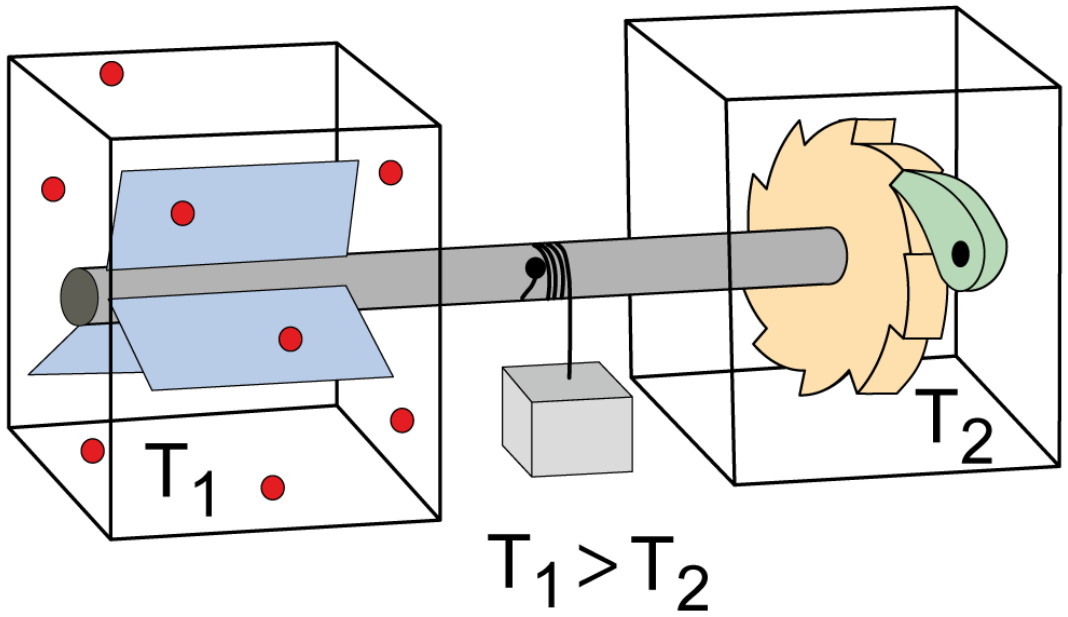
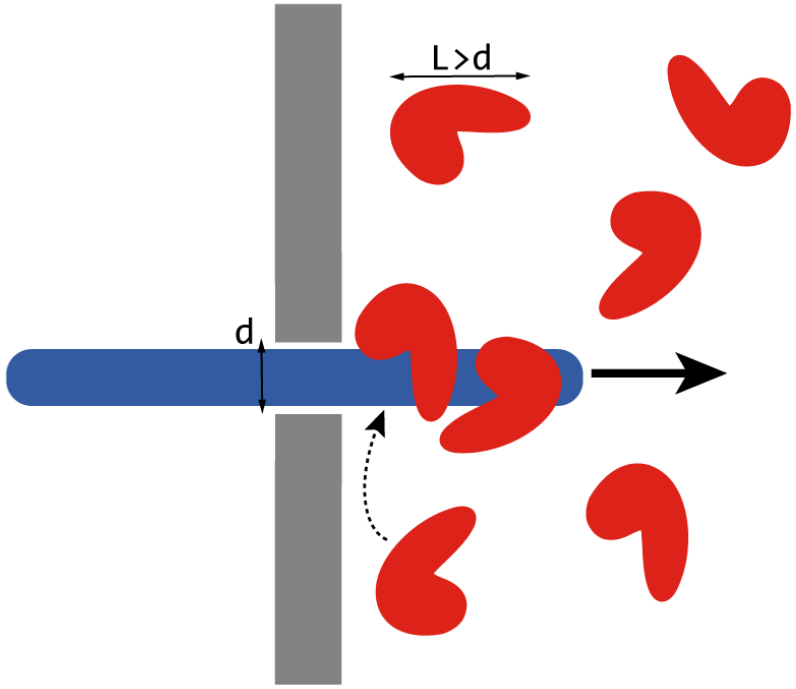
Brownian Ratchet



Feynman's ratchet and pawl

Feynman’s Lectures, 1963



Translocation ratchet

Oster et al., Biophysical Journal, 1993

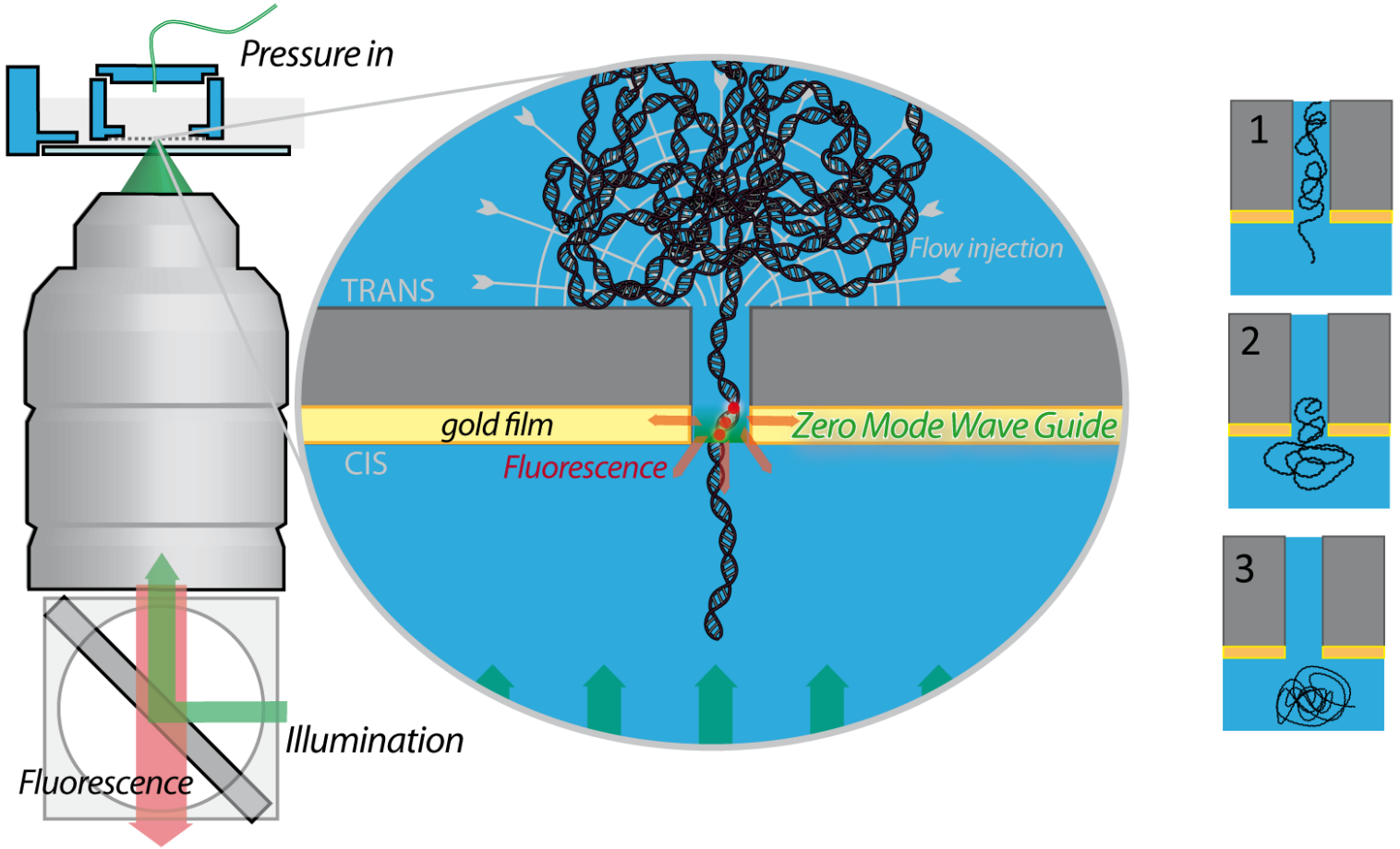
- System that selects brownian fluctuations toward a specific direction.

PhD Project

- Reproducing the translocation ratchet's mechanism in an artificial system
- Establishing the phase diagram of this system

Application to the biological nuclear pore to describe its efficiency

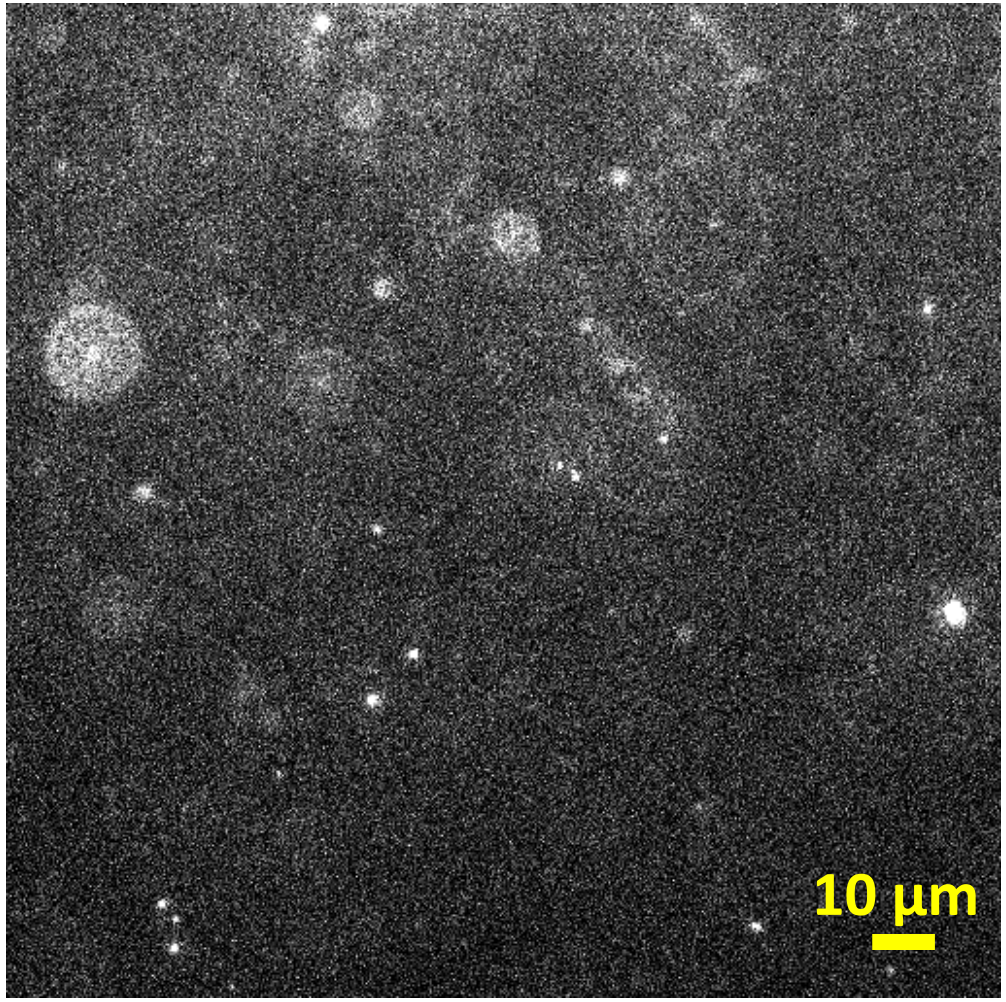
Zero Mode Waveguide for nanopores



- **Observation of translocation of single molecules**
- **High parallelization (until 10^4 nanopores)**

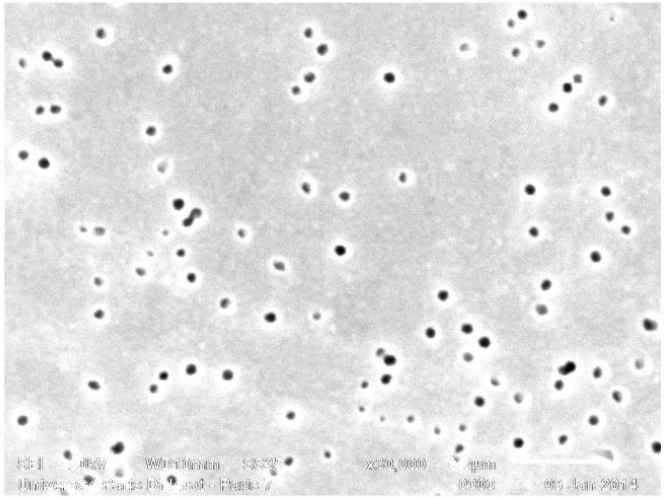
Auger et al., Physical Review Letters, 2014

