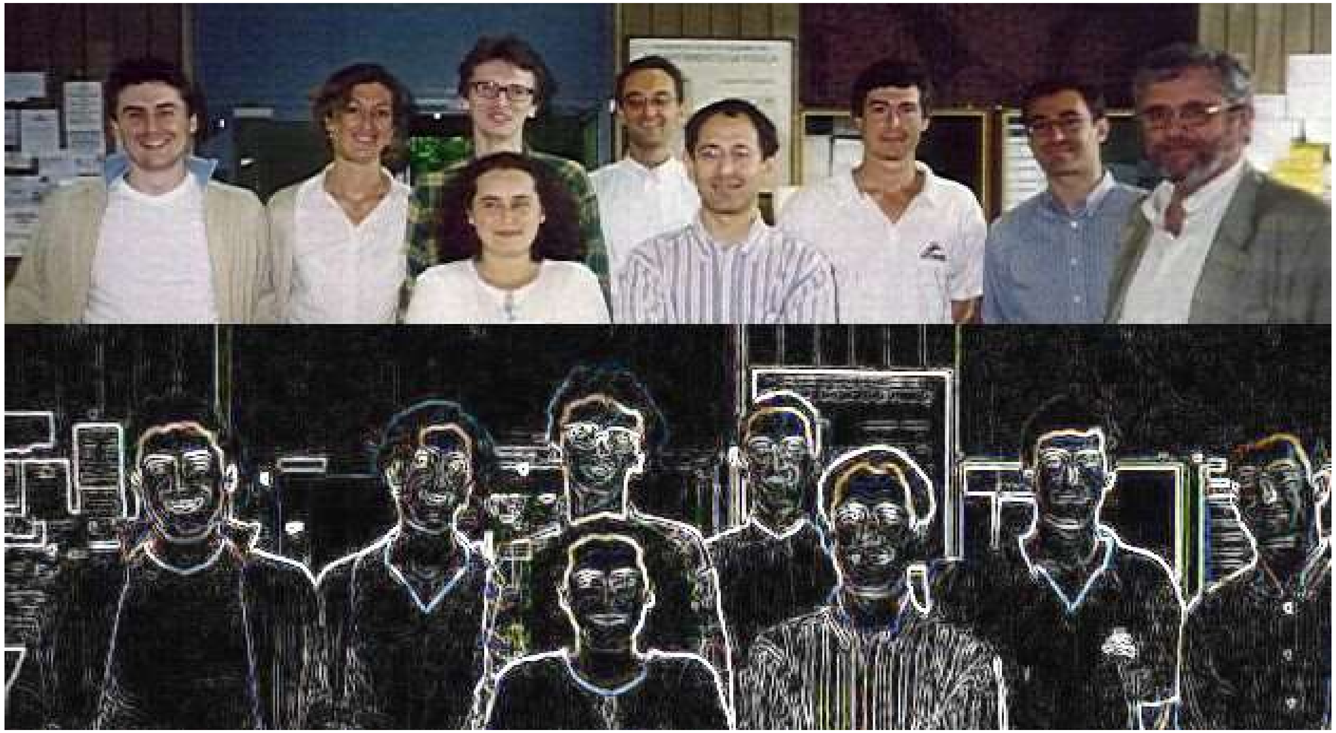
CO_2 Enhanced Storage (CO2ES)
An industrial Chair about CO_2 Storage

Fabrizio CROCCOLO

UniMi Physics Department Seminar – February 10th, 2022



Roberto CERBINO
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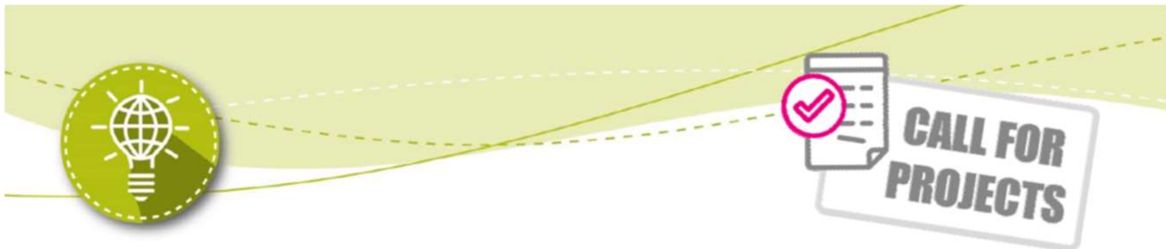
Uni-Pau (FR)

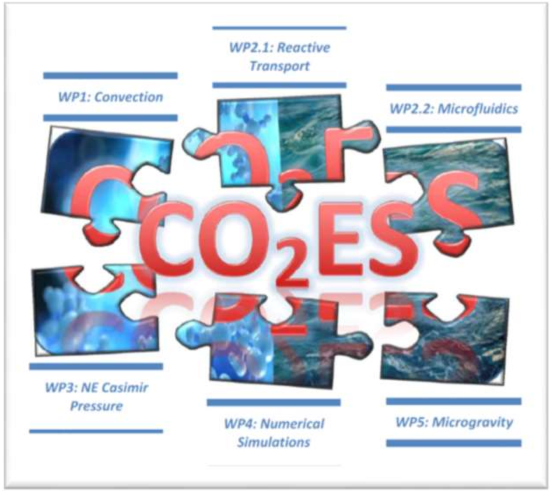
Doriano BROGIOLI
Uni-Bremen (DE)

Pietro CICUTA
Uni-Cambridge (UK)

INDUSTRIAL CHAIR CO_2ES



INDUSTRIAL CHAIR CO_2ES

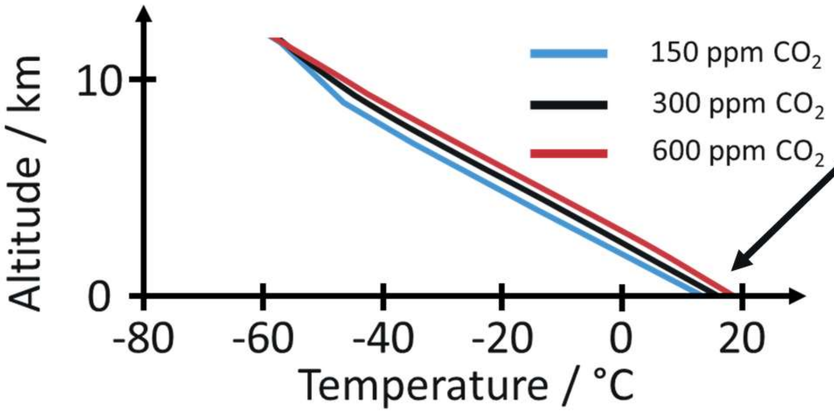


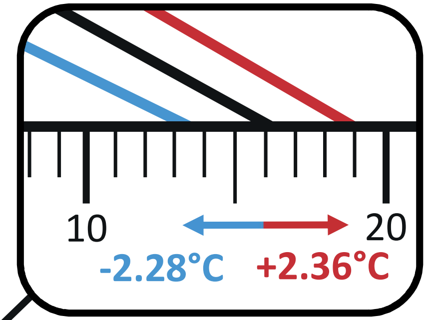
e2s UPPA energy environment solutions

CNES CENTRE NATIONAL D'ÉTUDES SPATIALES

Géosciences pour une Terre durable brgm

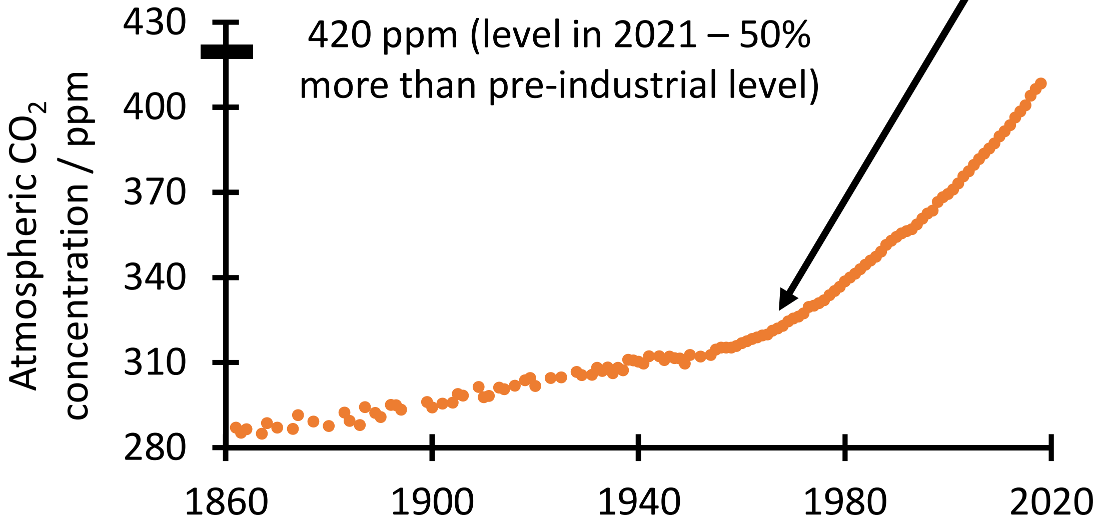
CO_2 IMPACT ON GLOBAL TEMPERATURE



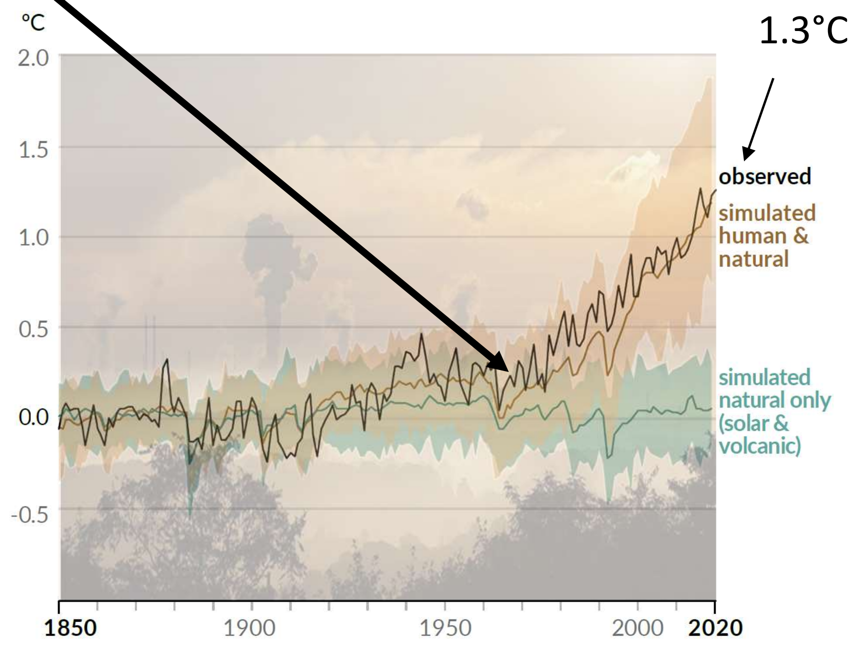


Manabe and Wetherald
(1967)

