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Trapping mechanisms during CO₂ sequestration: simulation and microfluidics

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Introduction

- **Carbon Capture and Storage**, or CCS: reduction of carbon dioxide emissions by injecting it in porous geological formation.
- Potential global storage capacity: around 30 000 Gt of CO₂, or 700 years of CO₂ emissions.
- Some questions remain: exact **storage capacity** of a formation? Risks of leakage? Optimal injection method ?
- Need to understand how CO₂ displaces the native fluid (brine) in a reservoir.
- 4 mechanisms responsible for trapping the carbon the carbon in the subsurface: structural trapping, dissolution and mineral trapping, residual trapping, residual trapping (Fig.1):

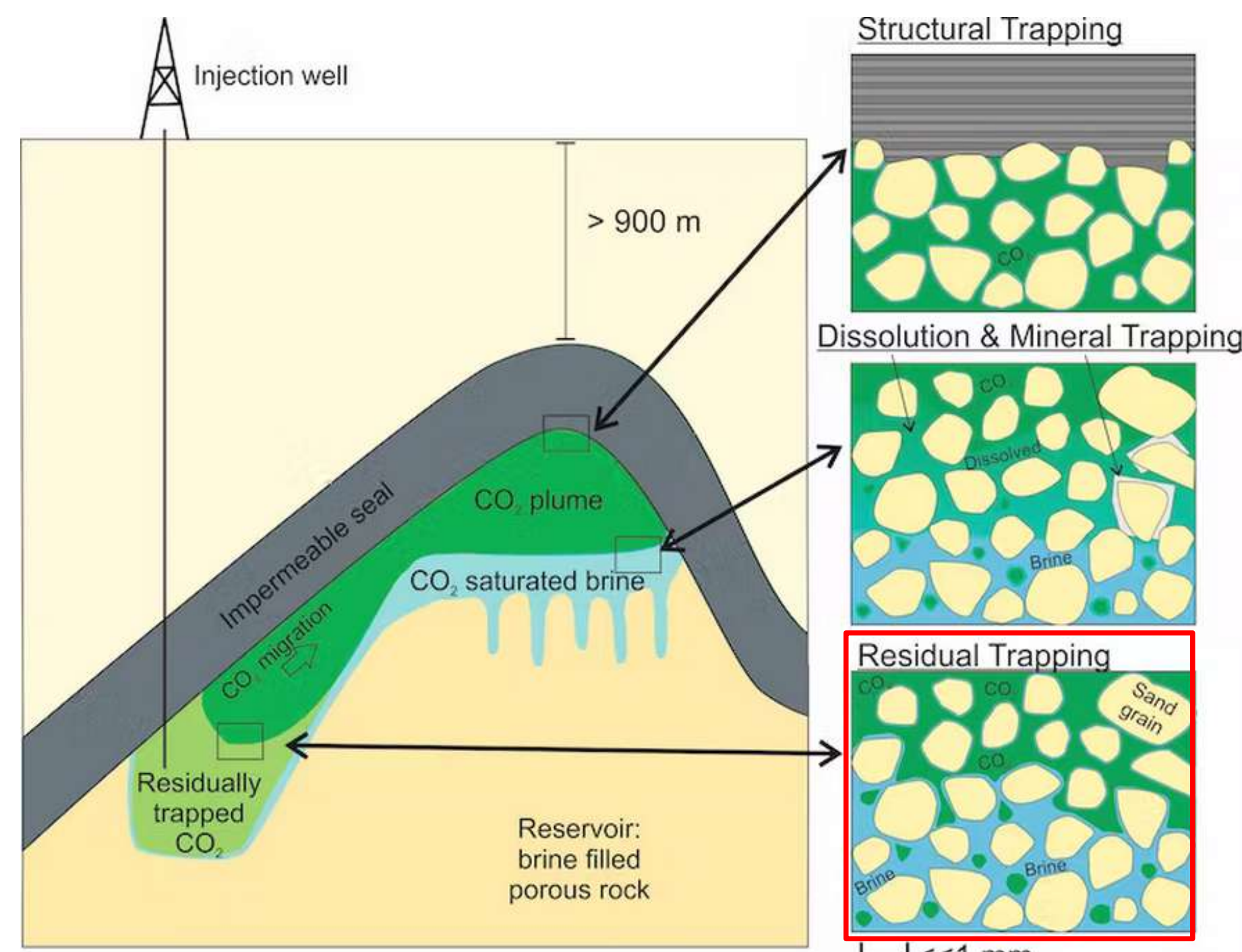


Fig.1. Trapping mechanisms of the supercritical CO₂, from theconversation.com

- The **residual trapping** relies on complex coupled interactions between the two fluids, and two mechanisms play a crucial role in the carbon storage: the **by-pass trapping** (Fig.2) and the **snap-off** (Fig.3).