Translocation Frequency



Density of nanopores
(6.10^8 cm^{-2})

(= 1 nanopore/µm)



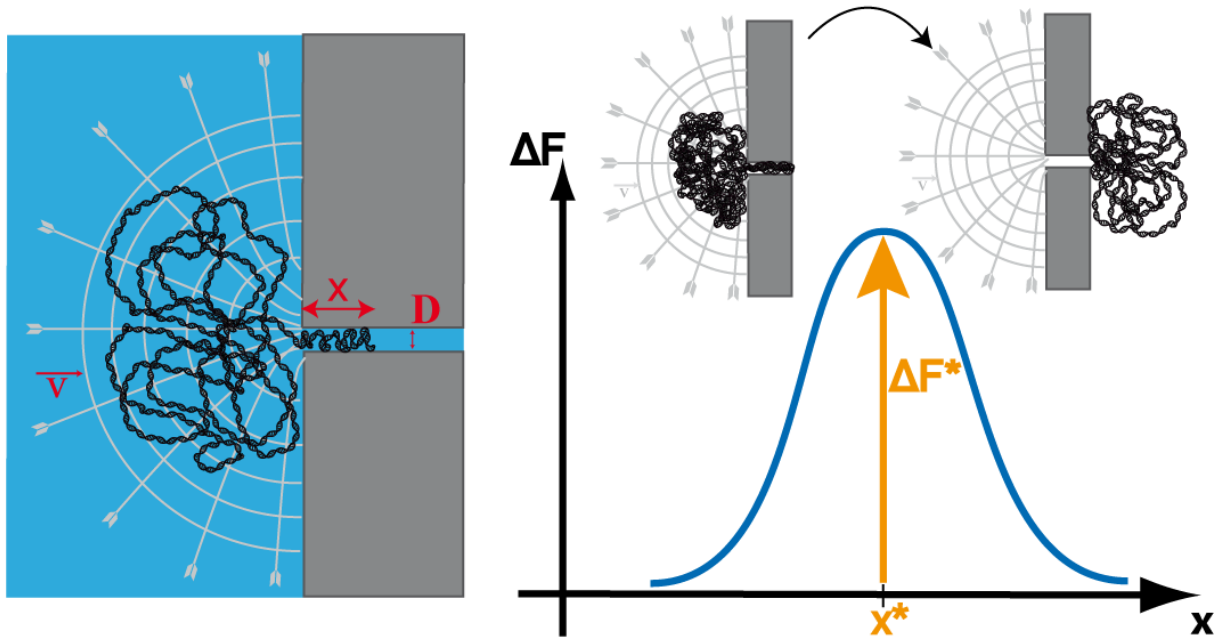
SEM image of polycarbonate track-etched membrane sputtered with 50 nm gold.
Pore diameter : 50 nm

Suction Model
Brochard, de Gennes, 1996

- **Free energy of injected polymer as function of the injection length X :**

Work of the flow

$$\Delta F(X) = \underbrace{k_B T \frac{X}{D}}_{\text{Confinement energy}} - 6\pi\eta D v \frac{X^2}{D}$$



- **Maximum of ΔF for :**

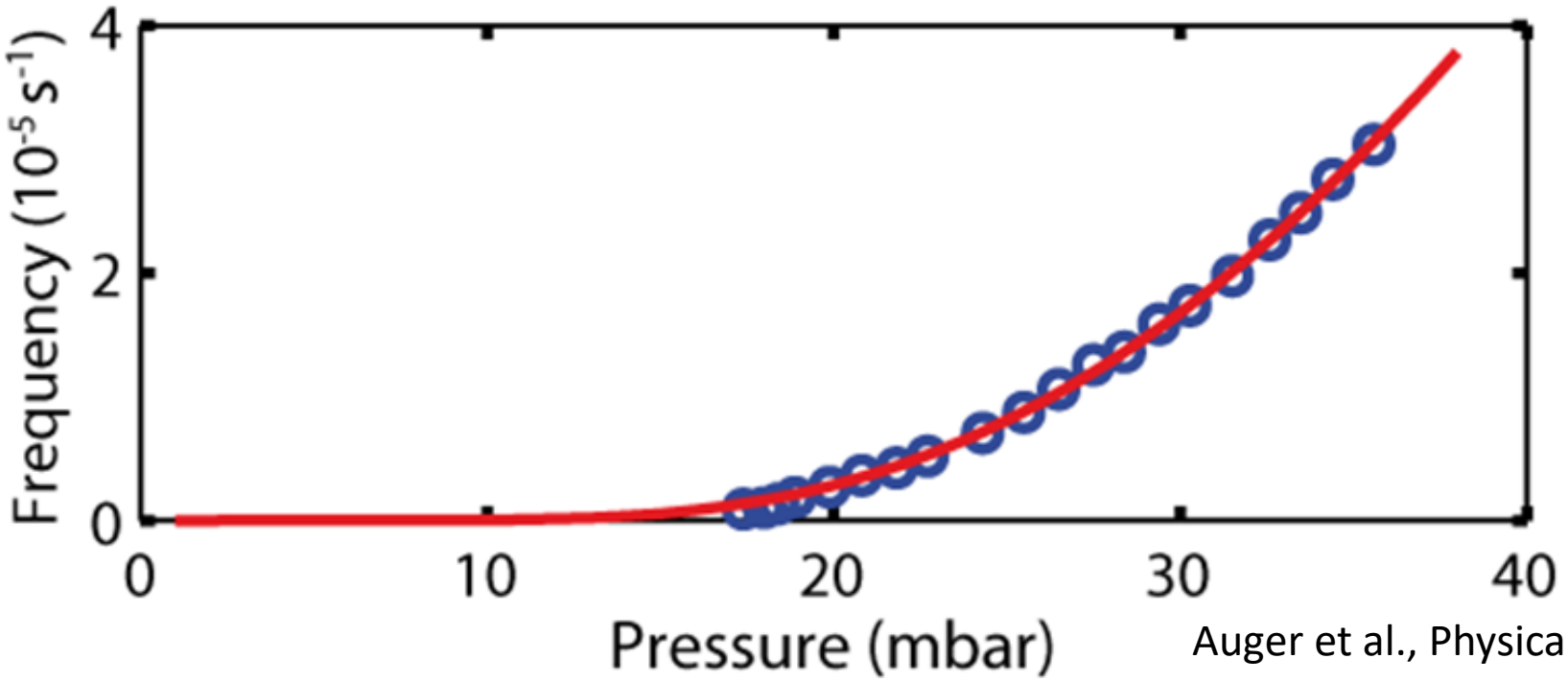
$$\Delta F^*(X^*) = k_B T \frac{J_c}{J}$$