Syukuro Manabe – Nobel price in Physics 2021
© Nobel Prize Outreach



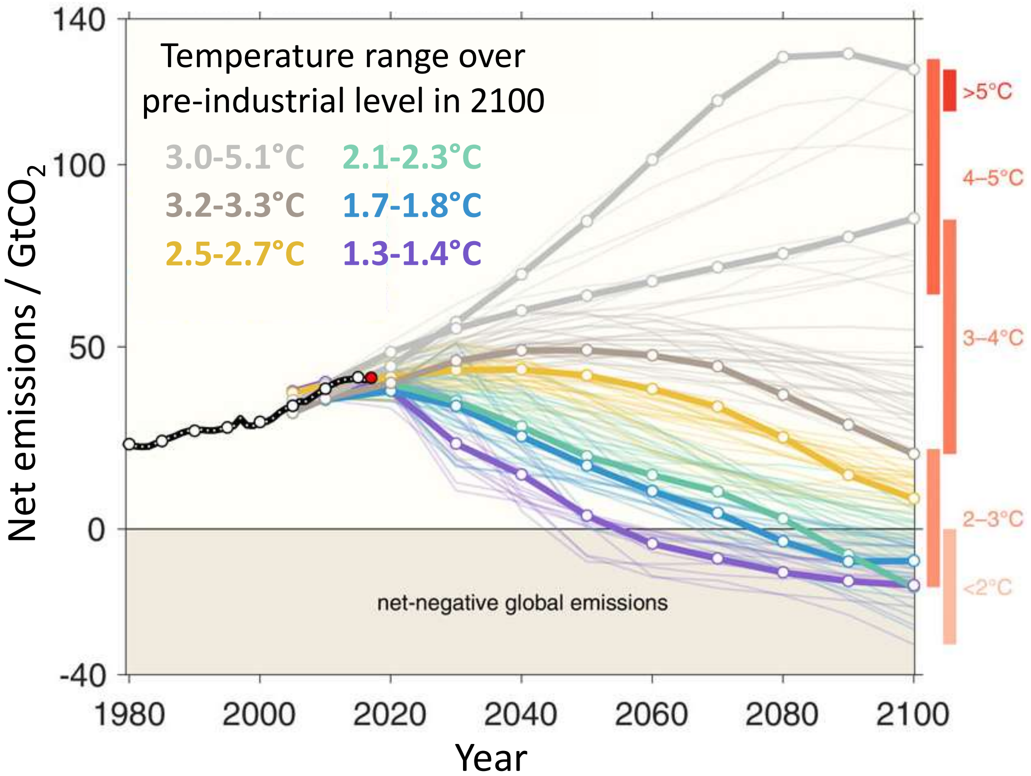
Data from NOAA/ESRL

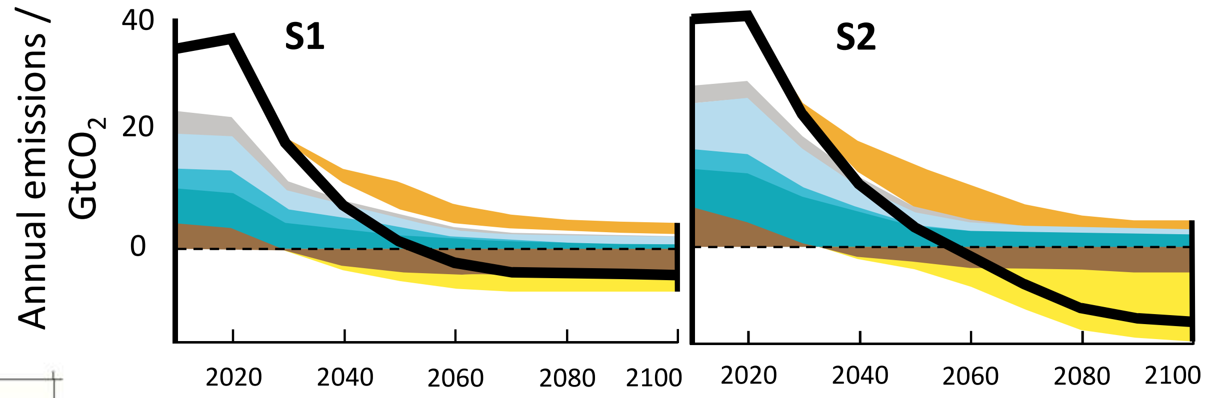


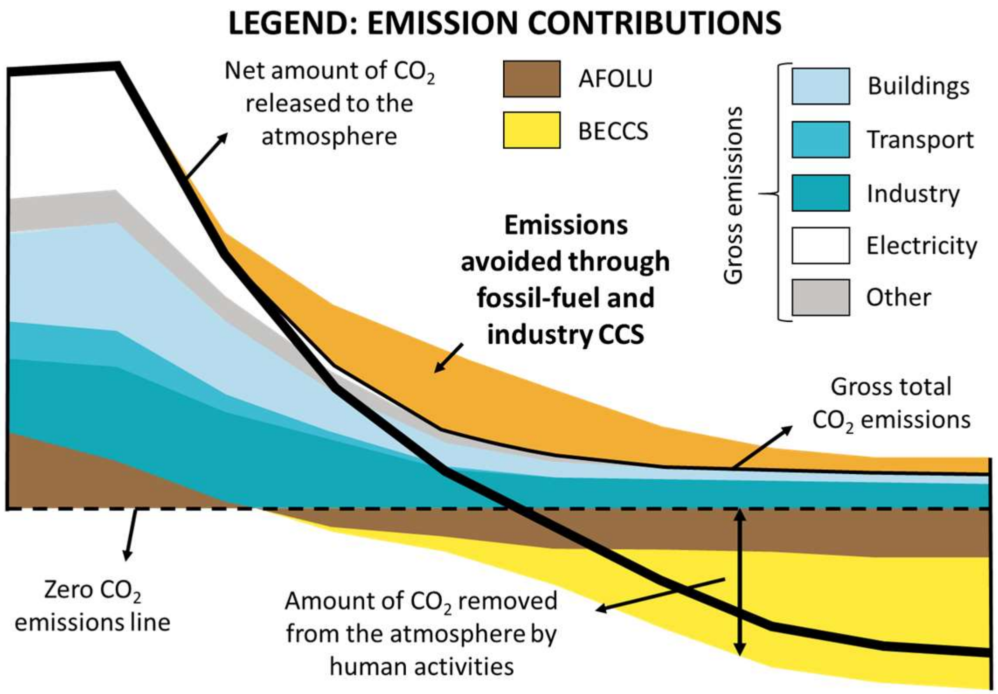
IPCC Climate change 2021 – The physical basis

PATHWAYS TO LIMIT GLOBAL WARMING TO 1.5°C

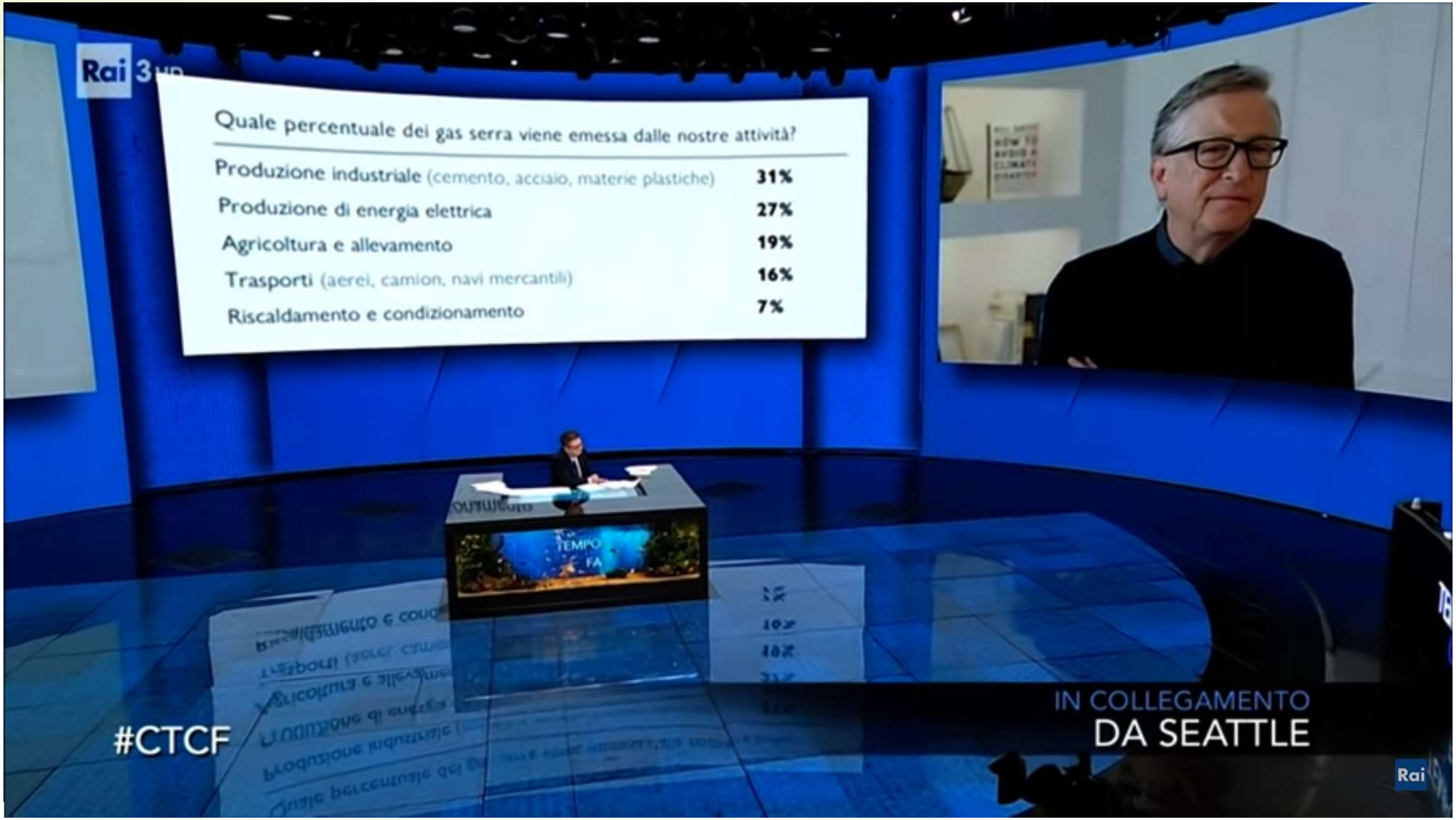
Simulated carbon net global emissions
from the Global Carbon Project





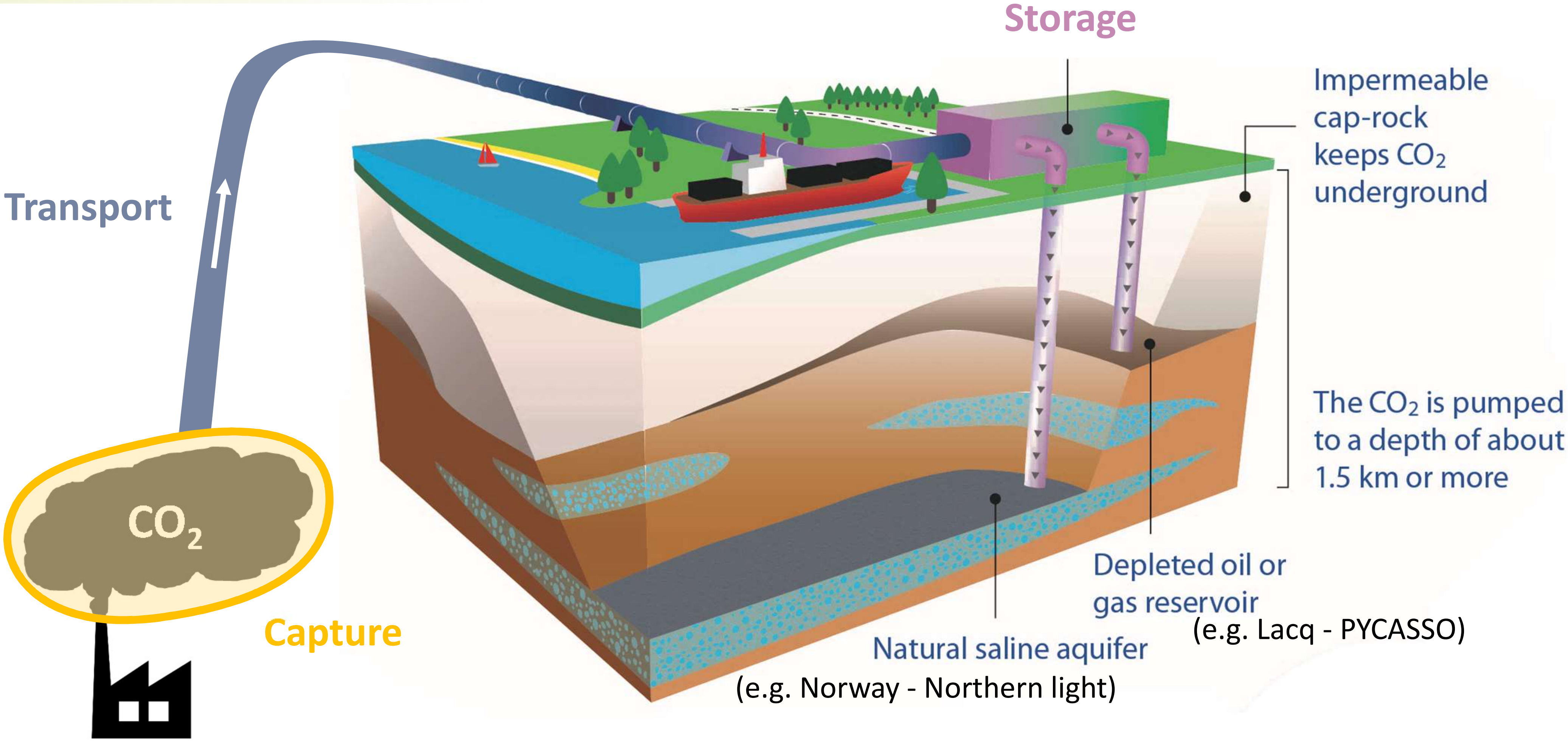


IPCC Special report – Global warming of 1.5°C (2018)



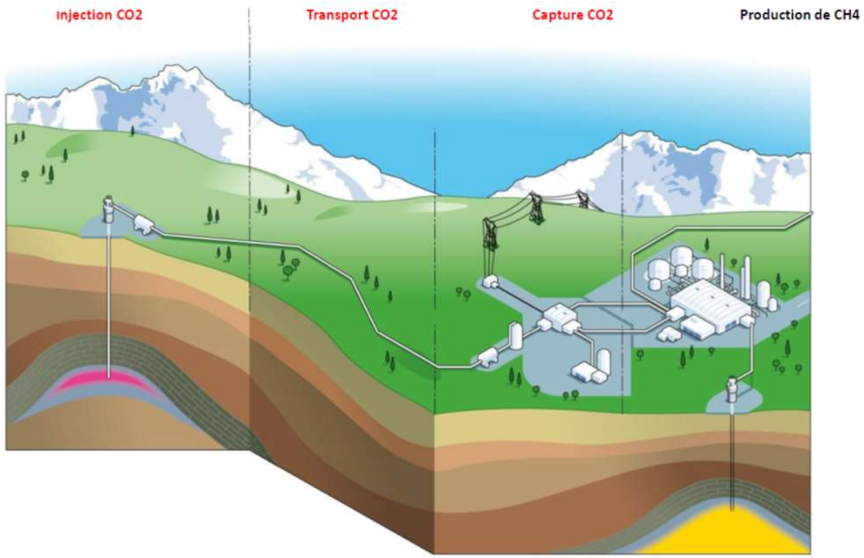
Rai 3
Quale percentuale dei gas serra viene emessa dalle nostre attività?
Produzione industriale (cemento, acciaio, materie plastiche) 31%
Produzione di energia elettrica 27%
Agricoltura e allevamento 19%
Trasporti (aerei, camion, navi mercantili) 16%
Riscaldamento e condizionamento 7%
#CTCF
IN COLLEGAMENTO
DA SEATTLE
Rai