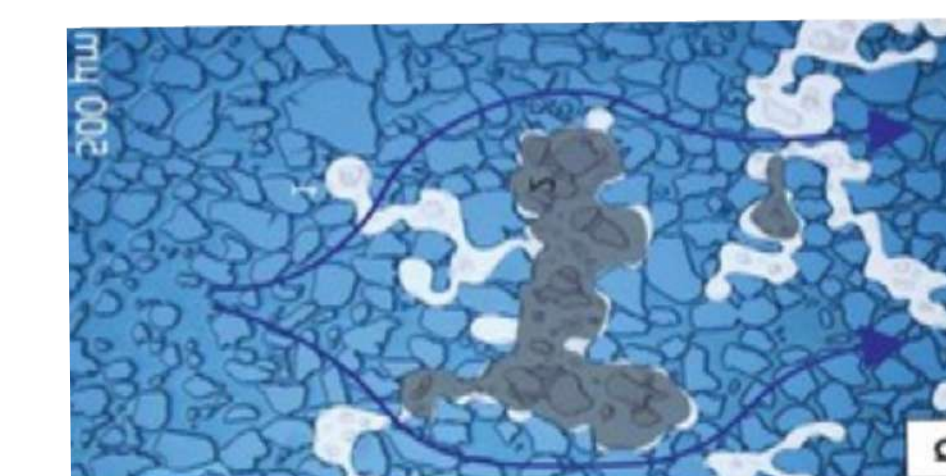


Fig.2. Trapping by by-pass, from Lysy et al. 2022

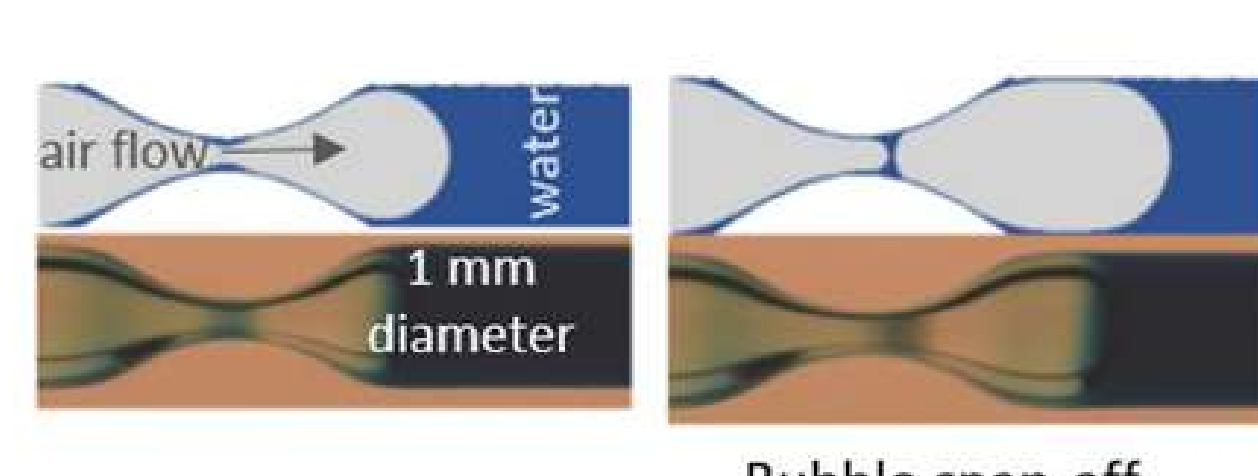


Fig.3. Trapping of ganglia by snap-off, from Roman et al. 2017

Objectives

- Study of the residual trapping: under which conditions does this trapping occur? How much fluid can be trapped?
- Investigation at the pore scale, where we can isolate the different phenomenons, before up-scaling the results.

