3D parallel simulation of CO_2 injection into the SPE model using DuMu^x

Tri Dat NGO[1,*]

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Géosciences pour une Terre durable

Hydrodynamics Heterogeneity Homogenization

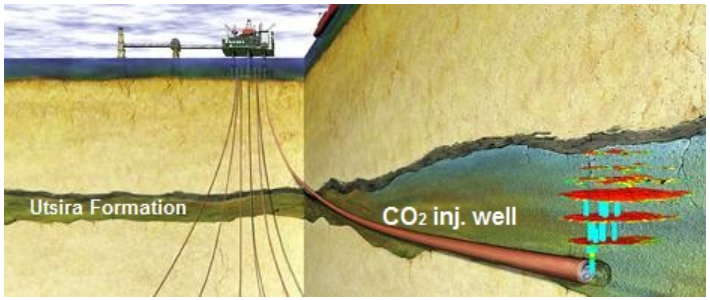
11, 12 June 2015

Géosciences pour une Terre durable

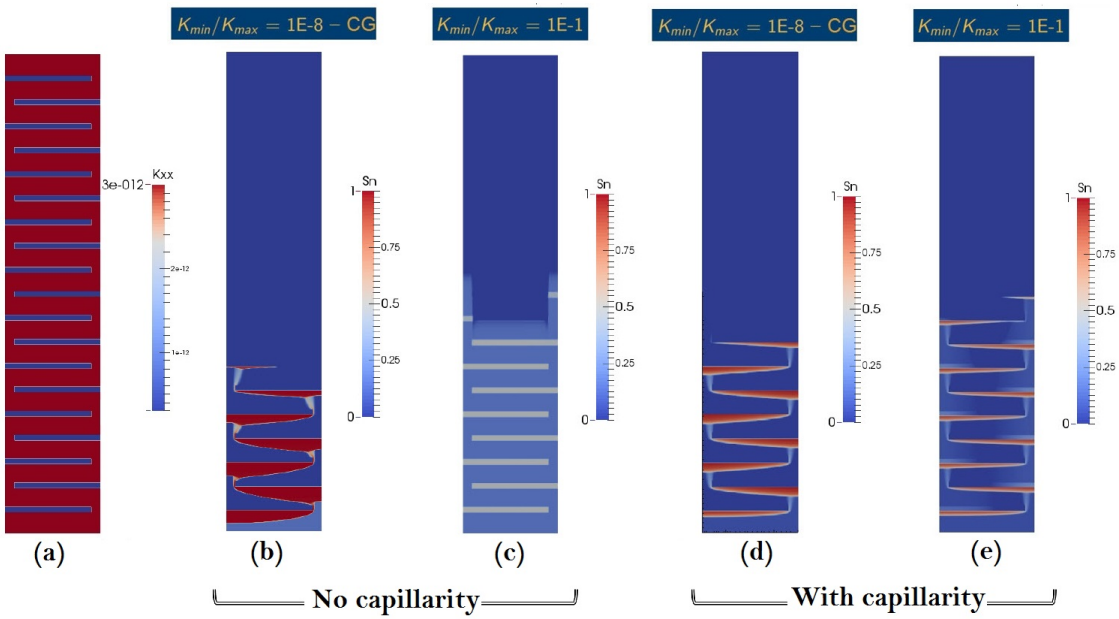
Outline

Outline

Geological storage of CO_2



Sleipner sequestration site (*Statoil*)



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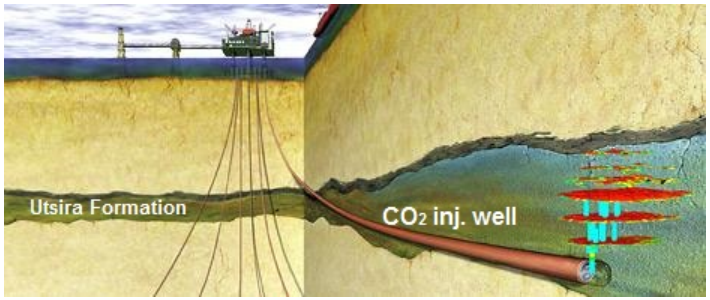

