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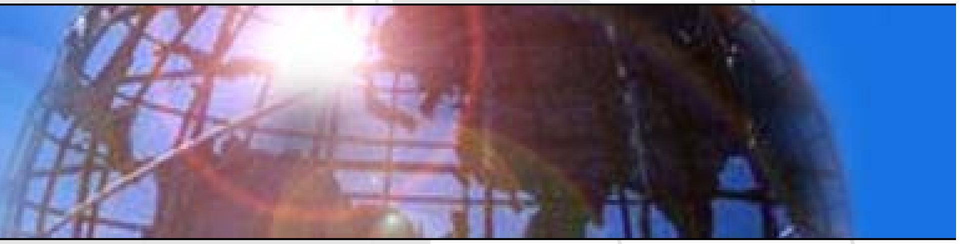
GCEP Global Climate & Energy Project



GCEP Symposium
September 20, 2006

Numerical Simulation Framework for CO2 Sequestration

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Department of Energy Resources Engineering
Stanford University

Heterogeneous, Large Systems
Sparse Data

Different Sources, Varying Quality & Quantity

Multi-Scales, Multi-Physics

10^{-5} 10^{-4} 10^{-3} 10^{-} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8} 10^{9} 10^{10}
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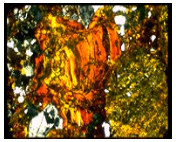
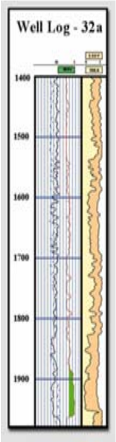
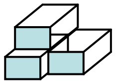


Thin Sections

Core Data

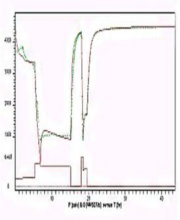


Well Log

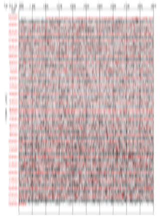


Geological Model Cells

Up-scaled Simulation Cells



Well Test



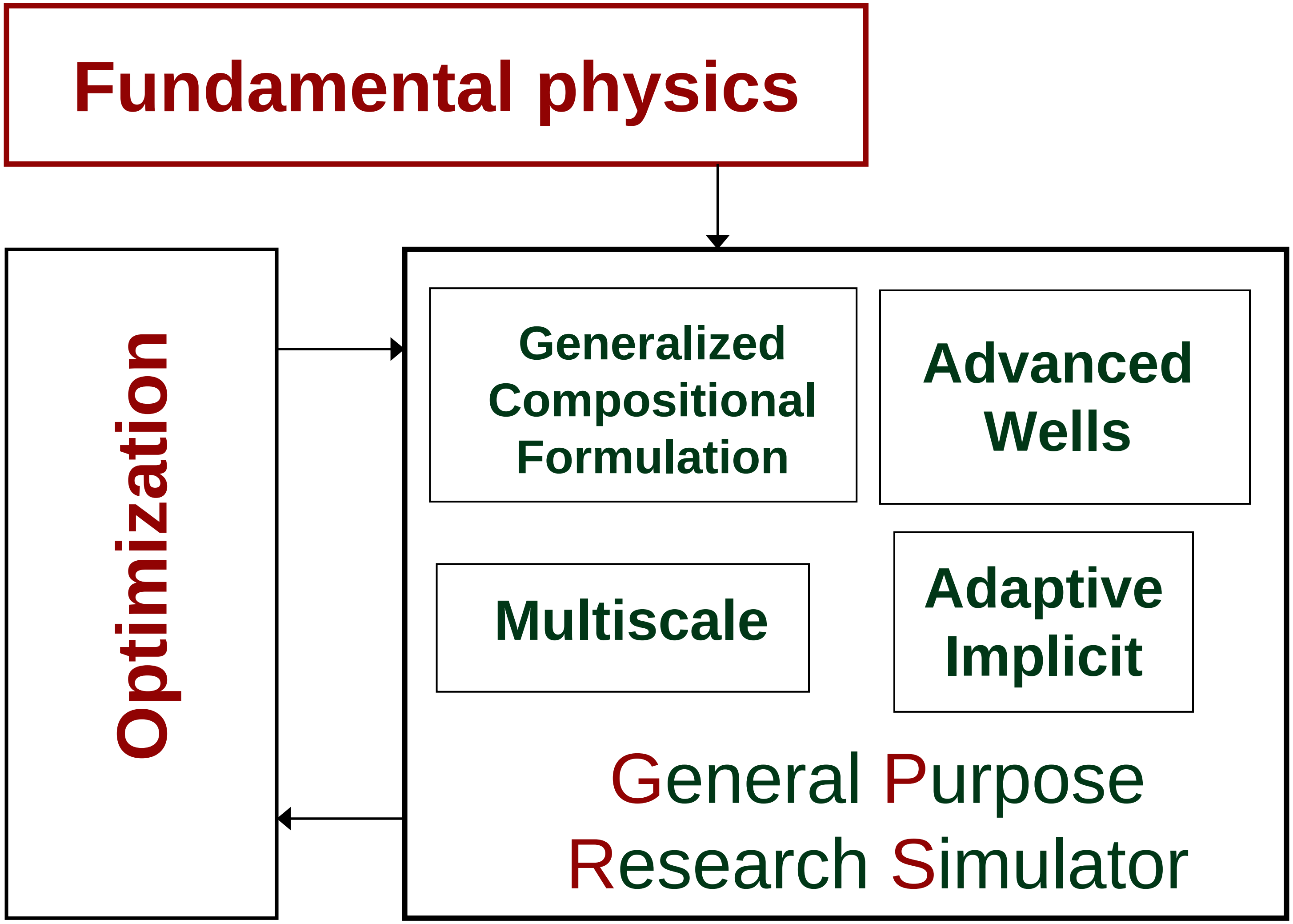
Seismic Data

Upscaling → ← Downscaling

CO2 Sequestration Modeling Framework

- Engineering Tool: Design & Management of CO2 Sequestration Projects
  - Advanced & smart wells
  - Control & optimization
  - Long-term monitoring
- Physics and Numerics
  - Detailed study and modeling of the physics
  - Robust, efficient numerical algorithms
- Flexible Extensible Computational Framework
  - Incorporate research results

CO_2 Sequestration Computational Framework



Fundamental physics

Optimization

Generalized Compositional Formulation

Advanced Wells

Multiscale

Adaptive Implicit

General Purpose Research Simulator

Research Activity

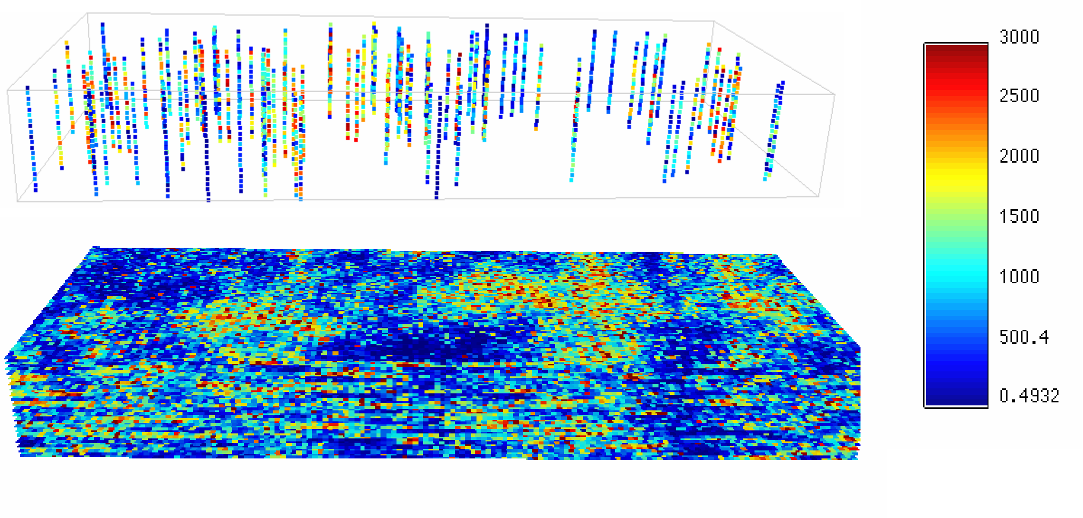
- Basic GPRS Capabilities - Fan, Pan
- Miscible & Immiscible Plumes - Riaz, Hesse
- Gravity Currents - Hesse with Lynn
- MultiScale Formulation - Zhou
- High-order AIM - De Louben, Riaz
- Particles for Nonlinear Flow
  - Tyagi with Prof. Jenny of ETH

GPRS Extensions

- Residual Trapping
  - Relative Permeability Hesteresis
  - Preliminary Results: Injection Strategies
- Diffusion and Dispersion
- Fast Flash for CO_2-Water Systems

SJ Saline Aquifer Modeling

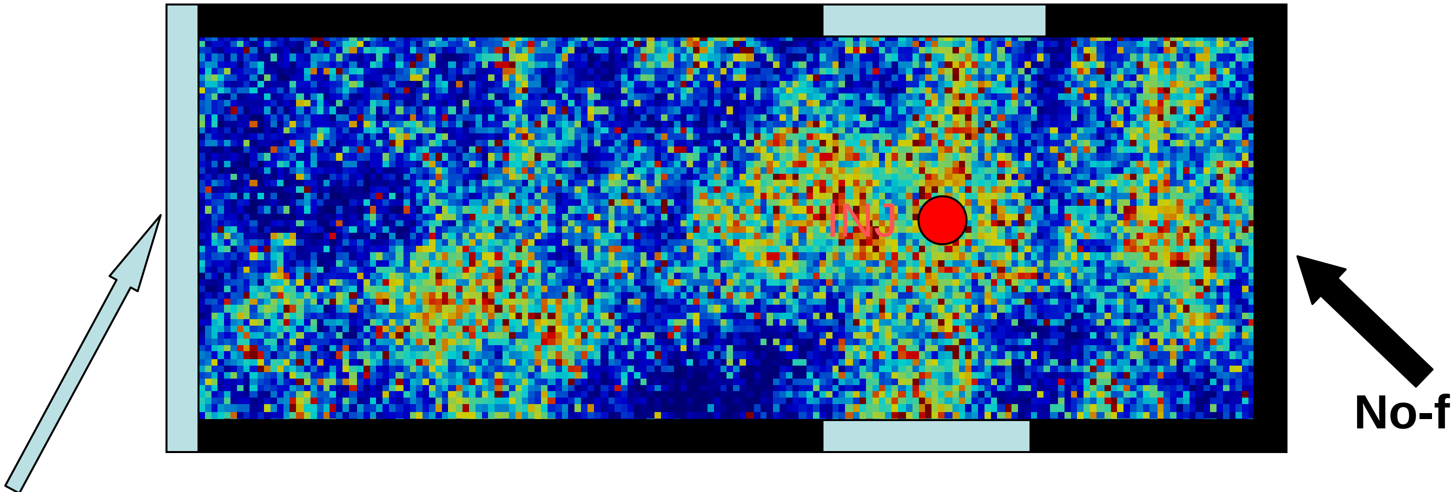
- Aquifer data determined from existing hydrological data (BEG database, UT Austin)
  - Size: 260,000 x 98,000 x 980 ft^3
  - Depth: 2000 ft
  - Porosity: 0.135
  - Temperature: 104^o F
  - Grid:160 x 60 x 20
  - Permeability:



