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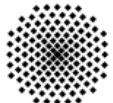
# *Numerical Investigation of CO<sub>2</sub> Sequestration in Geological Formations - Problem Oriented Benchmarks*

Holger Class, Anozie Ebigbo, Rainer Helmig, Melanie Darcis  
Universität Stuttgart



*Hamburg, 16th November 2006*

**GEO**TECHNOLOGIEN



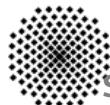
Universität Stuttgart Institut für Wasserbau, Lehrstuhl für Hydromechanik und Hydrosystemmodellierung

Status Seminar; Hamburg 2007/



# Project Coordination and Partners

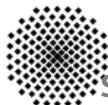
- Coordination:
  - Universität Stuttgart (Holger Class, Rainer Helmig, Anozie Ebigbo)
- National Partner:
  - Deutsche Montan Technologie, Essen (Ralph Schlüter, Heribert Meiners)
- International Partners
  - University of Bergen, Norway (Helge Dahle, Jan Nordbotten, Geir Terje Eigestad)
  - Princeton University, USA (Michael A. Celia)
  - De Norske Veritas, Oslo, Norway (Todd Flach)



# Outline

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- Motivation:
  - why are benchmarks necessary?
  - some exemplary issues on model concepts
  
- Benchmark study:
  - 3 benchmark problems
  - Workshop



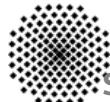
## ***Model Validation / Benchmarking***

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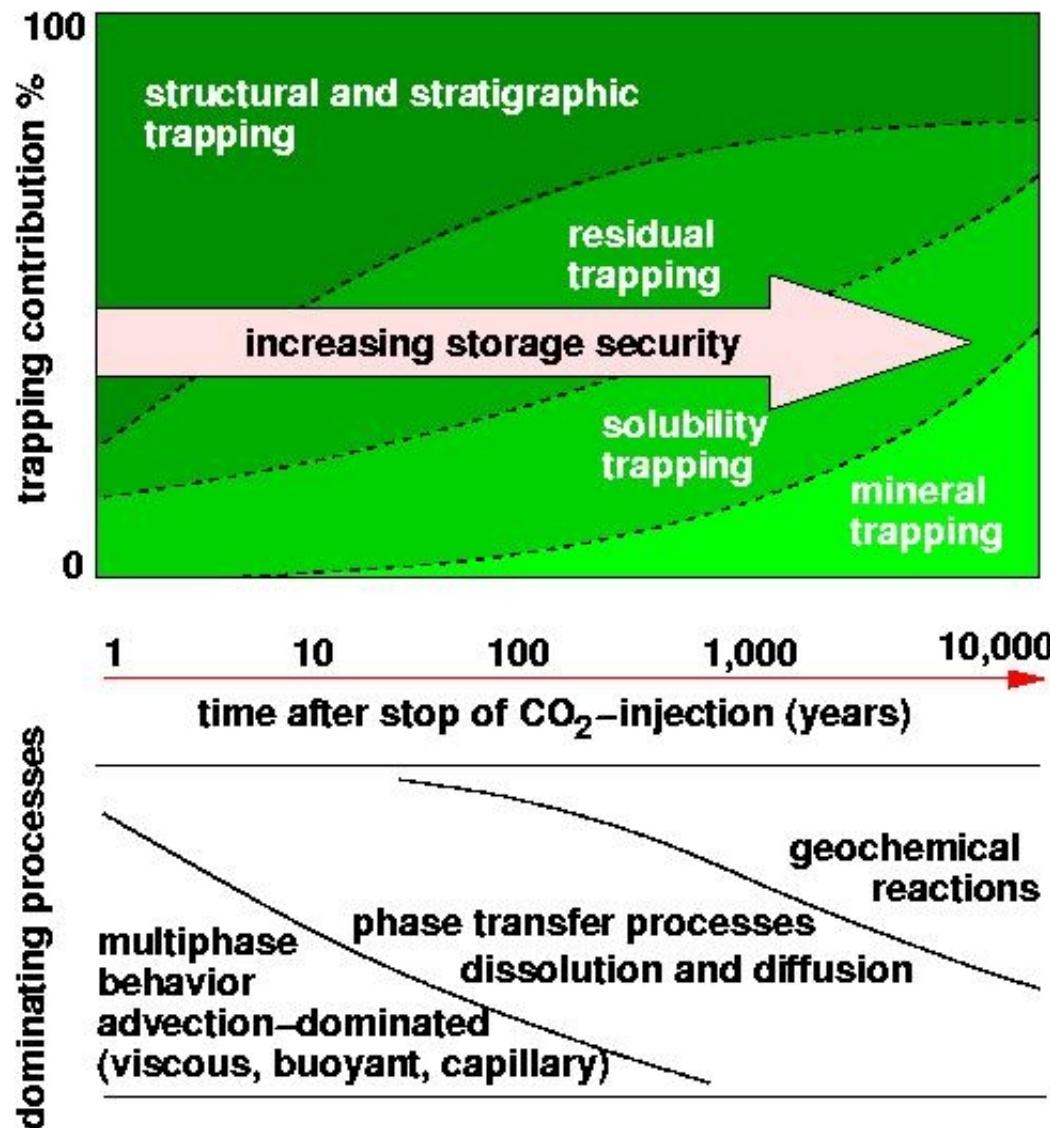
The reliability of numerical model results is difficult to determine since model validation with measurements from well-controlled laboratory or field experiments is hardly feasible.

Well-defined benchmark problems that consider problem-specific features may help to overcome this and improve the confidence in numerical simulation results.

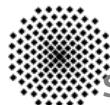
Uncertainties deal, for example, with different approaches for fluid properties, phase behavior, different discretization and solution methods, etc.



