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# UNDERGROUND GAS STORAGE LIMITED BY *Reaction-diffusion Patterns*

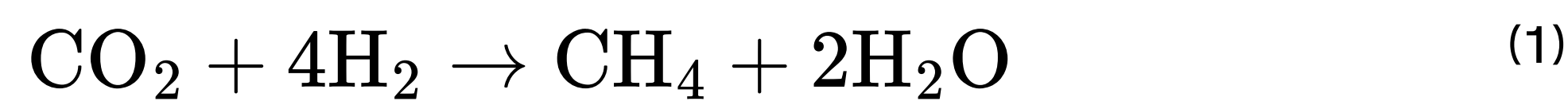
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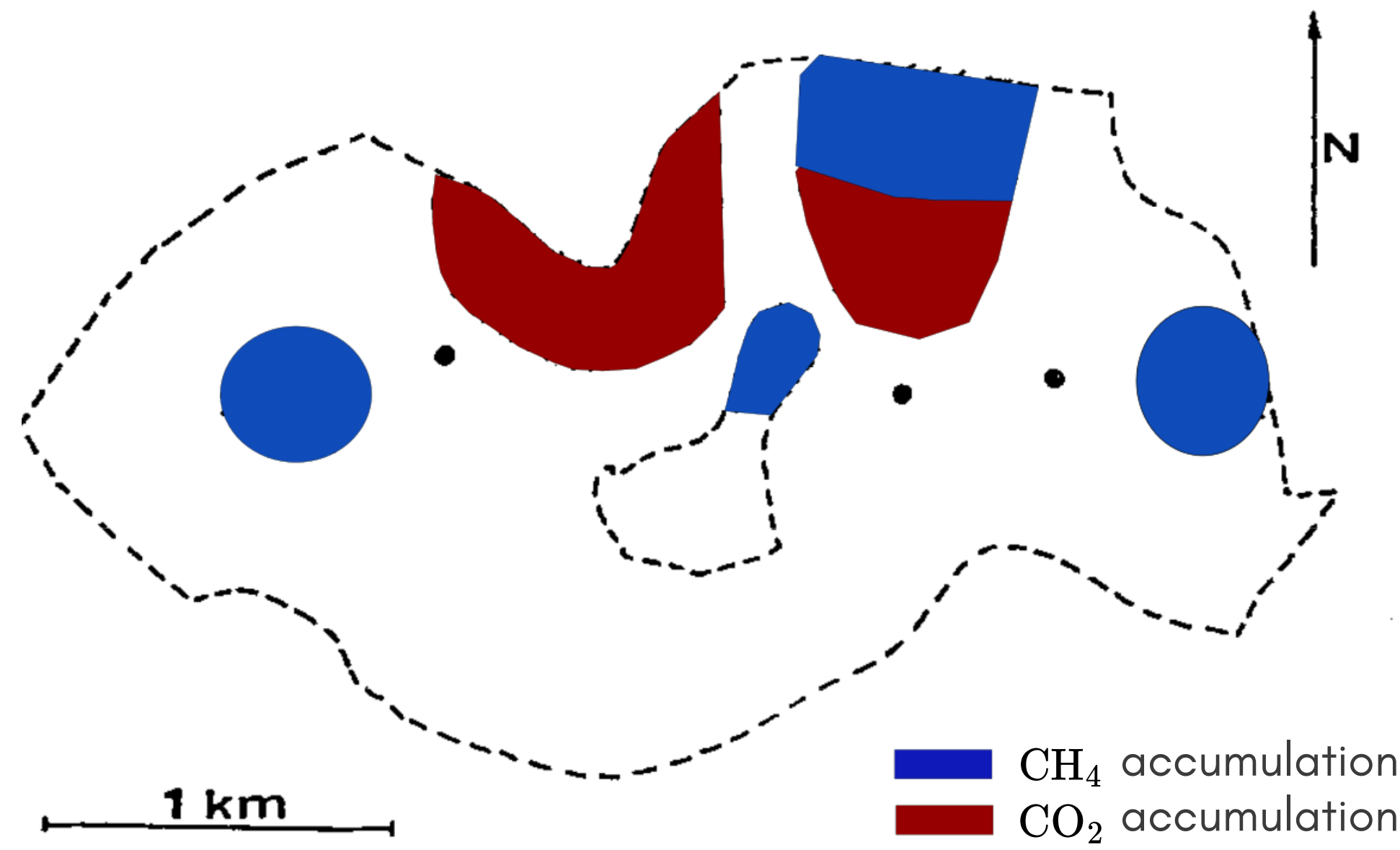