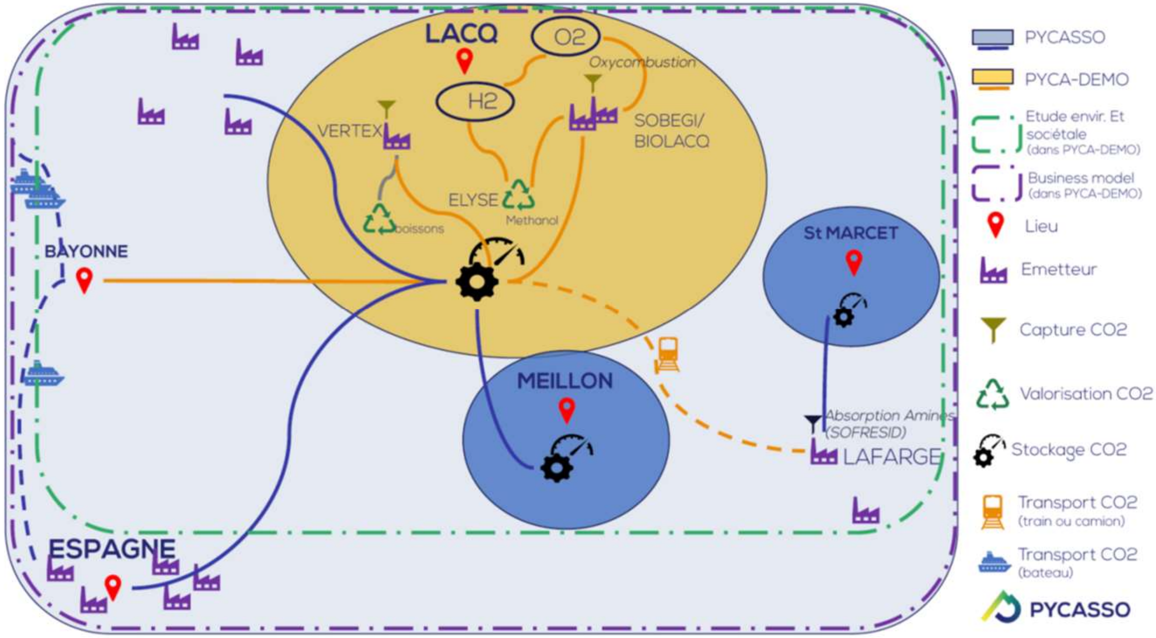
CARBON CAPTURE
TRANSPORT & STORAGE



European Comission, DG TREN

PYCASSO

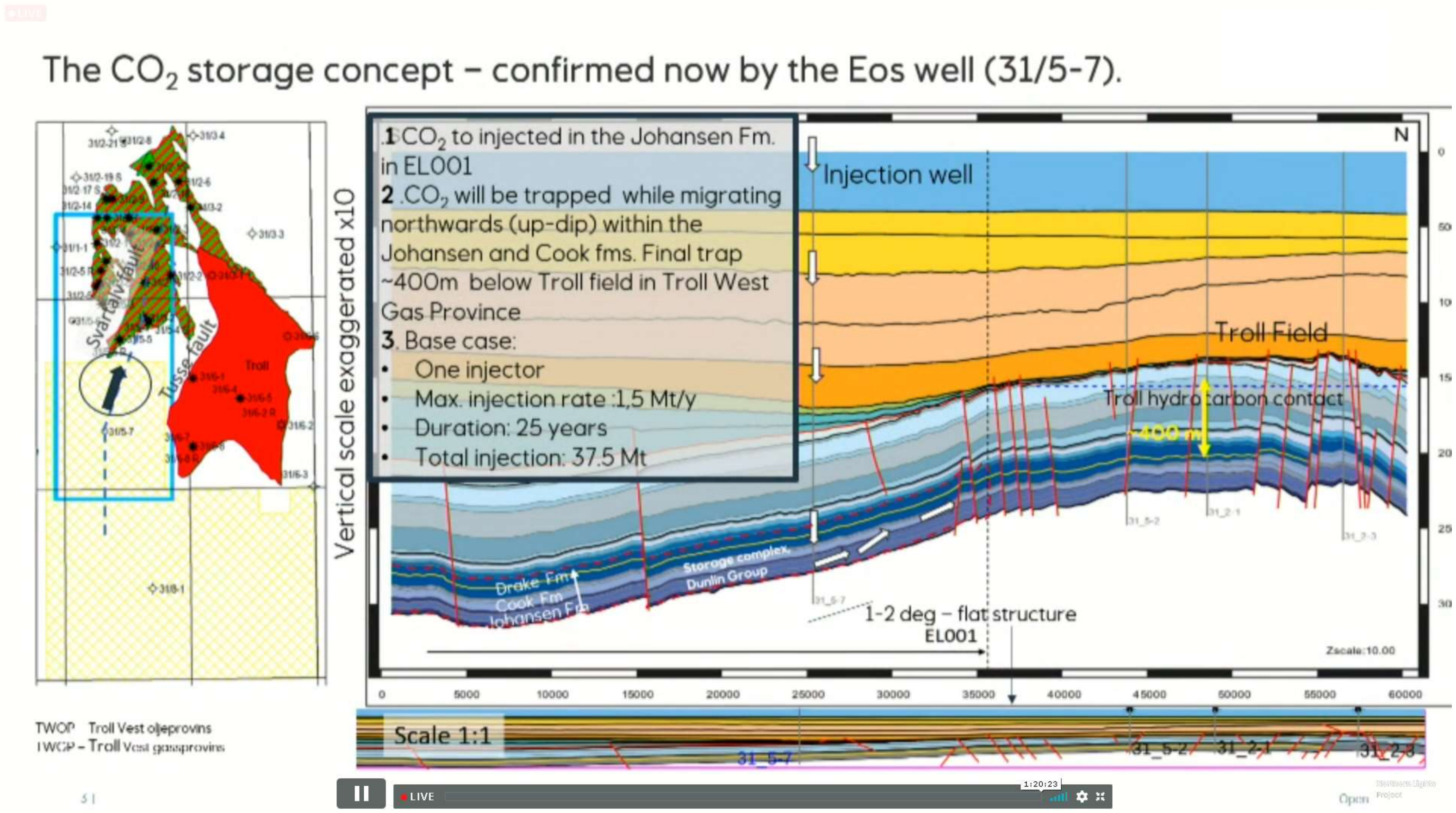




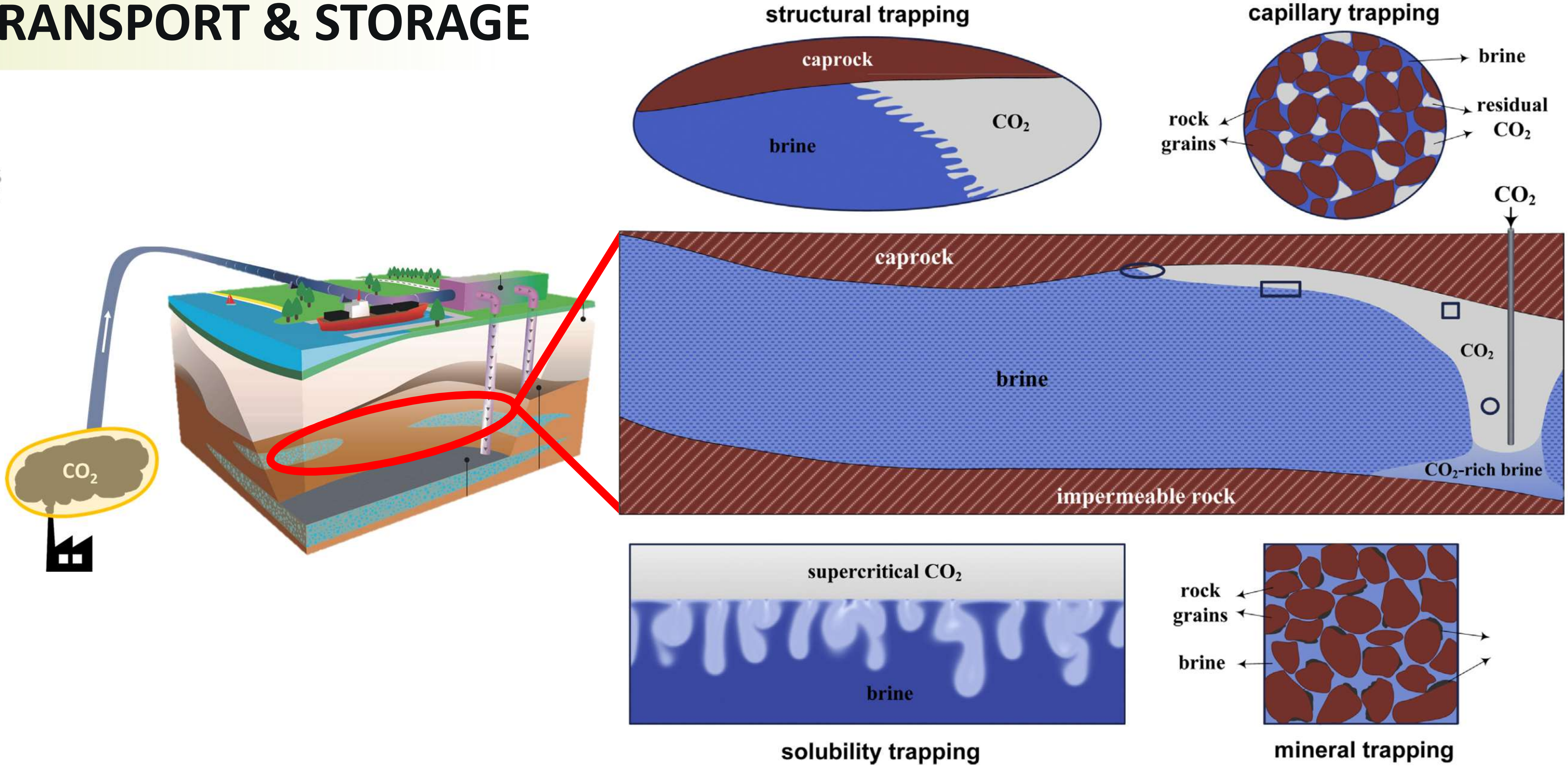
avenia brgm IFP Energies nouvelles Université de Pau et des Pays de l'Adour

TERĒGA snam LAFARGE SOFRESID ENGINEERING REPSOL Schlumberger

NORTHERN LIGHTS



CARBON CAPTURE TRANSPORT & STORAGE

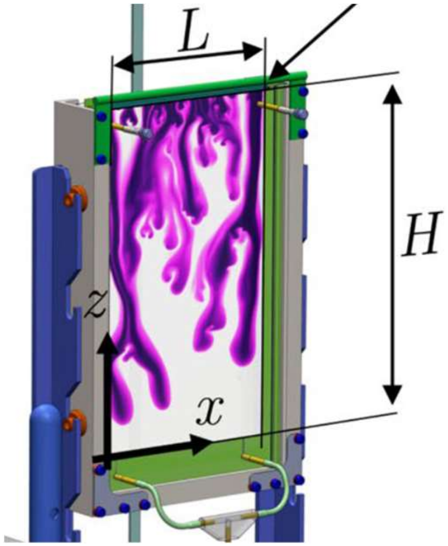


Emami-Meybodi et al. (2015))

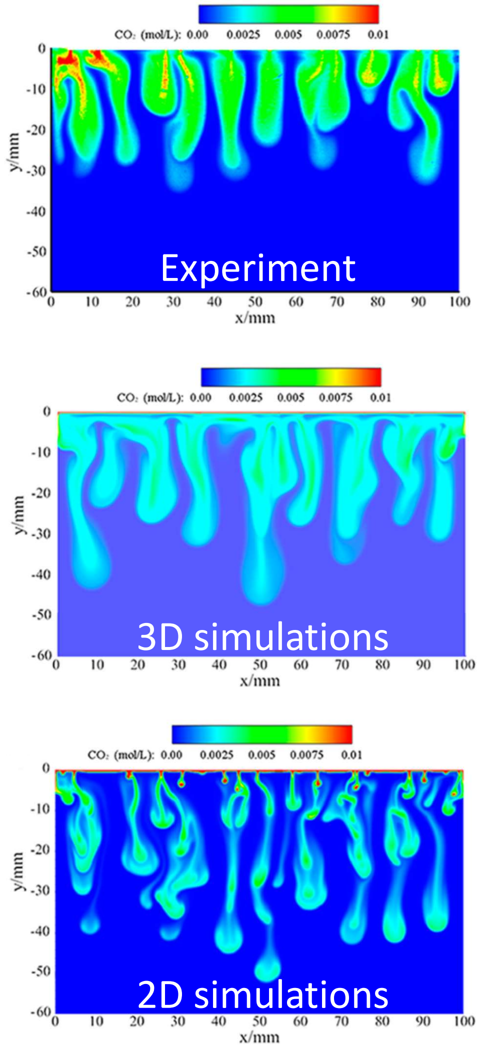
STATE-OF-THE-ART

Hele-Shaw cell

- Quasi-2D
- Mimics a porous medium
- Rayleigh-Darcy regime
- Atmospheric pressures



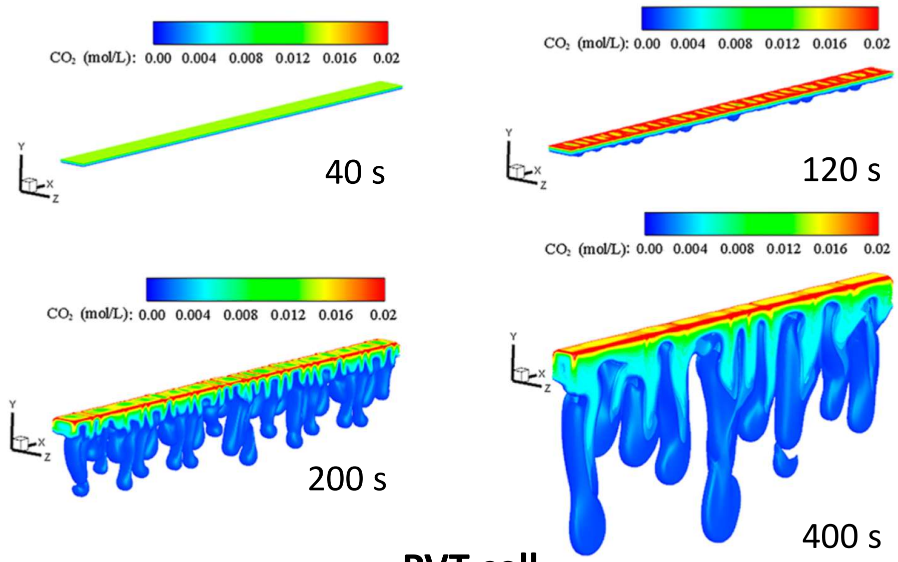
Alipour et al. (2020)



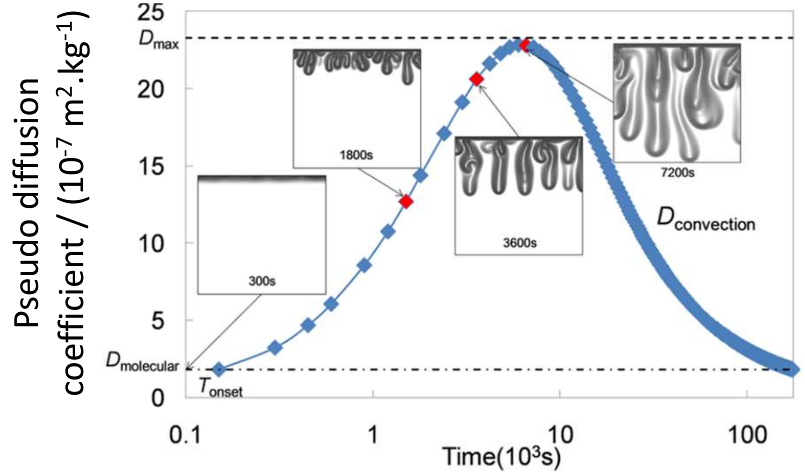
Zhang et al. (2020)

3D simulations

Zhang et al. (2020)



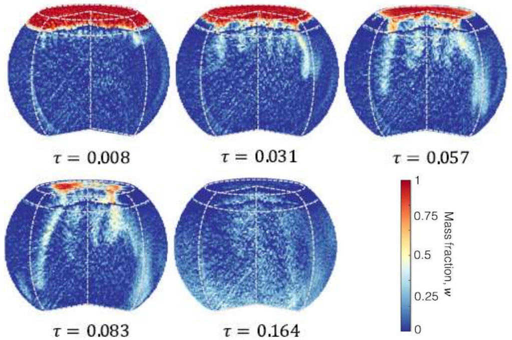
PVT cell



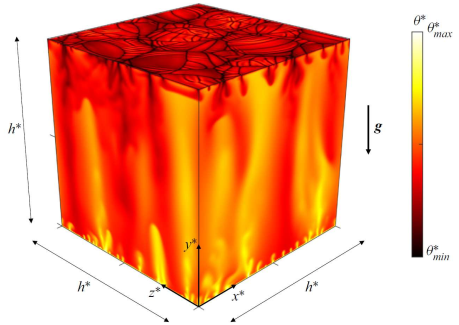
Tang et al. (2020)