Methods

- **Microfluidics devices** are used to replicate pore geometry on polymer chips, see Fig.6.

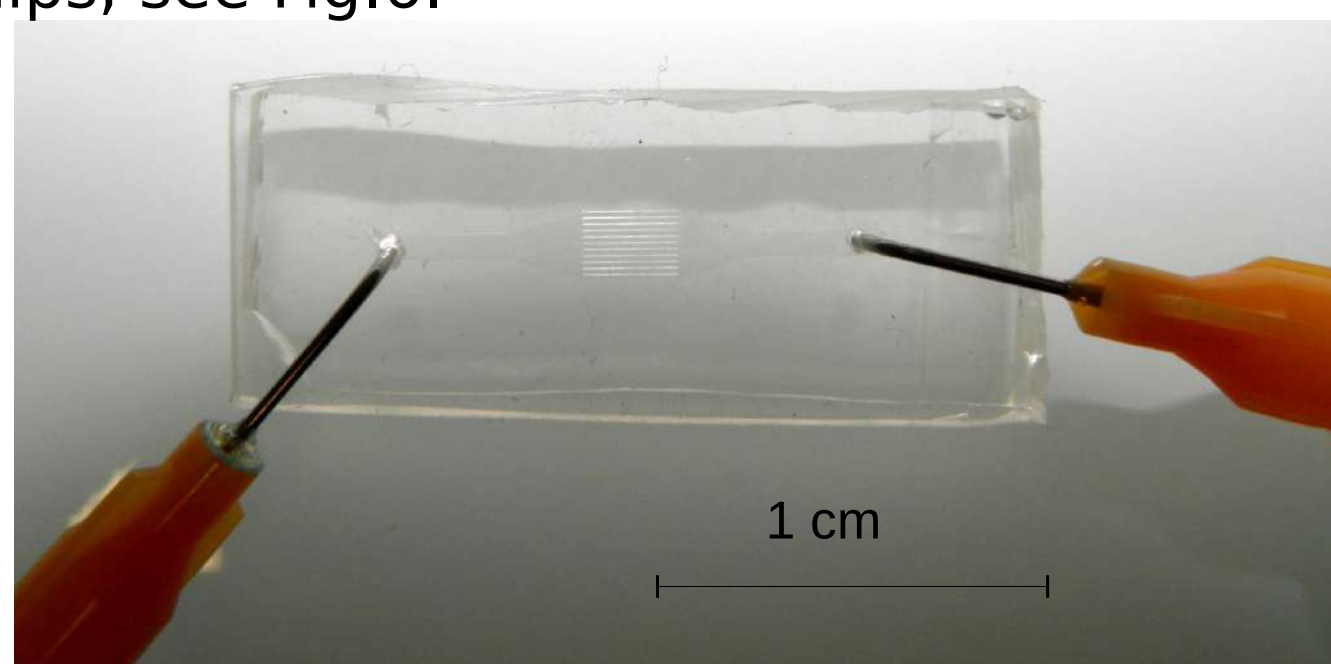


Fig.6. Aquifer-on-chips ready for experiments, from Pour la Science N°535, Soulaïne and Roman