# Trapping Mechanisms & Time-Scales



modified  
after IPCC 2006

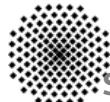


# Available CO<sub>2</sub> Simulation Capabilities

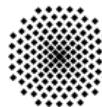
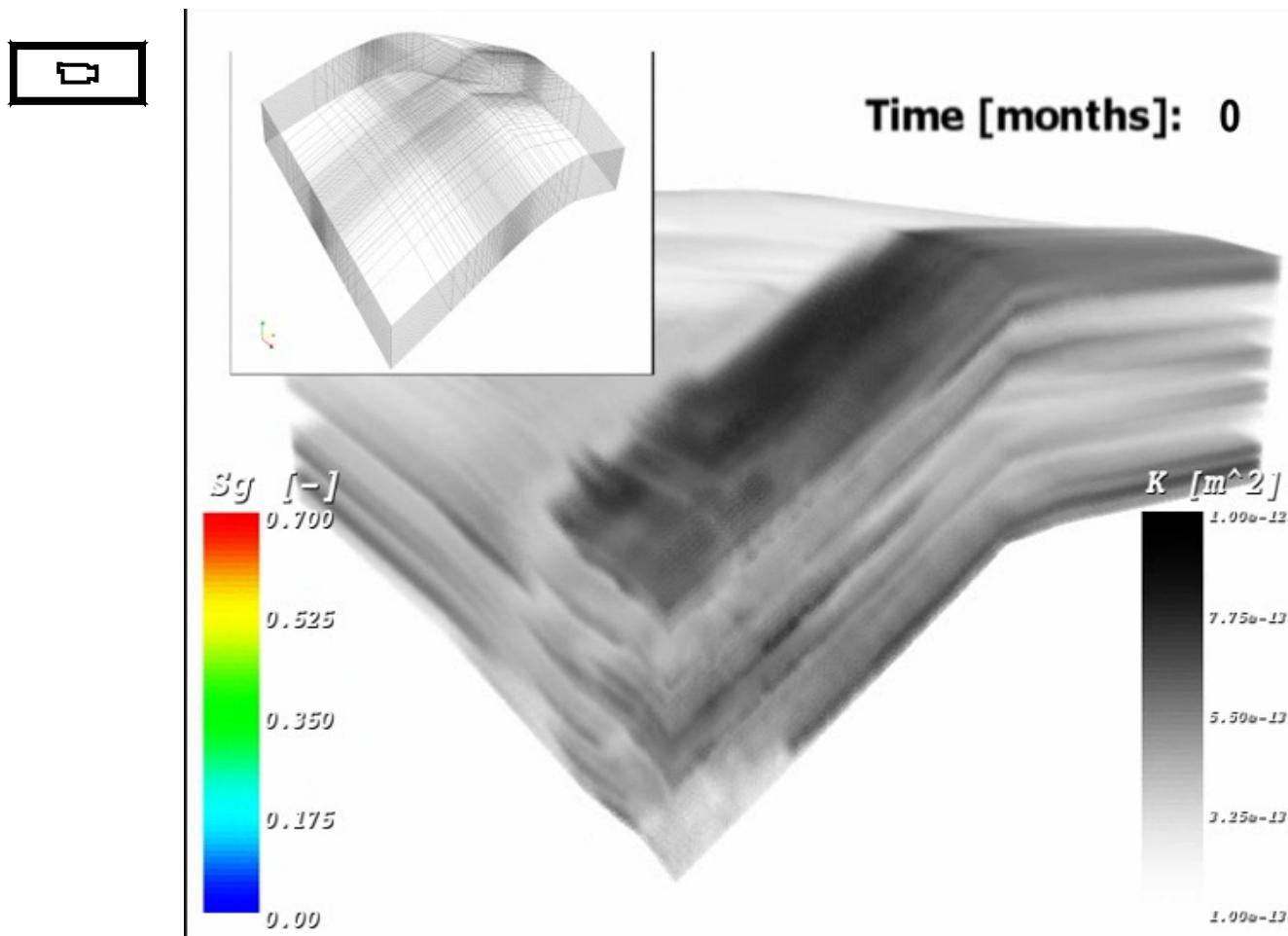
multiphase behavior	compositional effects	non-isothermal effects	geochemical reactions	geo-mechanics
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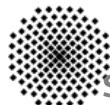
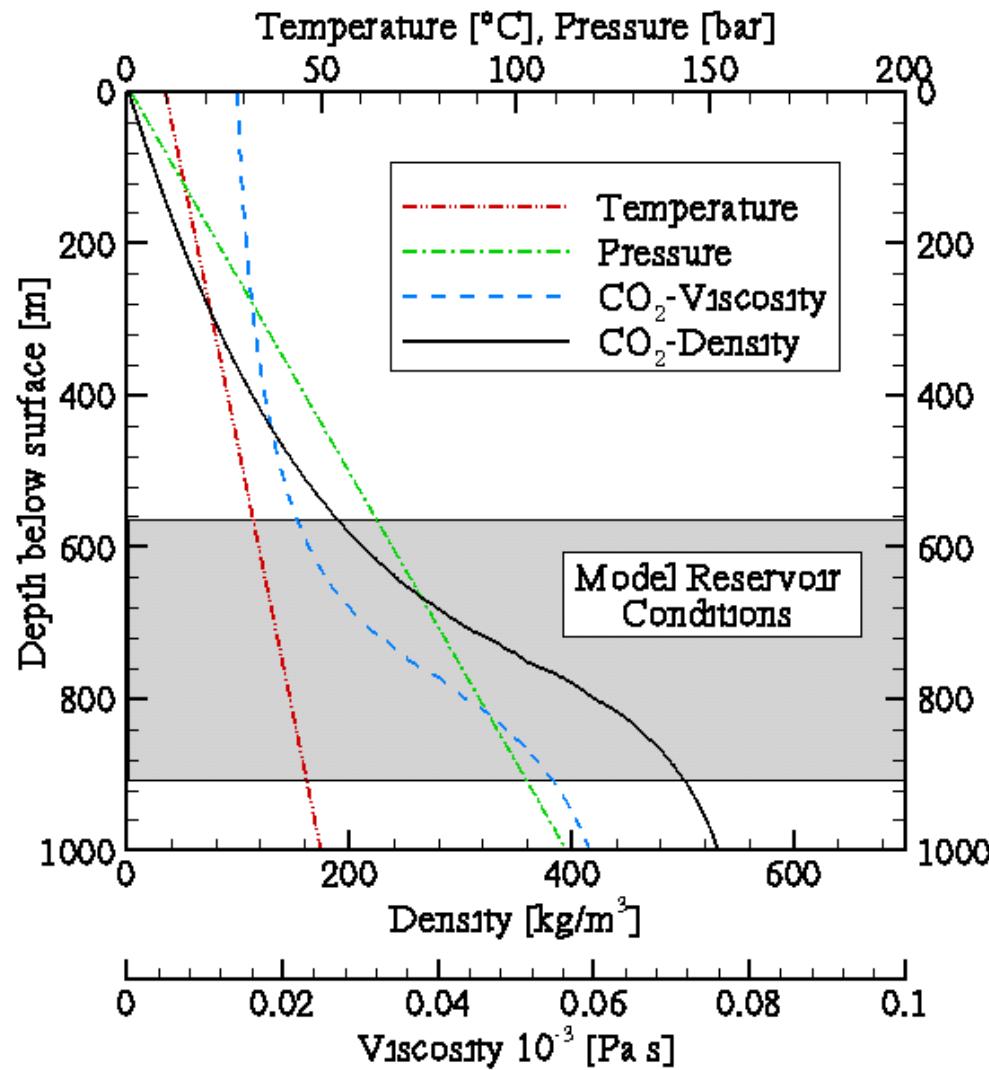
TOUGH, ECLIPSE, MUFTE, NUFT, FLOTTRAN, SHEMAT, GeoSys/Rockflow, STOMP, UTCOMP, STARS, SIMED, SIMUSCOPP, ....



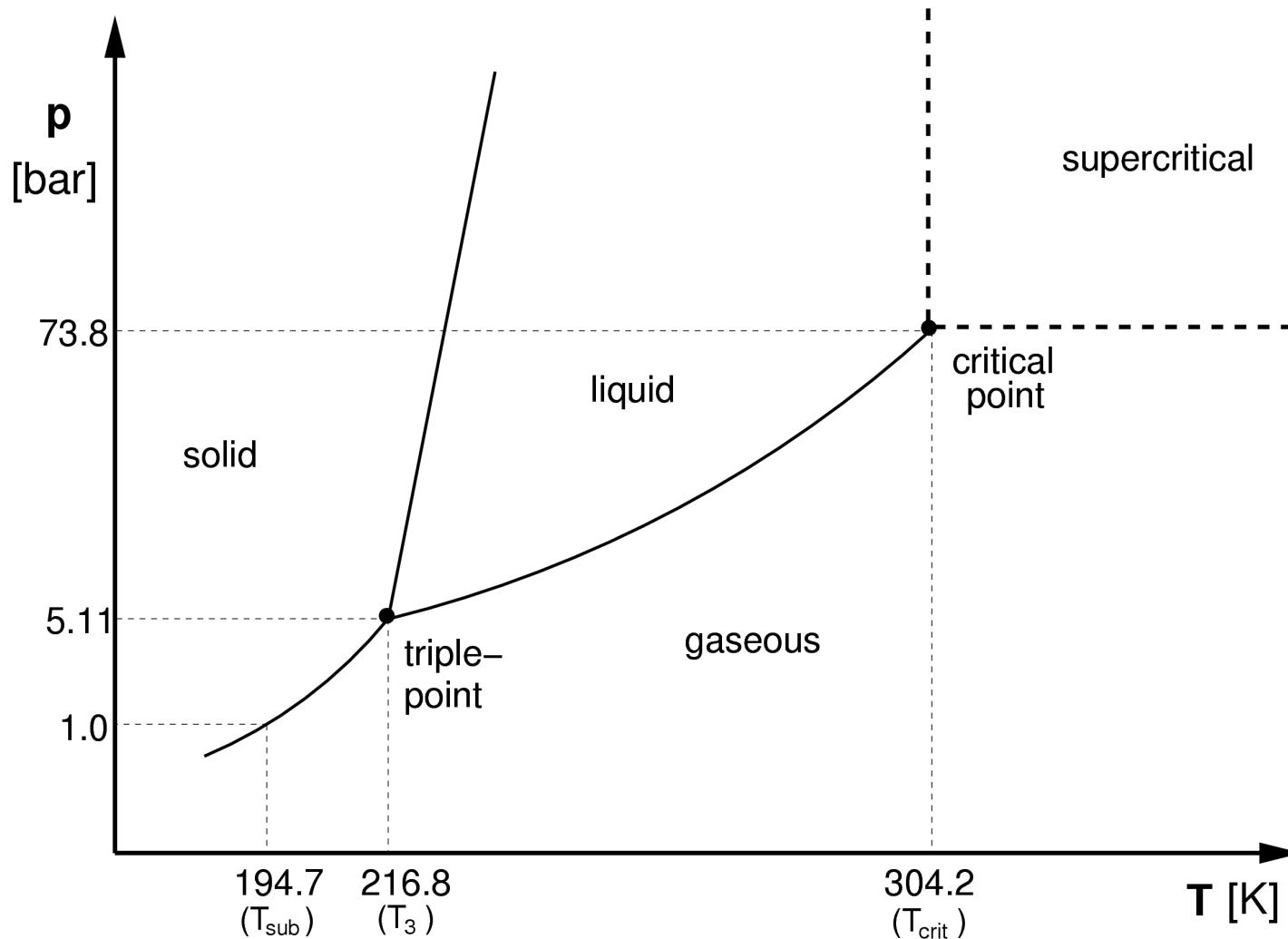
# Example: Modelled $CO_2$ Plume Evolution