STATE-OF-THE-ART

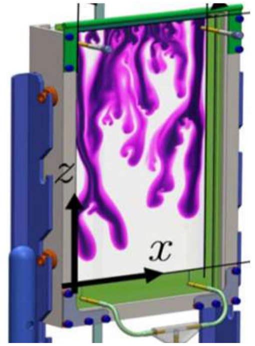
Rayleigh-Darcy (3D porous medium)	Rayleigh-Darcy – Hele-Shaw (2D free medium)	Rayleigh-Taylor (3D free medium)	Regime
10^{-19} - 10^{-7}	10^{-9} - 10^{-7}	1	Permeability / m^2



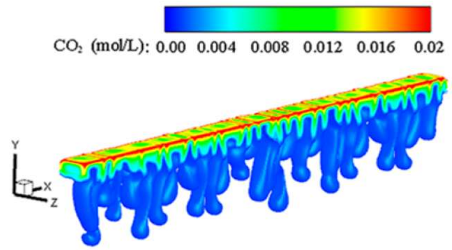
Liyanage et al. (2018)
Convective dissolution experiments in porous medium with X-ray tomography



Pirozzoli et al. (2020)
Simulations of heat convection in porous media



Alipour et al. (2020)
Convective dissolution experiments in Hele-Shaw cell

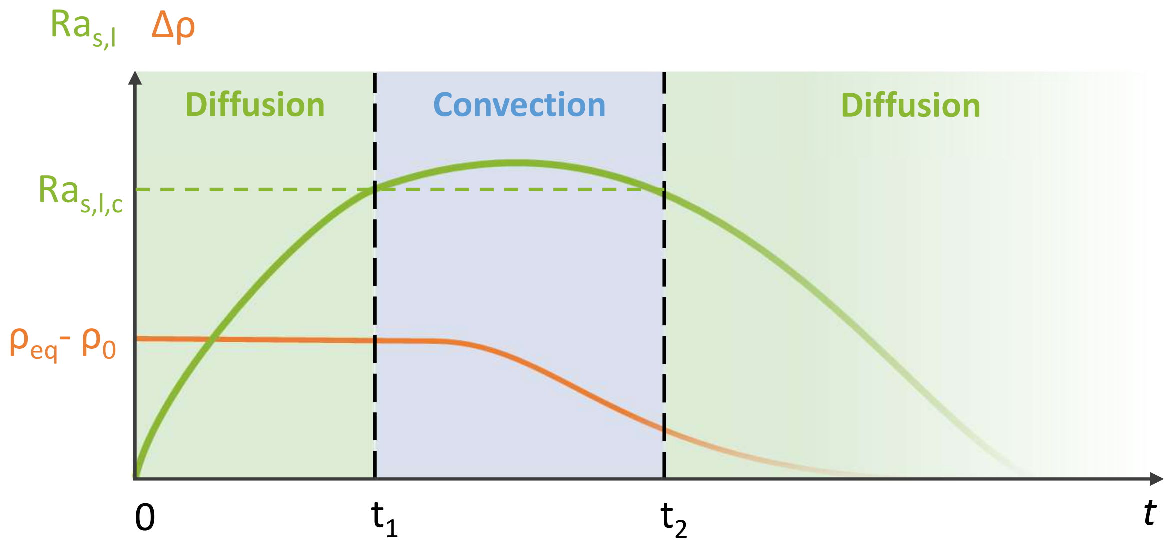


Zhang et al. (2020)
Simulations of convective dissolution in Hele-Shaw-like configurations

- Development of a reliable experimental apparatus and methodology
- Shadowgraph using visible radiations
- Better understand convective dissolution in free medium (e.g., CO_2 capture, safety of nuclear generation, protein crystallysation, etc.)
- Starting point in CO_2ES project before porous medium

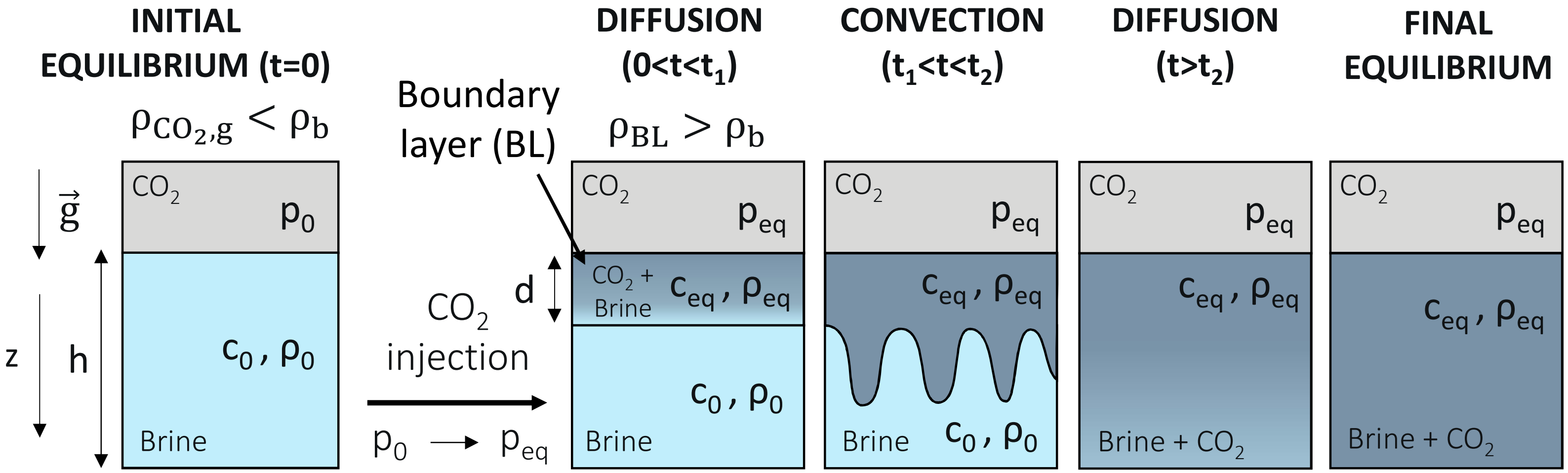
FUNDAMENTALS

p_0, p_{eq}	Initial and equilibrium pressures
c_0, c_{eq}	Initial and equilibrium concentrations of CO_2 in brine
ν, η	Kinematic and dynamic viscosities
ρ_b, ρ_{BL}	Densities of brine and BL
D	Fick diffusion coefficient
g	Gravitational acceleration
d, h	Thicknesses of the boundary and brine layers
$Ra_{s,l}$	Local solutal Rayleigh number



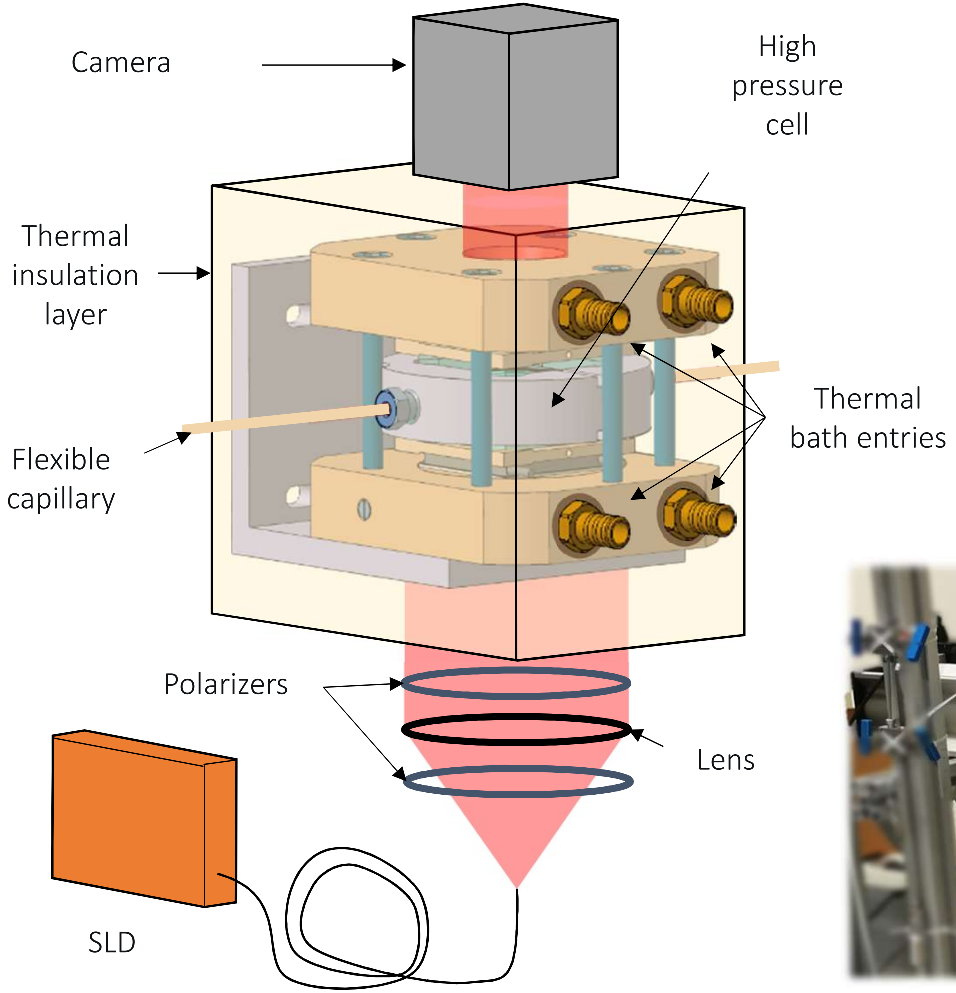
GRAVITATIONNAL INSTABILITY

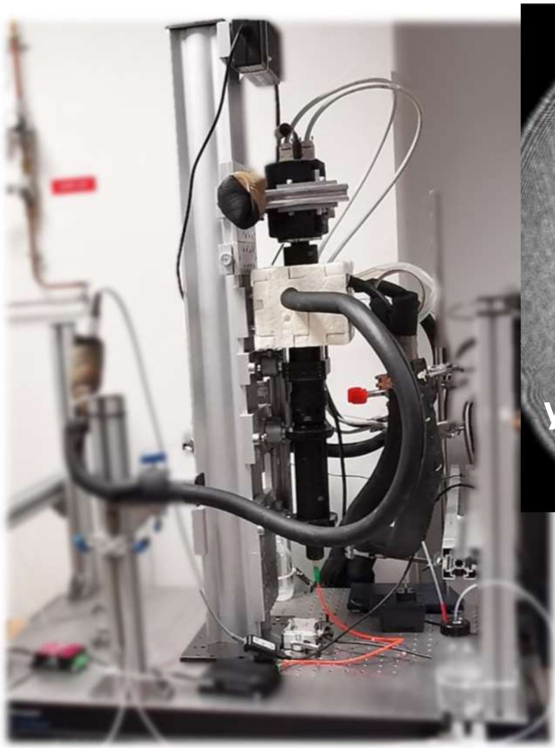
$$Ra_{s,l} = \frac{\beta \, \vec{g} \cdot \overrightarrow{\nabla c} \, d^4}{\nu D}$$