$$J_c = \frac{k_B T}{\eta}$$

Suction Model

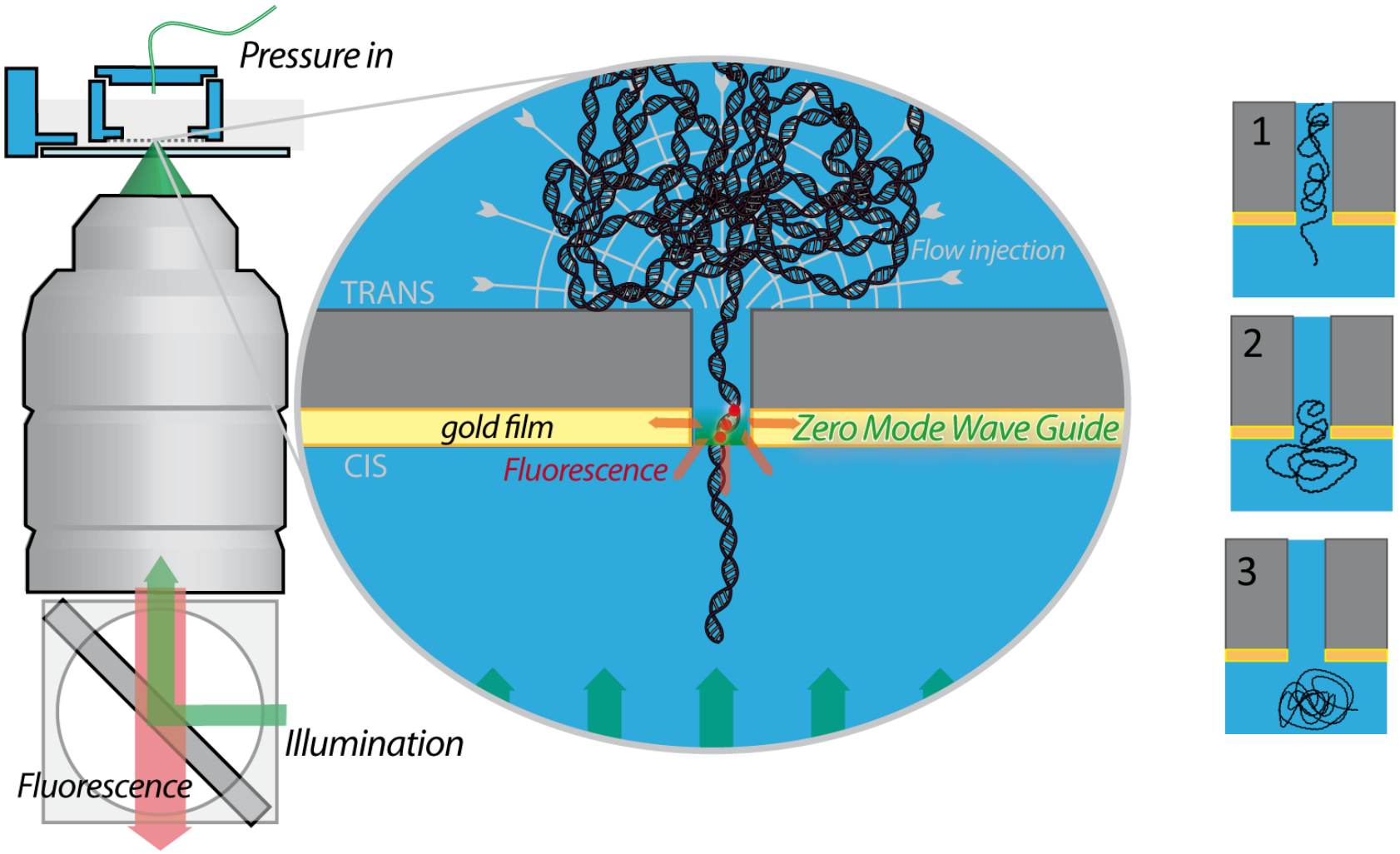
Brochard, de Gennes, 1996

$$f_{pass} = k \frac{J}{J_c} e^{-J_c/J}$$



Auger et al., Physical Review Letters, 2014

Artificial Translocation Ratchet



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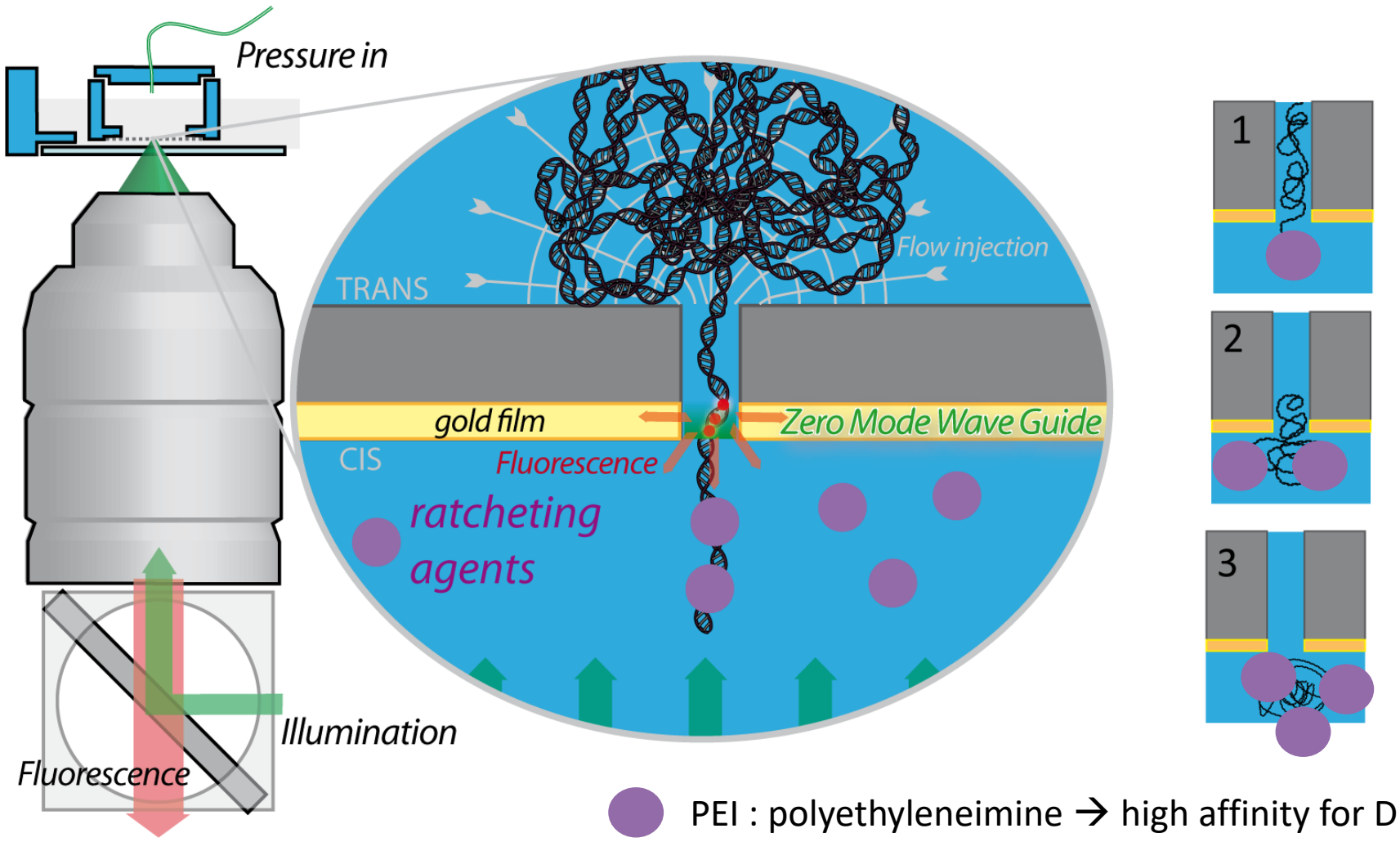
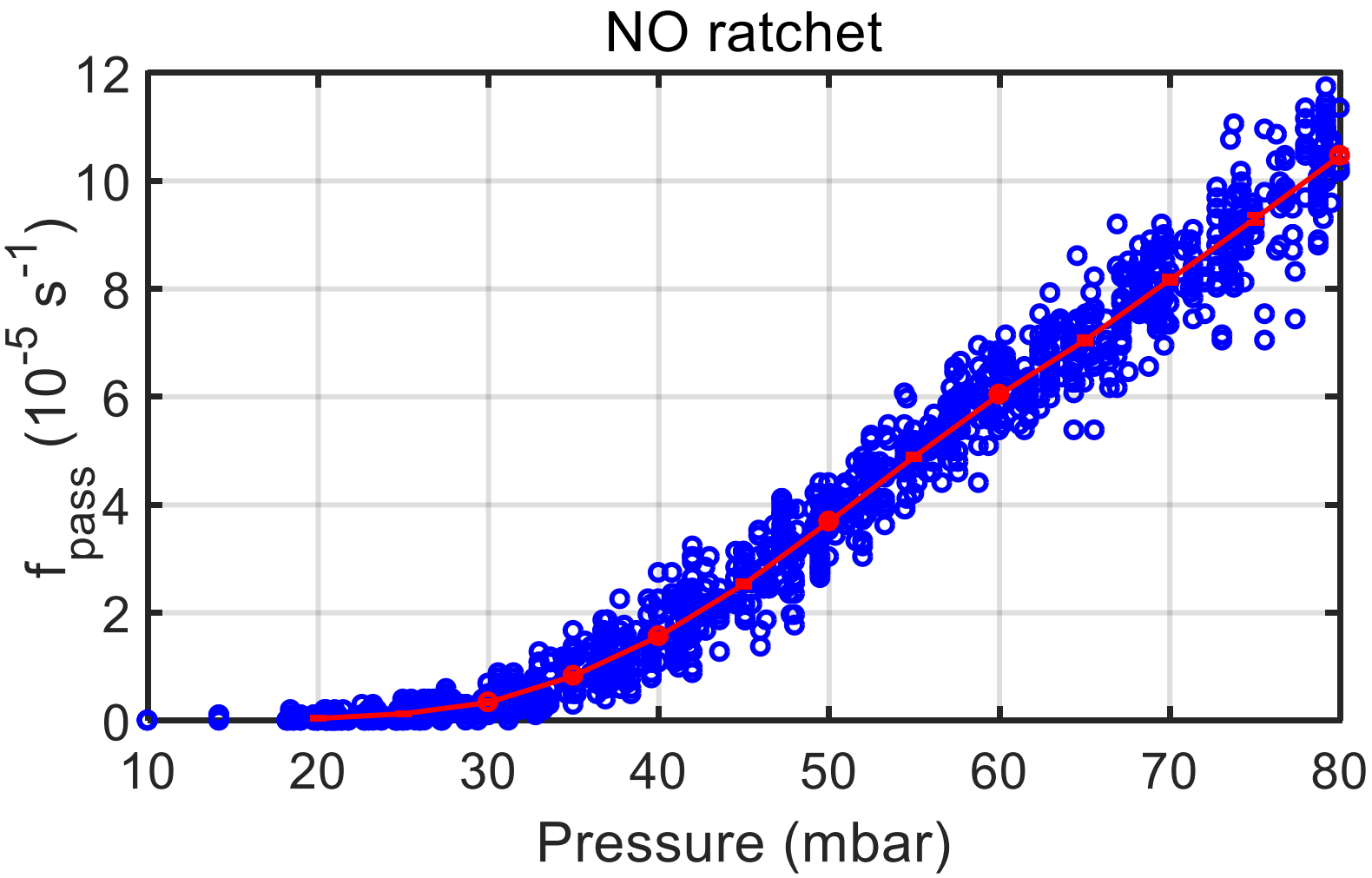


PEI : polyethyleneimine → high affinity for DNA

→ $R_{PEI} >> R_{pore}$

Effect of ratchet



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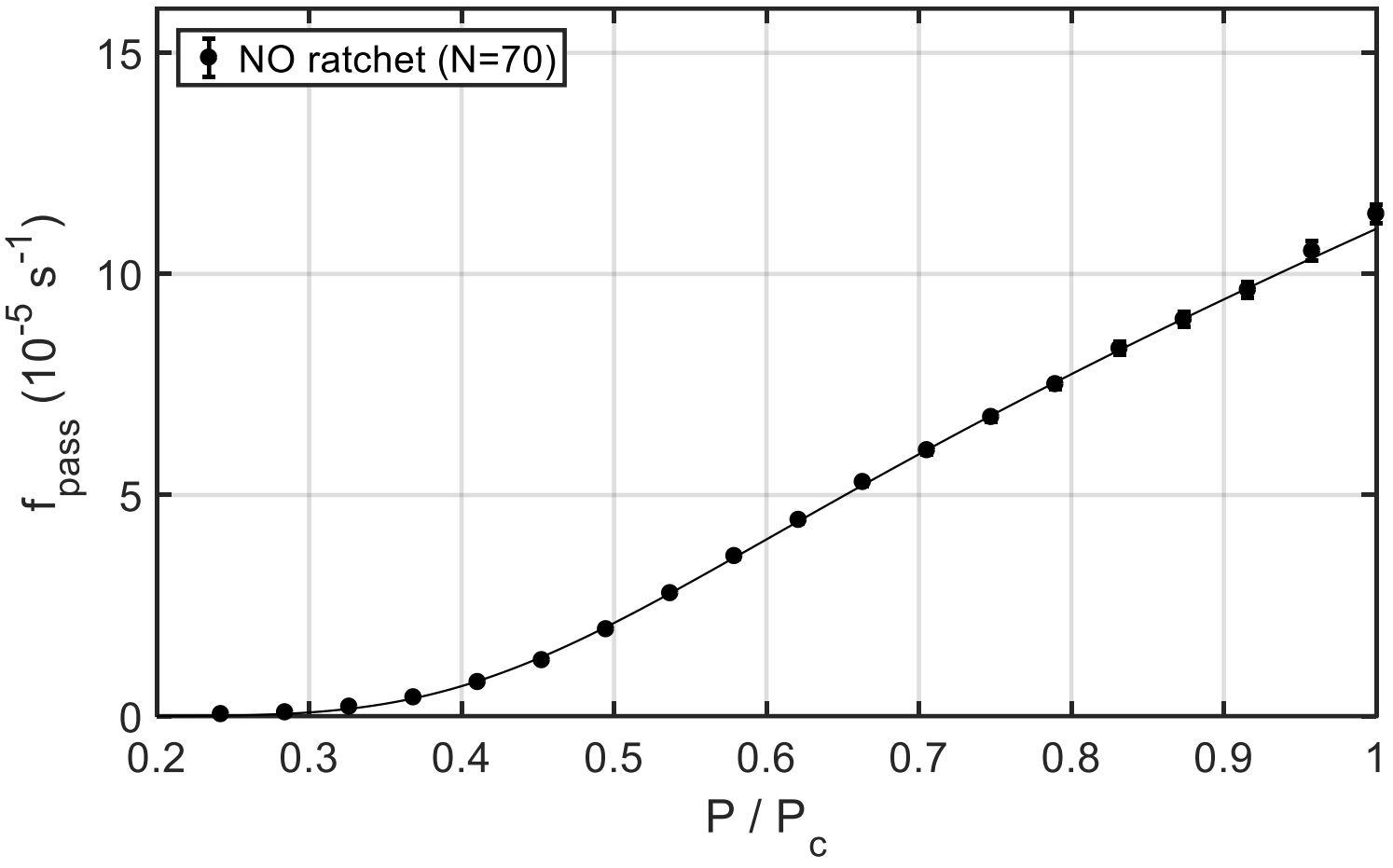

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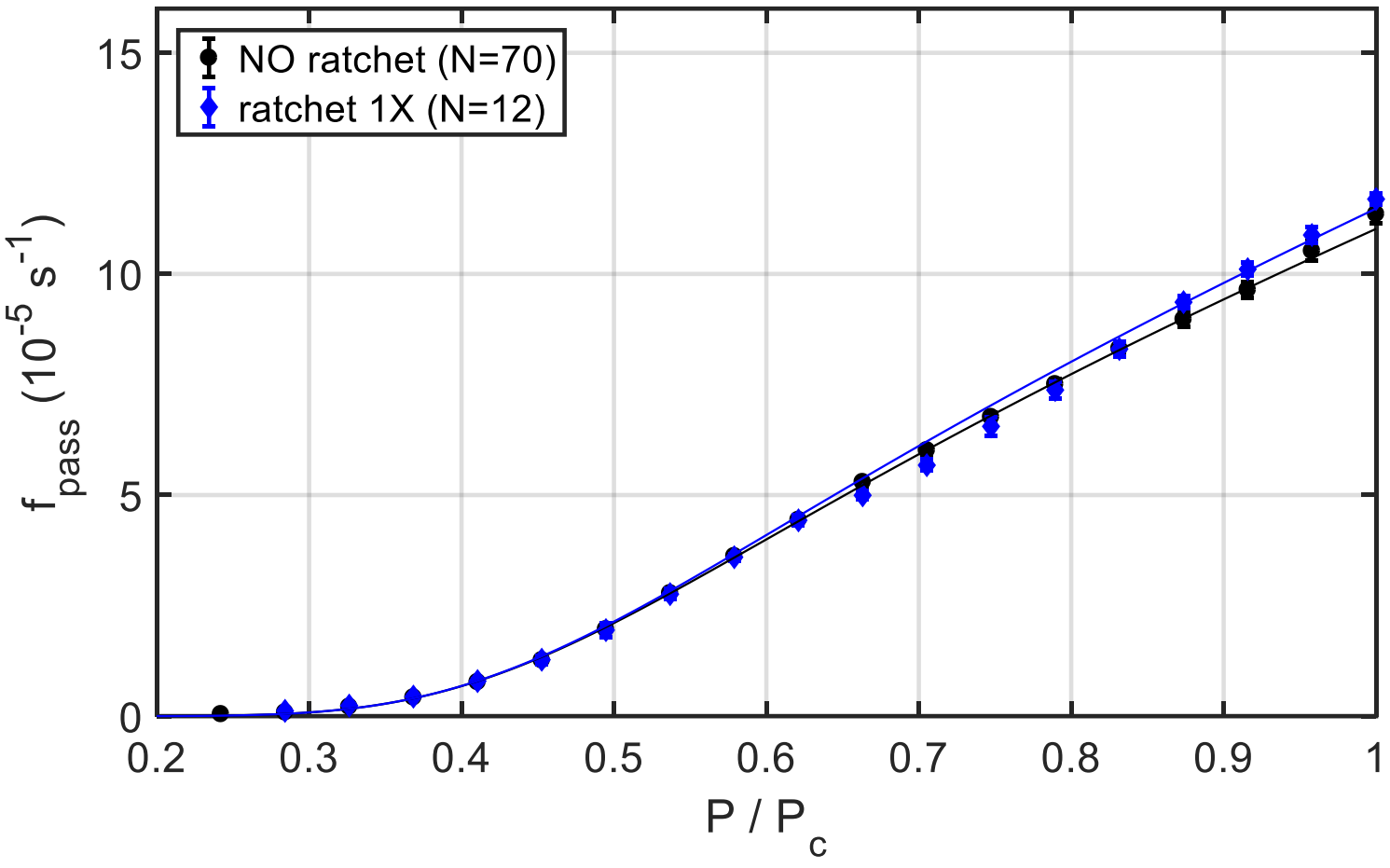