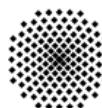
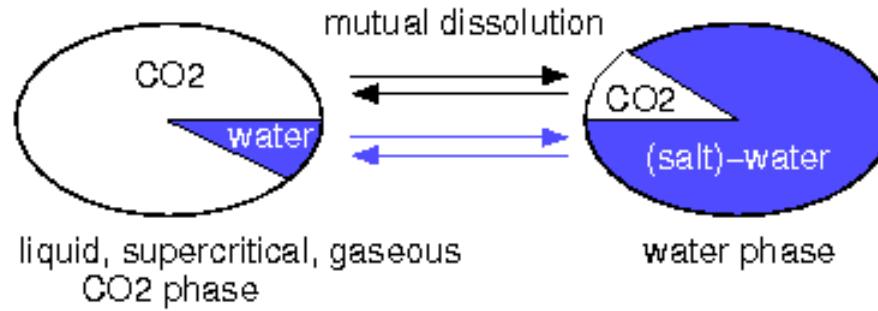
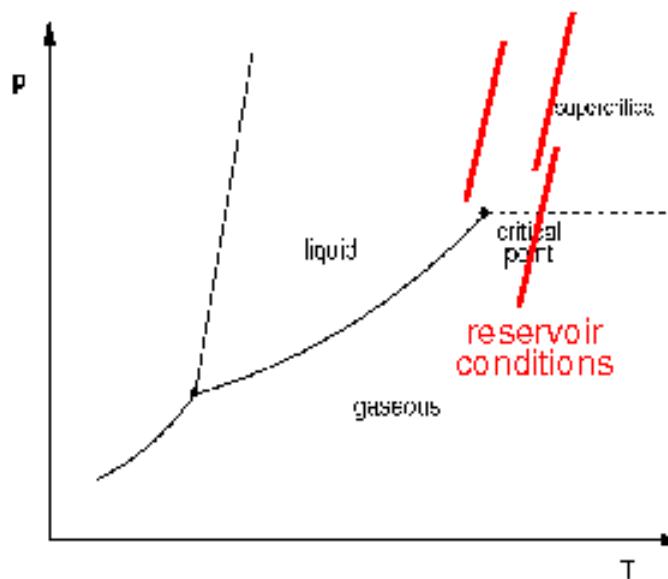
## Example: $p, T$ -Conditions and Fluid Properties



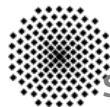
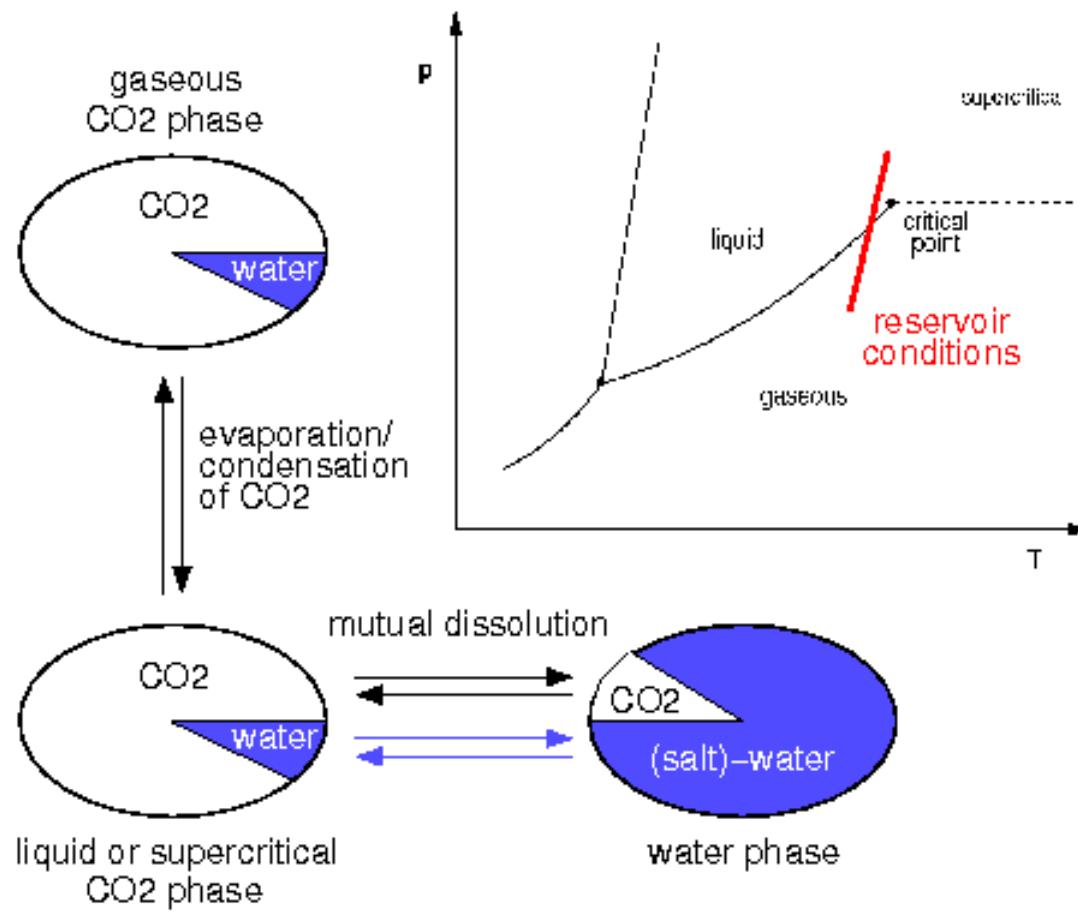
# $\text{CO}_2$ Phase Diagram