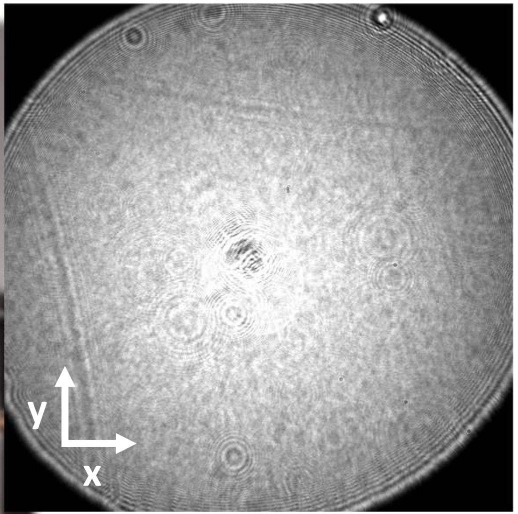


$\delta\rho \rightarrow \delta n \rightarrow$ Intensity variations

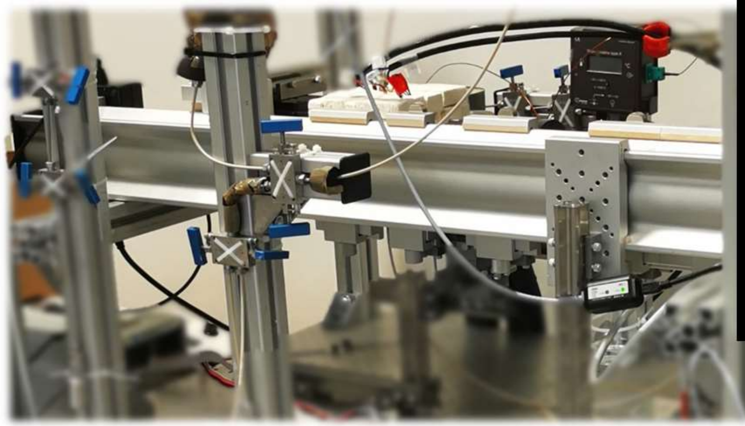
EXPERIMENTAL SET-UP

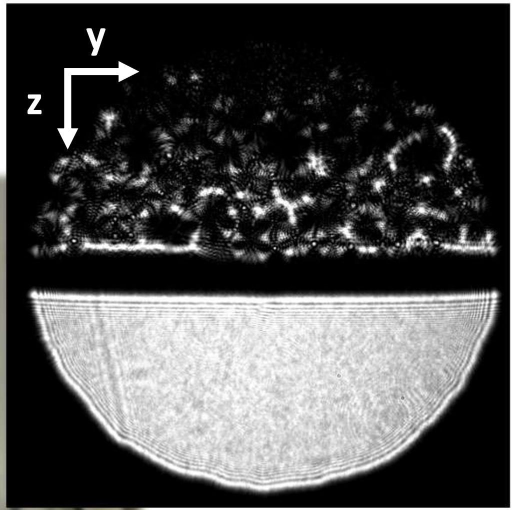






Vertical configuration



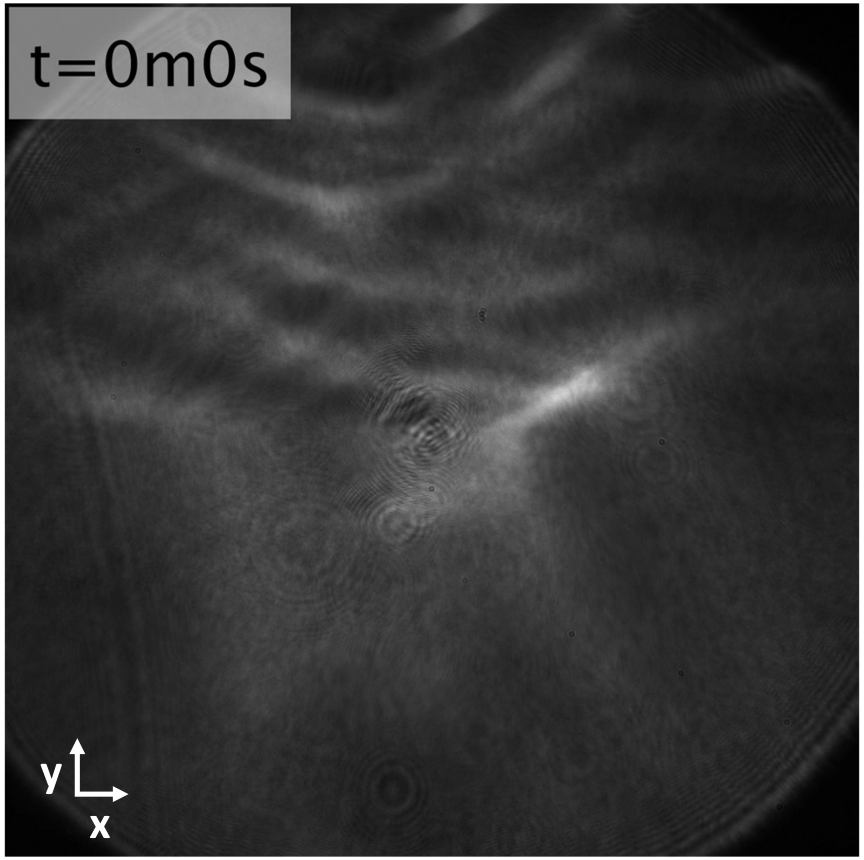


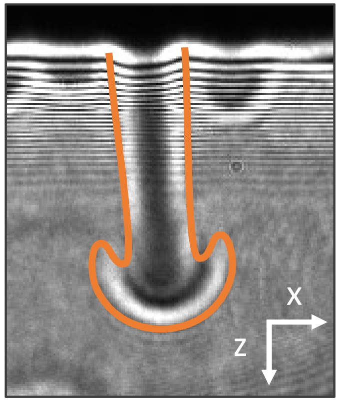
Horizontal configuration

PRELIMINARY ANALYSIS

Observation from above

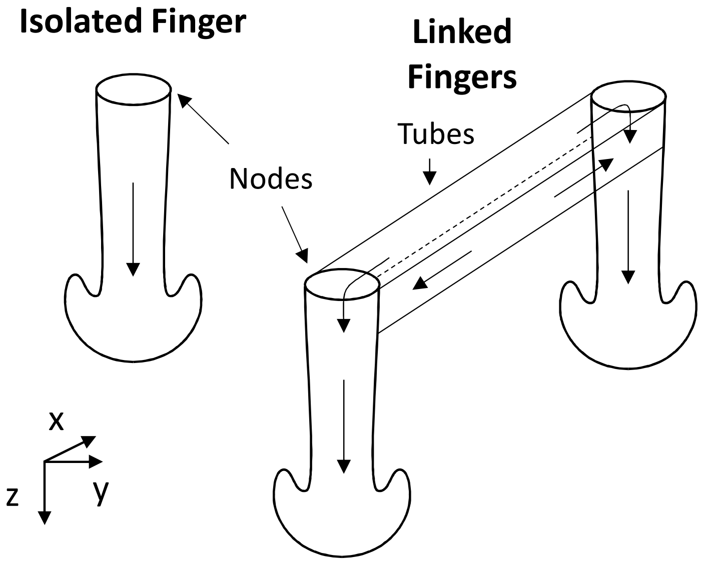
p_0 = 0.1 MPa p_{eq} = 2.1 MPa
Pure water



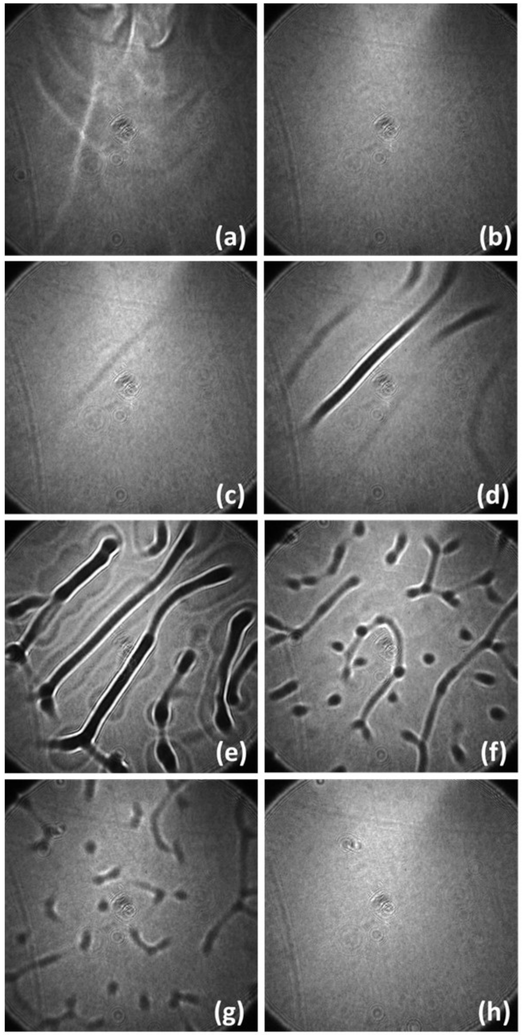


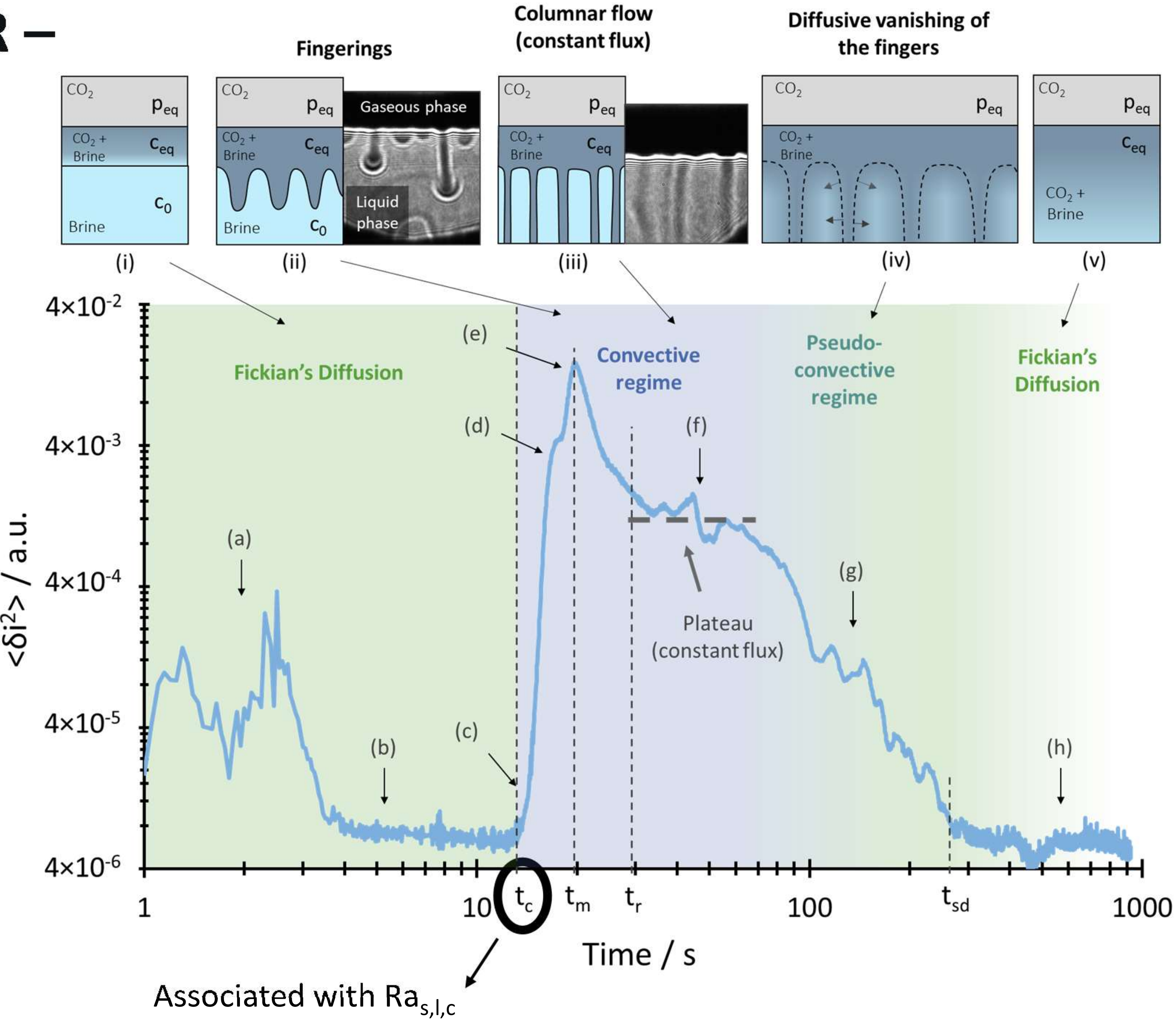
Hele-Shaw like configuration

Transversal observation



TEMPORAL BEHAVIOUR – VARIANCE ANALYSIS





GENERAL BEHAVIOUR

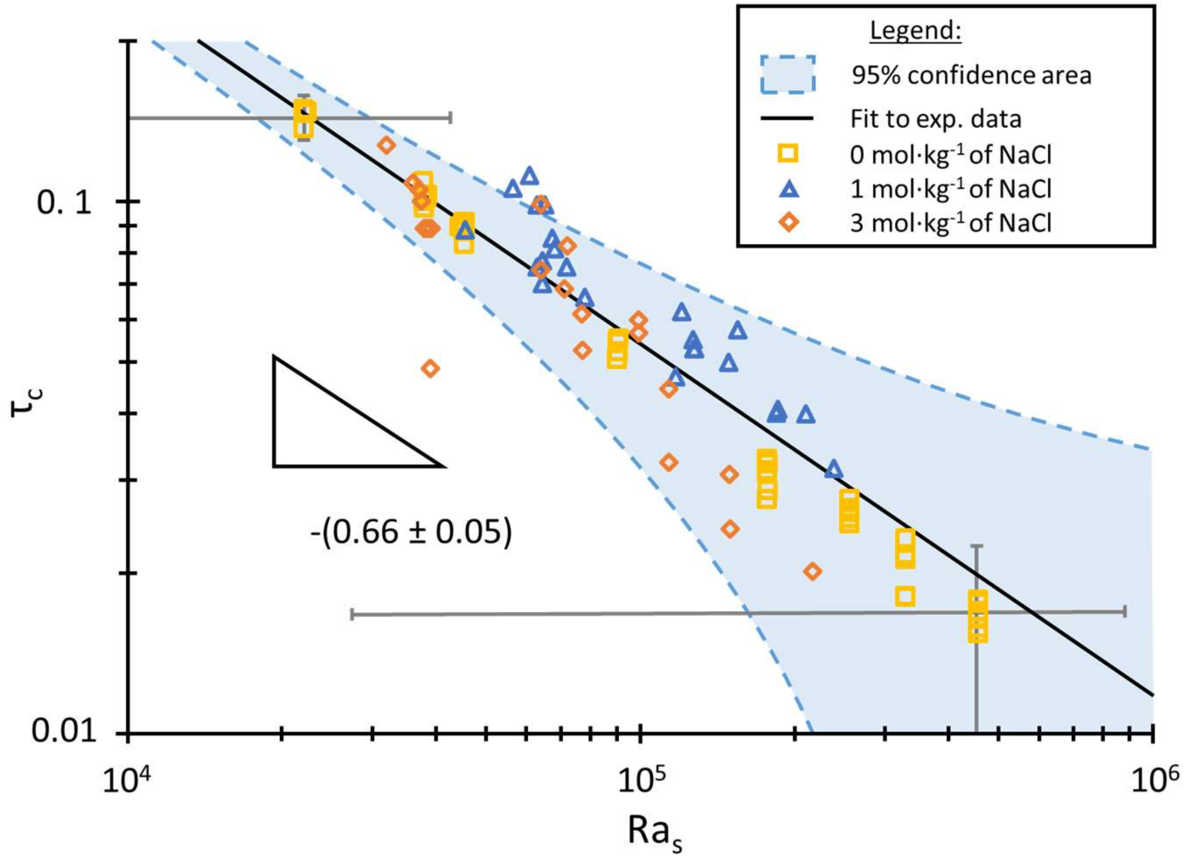
$$t_c = \underbrace{\frac{h^2}{\pi D}} Ra_{s,l,c}^{2/3} Ra_s^{-2/3}$$

Diffusive time over the entire brine layer $t_D = \frac{h^2}{\pi D}$

Dimensionless critical time $\tau_c = \frac{t_c}{t_D}$

Universal law in free media

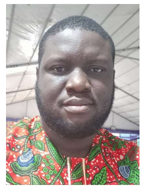
$$\tau_c = \left(\frac{Ra_s}{Ra_{s,l,c}}\right)^{-2/3}$$



P. Fruton *et al,* Nature Comm. submitted (2021)

Cédric GIRAUDET postdoc

Paul FRUTON PhD and postdoc



Happiness IMUETINYAN PhD

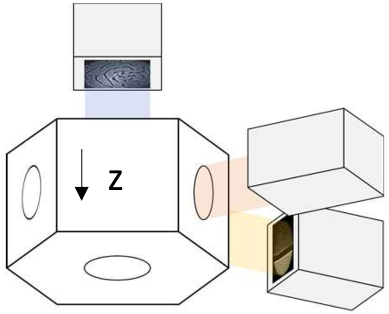
Aziza NAURUZBAEVA stage MS

PERSPECTIVES

Development of a new sample cell

Larger & thicker → Avoid meniscus effects, Better control of h

Multiple observations → Reconstruction of the concentration-field



Rayleigh-Darcy | Rayleigh-Taylor

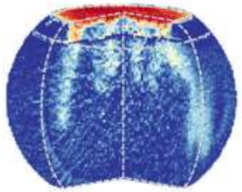
Permeability / m^2: 10^{-19}, 10^{-10}, 10^{-9}, 10^{-7}, 10^{-4}, 10^{-1}, 10^{0}

Vycor — SMs / Aquifers — Slits — Beads

Porous media — Free media

IN PREPARATION

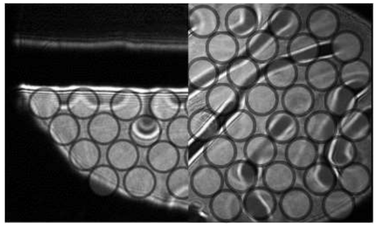
Core of water permeable rocks



Platform DMEX

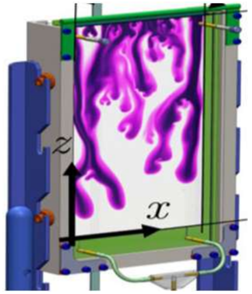
X-ray tomography (3D)