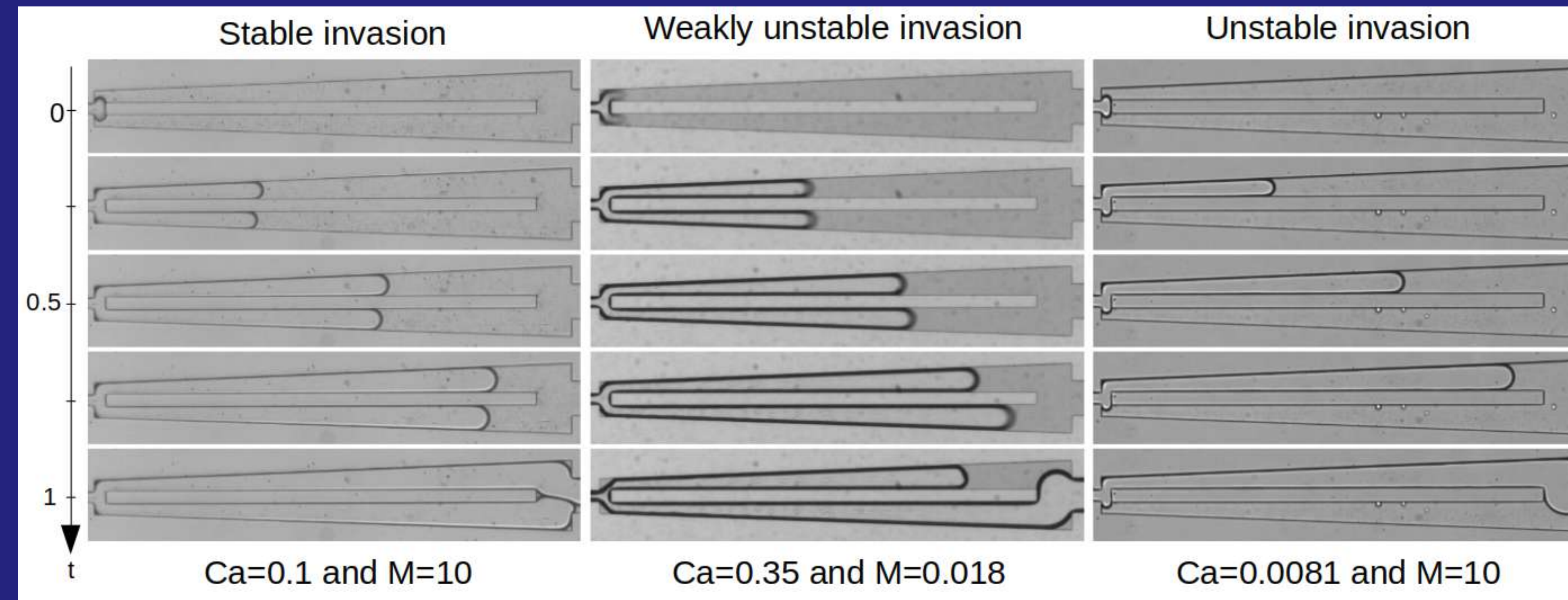


Fig.4. Drainage experiments highlighting the stability regime. Ca is the capillary number, which is the ratio between viscous and capillary forces. M is the ratio between the invading and defending fluids. Stable invasion occurs when both meniscus move simultaneously in the channels, and unstable invasion when one meniscus reaches the outlet first.

“Wetting films influence two-phase flow stability condition in porous media”