Generated by S-GeMS

Well Configuration and BCs

- One CO_2 injection well completed in bottom layer
- CO_2 rate 141,300 MCF/day (29M t/year)



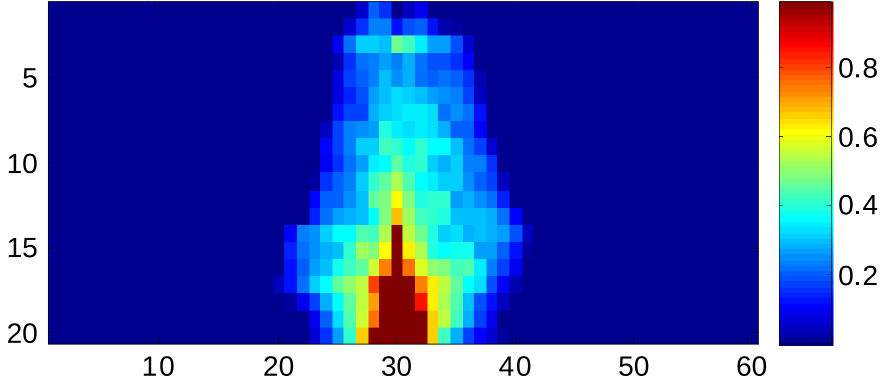
No-flow BC

Constant pressure

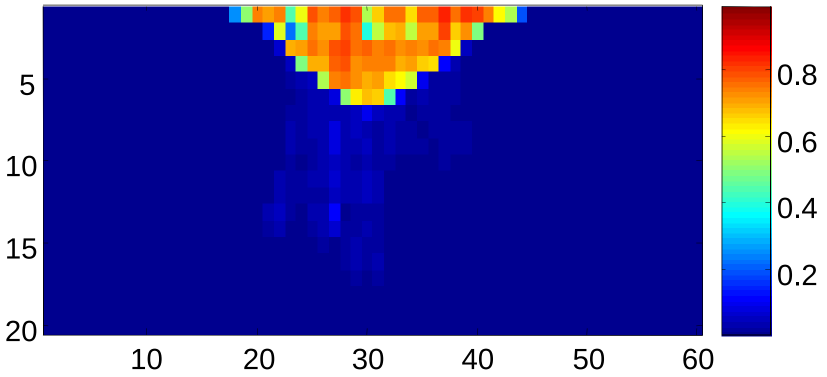
(continuous aquifer)

Simulation Results

S_g after CO_2 injected for 20 years



S_g at 100 years (80 years of well shut-in)
without hysteresis



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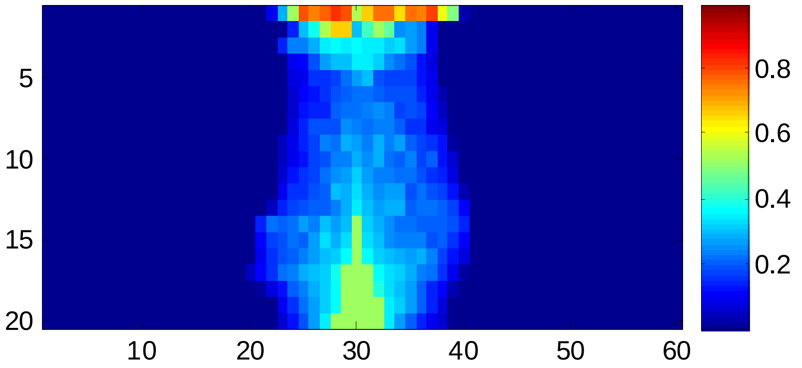

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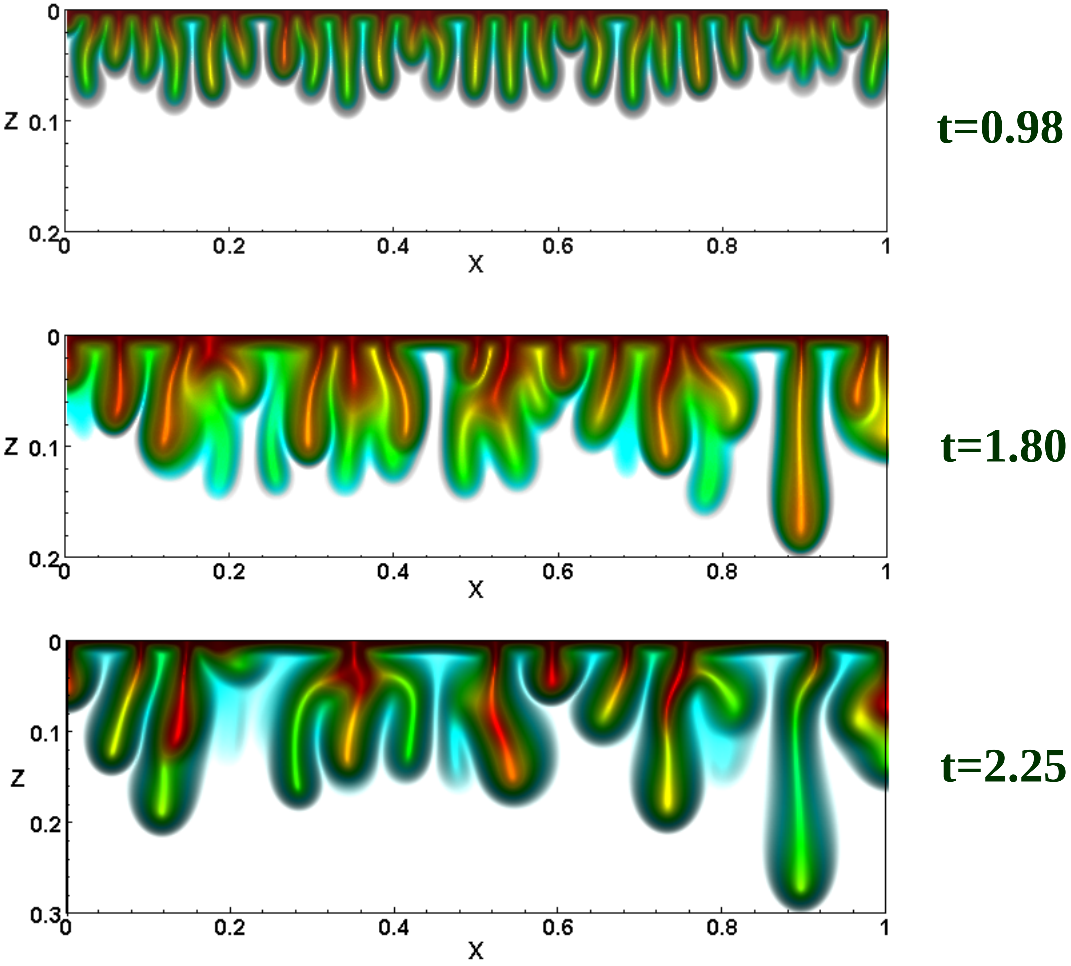
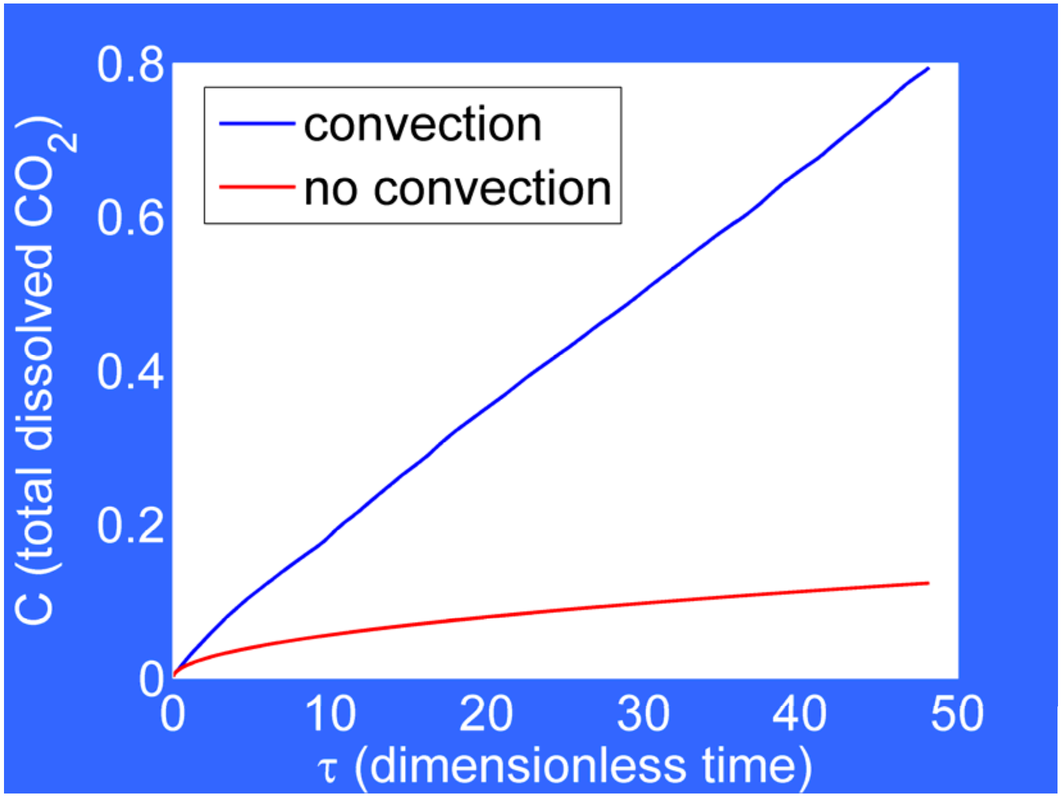
Miscible Convection

Ra = 4000



Riaz, Hesse, Tchelepi, Orr

Why is Convection Important?



Dissolution of CO_2 increases significantly!