Beads / Silica monoliths (SMs) /Vycor glass

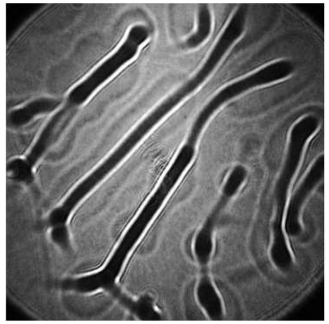


Refractive index matching (3D)

Thin slits

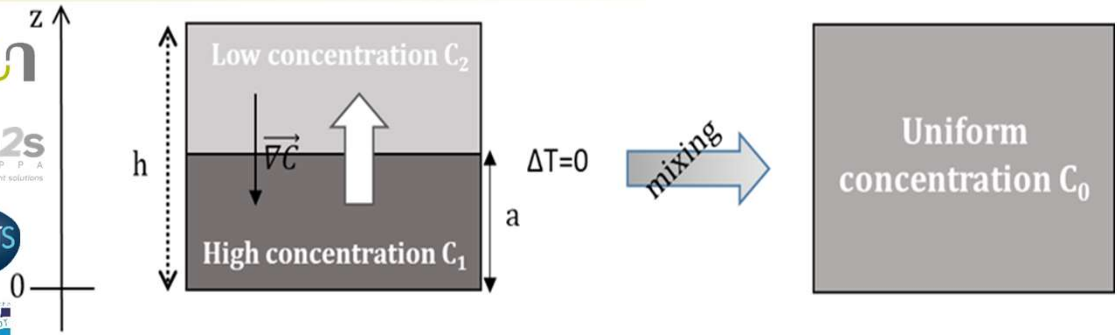


Hele-Shaw (2D)



CO2ES (3D)

FREE DIFFUSION OF SALT MIXTURES



Fickian diffusion: $\vec{j} = -\rho D \overrightarrow{\nabla C}$

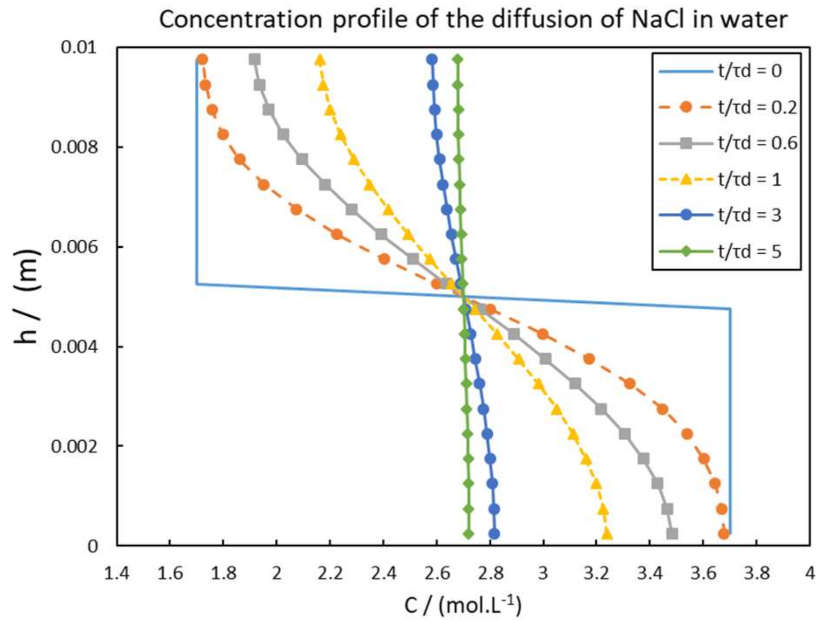
Initial conditions

$$C(z,0) = \begin{cases} C_1, & 0 < z < a \\ C_2, & a < z < h \end{cases}$$

$C_{mean} = (C_1 + C_2) / 2$

$\Delta C = C_1 - C_2$

Plot of the concentration profile with PHREEQC

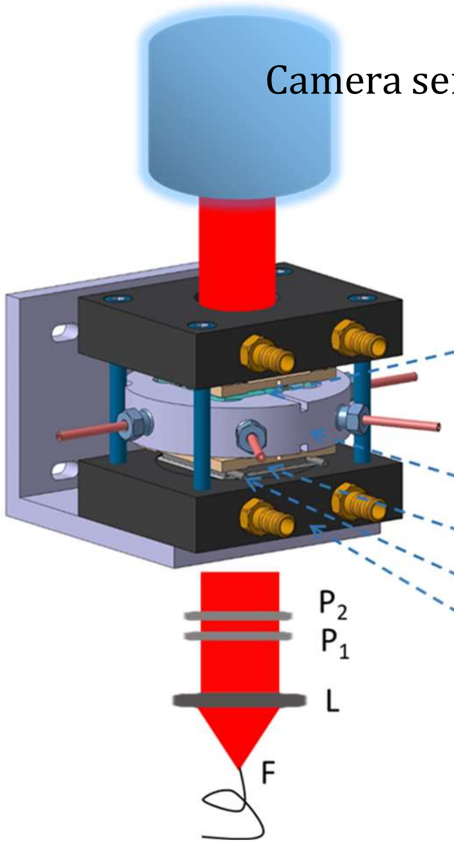


$$\tau_d = \frac{(h/2)^2}{(\pi D)} \approx 1.43 \text{ hours}$$

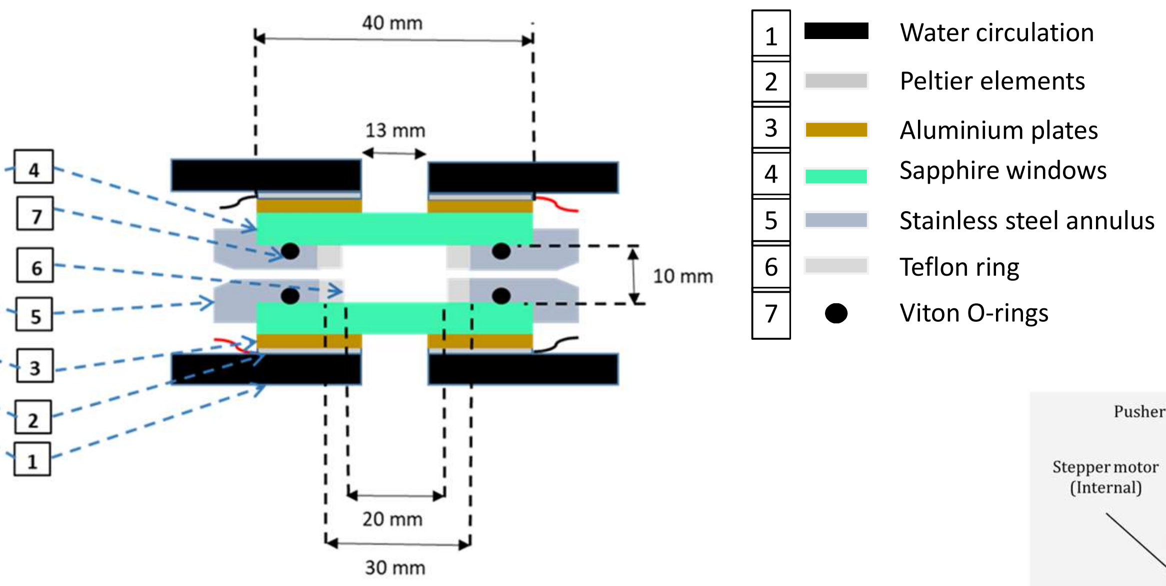
- C_1= 3.7 mol.L^{-1}
- C_2= 1.7 mol.L^{-1}
- C_0= 2.7 mol.L^{-1}
- D= 1.55×10^{-5} $cm^2.s^{-1}$
- h= 1 cm

DIFFUSION CELL & SHADOWGRAPH SET-UP

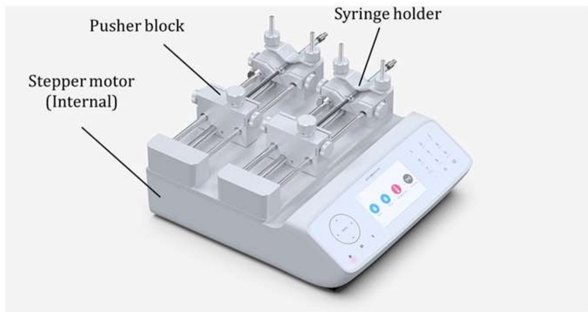
Camera sensor
- setup#1 : scientific-CMOS camera (Hamamatsu Digital Camera C13440, ORCA - Flash 4.0)
- setup#2 : CCD progressive PIKE camera (Allied Vision Technologies, PIKE-F421B)



Experimental setup



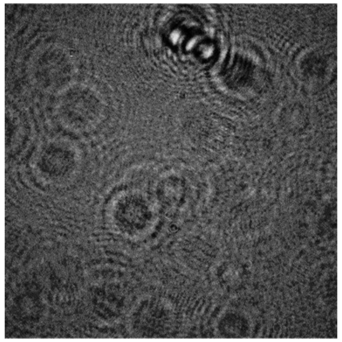
A. T. Ndjaka *et al,* Eur. Phys. J. E submitted (2021).



Fusion 4000 independent dual-channel infusion and withdrawl syringe pump from Chemyx.

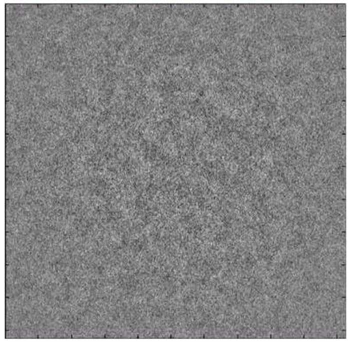
DIFFERENTIAL DYNAMIC ALGORITHM

Free diffusion experiment of NaCl into water ($C = 2.7\ mol.L^{-1}$ and $\Delta C = 2\ mol.L^{-1}$).



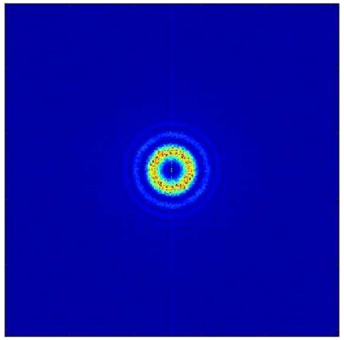
Near field image 1024x1024 pix^2 recorded image

$I(\vec{x}, t)$



Difference between two images separated by $\Delta t = 2$ s

$\Delta \boldsymbol{i}(\vec{x}, t, \Delta t) = \boldsymbol{i}(\vec{x}, t) - \boldsymbol{i}(\vec{x}, t + \Delta t)$

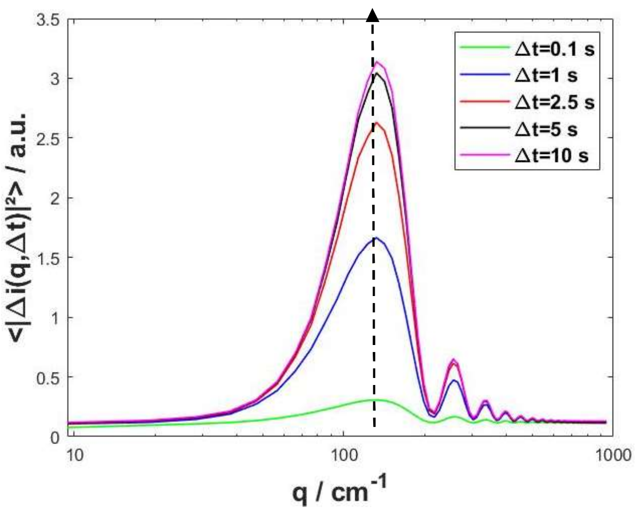


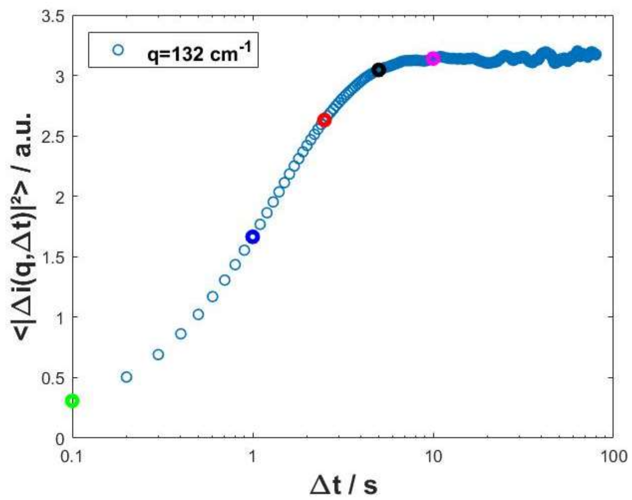
2D FFT of image differences

$|\Delta \boldsymbol{i}(\vec{q}, t, \Delta t)|^2 = |\boldsymbol{i}(\vec{q}, t) - \boldsymbol{i}(\vec{q}, t + \Delta t)|^2$

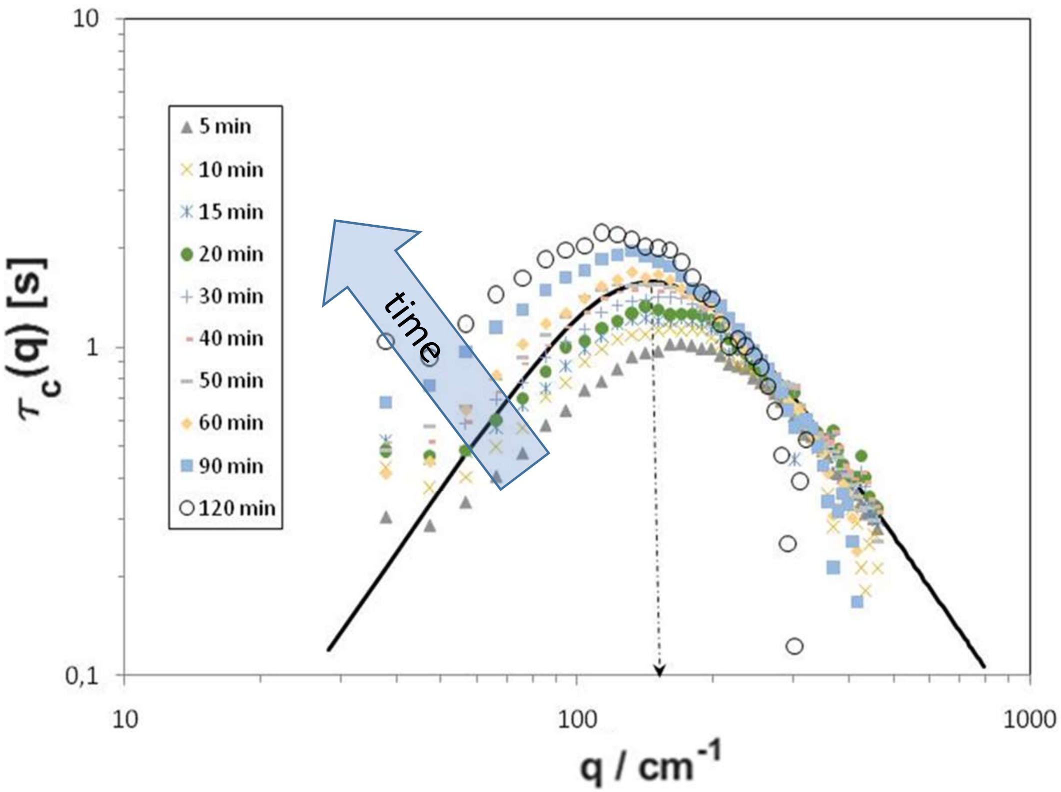
STRUCTURE FUNCTION

$SF(q, \Delta t)$





DYNAMIC ANALYSIS METHOD OF C-NEFS



Decay times of the c-NEFs as a function of the wave numbers and time after closing the inlet/outlet valves for the free-diffusion experiment :NaCl/water at C = 2.7 mol.L^{-1}, ΔC = 2 mol.L^{-1} and T=25 °C.