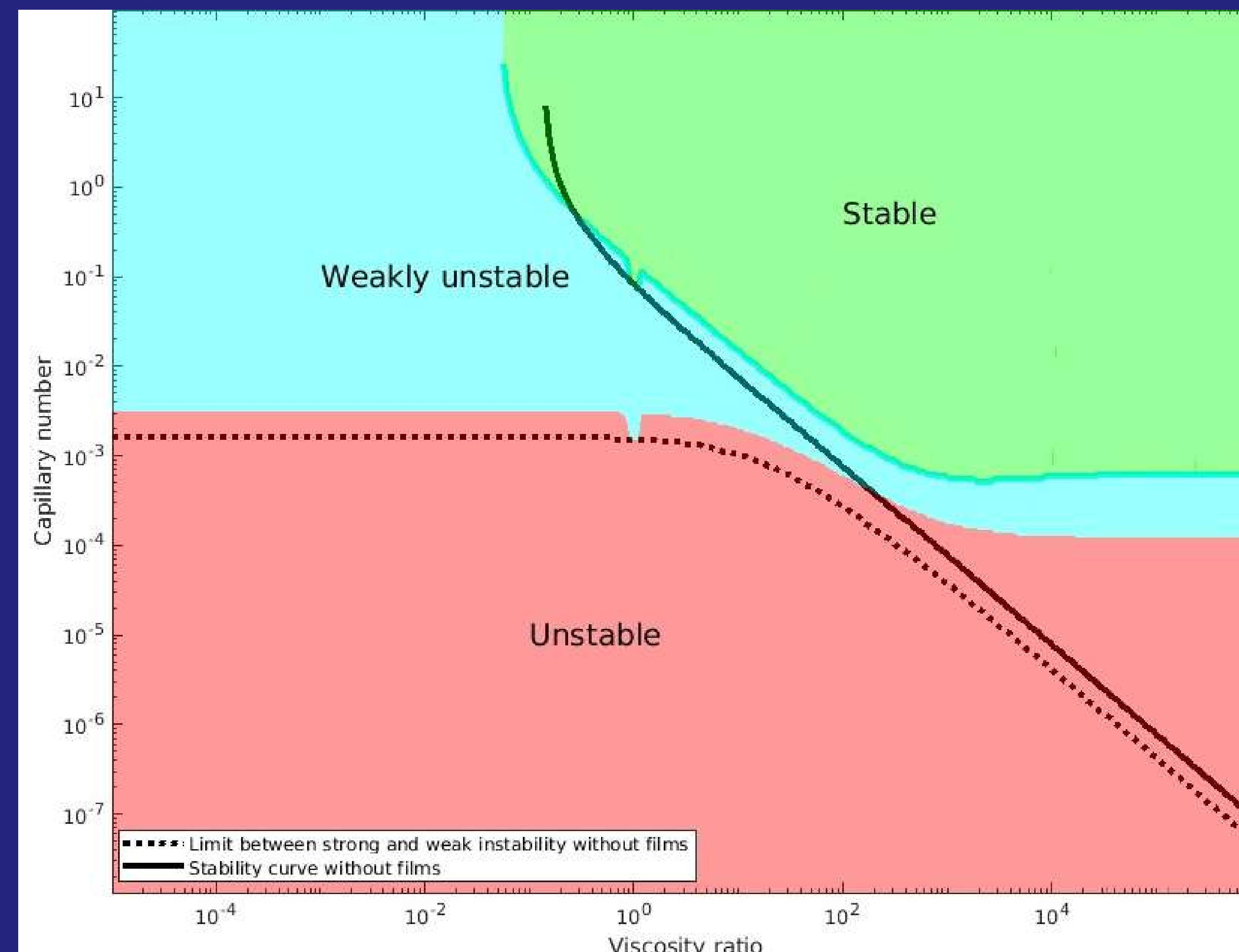


Fig.5. Stability diagram with the three regimes represented. The regions in color are the stability regimes determined using the model with films, and the black lines are the limits between the regimes determined using the model without films. At high viscosity ratio, the films act as a lubricant for the fluid in the middle of the channel, decreasing the viscous pressure drop.

- The experiments are coupled with **numerical models**, which helps us better understand the trapping mechanisms.
- **Pore-doublets** are of particular interest as they highlight the complexity of the two phase flow.

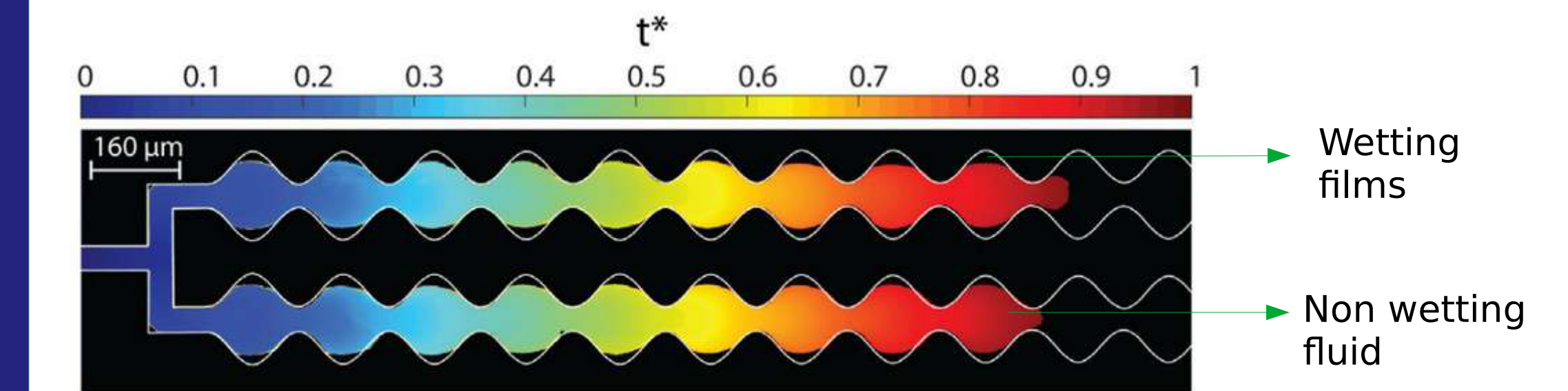


Fig.7. Spatiotemporal graph of the drainage of a sinusoidal pore doublet with uniform depth in the viscous regime, from Mansouri-Boroujeni et al. 2023 .