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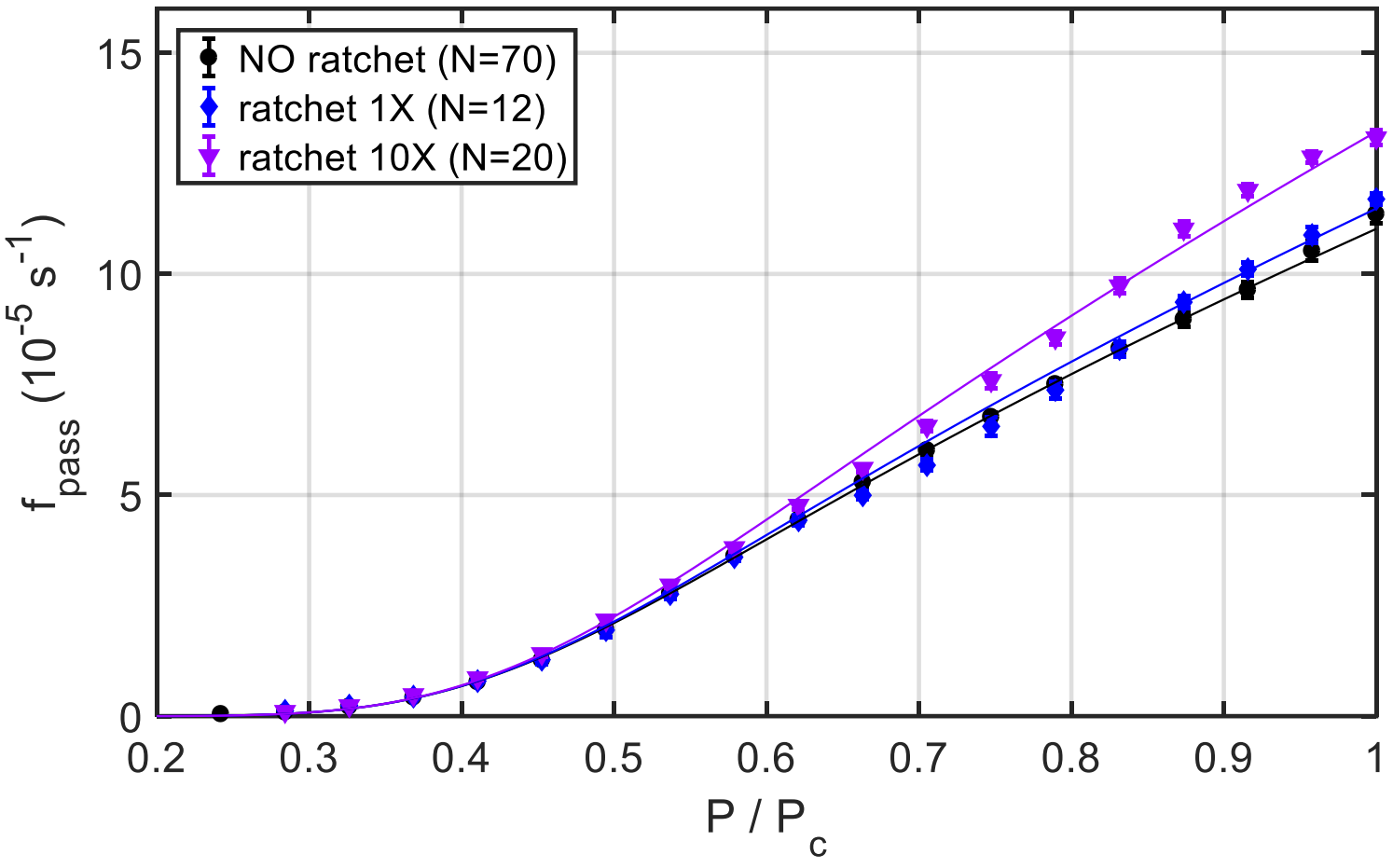
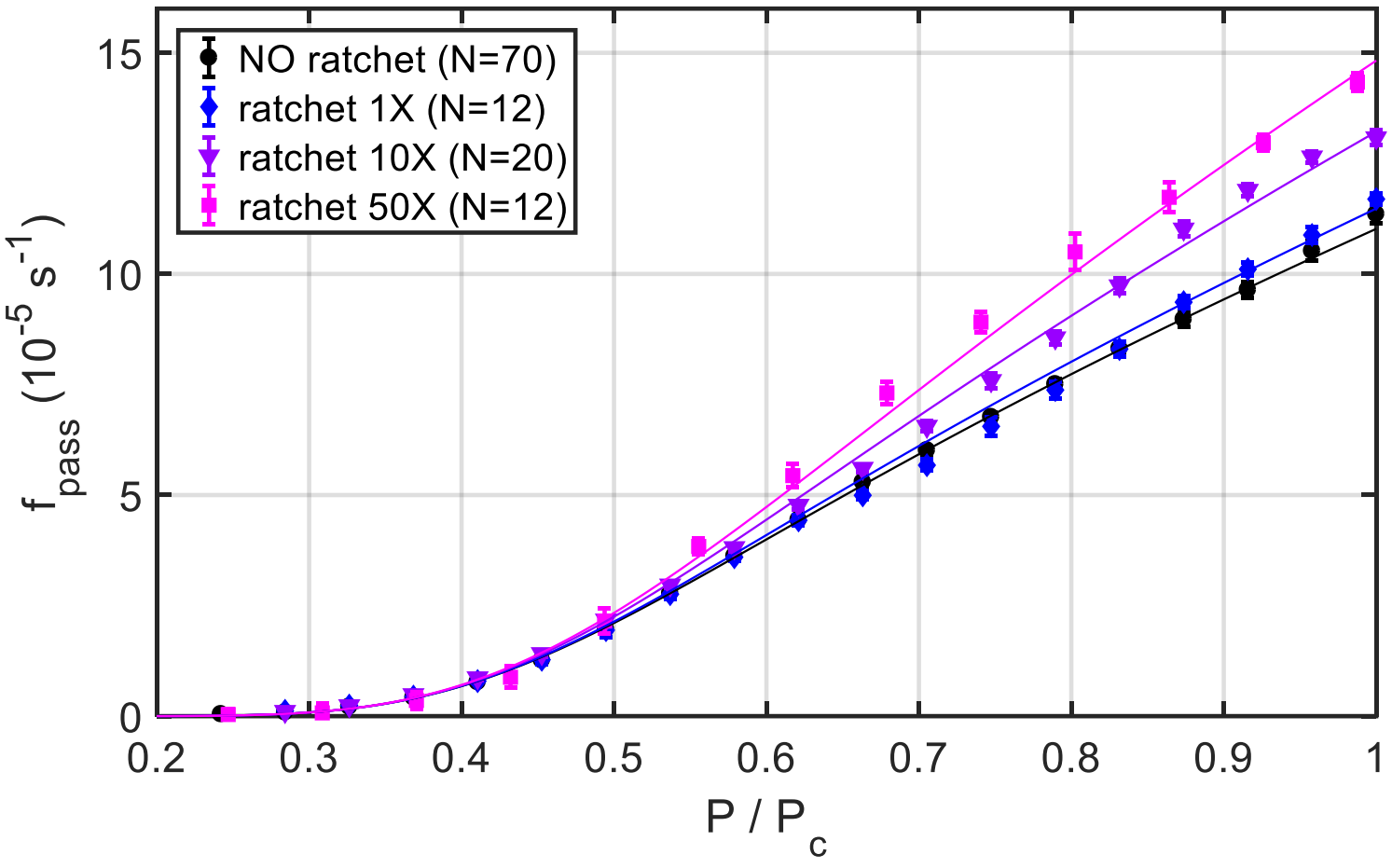
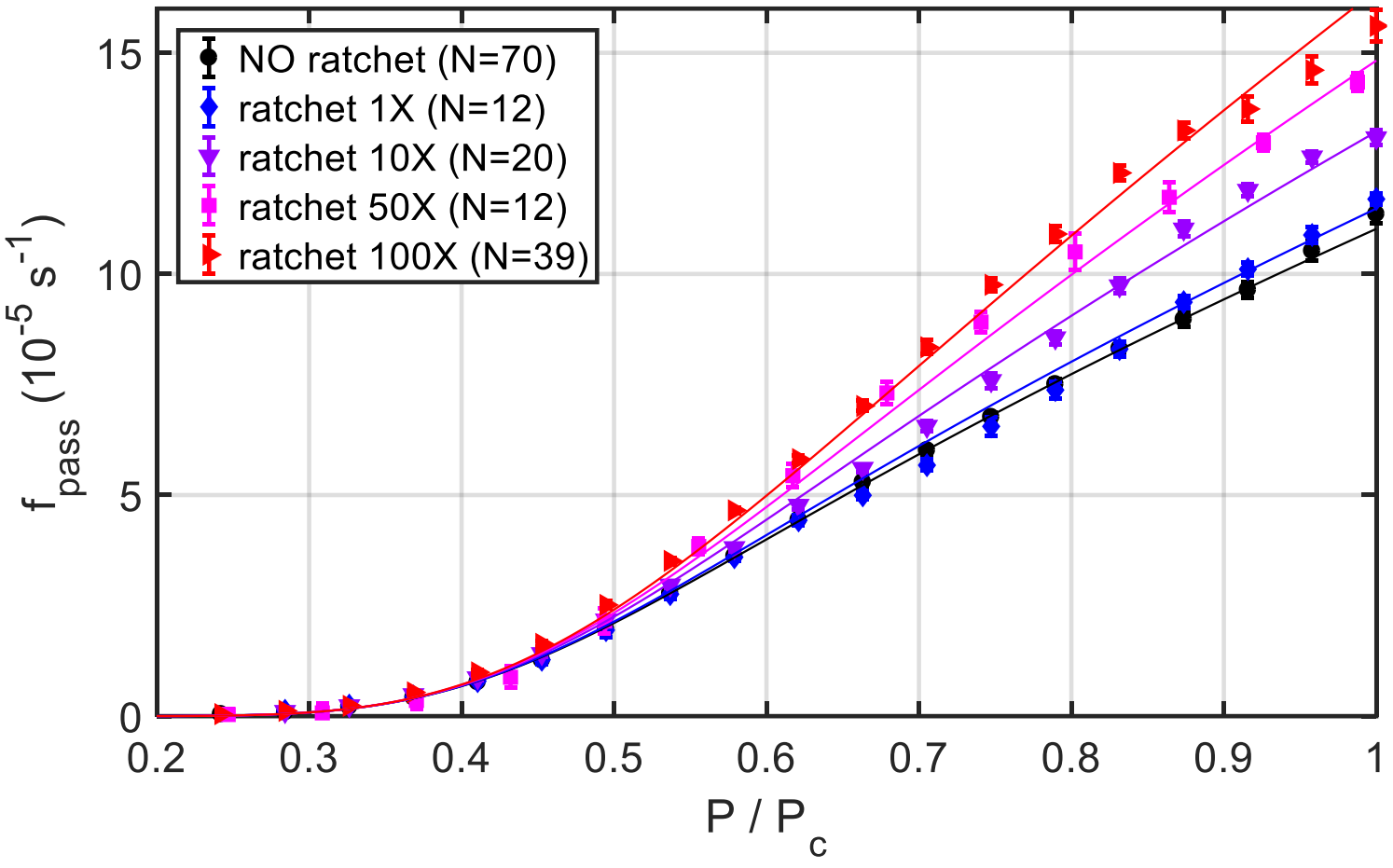