Fitting the SFs in the wave number range from 30 to 500 cm^{-1}

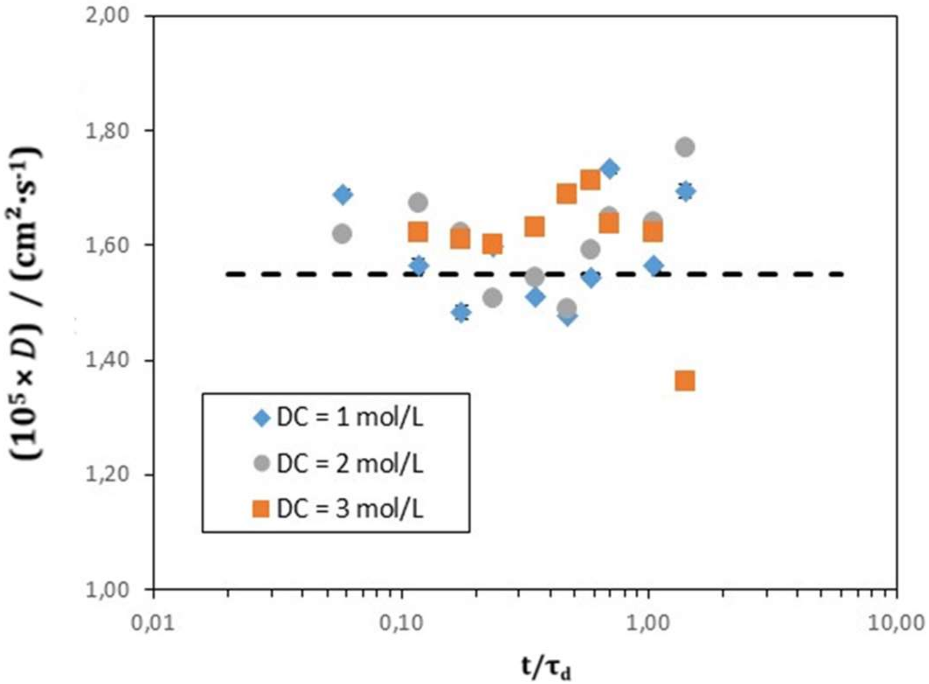
$$\tau_c(q) = \frac{1}{Dq^2\left[1+\left(\frac{q_c}{q}\right)^4\right]}$$

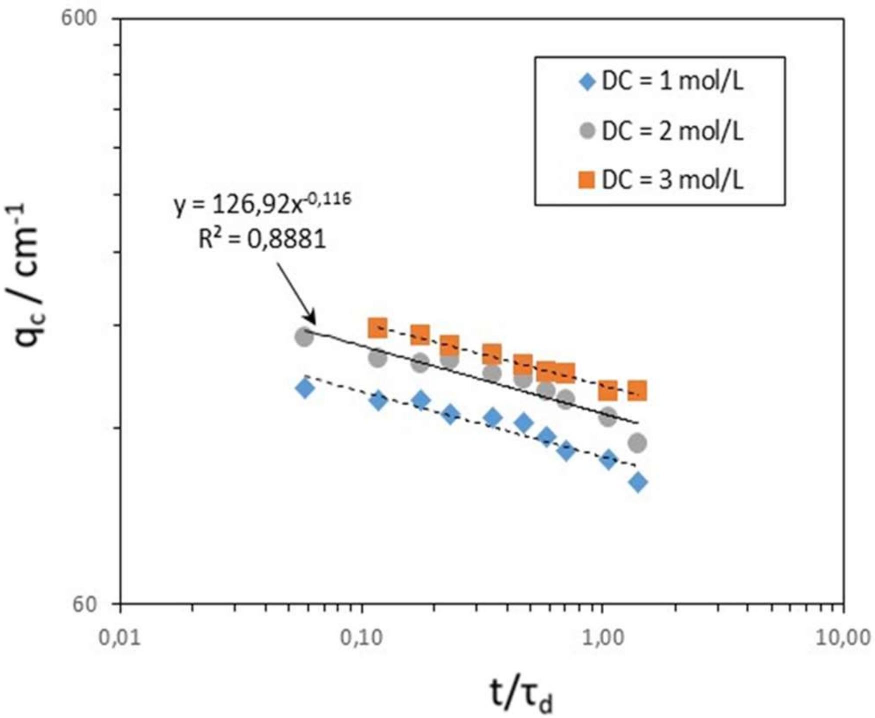
$$q_c(t) = \sqrt[4]{\frac{\beta g(C_1 - C_2)}{\nu D\sqrt{4\pi D t}}}$$

RESULTS: MEASUREMENTS OF *D* SALTS IN WATER

- Sodium Chloride / water mixture: C = 2,7 mol.L^{-1} , T = 25 °C & **ΔT = 0 °C** & P=1 atm

Diffusive time $\tau_d = \frac{(h/2)^2}{(\pi D)} \approx 86$ min.





Rard and Miller (1979), *Journal of Solution Chemistry,* **8**(10), 701–716

M. Schraml *et al*, Eur. Phys. J. E Soft Matter. 2021 Oct 18;44(10):128.

$$q_c(t) = \sqrt[4]{\frac{\beta g(C_1 - C_2)}{\nu D\sqrt{4\pi D t}}} \propto t^{-0,125}$$

SUPERIMPOSITION OF TWO AQUEOUS LAYERS OF NON-REACTIVE SALTS (OBSERVATIONS PARALLEL TO THE GRAVITY)

T = 25 °C & ΔT = 0 °C & P=1 atm)

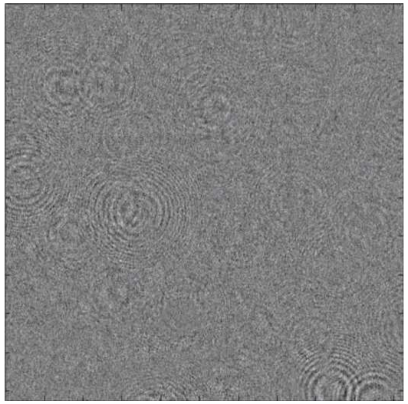
$CaCl_2 + H_2O$

$NaCl + H_2O$

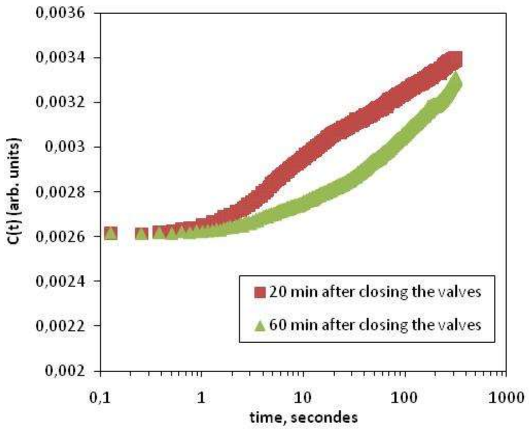
Light beam

C_{CaCl2} = 0.46 mol.L^{-1} (ρ = 1.038962 g.cm^{-3})

C_{NaCl} = 2.637 mol.L^{-1} (ρ = 1.098622 g.cm^{-3})



Normalized image differences 20 minutes after closing



Contrast of shadowgraph image sequences $C(t)$ as a function of time and for different moments after closing the valves

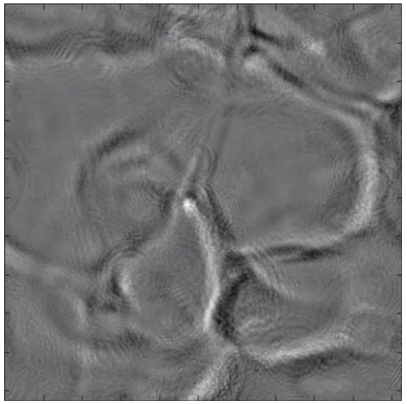
$NaCl + H_2O$

$Na_2SO_4 + H_2O$

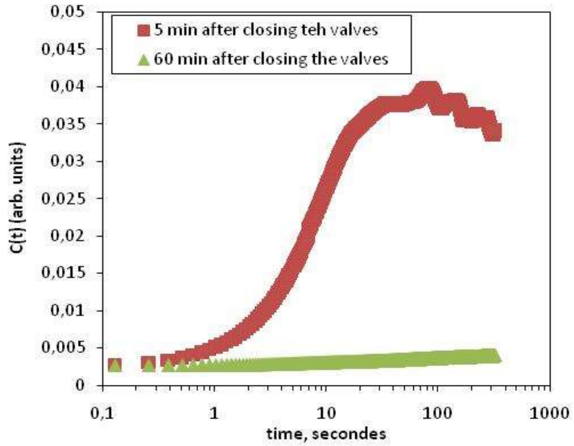
Light beam

C_{NaCl} = 2.637 mol.L^{-1} (ρ = 1.098622 g.cm^{-3})

C_{Na2SO4} = 1.484 mol.L^{-1} (ρ = 1.168653 g.cm^{-3})



Normalized image differences 20 minutes after closing



Contrast of shadowgraph image sequences $C(t)$ as a function of time and for different moments after closing the valves

SUPERIMPOSITION OF TWO AQUEOUS LAYERS OF REACTIVE SALTS: (OBSERVATIONS PARALLEL TO THE GRAVITY)

$l_1 = l_2 = 3/8$ cm

a = 1/4 cm

$CaCl_2 + H_2O$

$NaCl + H_2O$

$Na_2SO_4 + H_2O$

$C_{CaCl2} = 0{,}46$ mol.L^{-1} (ρ = 1,038962 g.cm^{-3})

$C_{NaCl} = 2.637$ mol.L^{-1} (ρ = 1,098622 g.cm^{-3})

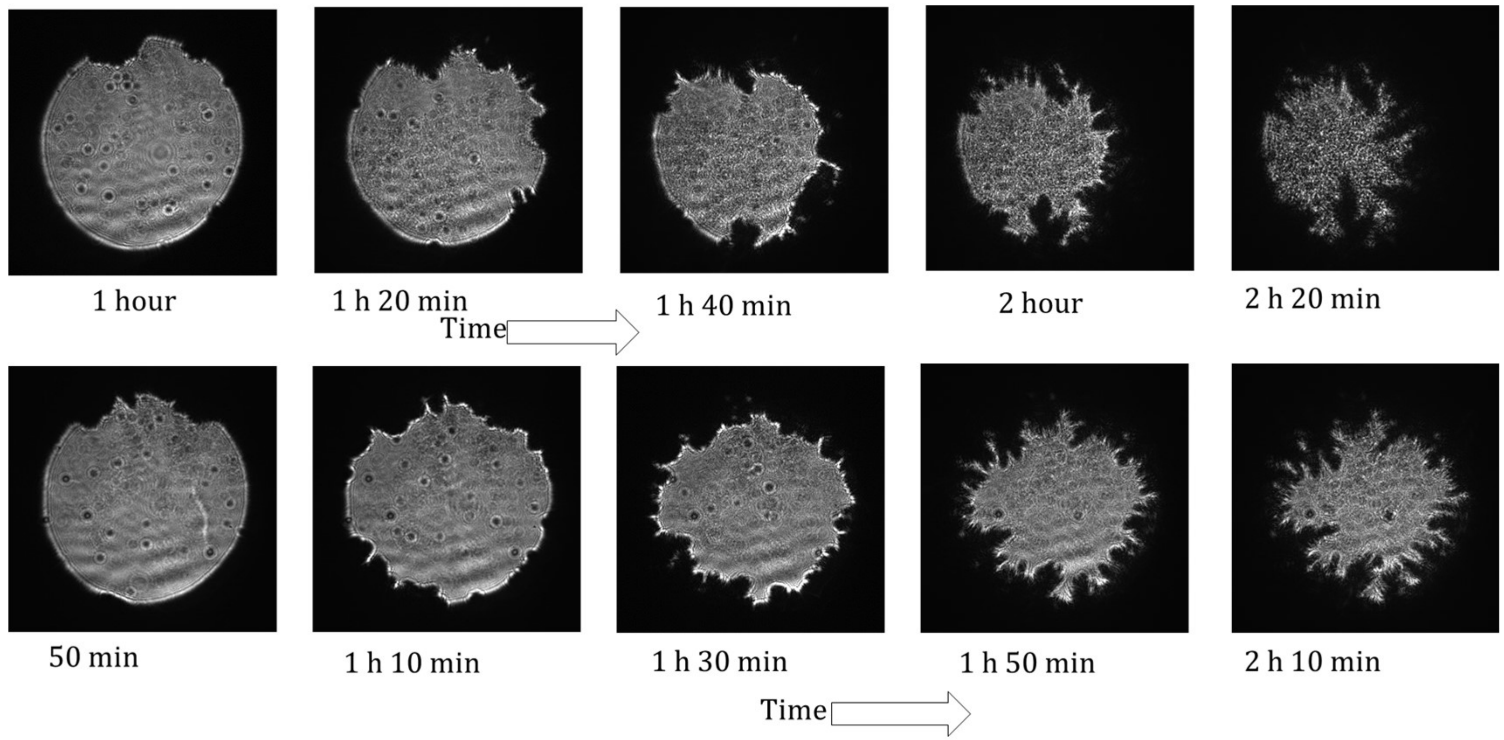
$C_{Na2SO4} = 1{,}484$ mol.L^{-1} (ρ = 1,168653 g.cm^{-3})