- In porous media, during the invasion by a non-wetting fluid (or drainage), there is a layer of **wetting film** left on the walls, behind the interface (see Fig.7). These layers were described by Bretherton (1961) for straight channels.
- These films create a ‘slip’ phenomenon, where the invading fluid seems to have a **non-zero velocity at the wall**.
- Very few authors takes these films into account, and we want to see what impact they may have on the two phase flow.

Results

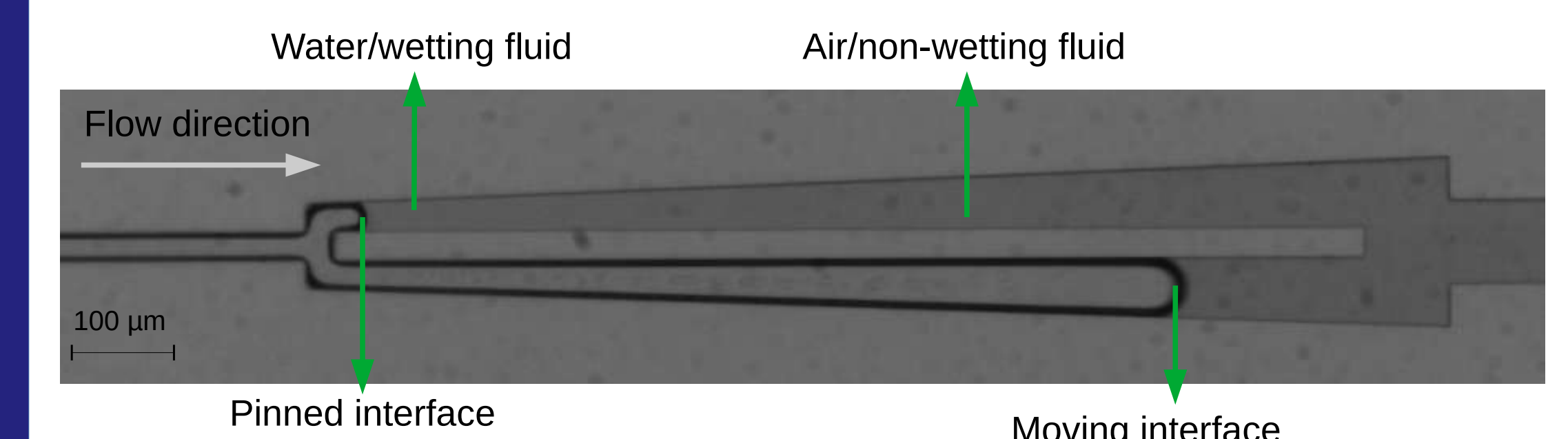


Fig.8. Drainage of a symmetrical pore doublet highlighting the preferential invasion instability. The micromodel was chemically treated to be hydrophilic.

- In a symmetrical pore-doublet with channels of increasing width (see fig.8), Al.Housseiny et al. 2014 showed numerically the existence of an **instability** that leads to by-pass trapping for capillary dominated flow. We experimentally reproduces their study, and highlighted three regimes: stable, weakly unstable and unstable, see Fig.4.

- Wetting films were added to the model. Via **viscous coupling**, they act as a lubricant on the wall that reduces the resistance to the flow of the channel for M>1 and increases it for M<1. This changes the instability regime and the amount of fluid trapped inside the pore-doublet.

Conclusion

- Wetting layers, often neglected in porous media, impact two-phase flow. They need to be taken into account in pore-doublet models, especially at high viscosity ratio, where their lubricating effect becomes important.

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Al-Housseiny, Hernandez , and Stone: *Preferential flow penetration in a network of identical channels*, 2014.
 Roman, Abu-Al-Saud, Tokunaga, Wan, Kovscek, Tchepeli: *Measurement and simulation of liquid films during drainage displacement and snap-off in constricted capillary tubes* (2017)
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