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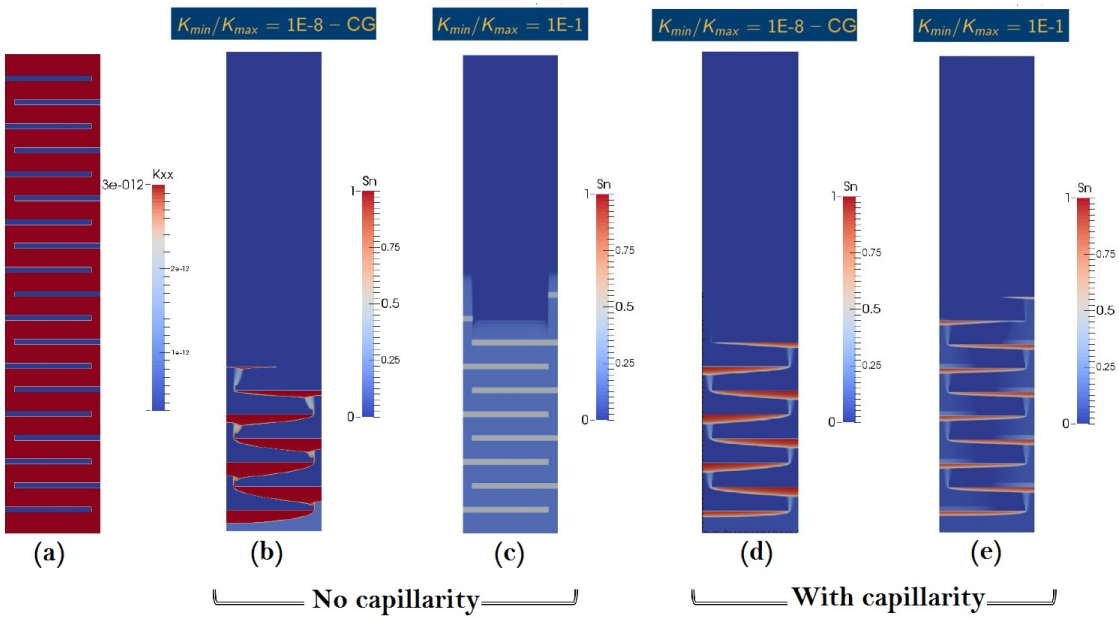
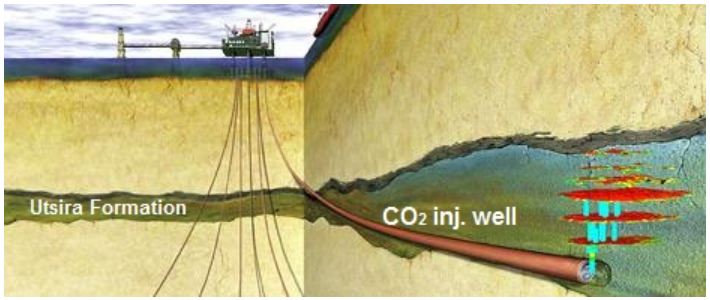


"Upscaling of buoyancy-driven two-phase flow CO_2 - brine in a heterogeneous media"