## Two-Phase Approach

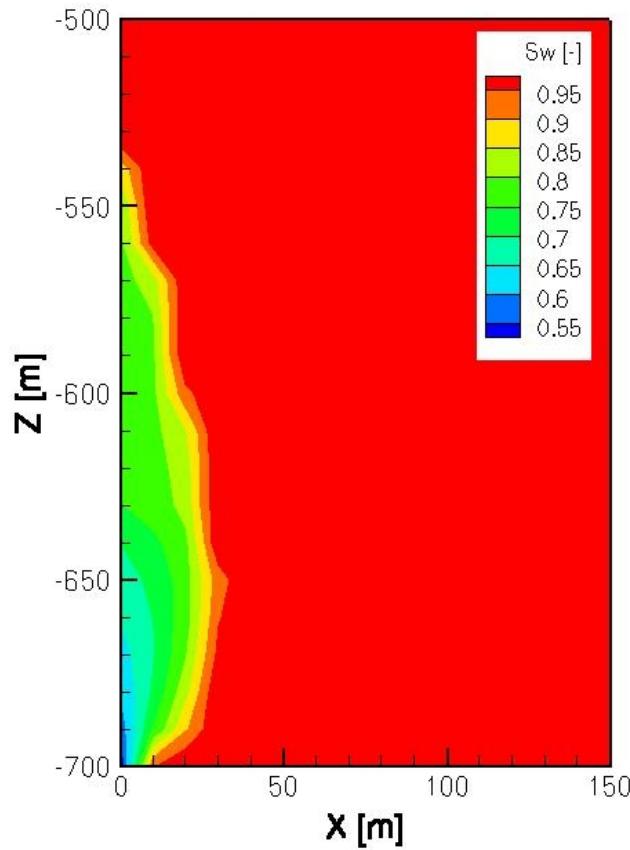


# Three-Phase Approach

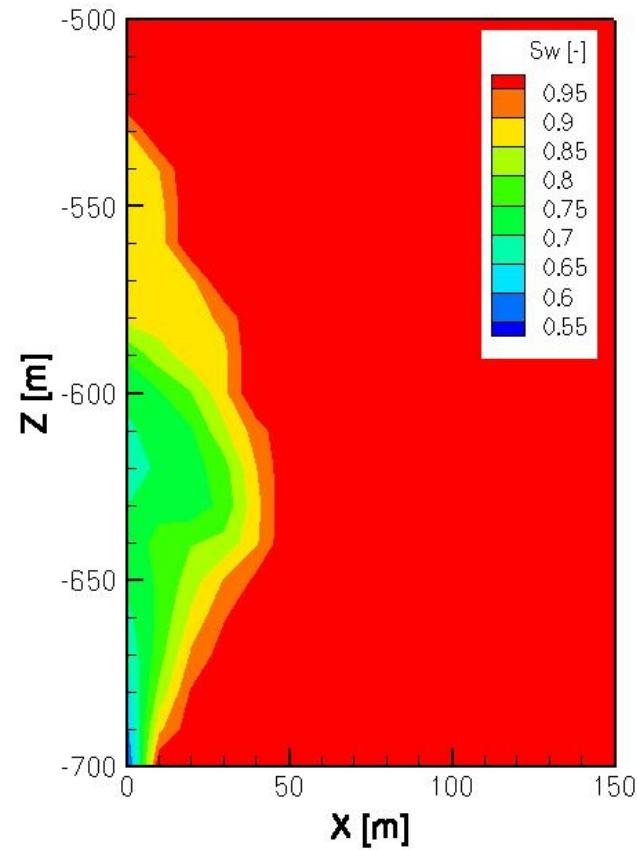


# Gaseous and Liquid CO<sub>2</sub>

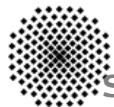
Water saturation after 72 months of injection



two phase model

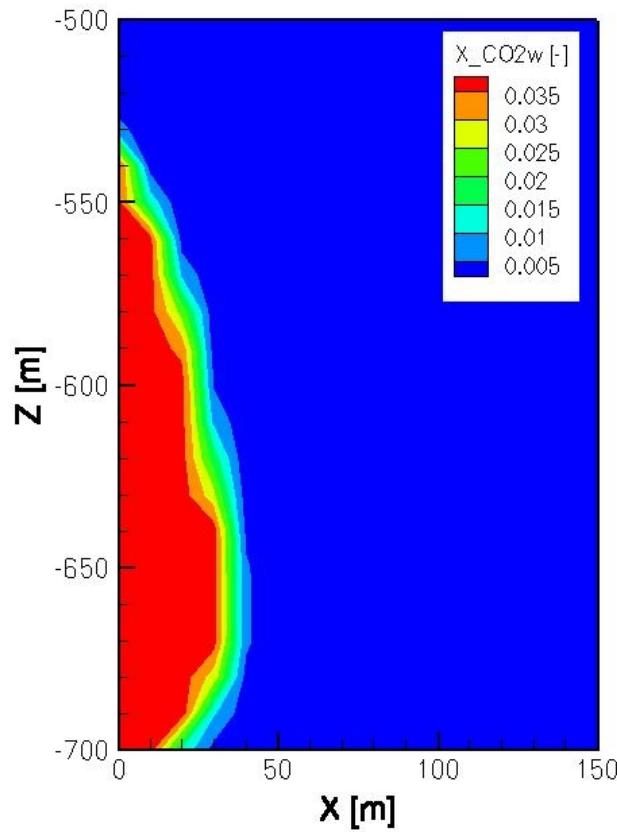


three phase model

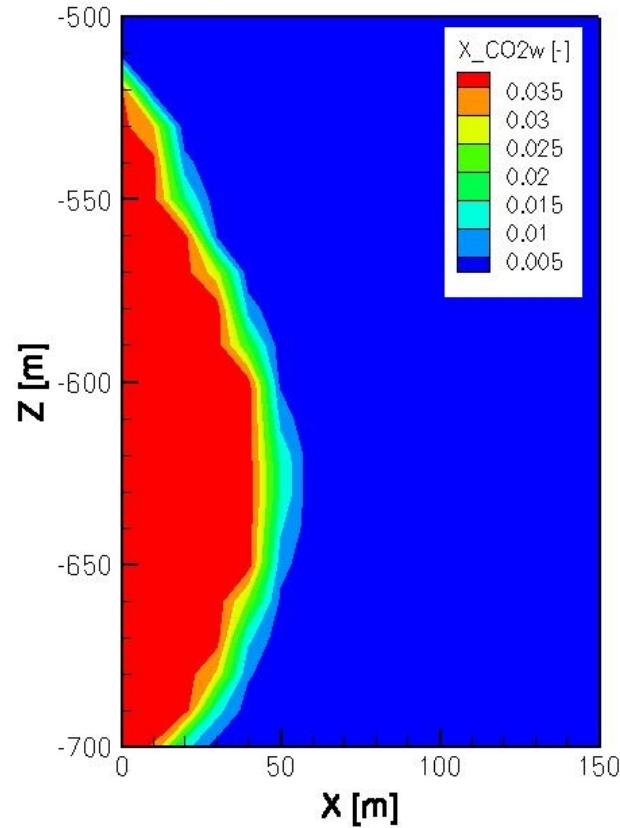


# Gaseous and Liquid CO<sub>2</sub>

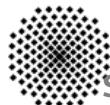
Dissolved CO<sub>2</sub> mass fraction in water after 72 months of injection