Effect of ratchet



Effect of ratchet



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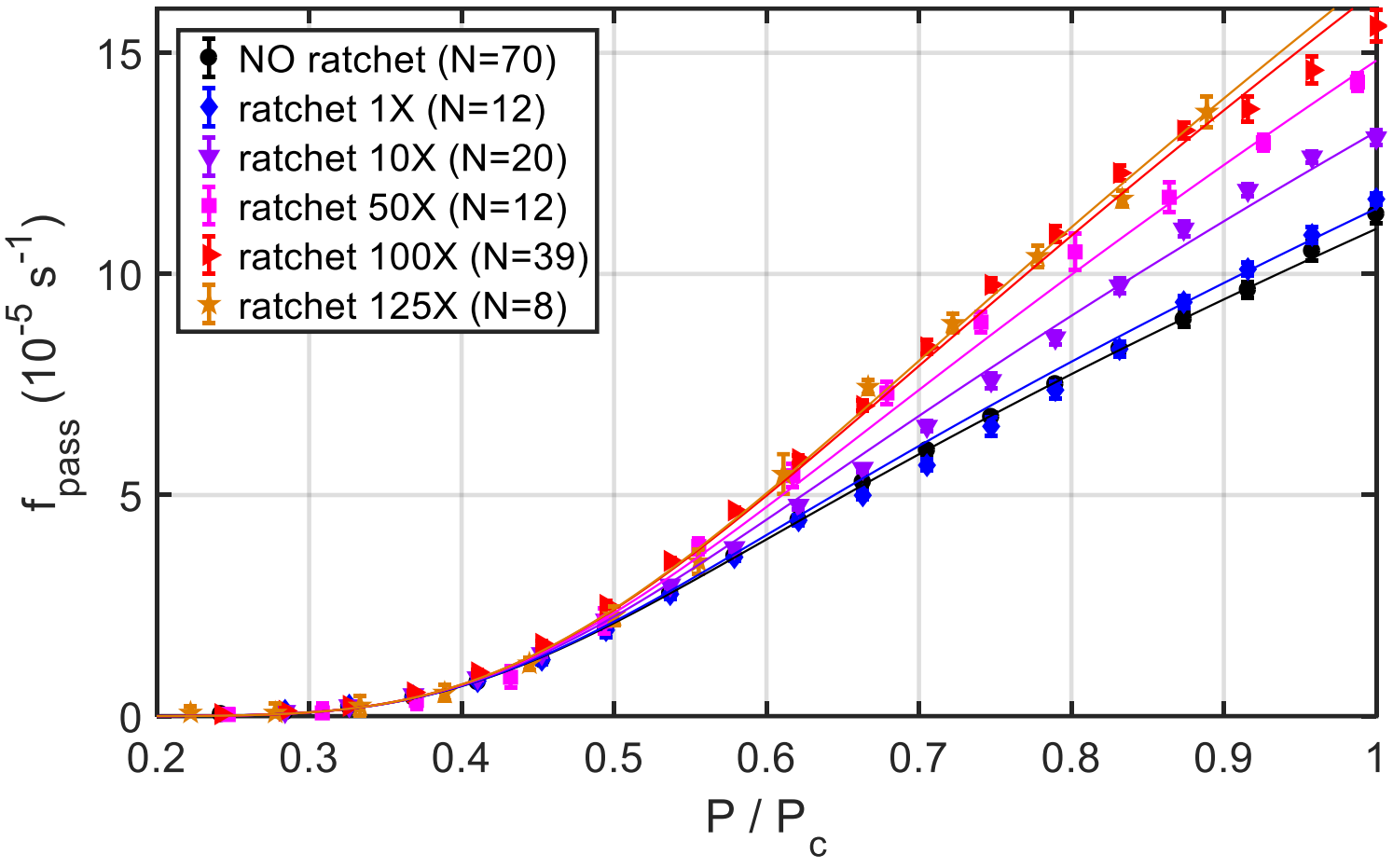

Osmotic effect ?

Ratchet effect or osmotic pressure ?

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Heparin

- High affinity for PEI (ratchet)

➔ **Suppress interaction between ratchet and DNA**

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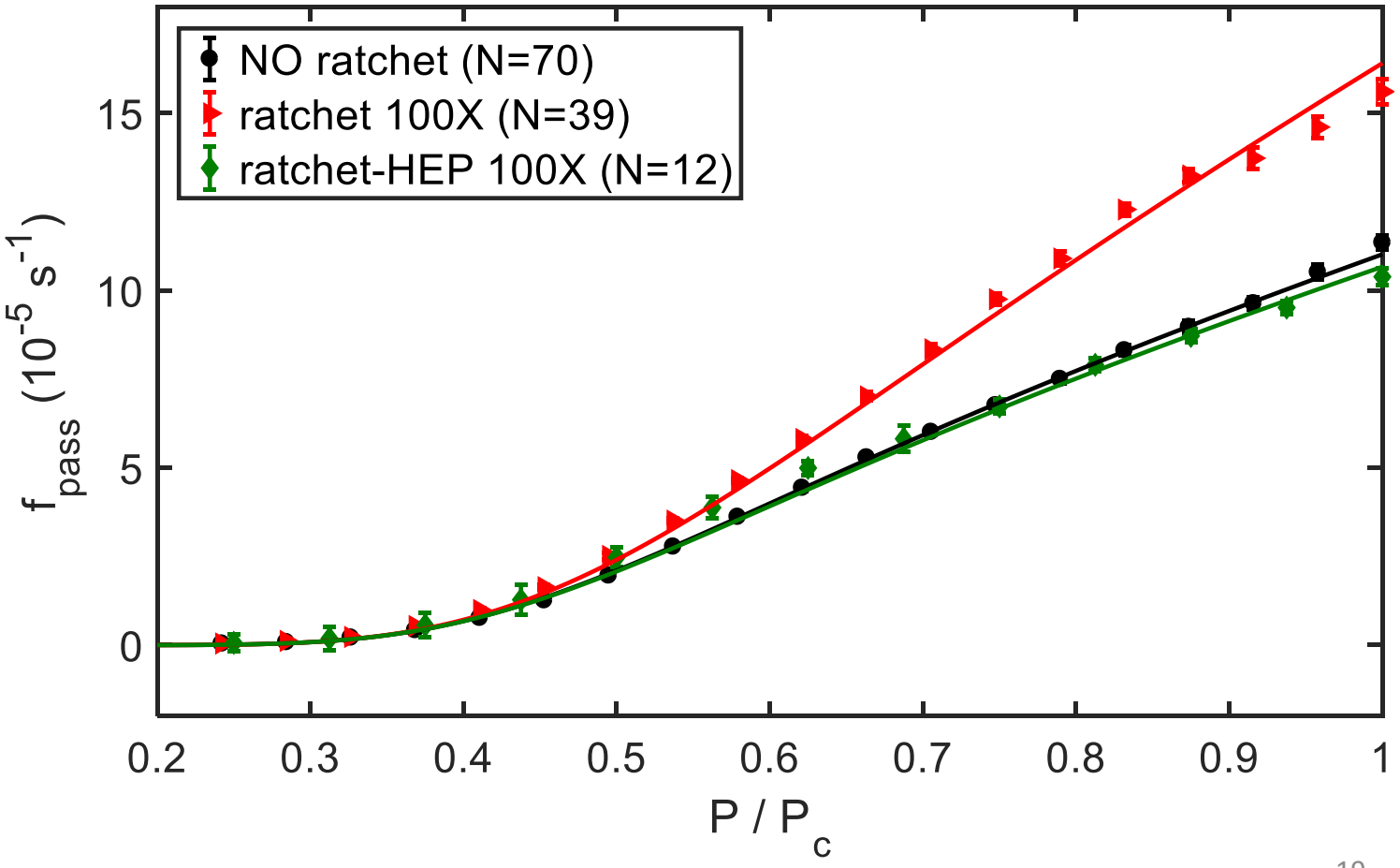

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Heparin

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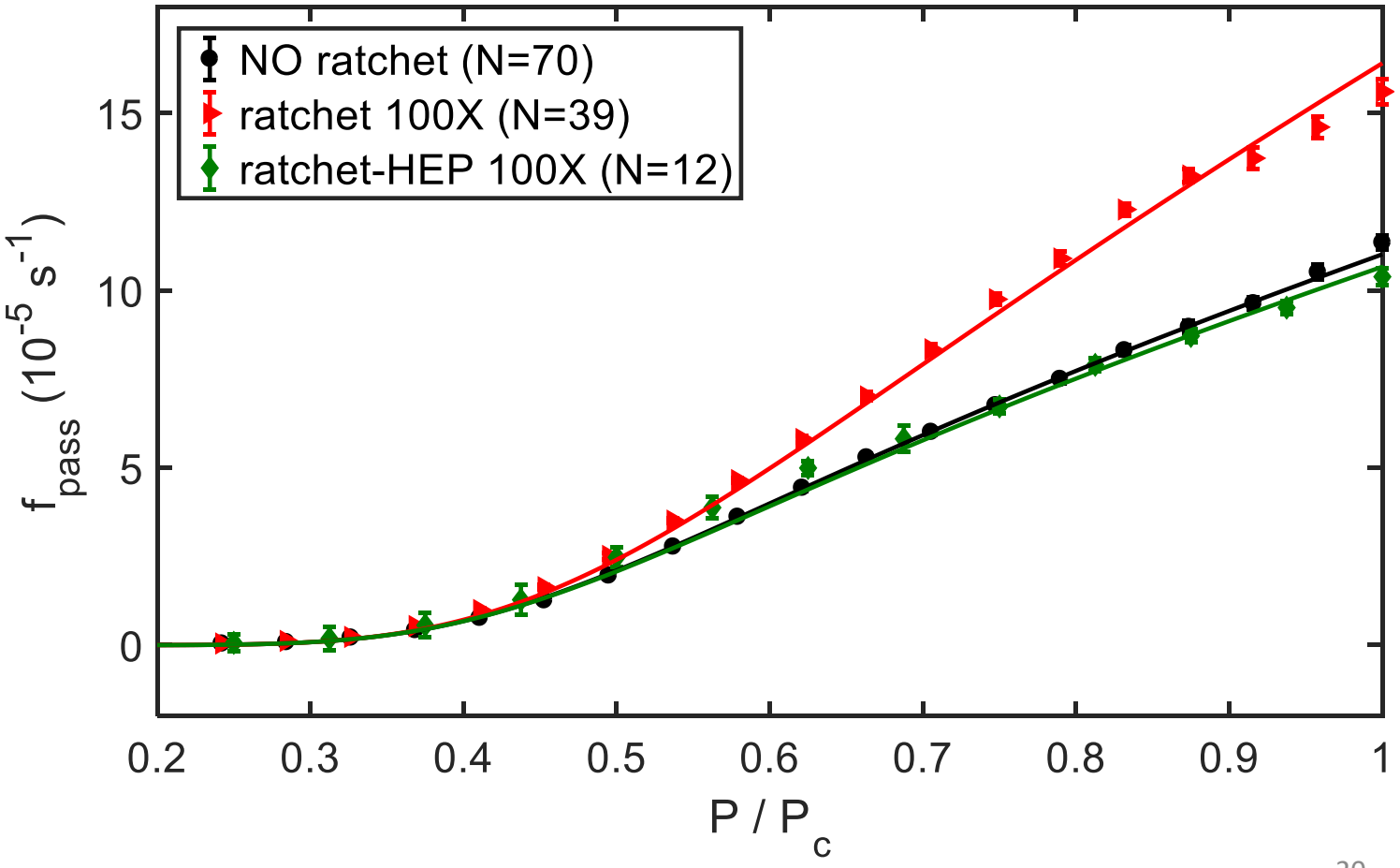
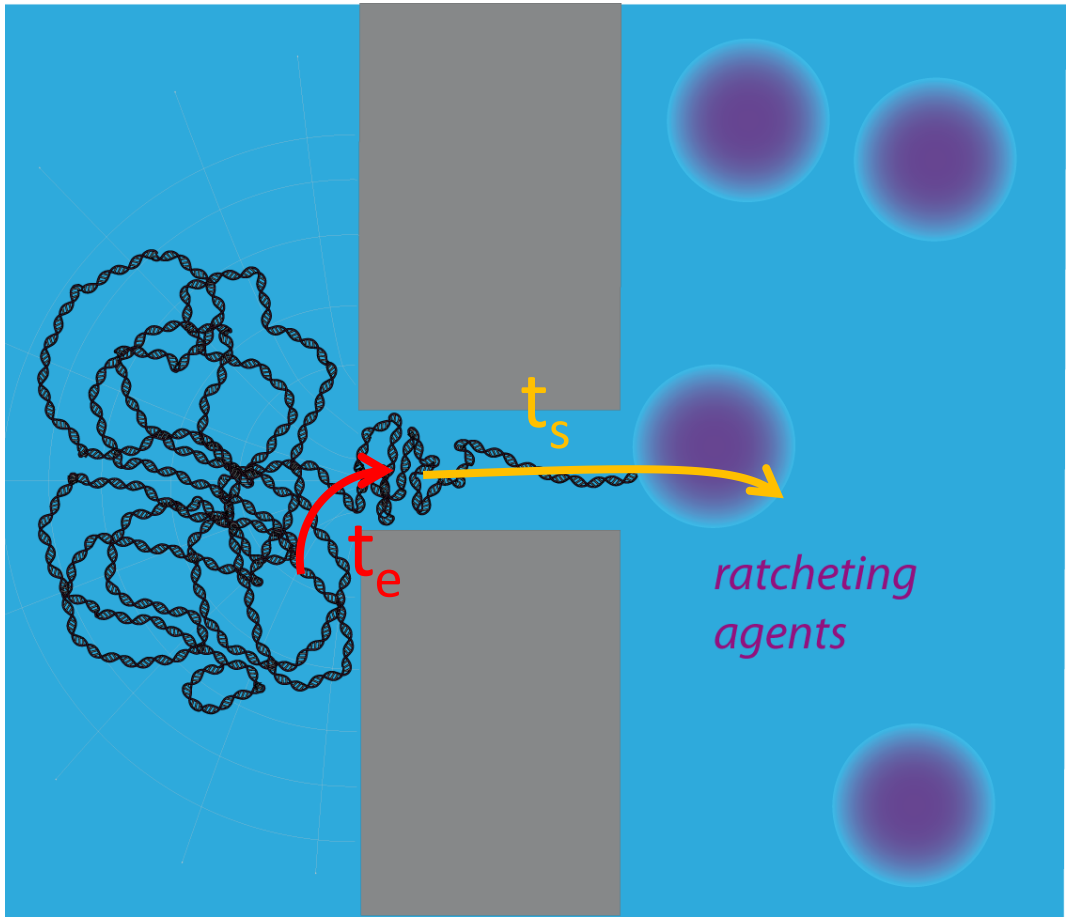
➔ **Suppress interaction between ratchet and DNA**