Light beam

Shadowgraph images during the reactive transport

T = 25 °C & ΔT = 0 °C

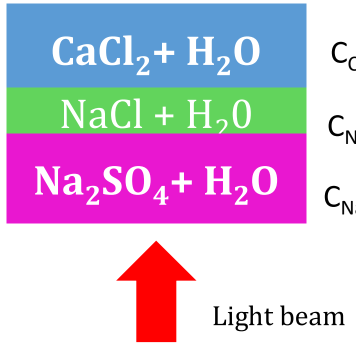
T = 25 °C & ΔT = 20 °C



SUPERIMPOSITION OF TWO AQUEOUS LAYERS OF REACTIVE SALTS (OBSERVATIONS PARALLEL TO THE GRAVITY) : IMPACT OF ΔT

$l_1 = l_2 = 3/8$ cm

a = 1/4 cm

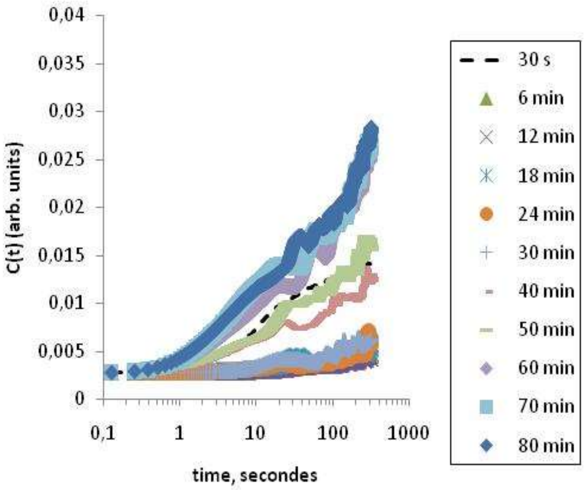


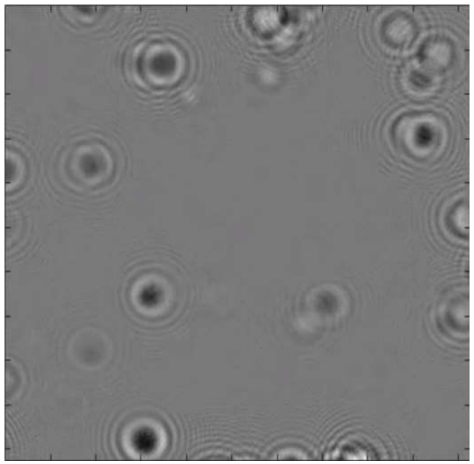
C_{CaCl2} = 0,46 mol.L^{-1} (ρ = 1,038962 g.cm^{-3})

C_{NaCl} = 2.637 mol.L^{-1} (ρ = 1,098622 g.cm^{-3})

C_{Na2SO4} = 1,484 mol.L^{-1} (ρ = 1,168653 g.cm^{-3})

- Precipitation speed depends on the thickness of the buffer solution : $t_p = \frac{a^2}{\pi D}$ and $\Delta t_p = 2 t_p \frac{\Delta a}{a}$





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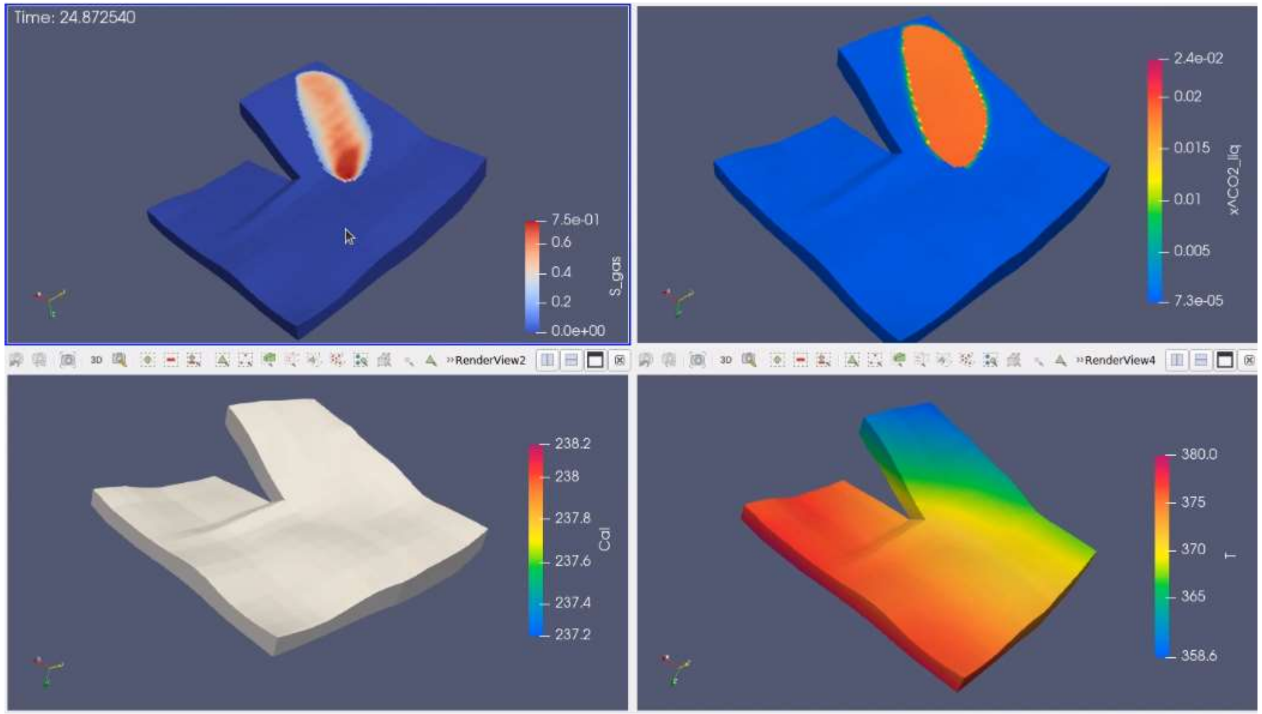
Ange Tatiana NDJAKA PhD and postdoc

Christian OKO PhD

Rizwan MINHAS stage MS

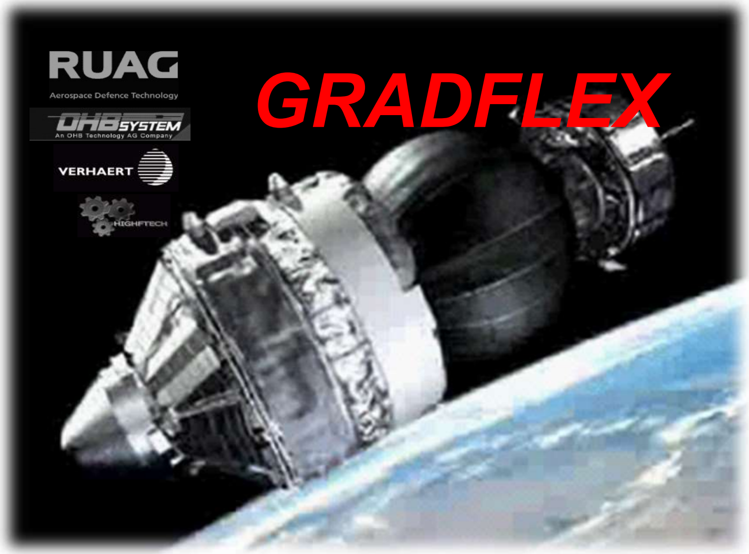
NUMERICAL SIMULATIONS AT BASIN SCALE

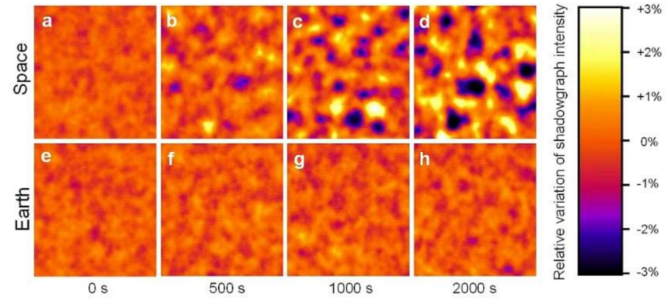


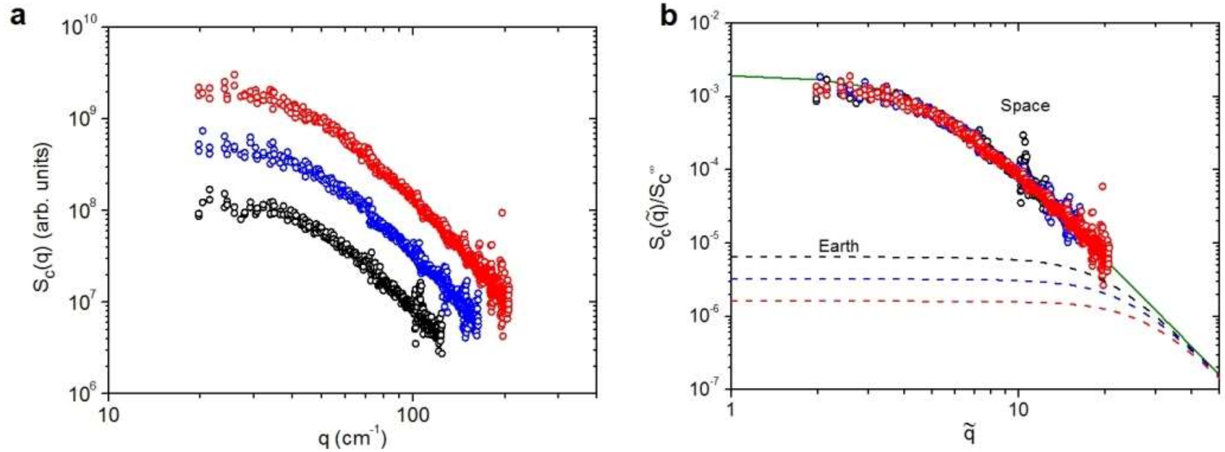
Brahim
AMAZIANE
Ass. Pr.

Nicolas
PILLARDOU
PhD

GRADFLEX – FOTON M3 (2007)





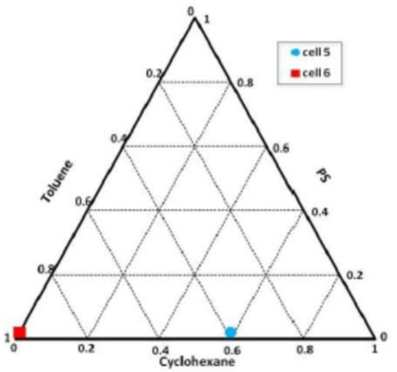


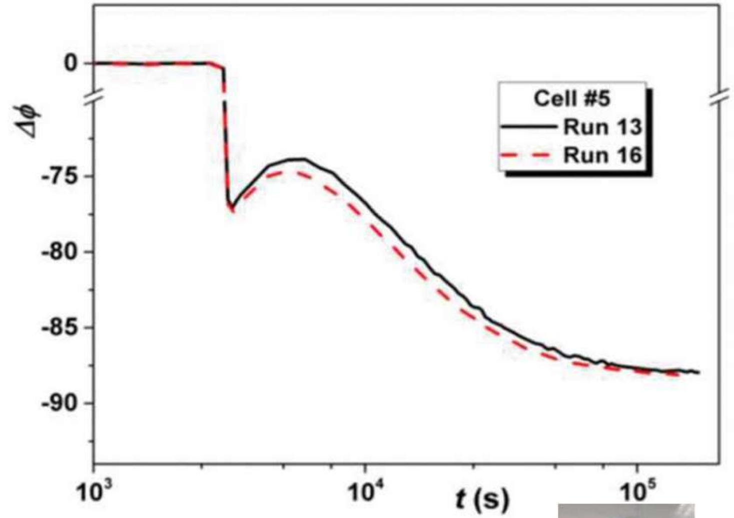
Vailati et al. (2011)

Croccolo et al. (2016)

DCMIX #4 – ISS (2018)

Polystyrene
+ Toluene + Cyclo-hexane



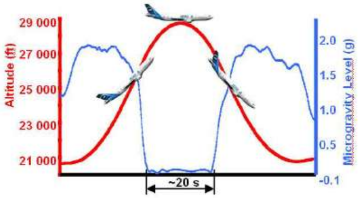


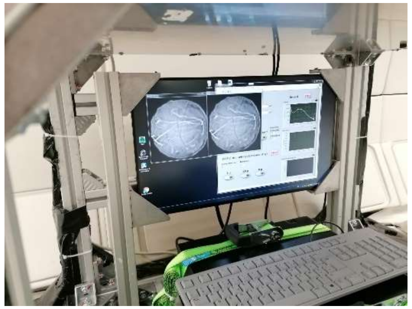
Mialdun *et al.*, EPJE

Henri
BATALLER
Ass. Pr.

Loreto
GARCIA-
FERNANDEZ
postdoc

CO2EX – PARABOLIC FLIGHT (2019 AND 2020)





cnes
CENTRE NATIONAL D'ÉTUDES SPATIALES

C. Giraudet et al. To be submitted

Cédric GIRAUDET postdoc

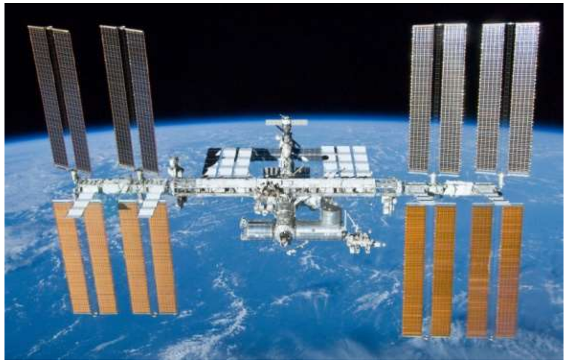
Paul FRUTON PhD and postdoc

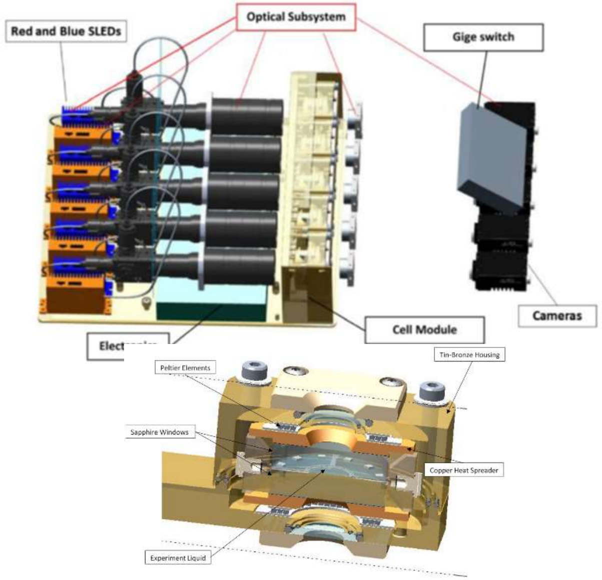
Mohammed CRAGA PhD

Emma LISOIR stage BS

GIANT FLUCTUATIONS – ISS (2025 - 2028)

Giant Fluctuations, ISS, 2024





A Vailati et al. Microgravity Sci. and Technol. (2020)

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Mathilde SAN BAUDELIO stage BS

THANK YOU! QUESTIONS?