two phase model

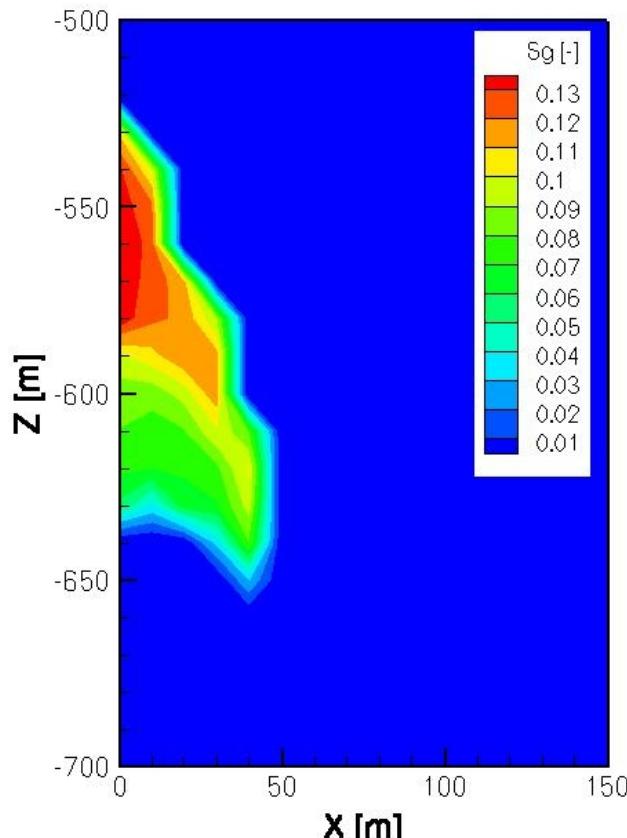


three phase model

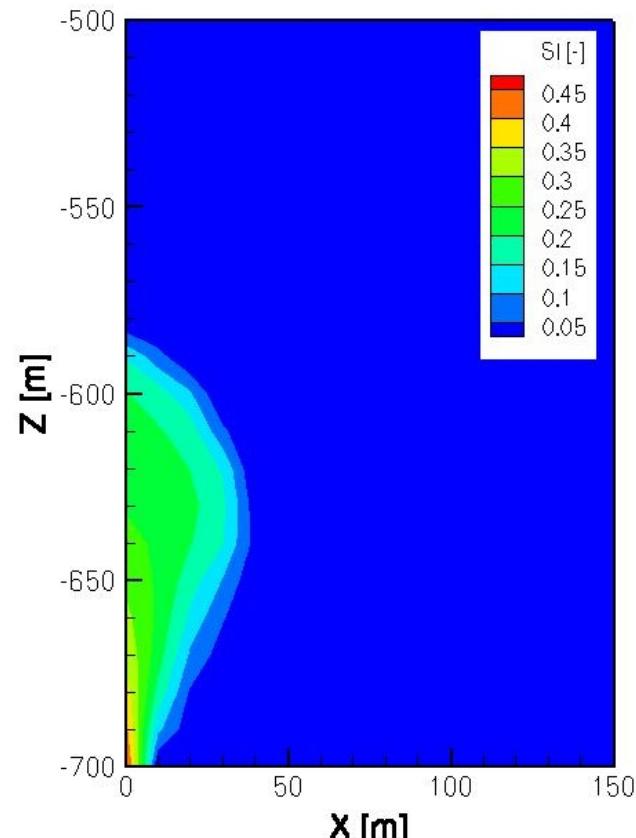


# Gaseous and Liquid CO<sub>2</sub>

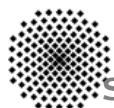
Three phase model: saturations of the two CO<sub>2</sub> phases



gaseous CO<sub>2</sub> phase



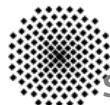
liquid CO<sub>2</sub> phase



# *Model Intercomparison: Further Issues*

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- Fluid properties
  - density, viscosity, enthalpy
- Physical-mathematical (chemical) model concepts
  - processes, phases, components, etc.
- Mathematical and numerical solution methods
  - discretization, meshing, coupling of equations, etc.
- Capillary pressures and relative permeabilities including effects of hysteresis influencing the residual trapping behavior
- ...



# Workshop on CO<sub>2</sub> Storage Modelling

## Numerical Models for CO<sub>2</sub> Storage in Geological Formations

Aims:

- presenting the current capabilities of mathematical and numerical models for CO<sub>2</sub> storage in geological formations
- discussing the future developments and application of numerical models for large-scale CO<sub>2</sub> storage projects
- model intercomparison study: **benchmarks** available on website

[www.iws.uni-stuttgart.de/co2-workshop](http://www.iws.uni-stuttgart.de/co2-workshop)

Organising Committee:

A. Ebigbo, H. Class, R. Helmig, A. Kopp

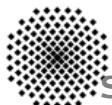
*Universität Stuttgart*

H. Dahle, J. Nordbotten

*University of Bergen (Norway)*

**Stuttgart, 2<sup>nd</sup>- 4<sup>th</sup> April, 2008**

*Princeton University (USA)*



Universität Stuttgart Institut für Wasserbau, Lehrstuhl

Status Seminar; Hamburg 2007



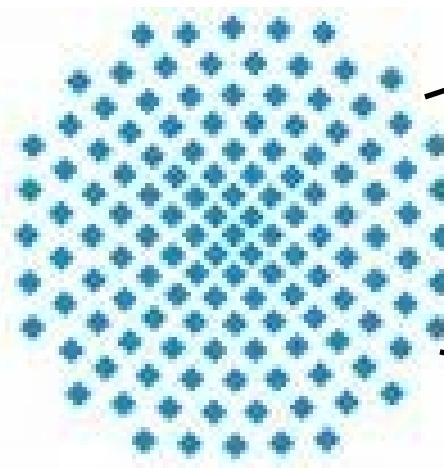
# Collaboration



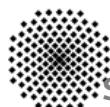
Problem 1



Problem 2



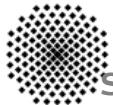
Problem 3



## Problem 3

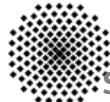
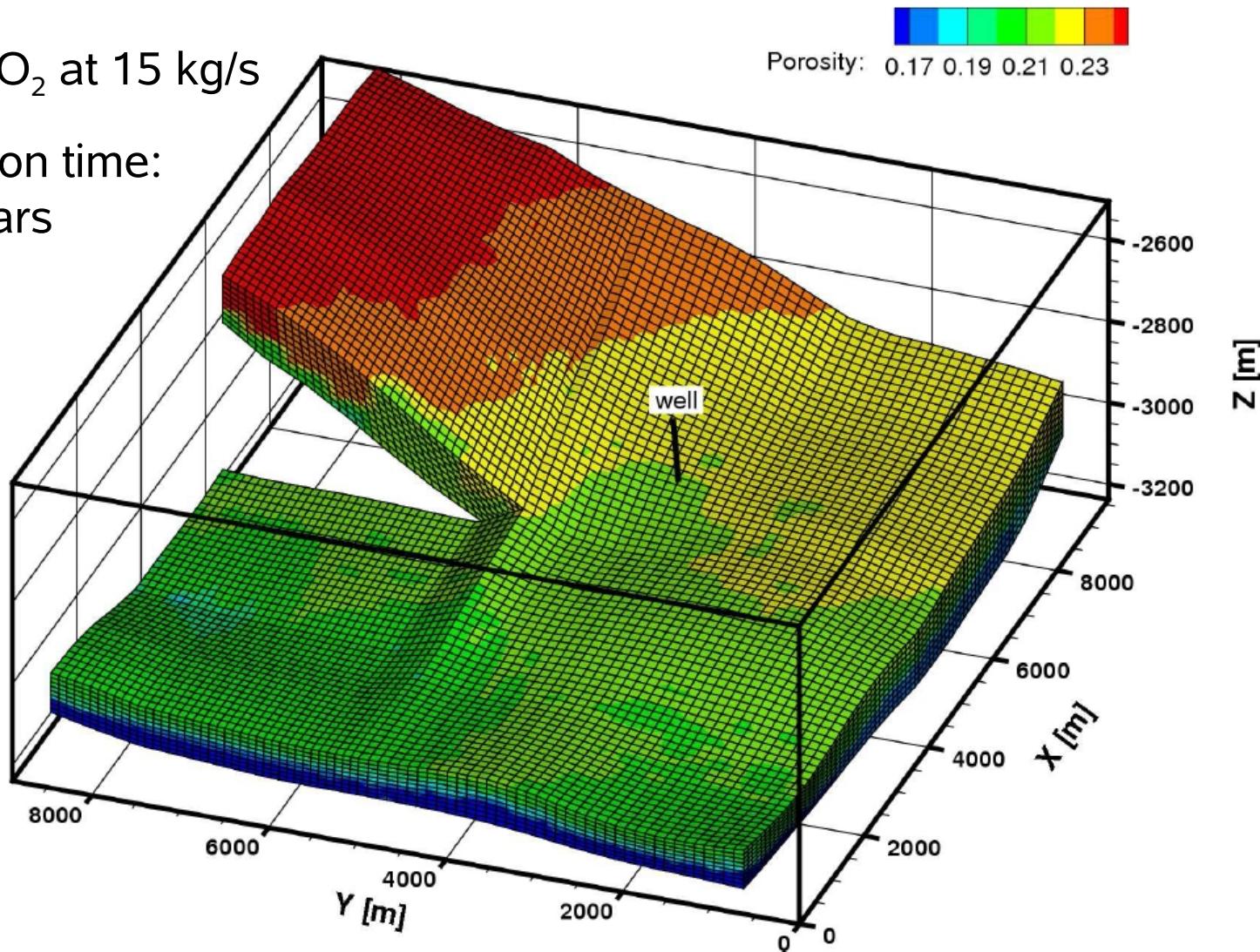
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- Title: Estimation of the CO<sub>2</sub> storage capacity of a geological formation
- Authors: H. Class<sup>1</sup>, H. Dahle<sup>2</sup>, F. Riis<sup>3</sup>, A. Ebigbo<sup>1</sup>, G. Eigestad<sup>2</sup>
  - <sup>1</sup> Dept. of Hydromechanics and Modelling of Hydrosystems, Universität Stuttgart
  - <sup>2</sup> Dept. of Applied Mathematics, University of Bergen
  - <sup>3</sup> Norwegian Petroleum Directorate
- Geological data based on a study of the Johansen formation by the Norwegian Petroleum Directorate