➔ **Translocation ratchet!**



Model for the effect of ratchet

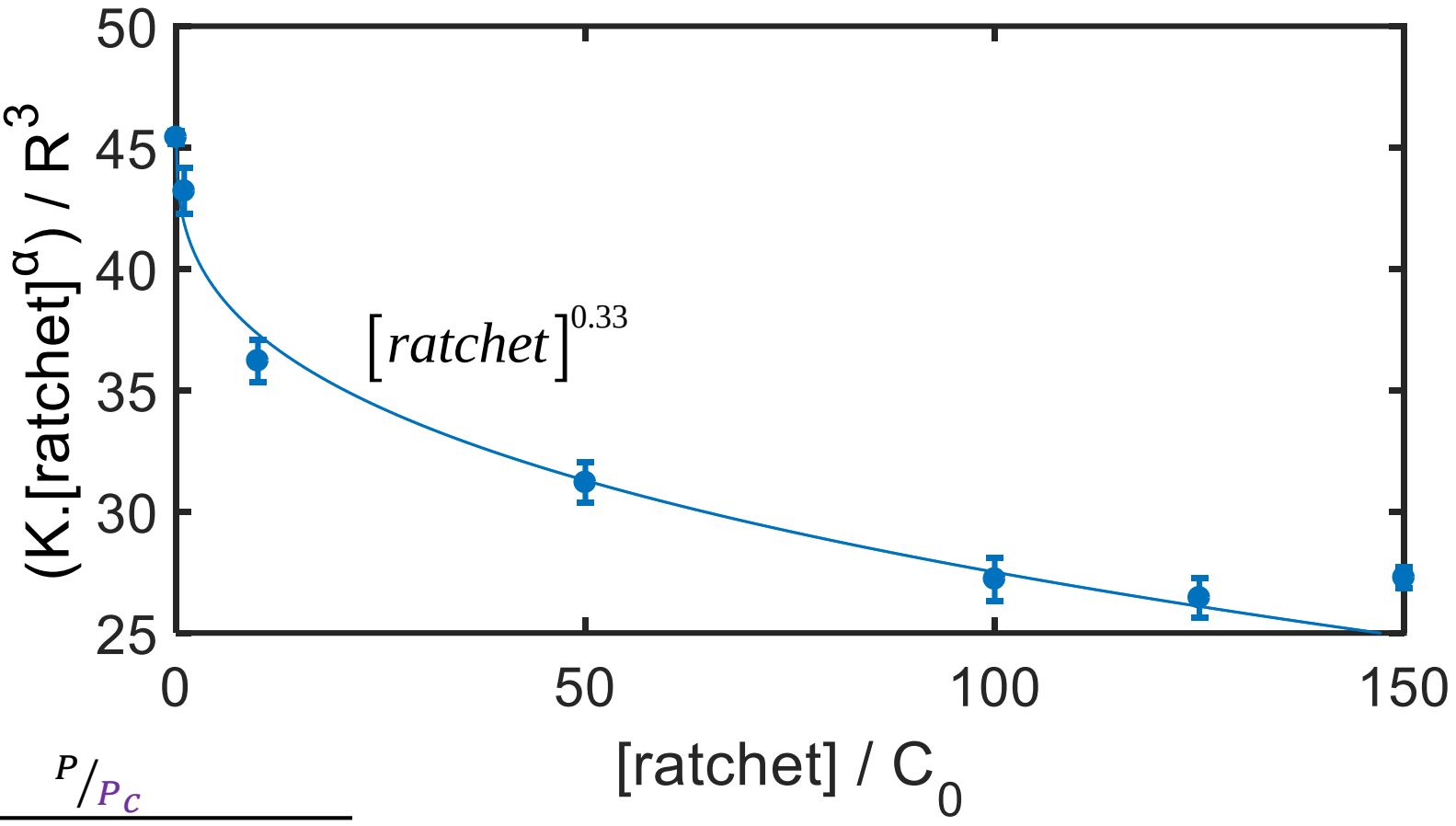


$$t_{tot} = t_e + t_s$$

$$= \frac{R^3}{J} \exp\left(\frac{P_c}{P}\right) + \frac{K}{J}.[ratchet]^{\alpha}$$

$$f_{pass} = \frac{P/P_c}{\frac{R^3}{Jc}\exp\left(\frac{P_c}{P}\right)+\frac{K}{Jc}.[ratchet]^{\alpha}}$$

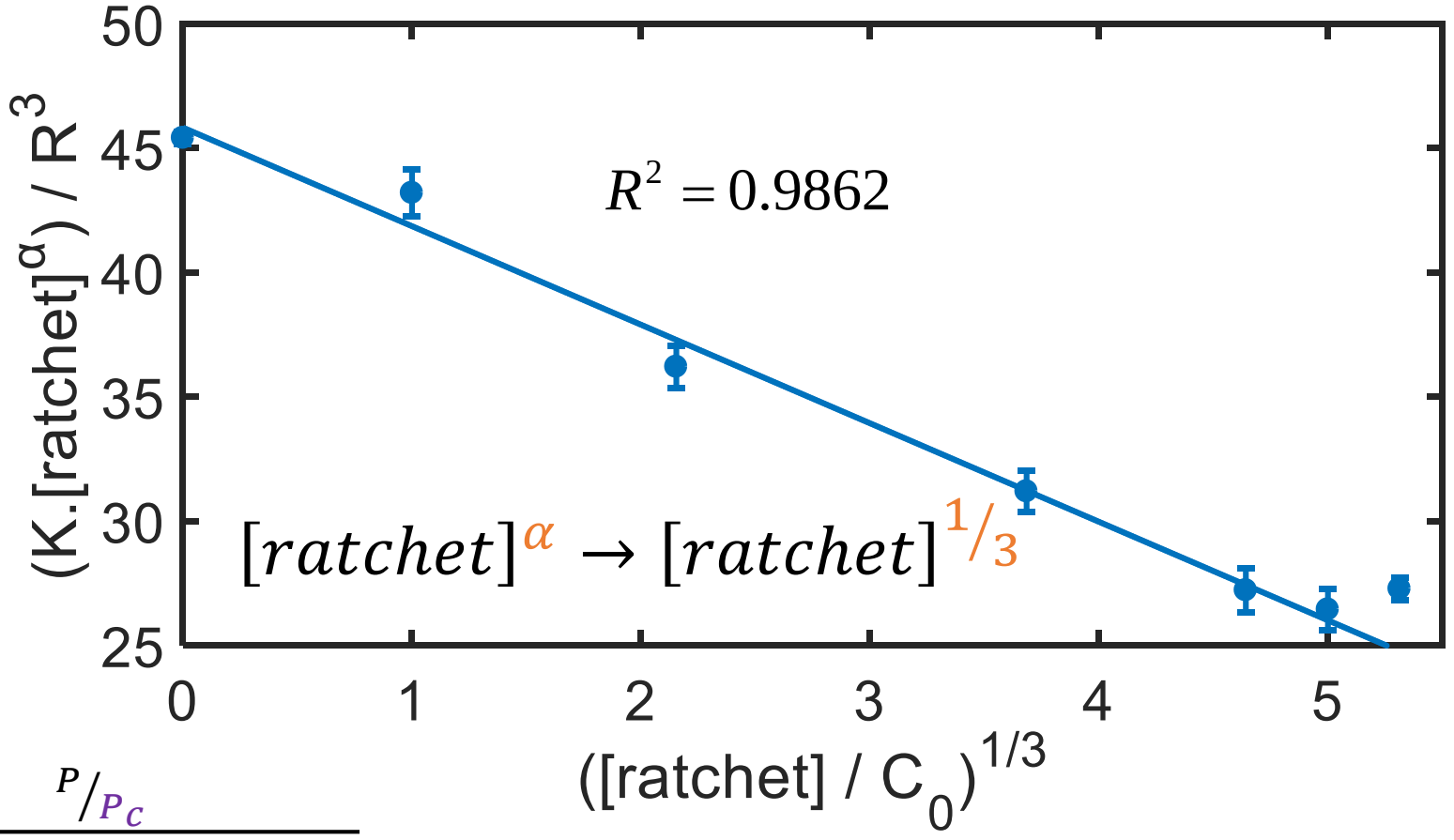
Ratchet effect vs. [ratchet]



$C_0 = 60pM$

$$f_{pass} = \frac{P/P_c}{\frac{R^3}{J_c}\exp\left(\frac{P_c}{P}\right)+\frac{K}{J_c}.[ratchet]^{\alpha}}$$