## Overview

New technology in underground gas storage (UGS) is proposed, which consists of injecting hydrogen and carbon dioxide into aquifers; bacteria use them for metabolism and transform into methane, which leads to the enrichment of the stored gas.



- To transform the injected mixture of  $\text{H}_2/\text{CO}_2$  into  $\text{CH}_4$ , the gas composition should be **stoichiometric** and **uniform in space**.
- An **unexpected behavior** of the gas was reported in Lobodice town gas storage reservoir, Czech Republic (Buzek et al. 1994).



The existence of such stationary structures implies spatial heterogeneity of carbon dioxide and methane, indicating incomplete methanation.

- Can these patterns be effectively prevented or avoided?

## Objective

Maintain the reservoir outside of the pattern formation regime by understanding the mechanisms behind pattern emergence and identifying the key criteria that lead to their development in UGS.

## Reaction-diffusion model behind pattern formation in UGS

- Reduced model of two diffusion-reaction equations:

The reservoir is assumed homogeneous and isothermal, and species mixing is ideal, advective transport, gravity and capillary pressure effects are ignored. The aqueous phase is consisting essentially of water, while the gas phase consists of 98% of  $\text{H}_2$ . Under these conditions, the conservation laws governing chemical species and bacterial dynamics reduce to a system of two reaction-diffusion equations:

$$\partial_\tau \mathbf{U} = D\nabla^2 \mathbf{U} + \mathbf{F}(\mathbf{U}), \quad (2)$$

$$\mathbf{U} = \begin{bmatrix} c \\ n \end{bmatrix}, D = \begin{bmatrix} 1 & 0 \\ 0 & \xi \end{bmatrix}, \mathbf{F}(\mathbf{U}) = \begin{bmatrix} f(c, n) = q - \lambda_1 n^{\alpha+1} c \\ g(c, n) = n^{\alpha+1} c - \lambda_2 n^\beta \end{bmatrix}, \quad (3)$$

$$\xi = \frac{\text{Bacteria diffusion}}{\text{CO}_2 \text{ diffusion}} \quad \text{and} \quad q = \frac{\text{CO}_2 \text{ injection rate}}{\text{Bacteria growth rate}}$$

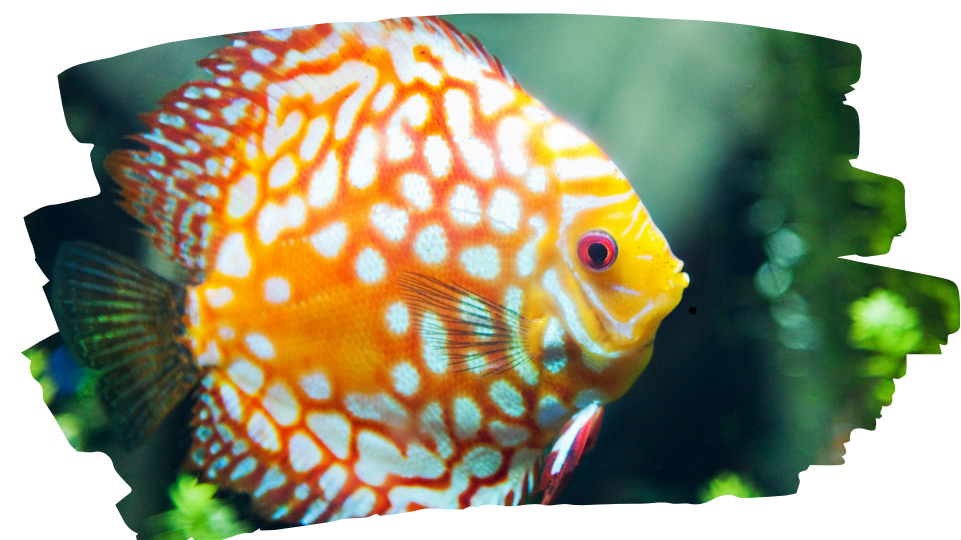
- Stability analysis and criteria of patterns emergence:

The base state solution corresponds to  $\mathbf{F}(\mathbf{U}) = 0$ . If the base state solution is **stable**, there is **no pattern**. If the solution is **unstable**, **three patterns are identified**:

- Stationary oscillatory in space (**Hopf-Andronov oscillations**)
- Non-stationary uniform in space and oscillatory in time (**Turing pattern**)
- Non-stationary and oscillatory in both space and time (**Hopf-Turing pattern**)

## Turing pattern and self-organization in nature

The theory of reaction-diffusion and self-organization determines the limits of the pattern zone with respect to the process parameters.



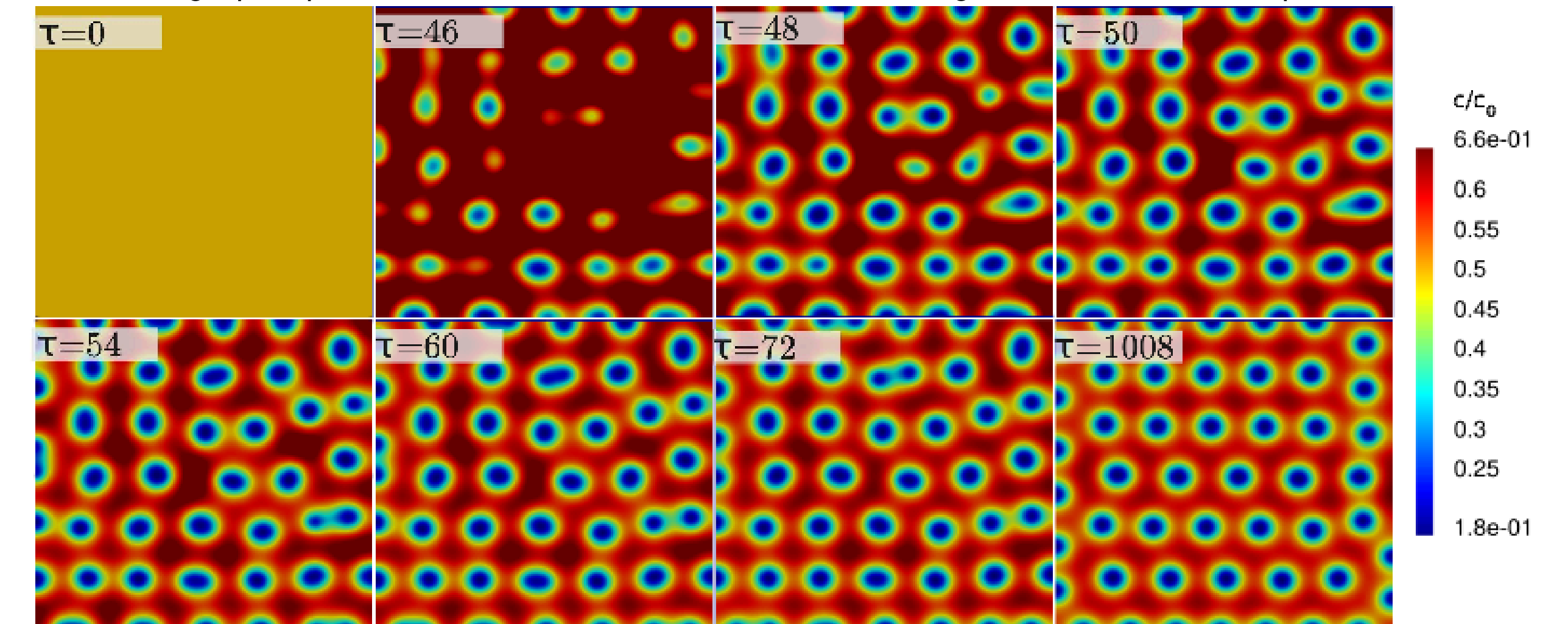
Reaction-diffusion competitions are behind the patterned skin of Leopard and discus fish