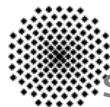
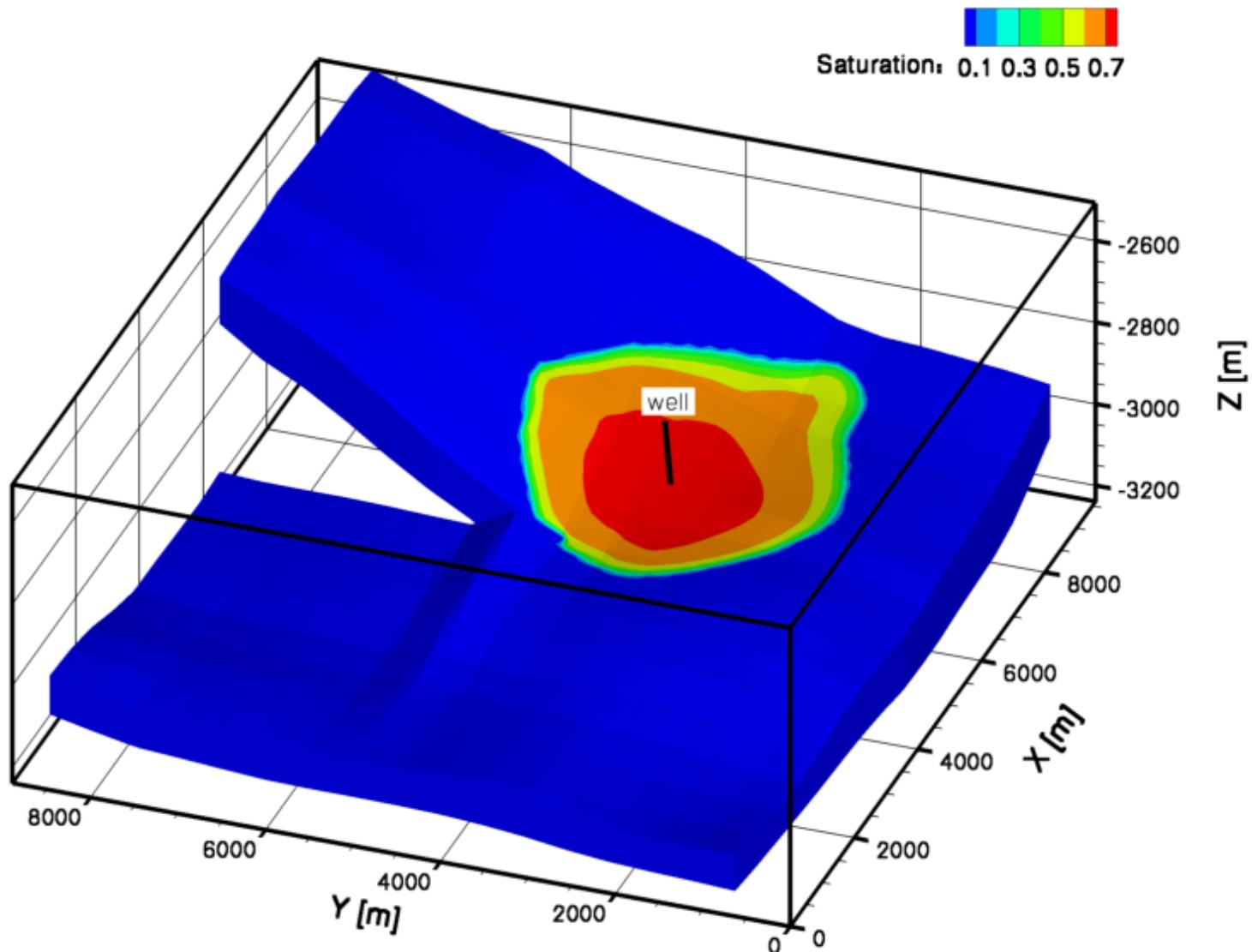


## Problem 3: Set-up

- Injection of CO<sub>2</sub> at 15 kg/s
- Total simulation time:  
50 years



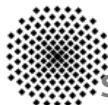
## Problem 3: Preliminary Simulation



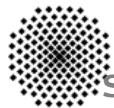
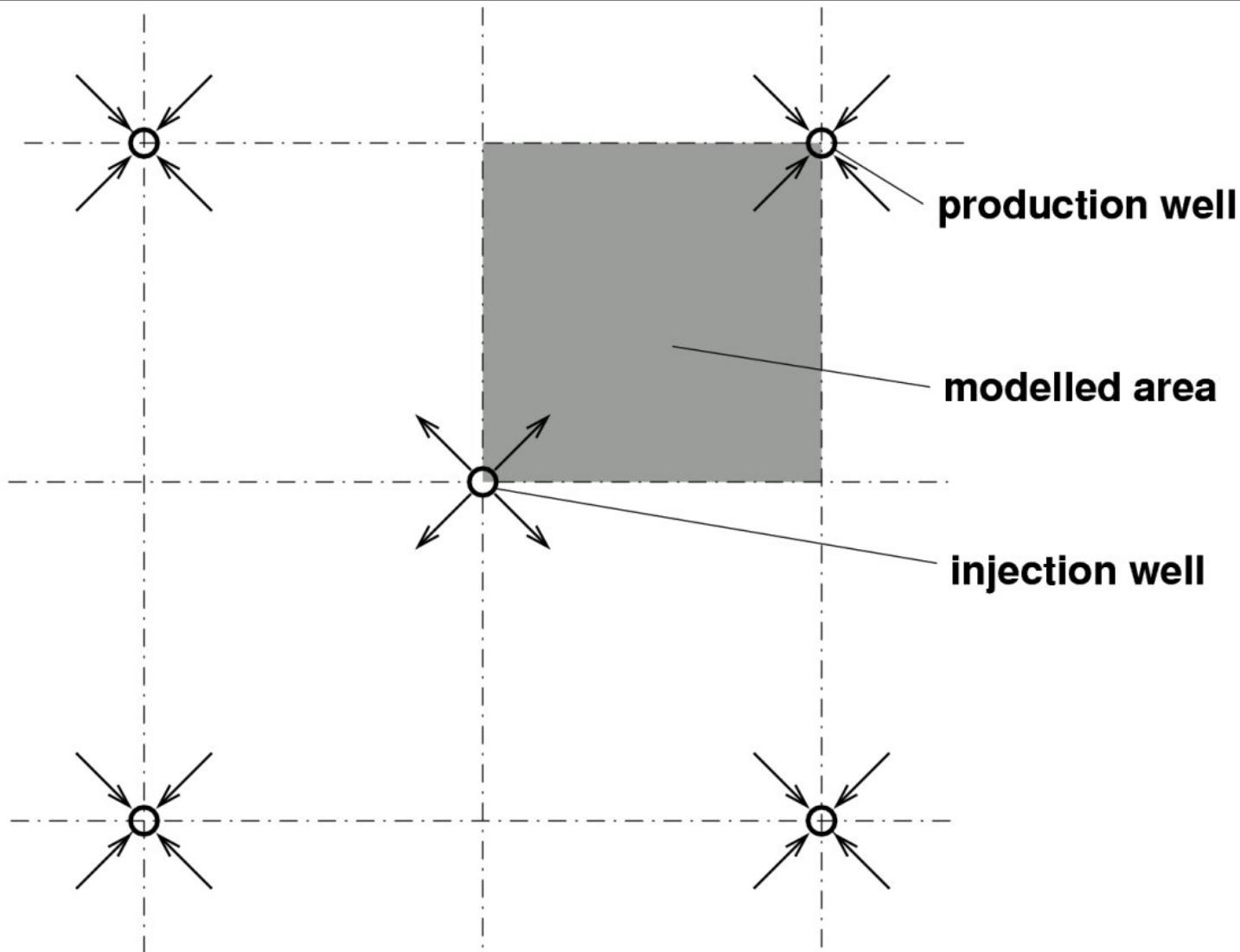
## Problem 2