Hesse, Riaz, Tchelepi, Orr

Summary

- Convection can be important:

  Constant dissolution rate
  $\Rightarrow$ Dissolved CO_2 increases linearly

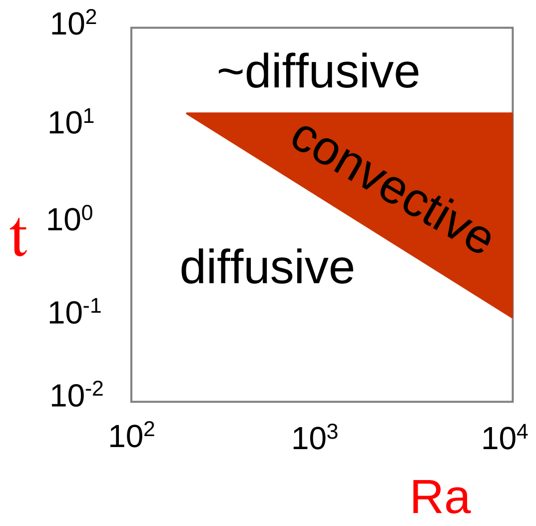
- Effective in large, high K aquifers:

  Onset time & critical wavelength decrease with K

- Not resolving the instability

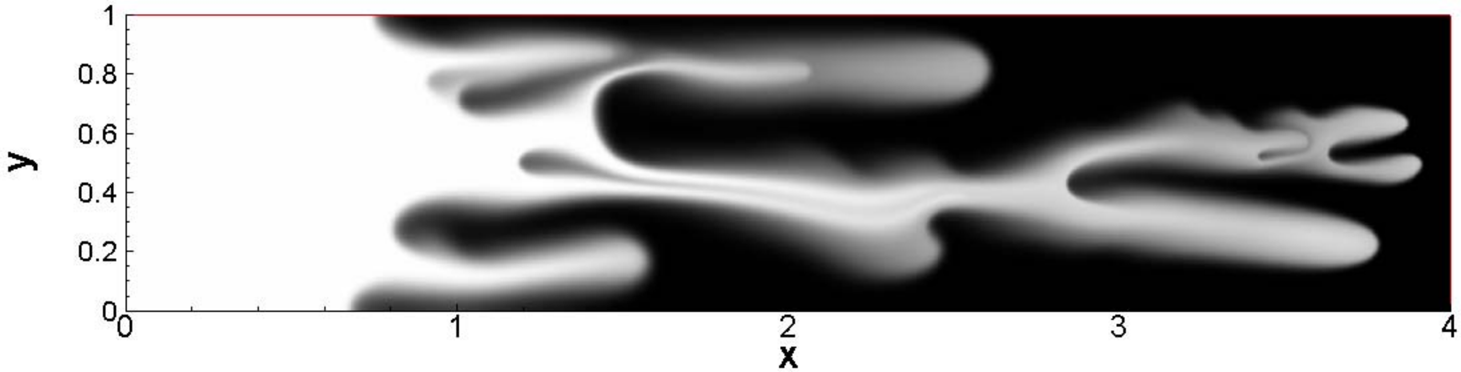
  shifts scales

- **Heterogeneity, anisotropy**

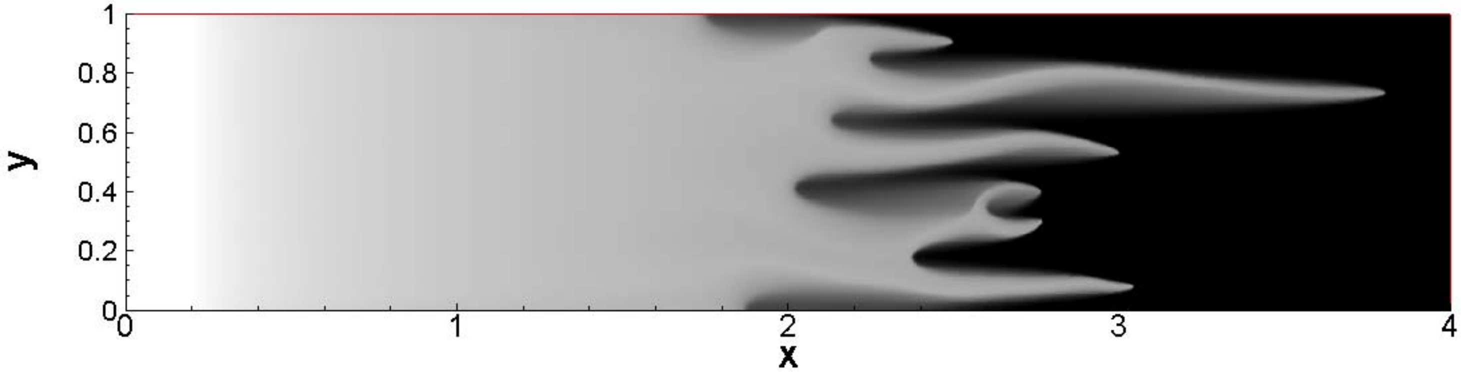


Unstable Flow
Miscible vs. Immiscible

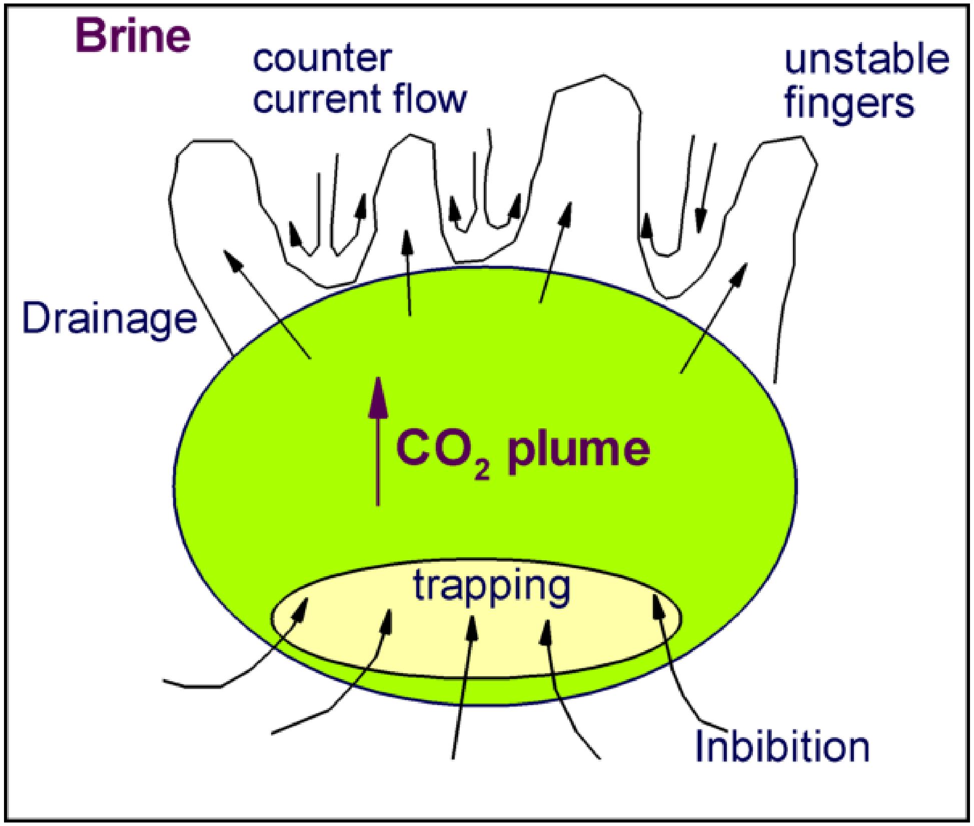
Miscible



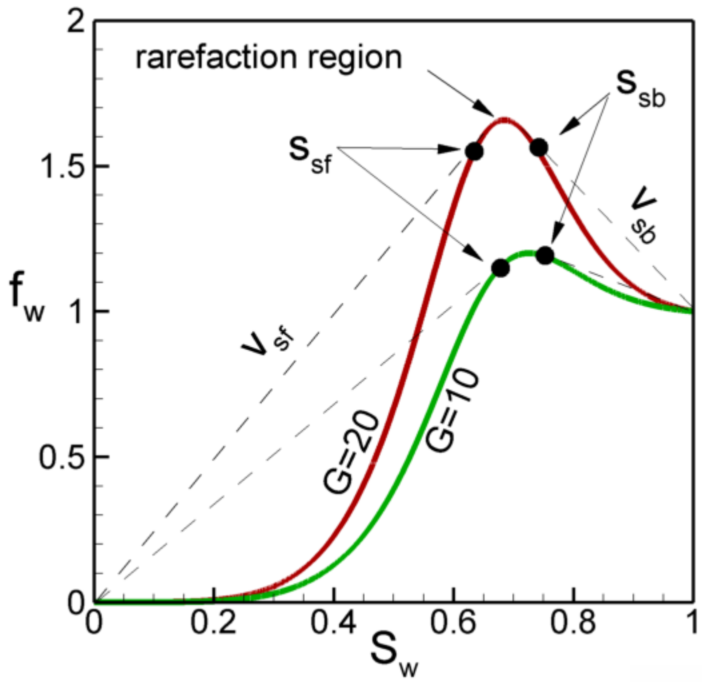
Immiscible



Immiscible Vertical Flow



Fractional Flow



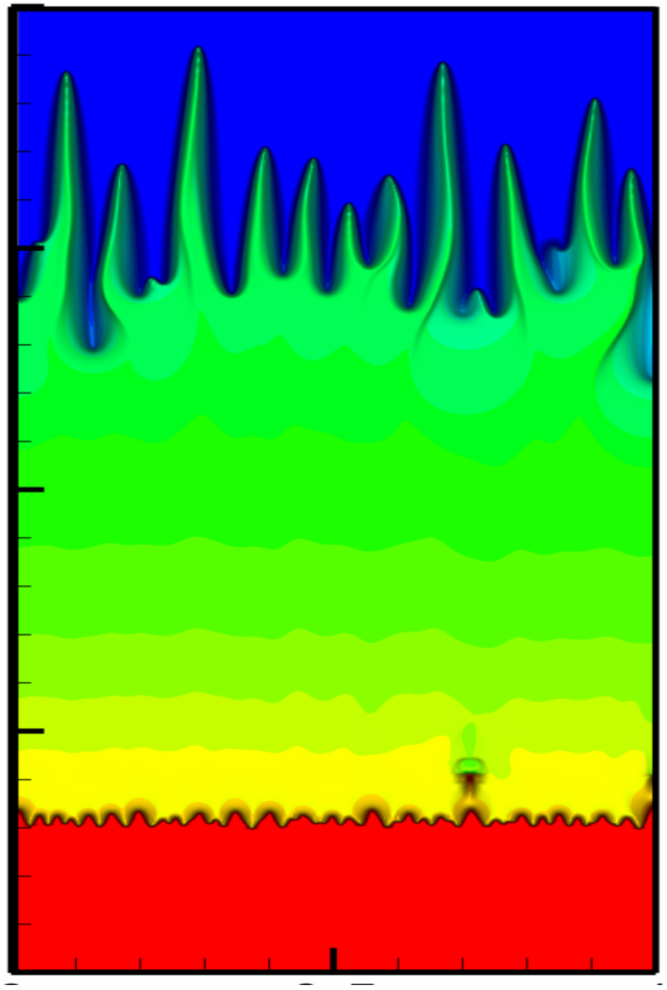
$$f_w = \frac{Mk_{rw}}{\lambda_T}\left(1 + G\frac{k_{rn}}{M}\right)$$