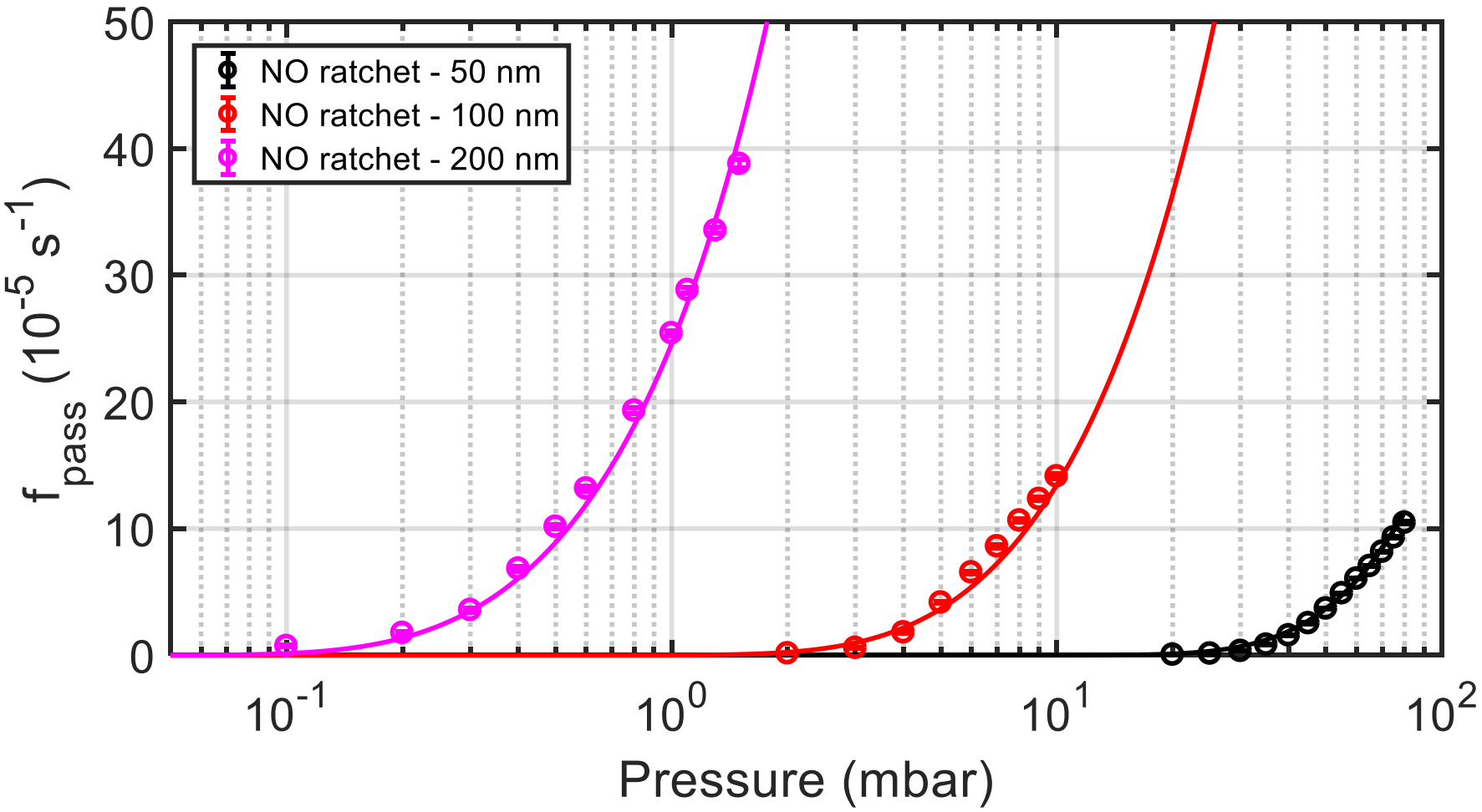
Ratchet effect vs. [ratchet]



$C_0 = 60pM$

$$f_{pass} = \frac{P/P_C}{\frac{R^3}{J_C}\exp\left(\frac{P_C}{P}\right)+\frac{K}{J_C}.[ratchet]^{\alpha}}$$

Ratchet effect vs. Nanopore diameter



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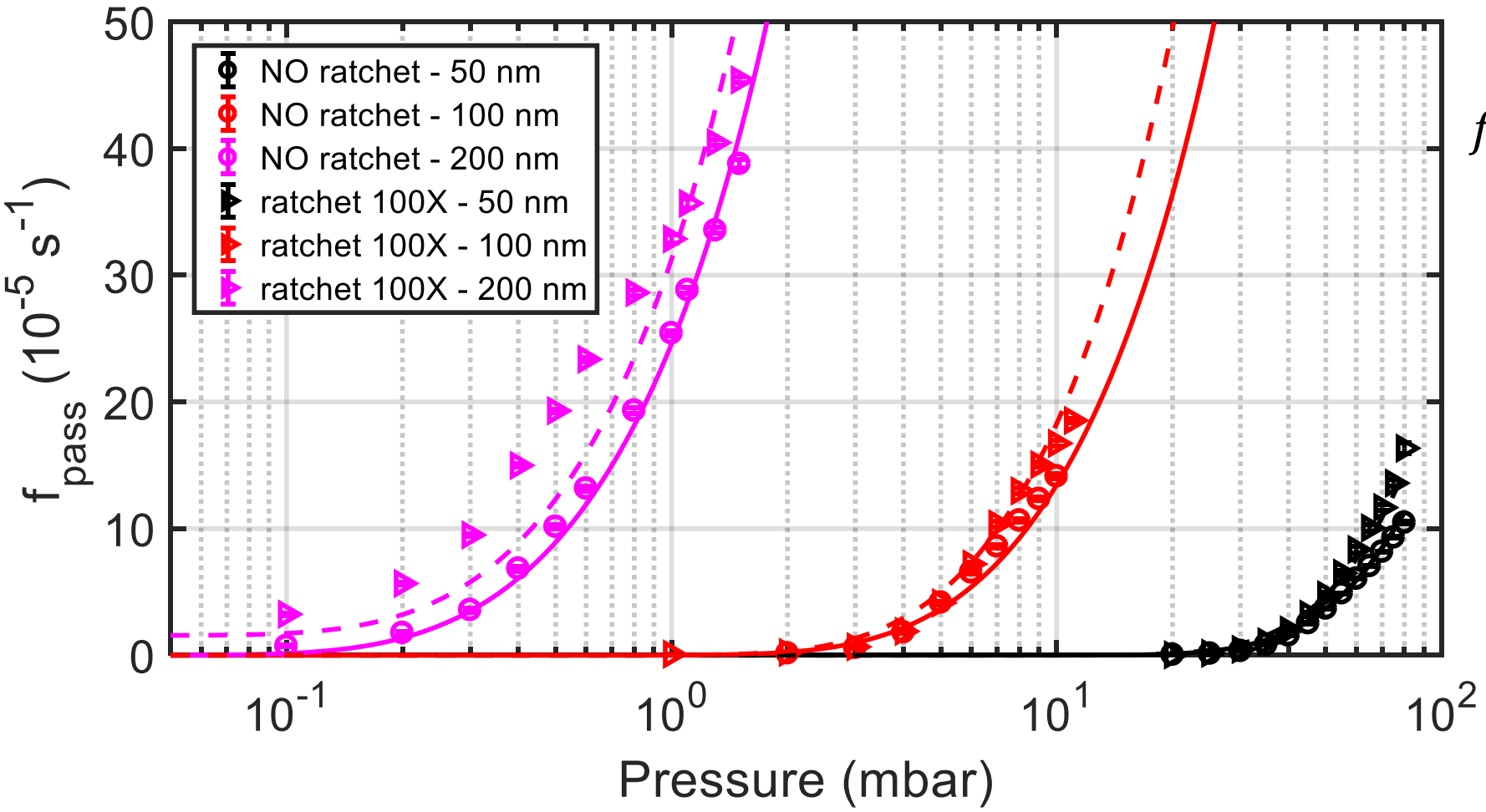
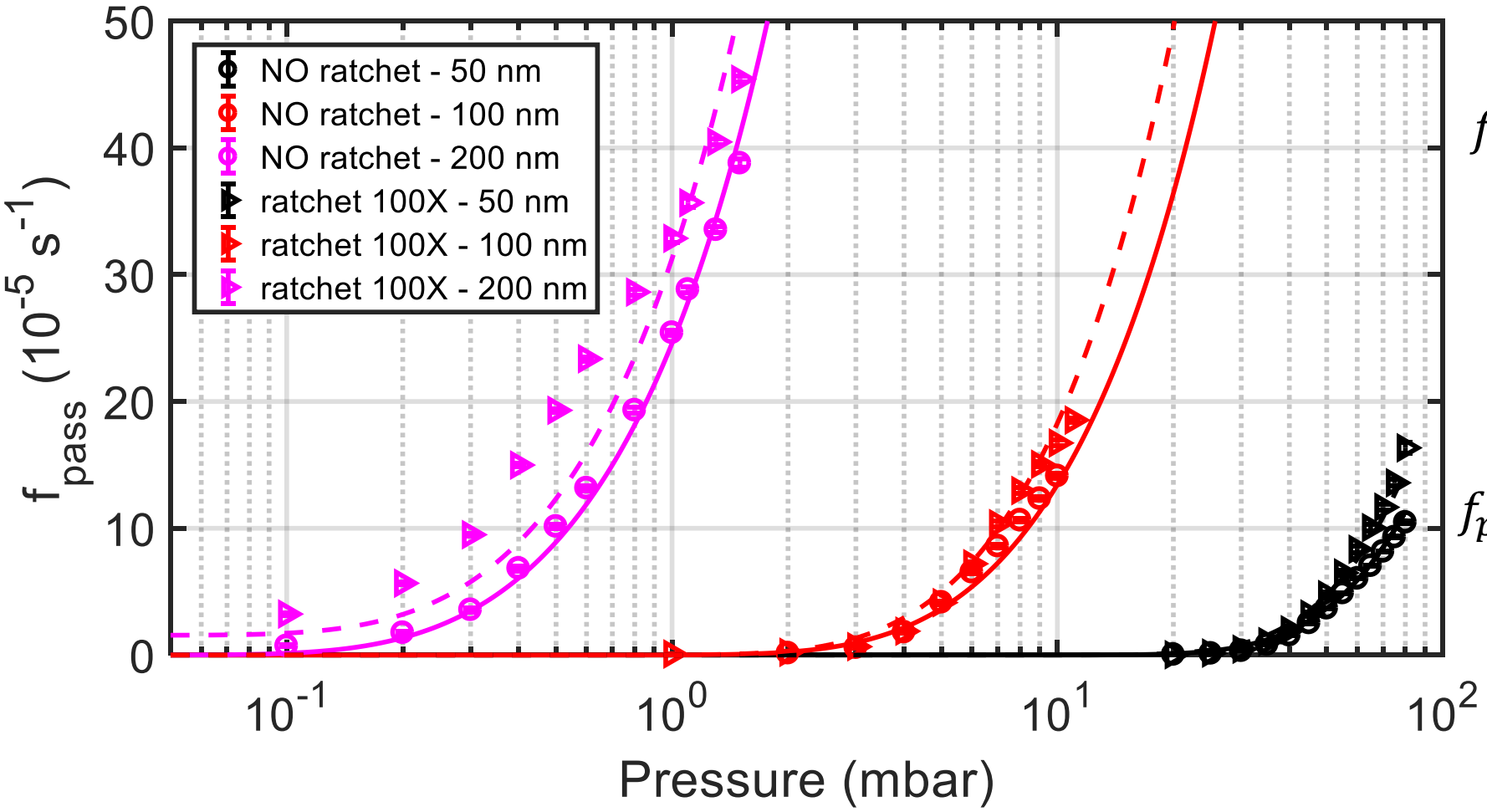


$$f_{pass} = \frac{{}^{P}/_{P_c}}{\frac{R^3}{J_c}\exp\left(\frac{P_c}{P}\right)+\frac{K(R)}{J_c}.[ratchet]^{1/3}}$$