Ripples in sand formed by wind and Zebra stripes

## Stationary structure ( $\xi = 0.012$ and $q = 1.1$ ): Turing pattern

Stabilizing spot pattern in  $\text{CO}_2$ : Low  $\text{CO}_2$  indicates high nutrient consumption



Temporal evolution of bacteria concentration

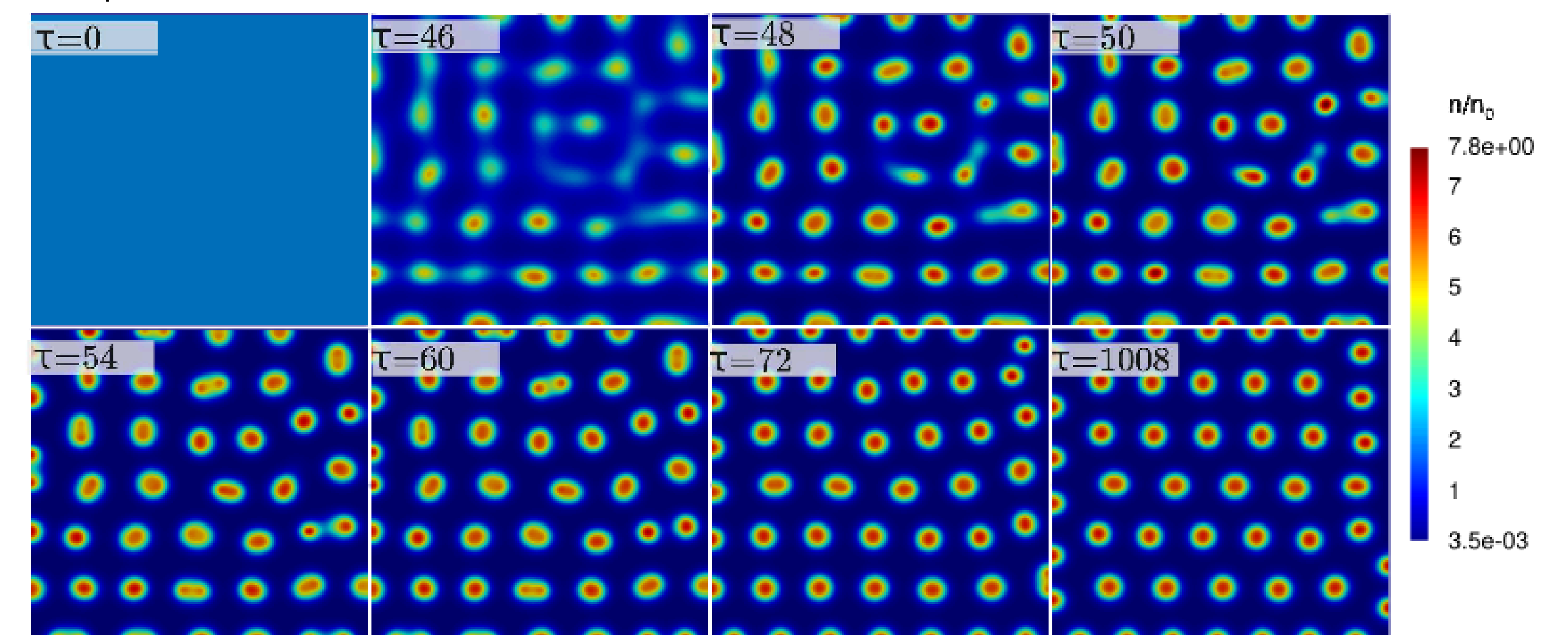
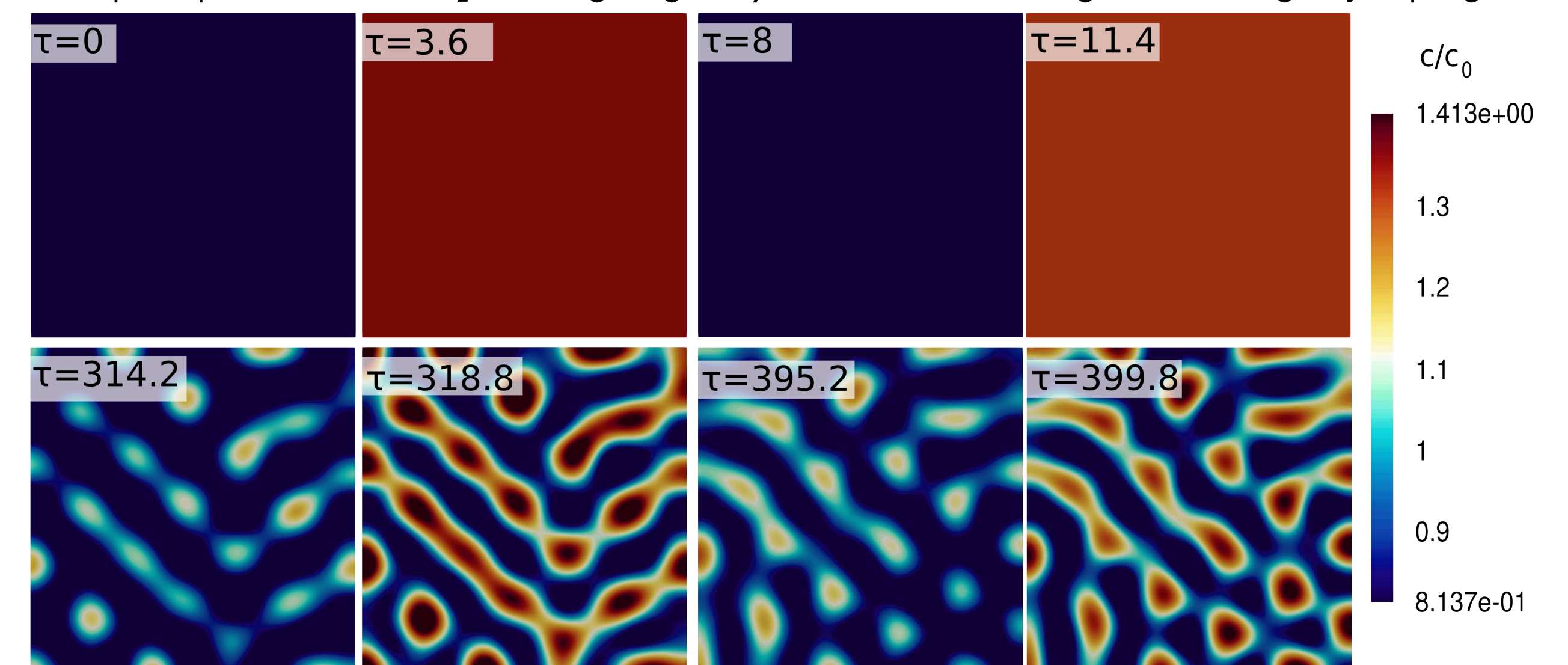


Figure 1. illustrates the temporal evolution of 2D Turing patterns in  $\text{CO}_2$  and bacteria.