Shock velocity

$$v_{sf} = \left.\frac{\mathrm{d}f_w}{\mathrm{d}S_w}\right|_{S_w=s_{sf}} = \frac{1}{s_{sf}}\{f_w(s_{sf}) - f_w(0)\}$$

$$v_{sb} = \left.\frac{\mathrm{d}f_w}{\mathrm{d}S_w}\right|_{S_w=s_{sb}} = \frac{1}{1-s_{sb}}\{f_w(1) - f_w(s_{sb})\}$$

Large Differences in Density & Viscosity



Viscously Unstable

Viscously Stable

M =1/50, G = 20

$$M = \frac{\mu_{CO2}}{\mu_{Brine}}$$

Immiscible Plumes: Remarks

- Linear analysis & high resolution simulations of immiscible two-phase flow (injection & post-injection)
- Complex behaviors in the presence of density and viscosity differences
- **Post-injection modeling challenges**
  - **Unstable drainage**
  - **Residual trapping**

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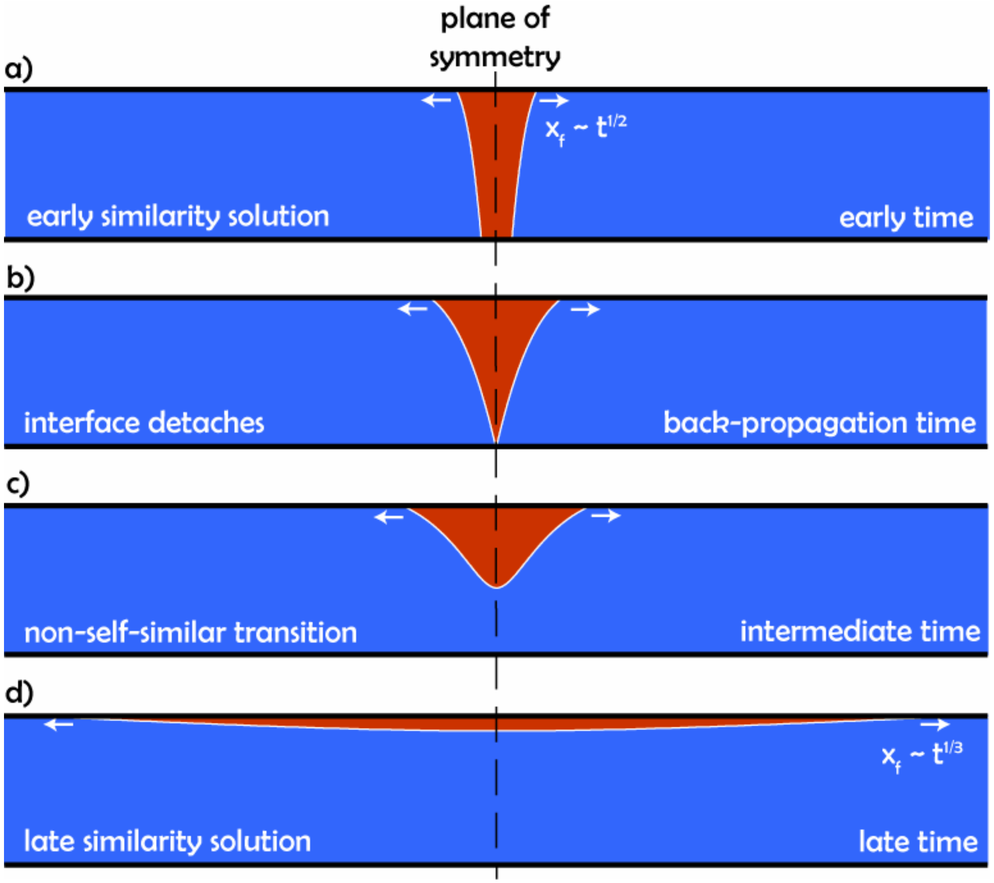
CO_2 Gravity Current

Finite plume: How fast does it spread?



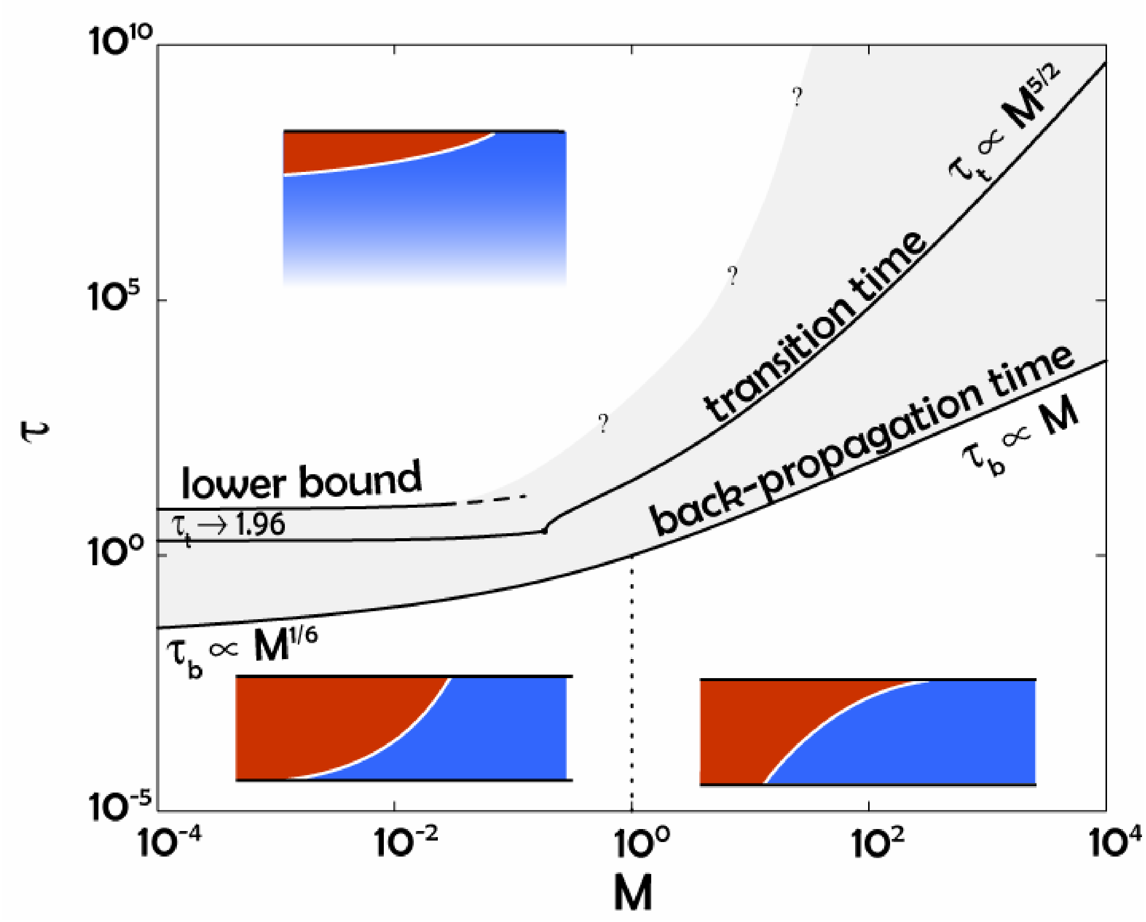
Simple Analytical Model

Consider two fluids separated by a sharp interface, the equation for the evolution of the height *h(x,t)* interface is:

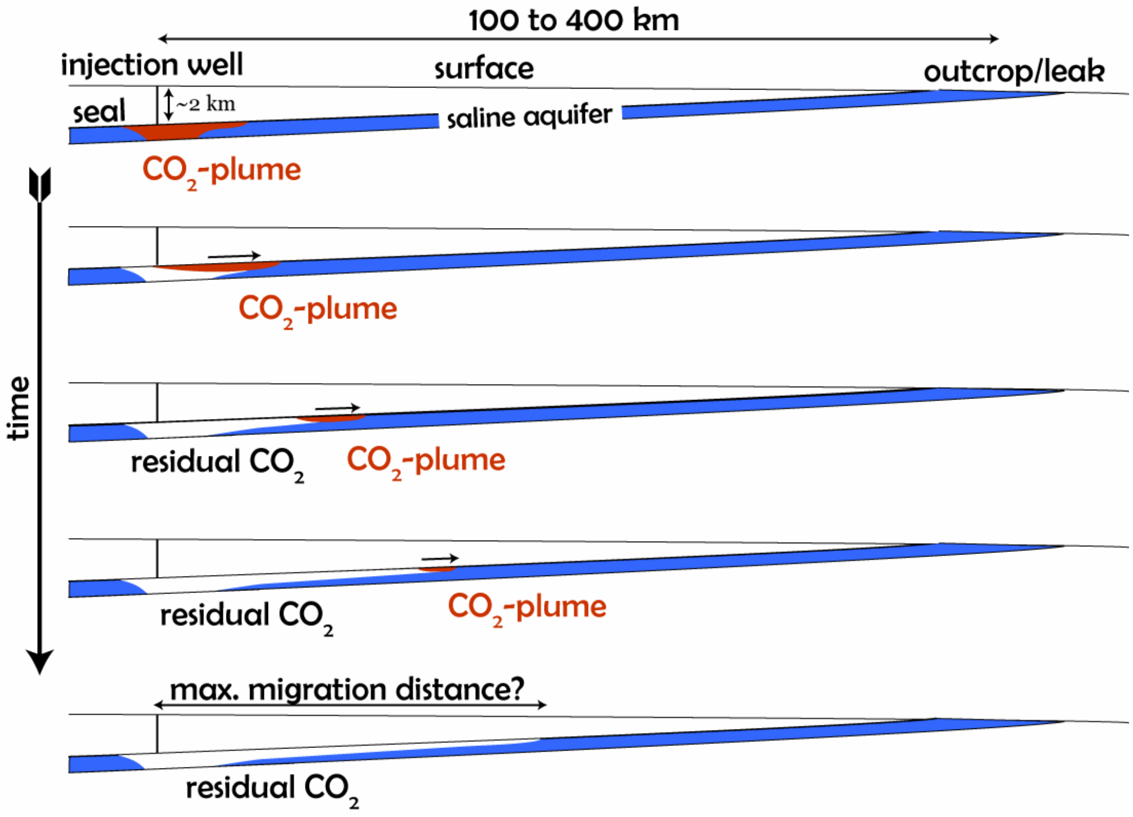
$$\frac{\partial h}{\partial t} = \kappa \frac{\partial}{\partial x}\left(\frac{h(H-h)}{h(M-1)+H} \frac{\partial h}{\partial x} \right)$$

$$\kappa = \frac{kg\Delta\rho k_{rg}^{*}}{\phi\mu_g} \qquad M = \frac{\lambda_g}{\lambda_w} = \frac{k_{rg}^{*}\mu_w}{k_{rw}^{*}\mu_g}$$

Regime Diagram



Storage in Open Sloping Aquifers



Many mid-continental saline aquifers are gently sloping, and lack a structural trap.