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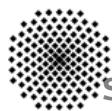
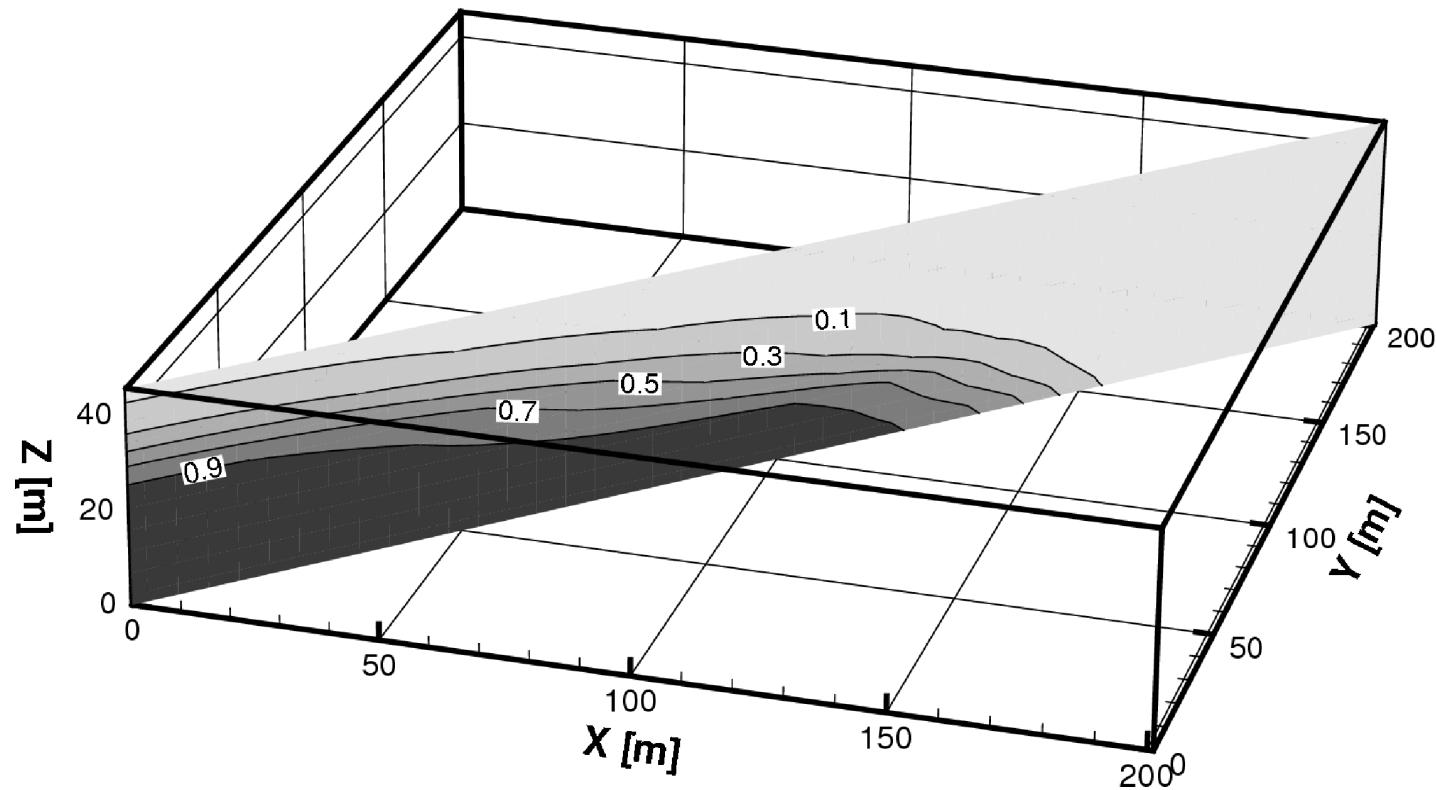
- Title: Enhanced  $\text{CH}_4$  recovery in combination with  $\text{CO}_2$  storage in depleted gas reservoirs
- Authors: A. Ebigbo, H. Class
- Problem description:
  - $\text{CO}_2$  injection and  $\text{CH}_4$  production in a five-spot pattern
  - Injection stopped at  $\text{CO}_2$  breakthrough at the production well
  - Two variations: homogeneous and layered reservoir



## Problem 2: Set-up



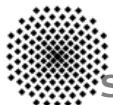
## Problem 2: Simulation



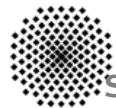
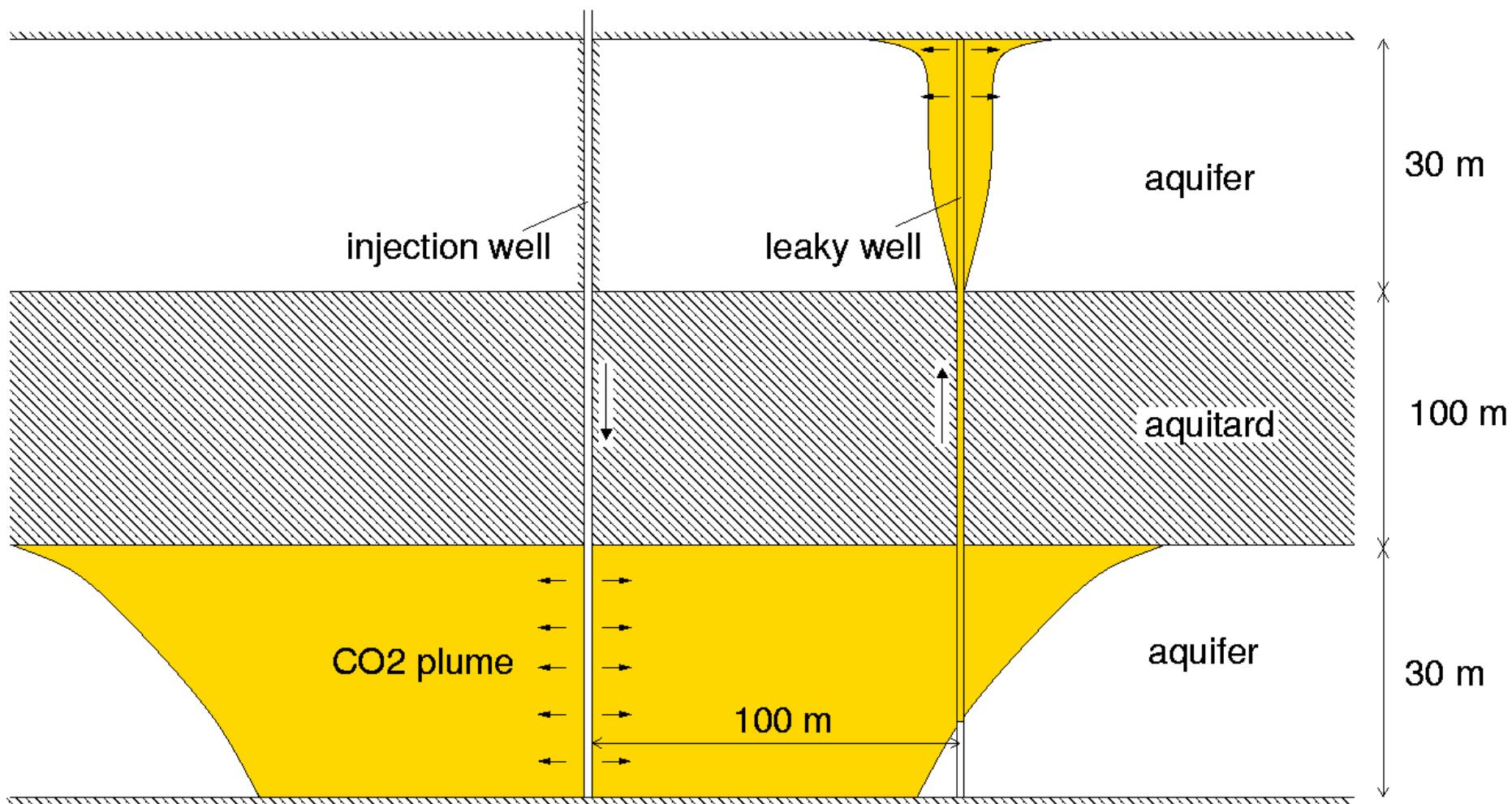
## Problem 1