Ratchet effect vs. Nanopore diameter



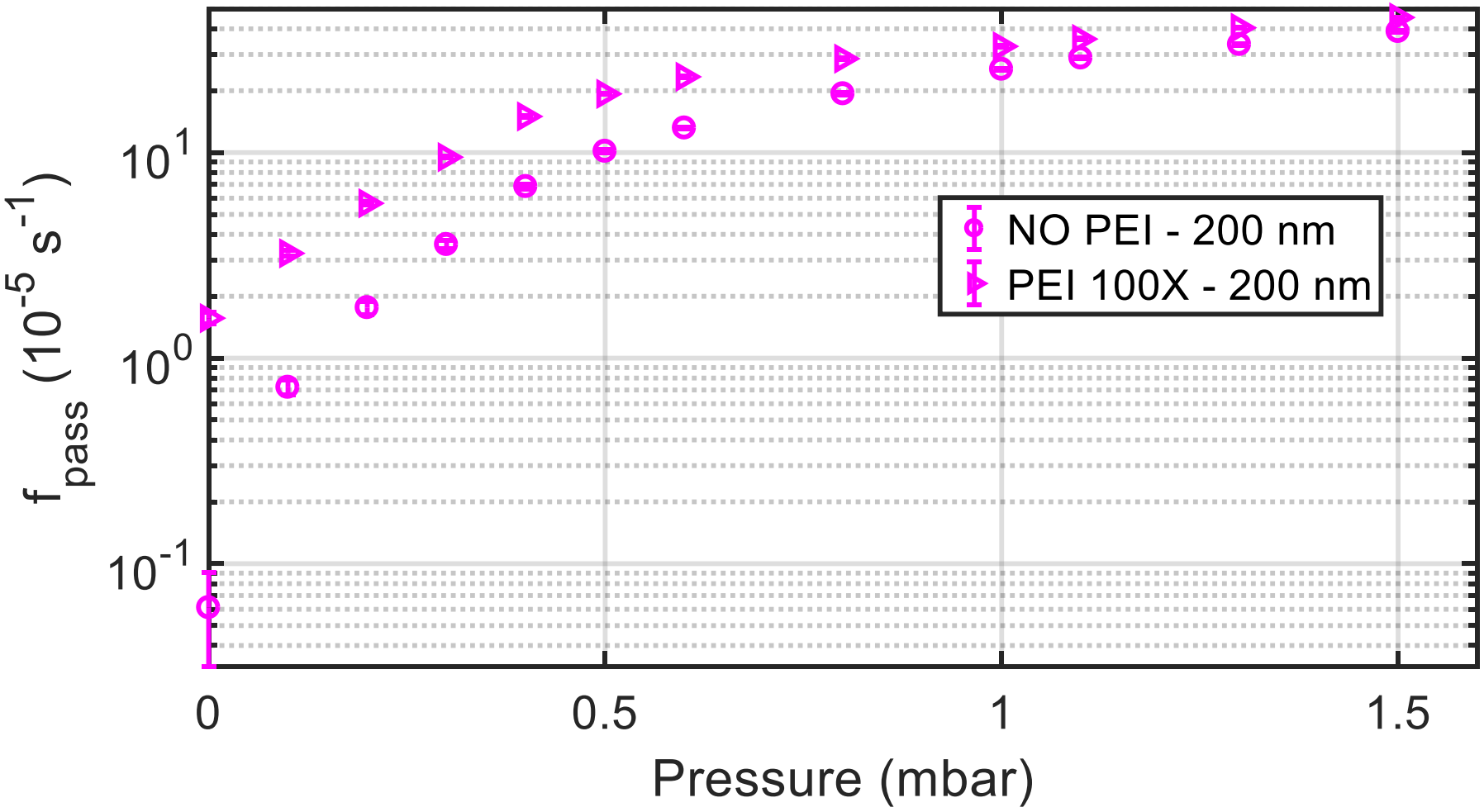
$$f_{pass} = \frac{{}^{P}/_{P_c}}{\frac{R^3}{J_c}\exp\left(\frac{P_c}{P}\right)+\frac{K(R)}{J_c}.[ratchet]^{1/3}}$$

$$t_s \propto R^2 \text{ (?)}$$

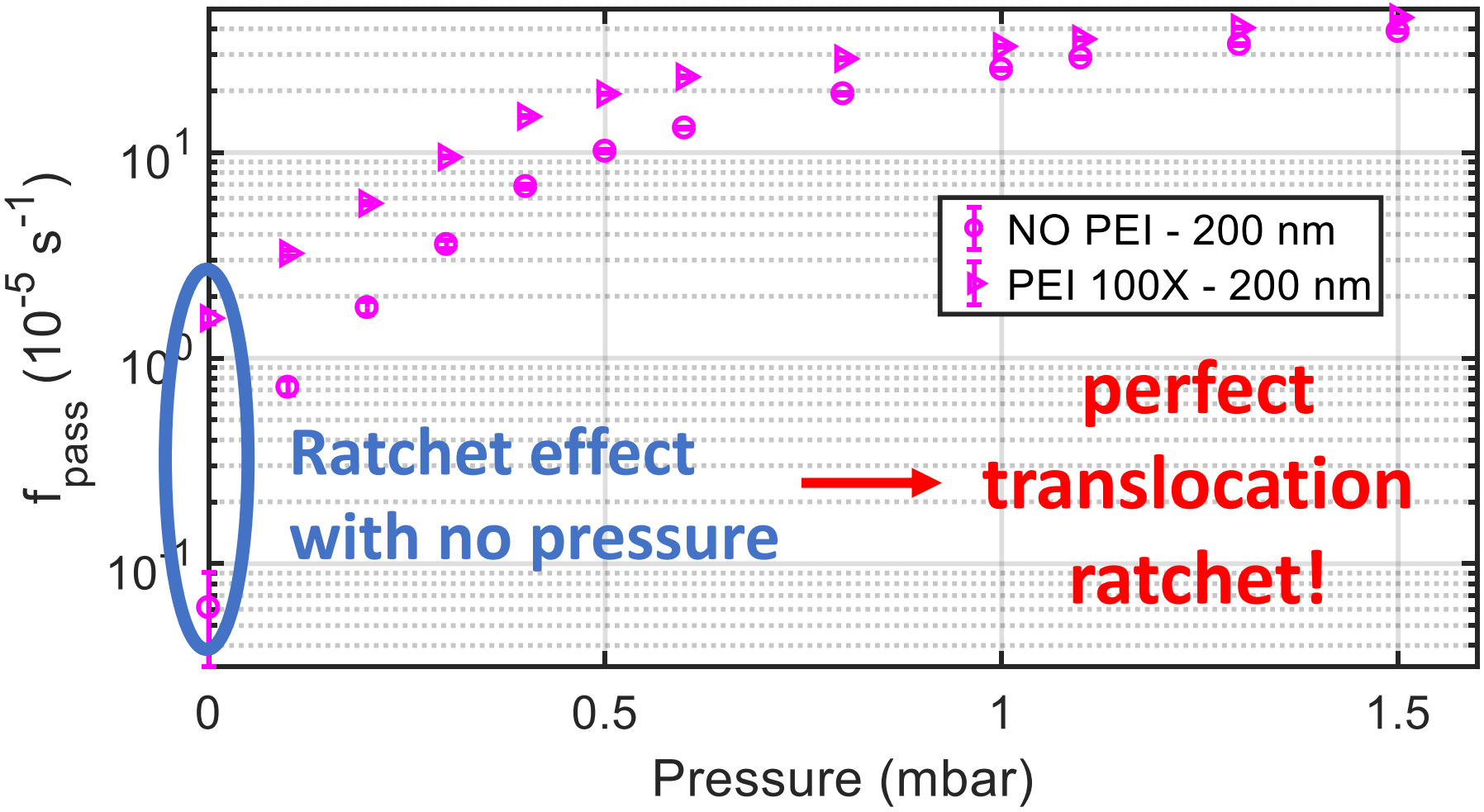
$$f_{pass} = \frac{{}^{P}/_{P_c}}{\frac{R^3}{J_c}\exp\left(\frac{P_c}{P}\right)+\frac{k.R^2}{J_c}.[ratchet]^{1/3}}$$

Work in progress…

Zero pressure Ratchet



Zero pressure Ratchet

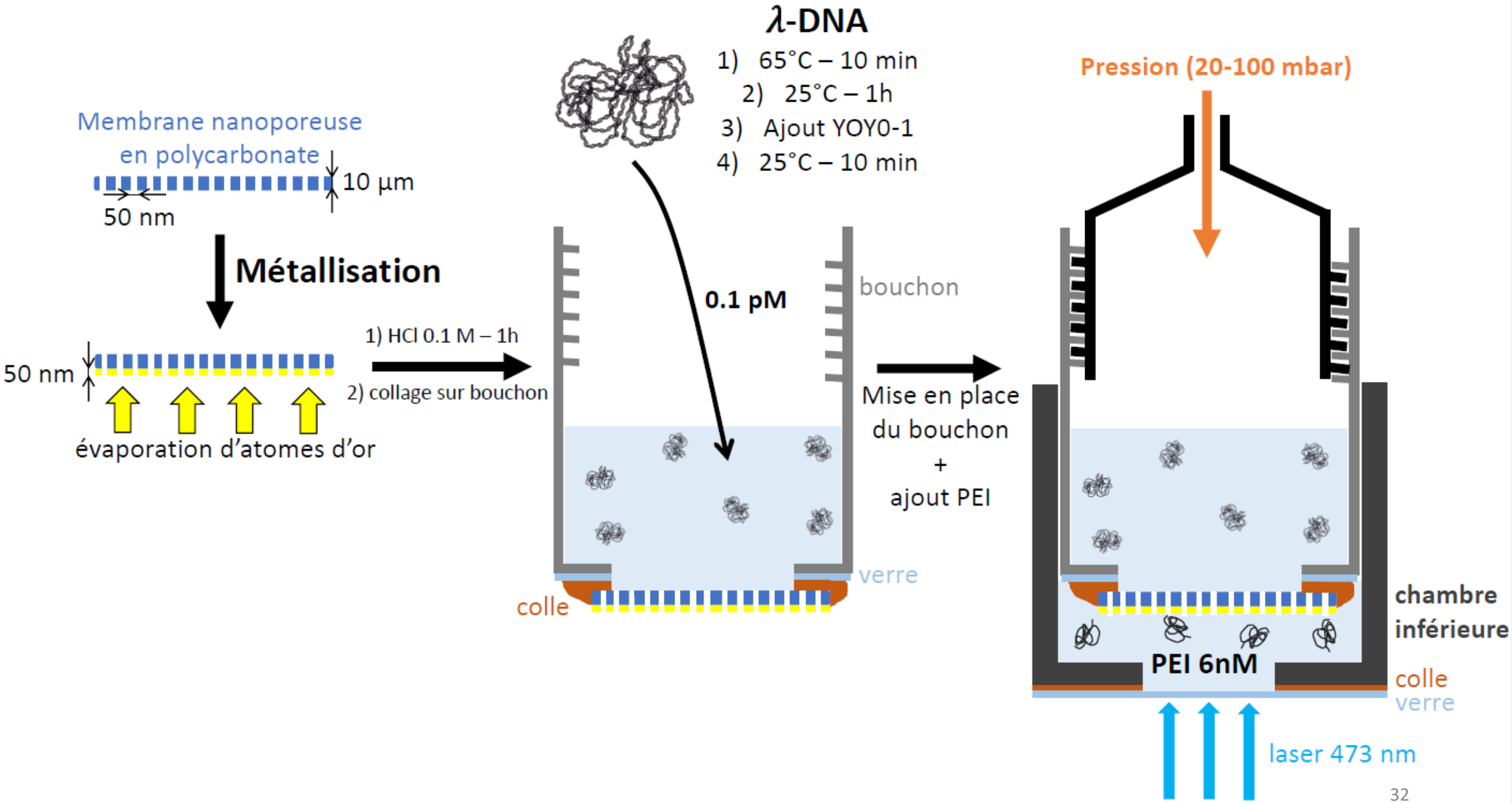


Conclusion

- ✓ Artificial translocation ratchet: OK!
- ✓ Extended suction model for polymers translocation
- ✓ Quantitative description of the ratchet's effect as a function of the ratchet's concentration

- ➢ Complete phase diagram : relative size between ratchet and nanopores, affinity constant with DNA…
- ➢ Application to the biological nuclear pore : proof of its ratchet behavior and measurements of its efficiency as a nanopump.

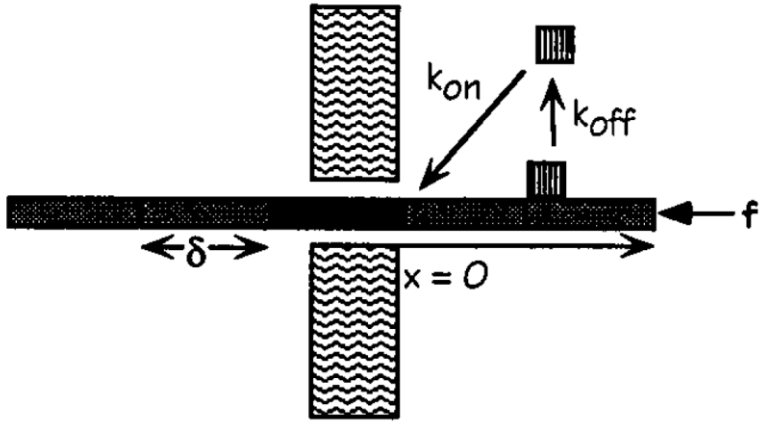
Thanks!


λ-DNA
1) 65°C – 10 min
2) 25°C – 1h
3) Ajout YOY0-1
4) 25°C – 10 min
Membrane nanoporeuse
en polycarbonate
10 µm
50 nm
Métallisation
50 nm
évaporation d'atomes d'or
1) HCl 0.1 M – 1h
2) collage sur bouchon
0.1 pM
bouchon
verre
colle
Mise en place
du bouchon
+
ajout PEI
Pression (20-100 mbar)
chambre
inférieure
PEI 6nM
colle
verre
laser 473 nm

Oster's translocation ratchet

Oster, 1993

$$v = \frac{2D}{\delta}\left[\frac{\frac{1}{2}\omega^2}{\left(\frac{e^{\omega}-1}{1-K(e^{\omega}-1)}\right)-\omega}\right]$$



$$\omega = \frac{f.\delta}{k_B T} \qquad K = \frac{k_{off}}{k_{on}}$$