## Dynamic pattern ( $\xi = 0.171$ and $q = 0.93$ ): Jumping waves

The spots patterns in  $\text{CO}_2$  undergoing a dynamic shifts in height, resulting in jumping Turing pattern



Temporal evolution of bacteria distribution

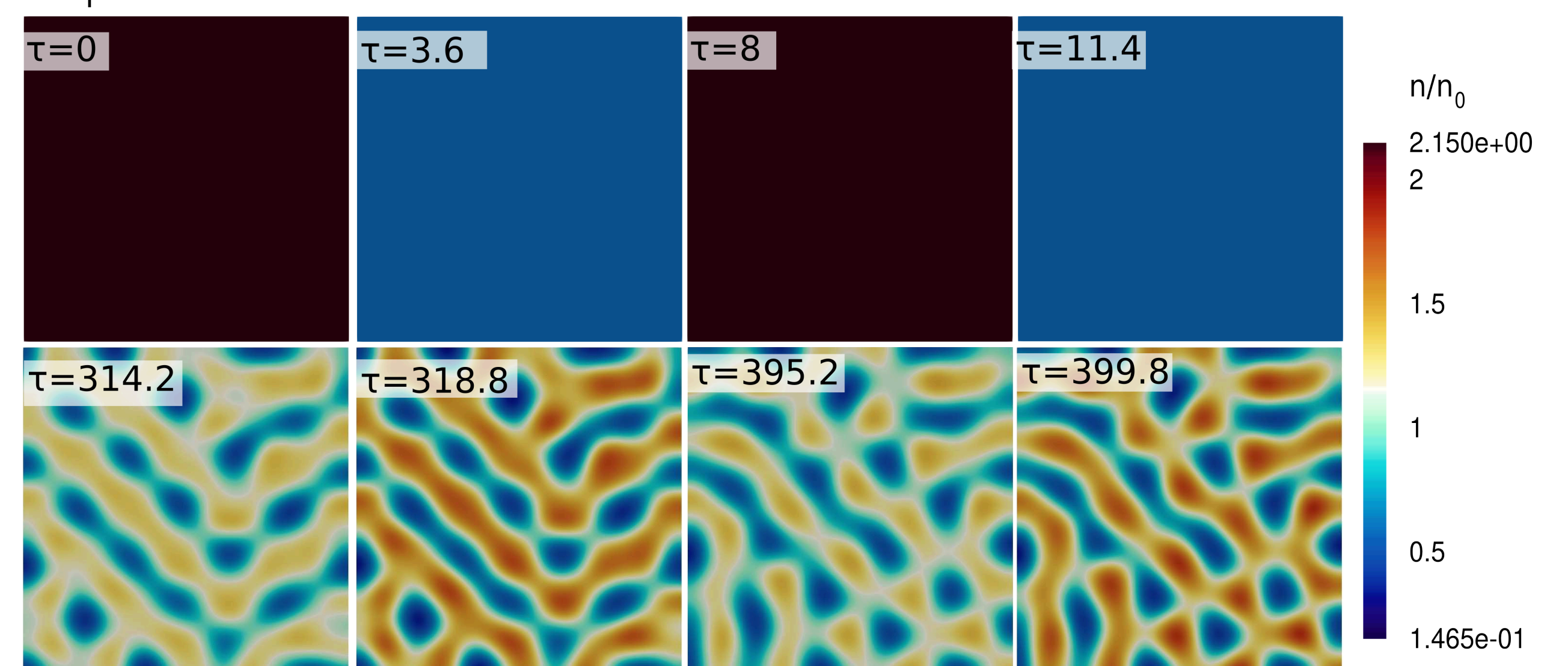


Figure 2. illustrates the 2D dynamic behavior of Hopf-Turing patterns in  $\text{CO}_2$  and bacteria.

## Conclusions and perspectives

- This study is **the first work to investigate spatio-temporal patterns in UGS context**.
- The gas composition oscillations observed in Lobodice can be due to the emergence of Turing patterns.
- An effective injection strategy is crucial to prevent the emergence of patterns.
- We anticipate that more complex patterns will become apparent in heterogeneous reservoirs.

## References

N. Eddaoui et al. "Underground Hydrogen Storage and In-situ Biomethanation Limited by Reaction-Diffusion Patterns" (Under Review)  
 Panfilov, M. (2010). "Underground storage of hydrogen: in situ self-organisation and methane generation". In: Transport in porous media 85, pp. 841-865.  
 Buzek, F. et al. (1994). "Carbon isotope study of methane production in a town gas storage reservoir". In: Fuel 73.5, pp. 747-752.

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