How does the maximum migration distance change with increasing slope?

Simple Model of Residual Trapping

(preliminary results!)

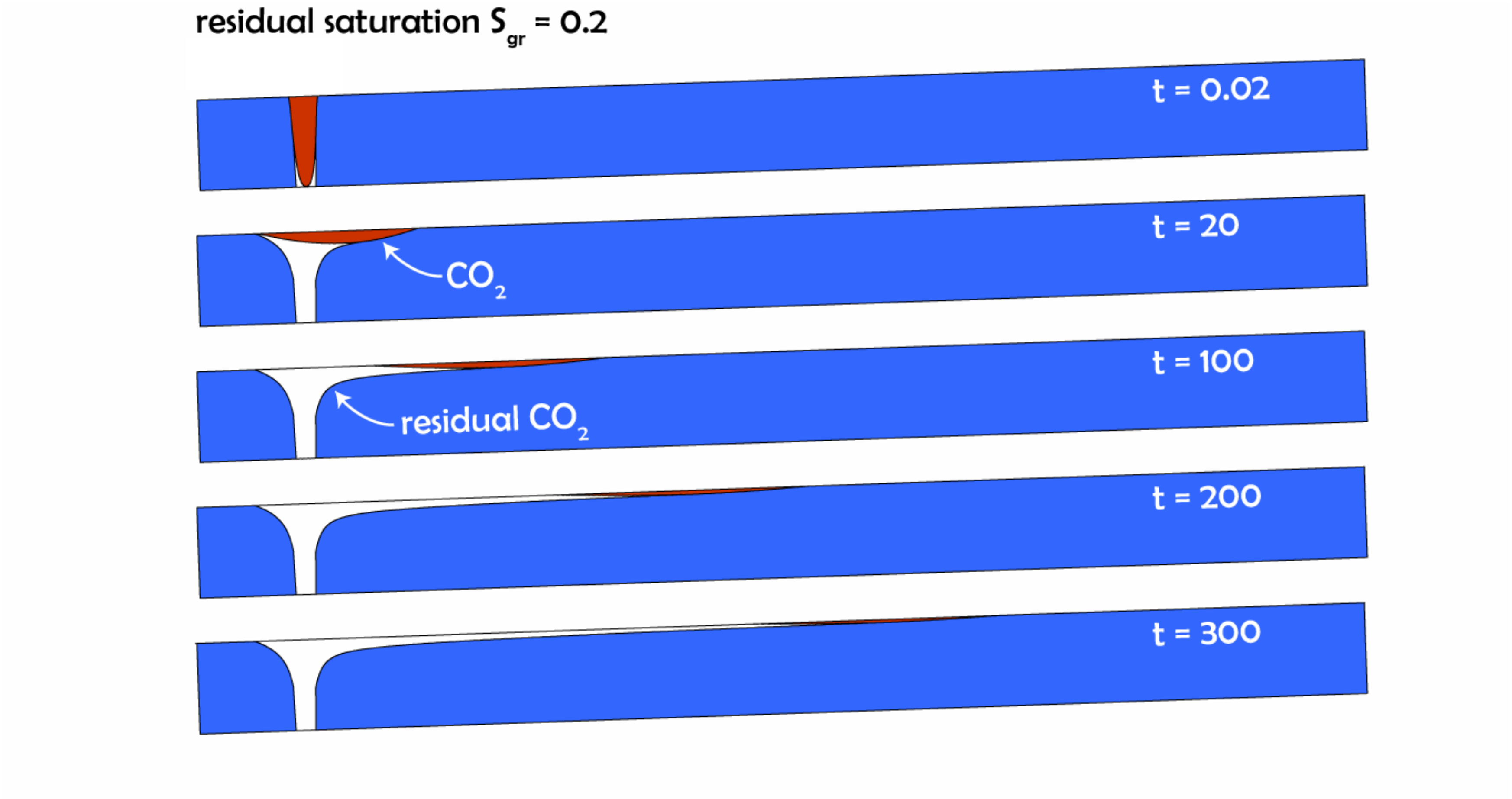
Incorporate loss of a constant residual saturation into gravity current model:

$$\frac{\partial h}{\partial t} + \kappa(x,t)\sin\theta \frac{\partial h}{\partial x} = \kappa(x,t)\cos\theta \frac{\partial}{\partial x}\left(h \frac{\partial h}{\partial x} \right)$$

$$\kappa(x,t) = \begin{cases} \kappa_1 = \dfrac{kg\Delta\rho\lambda_g}{\phi\left(1 - S_{wr} - S_{gr}\right)}; & \dfrac{\partial h}{\partial t} \le 0 \\ \kappa_1 = \dfrac{kg\Delta\rho\lambda_g}{\phi\left(1 - S_{wr}\right)}; & \dfrac{\partial h}{\partial t} > 0 \end{cases}$$

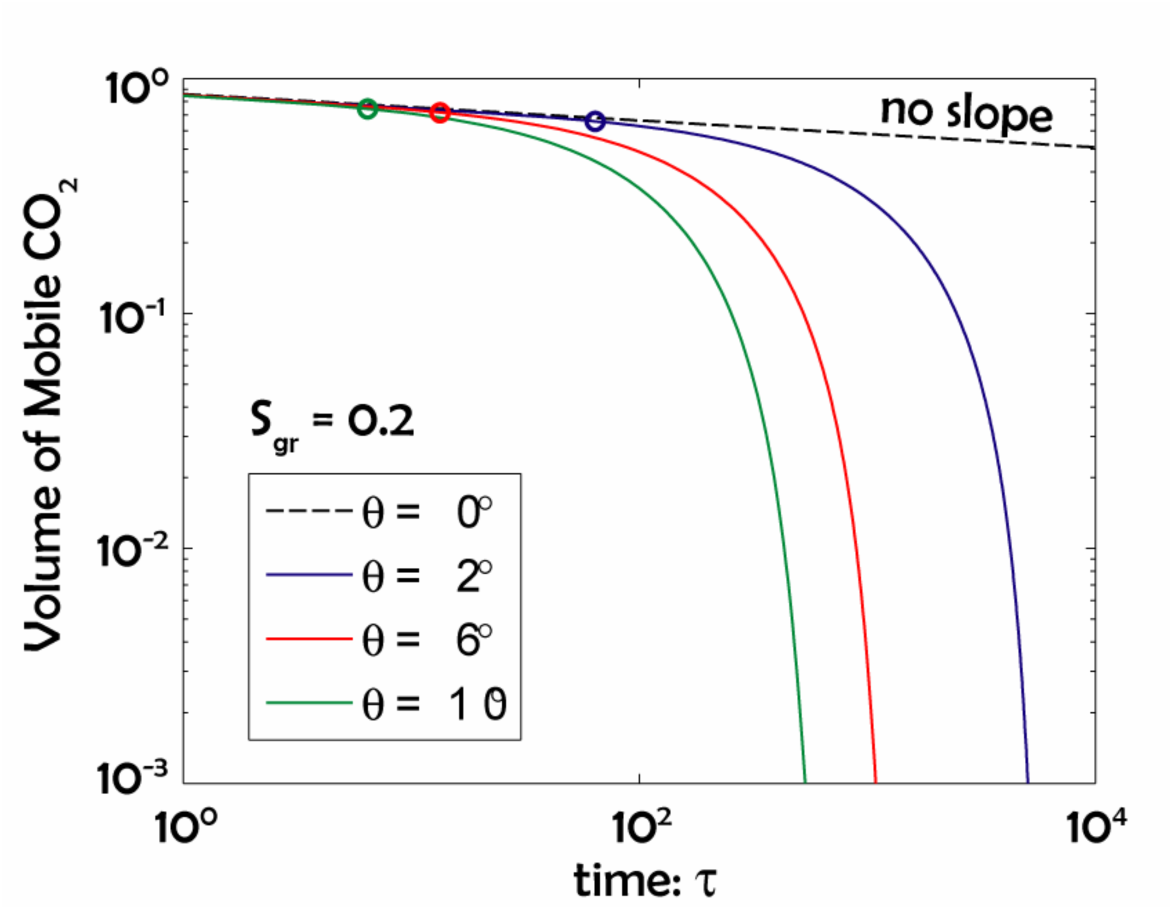
The effect of small slope on residual trapping?