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- Title: CO<sub>2</sub> plume evolution and leakage through an abandoned well
- Authors: A. Ebigbo<sup>1</sup>, J.M. Nordbotten<sup>2</sup>, H. Class<sup>1</sup>
  - <sup>1</sup> Dept. of Hydromechanics and Modelling of Hydrosystems, Universität Stuttgart
  - <sup>2</sup> Dept. of Applied Mathematics, University of Bergen
- Problem description:
  - CO<sub>2</sub> injection into an aquifer which is penetrated by a leaky well
  - Leakage occurring through well up to a higher aquifer
  - Two variations with different depths and assumptions
- *Ebigbo, Class, Helmig: Computational Geosciences (2006)*

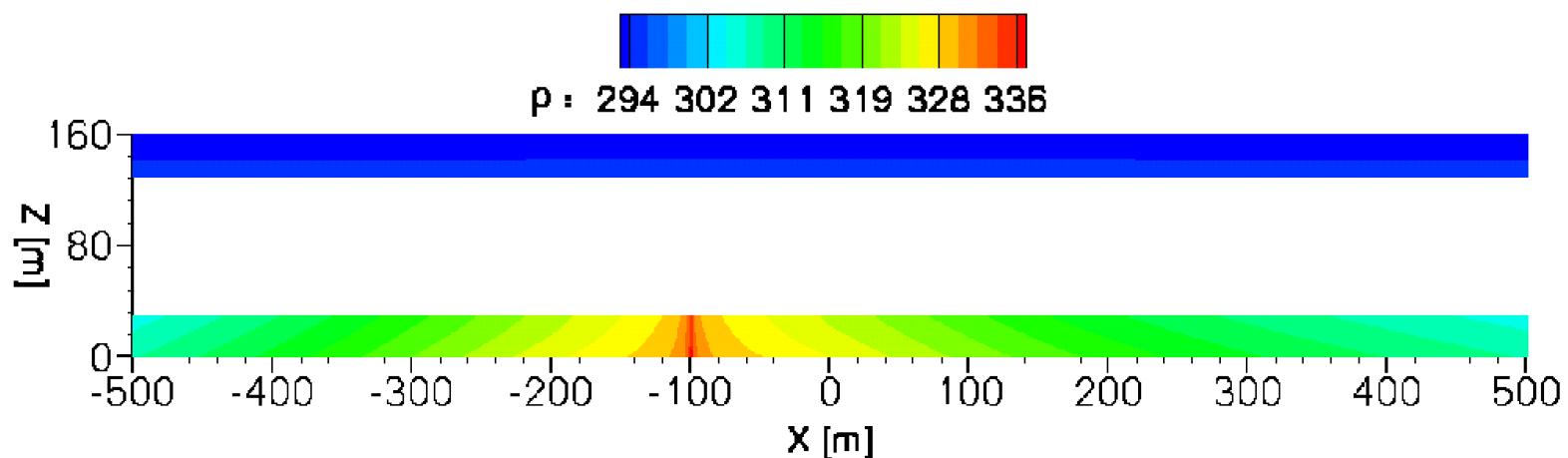
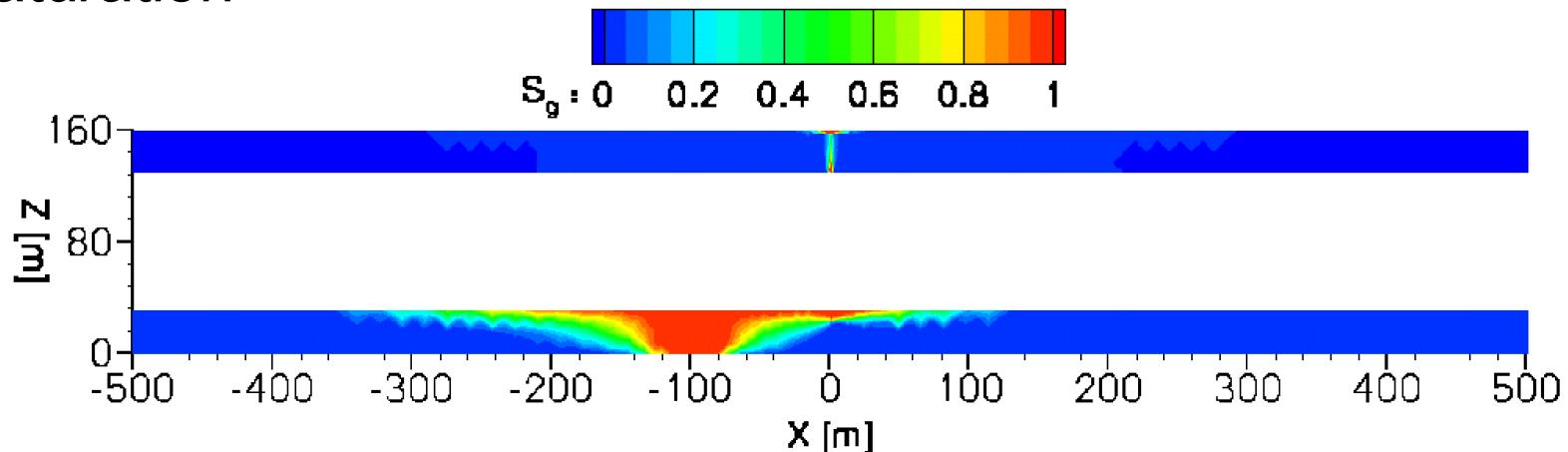


# Problem 1: Set-up

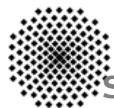


# Problem 1: Simulation

Saturation



Pressure [bar]



## Summary

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- The aim of the project is to provide challenging benchmark problems for model intercomparison which are specific to certain problems and open questions.
- Three benchmark problems including a number of variations are defined and available for modellers.
- An international code intercomparison study is currently initiated and will be concluded on a workshop in Stuttgart, 2.-4. April 2008.
- Publication of the benchmark examples is/will be done in peer reviewed journals.