Sloping Aquifer



Slope: 2 degrees

Residual Trapping



Gravity Currents: Remarks

- Scaling law of gravity-current tip changes when plume stops feeling aquifer thickness
- Residual trapping increases dramatically with aquifer slope
- Two regimes for a sloping aquifer
  - Initial power law decay (slumping > sliding)
  - Late stage with rapid decay (sliding > slumping)
- Migration distance decreases as slope increases
- **New family of similarity solutions**
- **Improved trapping model!**

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Motivation

- Interested in modeling flow in large-scale, highly heterogeneous formations
- Multiscale Formulations
  - Construct & solve coarse-scale problem
  - Reconstruct fine-scale solution locally
  - Existing methods deal with incompressible flow
- **Objective**
  - Multiscale method for compressible multiphase flow
  - Algebraic framework

Operator Based Multiscale Method

- Fine scale system

$$\mathbf{A}_f \mathbf{p}_f = \mathbf{r}_f$$

- Construct interpolation & projection operators

$$\mathbf{P}, \mathbf{R}$$

- Construct coarse scale system

$$[\mathbf{RAP}]\mathbf{p}_c = \mathbf{R}\mathbf{r}_f \Rightarrow \mathbf{A}_c \mathbf{p}_c = \mathbf{r}_c$$

- Reconstruction of fine-scale pressure

$$\mathbf{p}_f = \mathbf{P}\mathbf{p}_c$$

Operator Based MSFV

- Compressible flow equation

$$\nabla\cdot\left(\mathbf{k}\cdot\lambda_t\nabla p\right)=\phi_0\left(C_{fw}S_w+C_{fo}S_o+C_R\right)\frac{\partial p}{\partial t}+q$$

  - Existing multiscale methods for elliptic problems
  - General pressure equation is parabolic

- **OBMM**

$$\left.\begin{aligned}\int_{\bar{\Omega}_A}\nabla\cdot(\lambda\nabla p)dV&=[\mathbf{R}\mathbf{T}_f\mathbf{P}\mathbf{p_c}]_A\\ \int_{\bar{\Omega}_A}c(x)p(x)dV&=[\mathbf{R}\mathbf{C}_f\mathbf{P}\mathbf{p_c}]_A\end{aligned}\right\}\Rightarrow(\mathbf{T}_c-\mathbf{C}_c)\mathbf{p}_c=\mathbf{r}_c$$

Prolongation Operator

- The basis functions are given by

$$\nabla \cdot \left(\lambda \nabla \phi_A^{(I)}\right) = 0 \quad \text{in } \tilde{\Omega}_I$$

$$\frac{\partial}{\partial x_t}\left(\lambda \frac{\partial \phi_A^{(I)}}{\partial x_j}\right)_t = 0 \quad \text{on } \partial\tilde{\Omega}_I$$

$$\phi_A^{(I)}\left(x_B\right) = \delta_{AB}$$

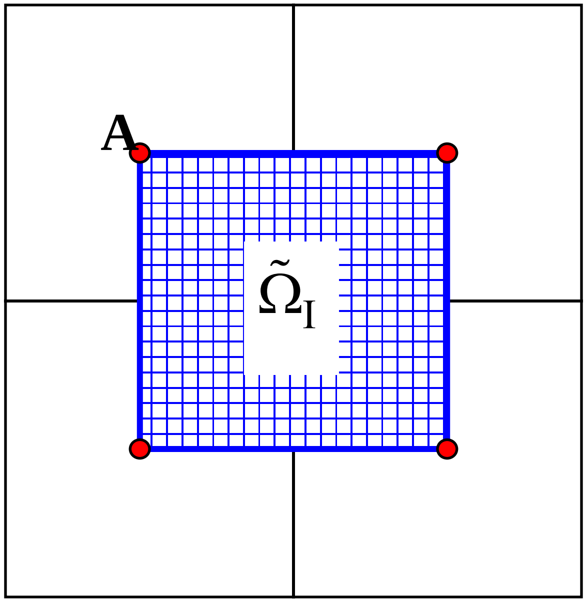
- Assemble prolongation operator

$$\phi_A = \sum_{I=1}^{n_c} \phi_A^{(I)}$$

$$[\mathbf{P}]_{a,A} = \phi_A(x_a)$$

“A” denotes coarse node;

“a” denotes fine node



Restriction operator for MSFV

- FVM equations in fine and coarse scale

$$\int_{\Omega_a} \nabla\cdot(\lambda\nabla p)\,\mathrm{d}V = \int_{\Omega_a} c(x)\frac{\partial p}{\partial t}\,\mathrm{d}V \qquad \left(a = 1,\ldots,n_f\right)$$

$$\int_{\bar{\Omega}_A} \nabla\cdot(\lambda\nabla p)\,\mathrm{d}V = \int_{\bar{\Omega}_A} c(x)\frac{\partial p}{\partial t}\,\mathrm{d}V \qquad \left(A = 1,\ldots,n_c\right)$$

- The Restriction operator sums the fine scale equations to form the coarse scale formula

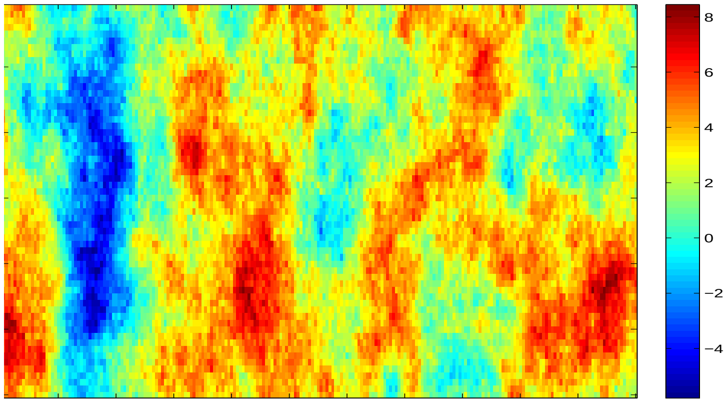
$$[R]_{A,a} = \begin{cases} 1 & \text{if } \Omega_a \subset \bar{\Omega}_A \\ 0 & \text{otherwise} \end{cases} \qquad \left(A = 1,\ldots,n_c;\; a = 1,\ldots,n_f\right)$$

Compressible Two-Phase System

- Depletion of liquid-gas reservoir
  - Initially 50% liquid and 50% gas
  - The PVT properties for the two fluids are

$$b_l = 1 + 10^{-3} p / p_0$$
$$b_g = 1 + p / p_0$$

  - Compressibility driven flow
  - SPE 10 top layer (220 X 60)



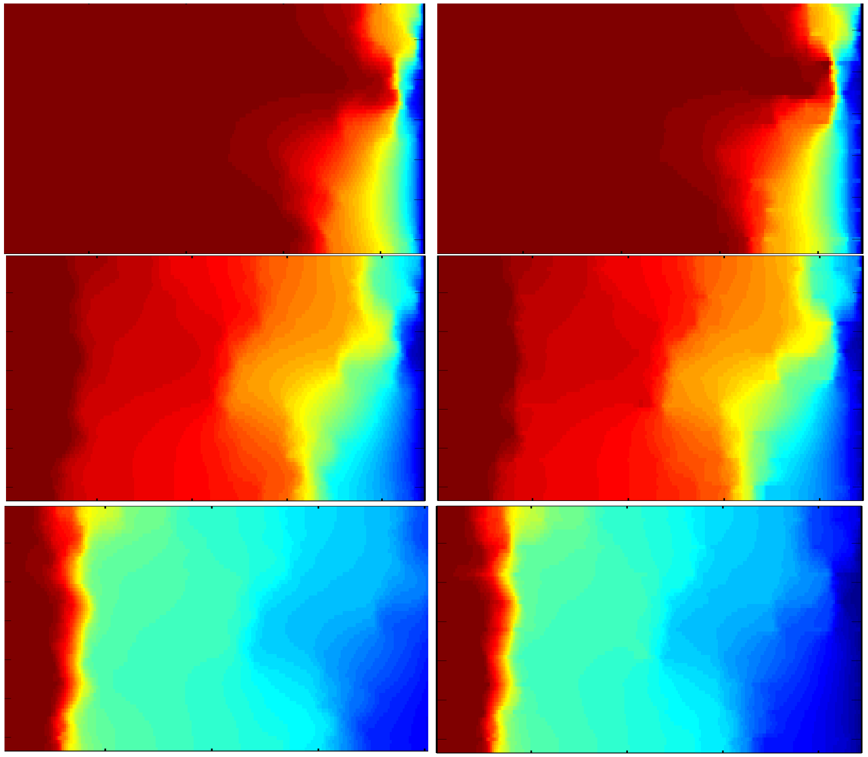
Algebraic MSFV: Pressure Field

Fine

220 x 60

Multiscale

22 x 6



$t = 0.005\tau$

$t = 0.05\tau$

$t = 0.5\tau$

Operator Based Multiscale Method

- Algebraic multiscale framework for high resolution modeling of CO2 Sequestration
- Advantages of OBMM
  - Extendible to unstructured grid
  - Easier to include more complicated physics
  - Allows for incorporating a multiscale formulation into existing reservoir simulators
- Adaptivity, GPRS implementation
- Multiscale formulation for nonlinear transport

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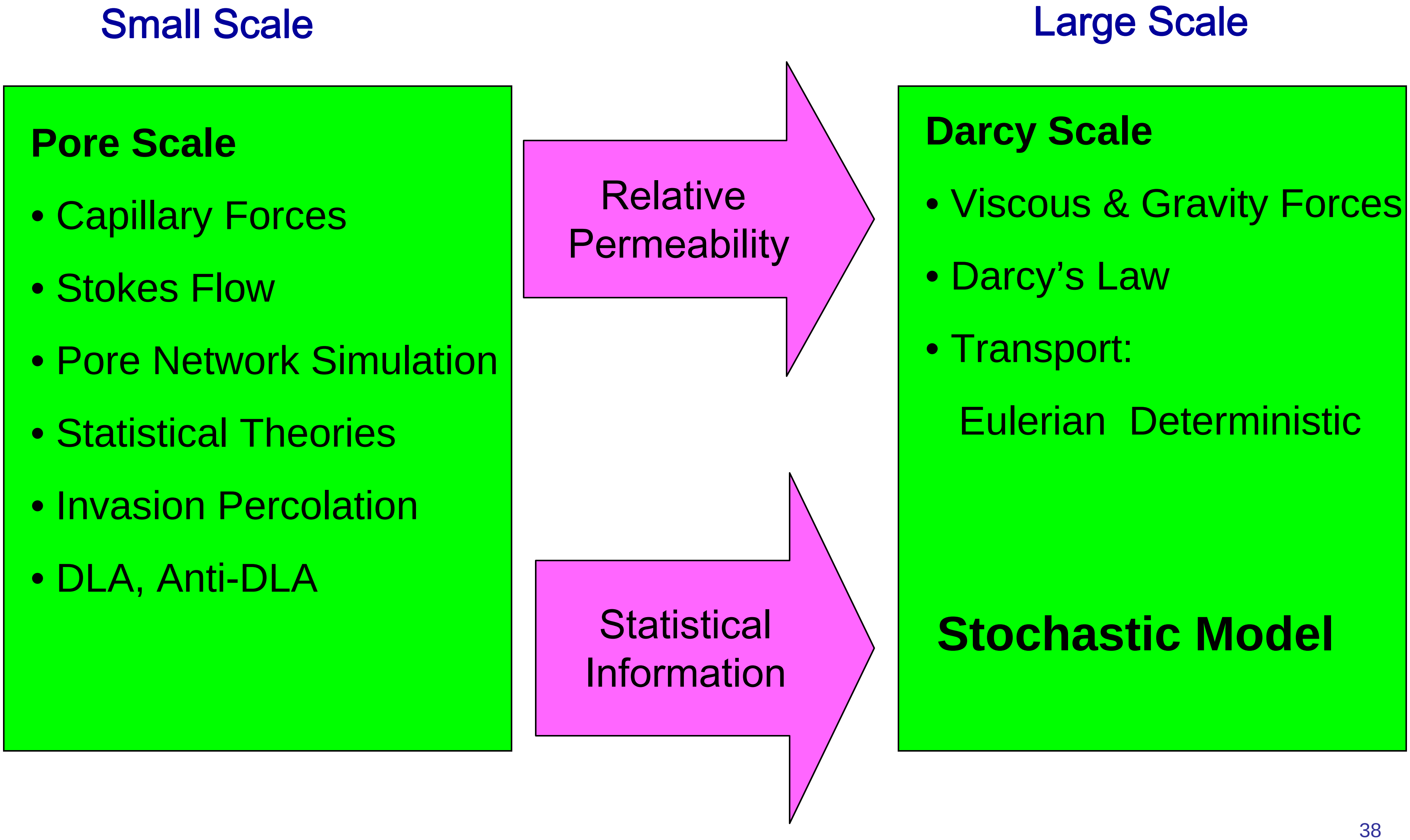
CO2 Sequestration
Multiscale Multi-Physics



Small Scale

Large Scale

Pore Scale

- Capillary Forces
- Stokes Flow
- Pore Network Simulation
- Statistical Theories
- Invasion Percolation
- DLA, Anti-DLA

Relative Permeability

Statistical Information

Darcy Scale

- Viscous & Gravity Forces
- Darcy’s Law
- Transport:

Eulerian Deterministic

Stochastic Model

Modeling Framework

- **Phase transport equation**

$$\frac{\partial S^{\alpha}}{\partial t} + \nabla \cdot v^{\alpha} = q^{\alpha}$$

Transport

- **Conservation of total mass**

$$\nabla \cdot \sum v^{\alpha} = \nabla \cdot v = \sum q^{\alpha} = q$$

Flow

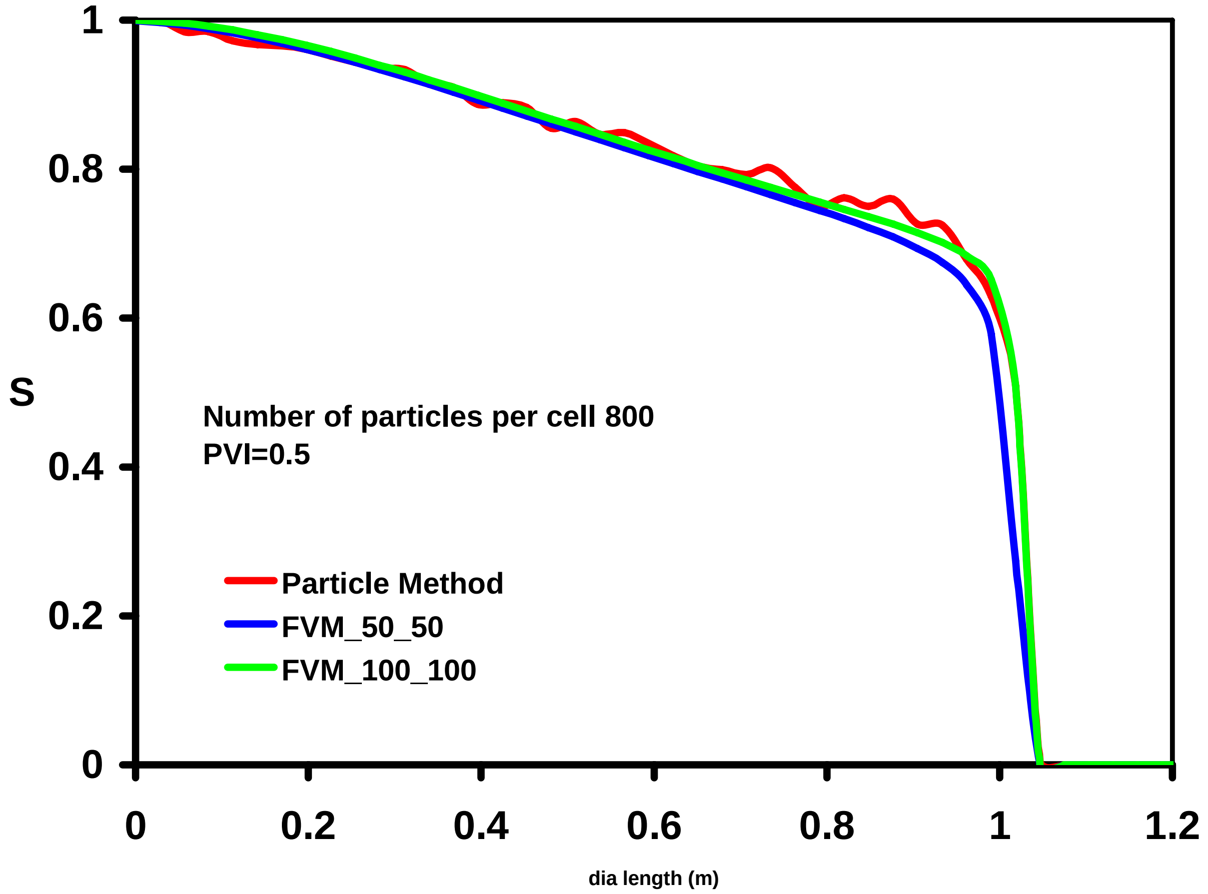
- **Elliptic equation for pressure**

$$\nabla \cdot \left(\sum \frac{k_r^{\alpha} k}{\phi} \nabla p^{\alpha} \right) = -q$$

Stochastic Model: Lagrangian Framework

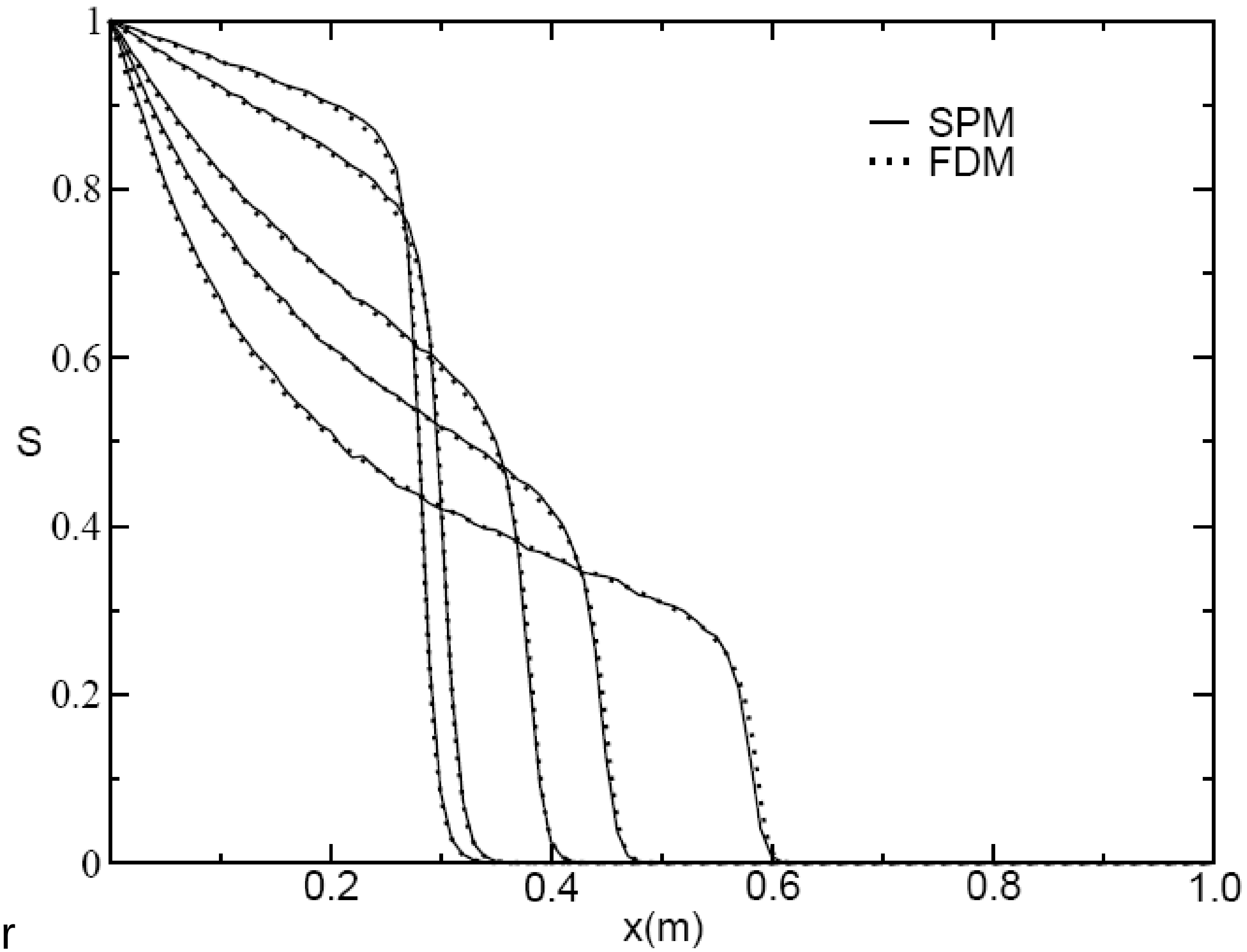
- Particle based method (Monte Carlo)
- A particle represents a phase (physical particles)
- Different from characteristic methods
- **Particle evolution: statistical rules (pore-scale physics)**
- **Natural modeling of multiscale, multi-physics processes**

2D Test Case



Saturation curve of injected phase along diagonal after 0.5 PVI

SPM: 1D Buckley-Leverett

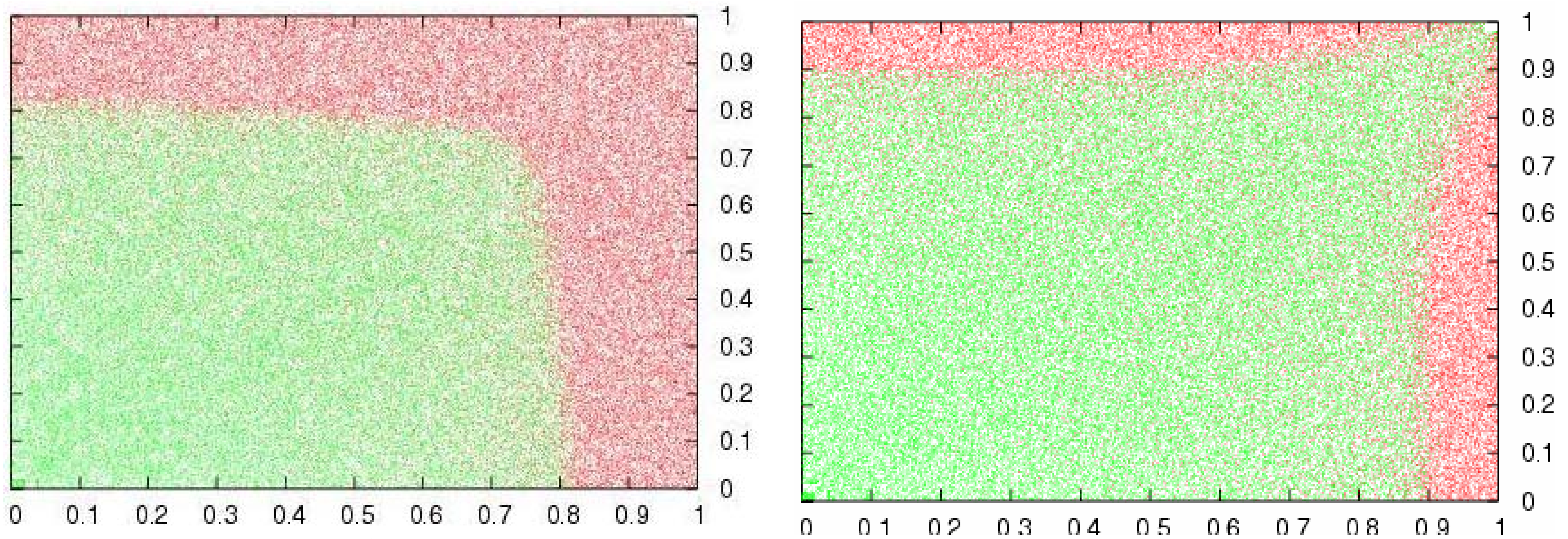


Quadratic Kr

M = 4, 2, 0.5, 0.25, 0.1

2D, Two-Phase, Homogeneous

Particle Distribution



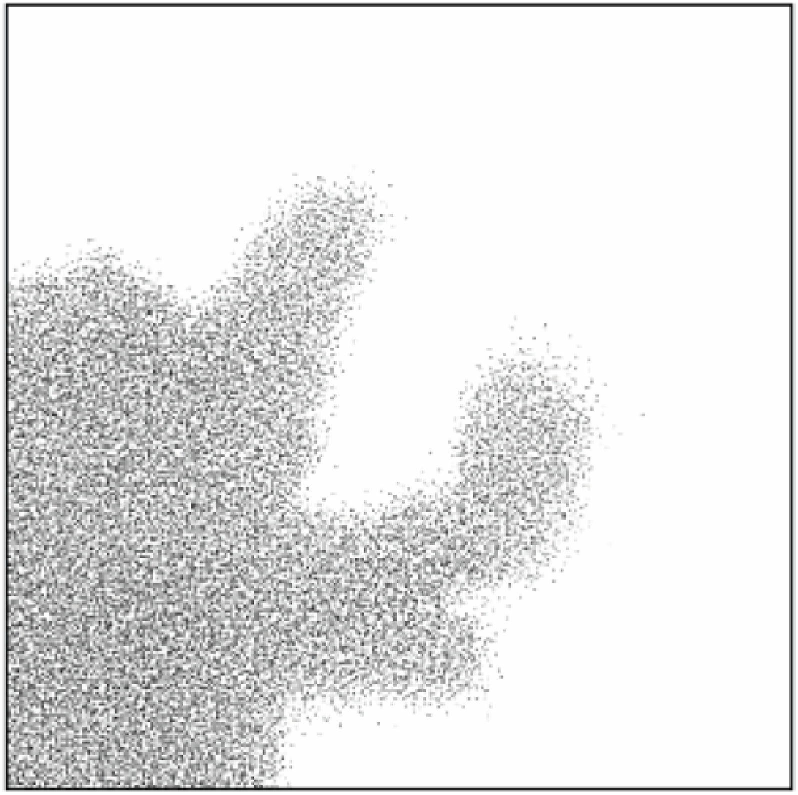
PVI=0.5

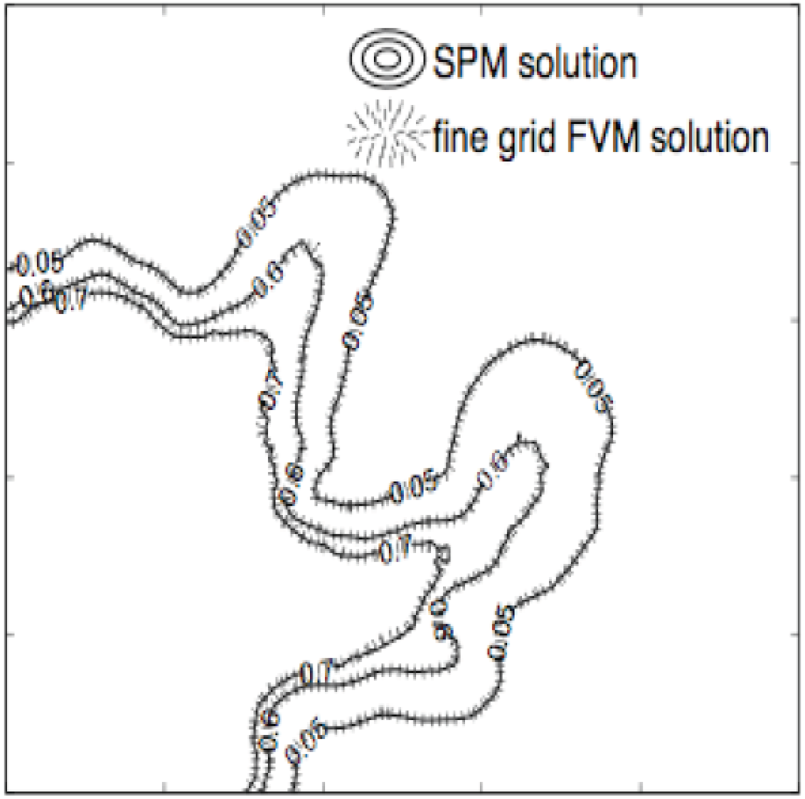
PVI=0.7

Before Breakthrough

After Breakthrough

2D, Two-Phase, Heterogeneous





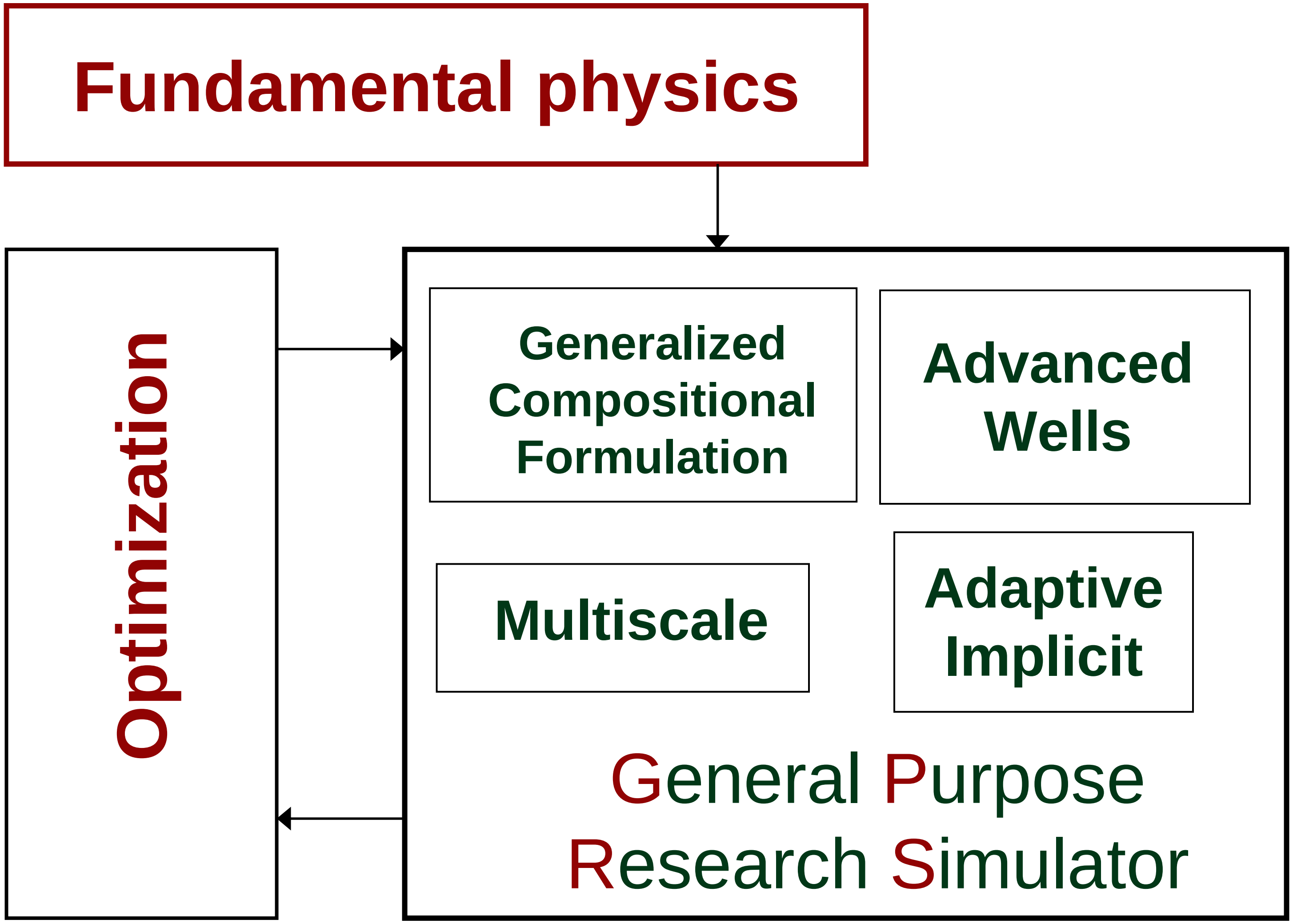
Quadratic Kr

Particle Method: Remarks

- Developed a stochastic framework that provides a consistent link between small and large scales
- Showed how stochastic particles can be used to solve nonlinear conservation equations
- Validation against exact solutions and FVM

- **Demonstrate power of the method:**
  - Statistical information from pore scale physics
  - Particle velocity pdf & multi-point statistics
  - Non-equilibrium: hysteresis, trapping, reactions
  - Pore-scale instability, …

CO$_2$ Sequestration Computational Framework



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Next Steps

- Continue investigation of post-injection miscible & immiscible CO_2-water systems
- Stochastic particle method for linking small and large scales
- Further develop and implement new algorithms in GPRS (e.g., OBMM, High-Order AIM)
- **GPRS-based optimization** of CO_2 injection strategies using advanced wells

Posters

1. CO2 Sequestration Capabilities in GPRS
2. Algebraic Multiscale Formulation for Compressible Multiphase Flow
3. Miscible Convection in Saline Aquifers
4. CO2 Gravity Currents and Residual Trapping in Saline Aquifers
5. Particle Tracking Method for Nonlinear Multiphase Flow