Geological storage of CO_2



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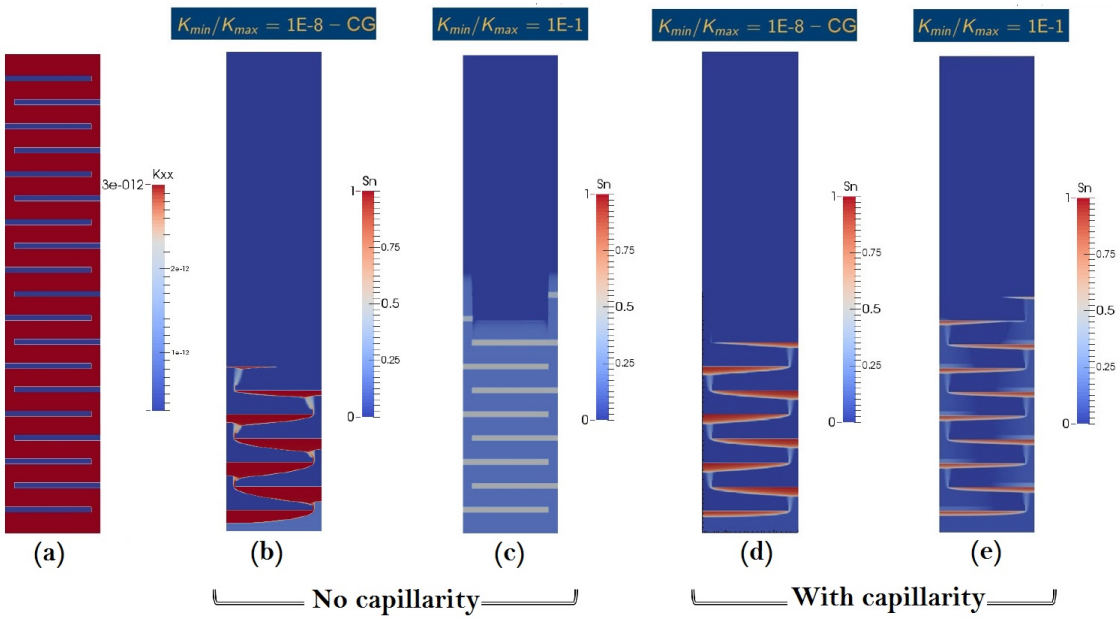
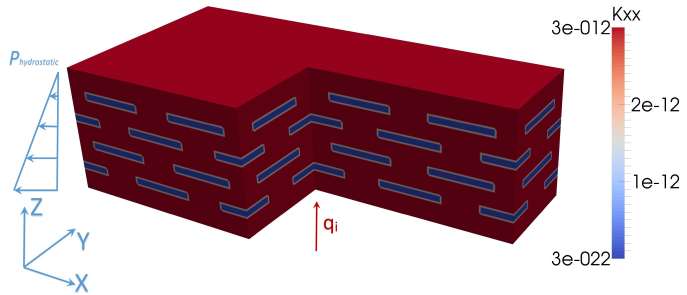


"Upscaling of buoyancy-driven two-phase flow CO_2 - brine in a heterogeneous media"

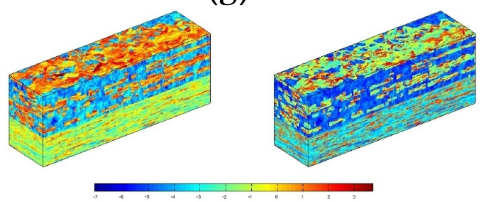
$\Rightarrow$ Need of a efficient code for:

(i) Validation of the 2D analytical model: Fine resolution of the CO_2 stratification beneath low permeability layers.

(ii) Simulation of CO_2 injection into 3D periodic or realistic reservoir.



(g)

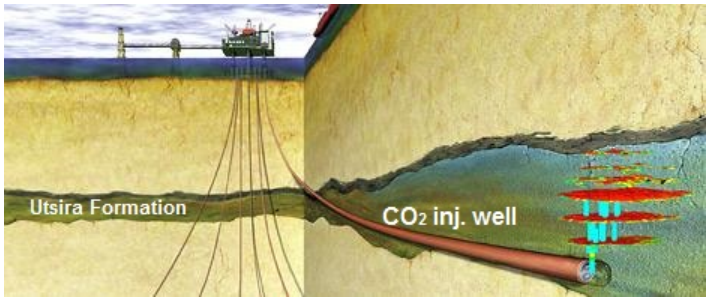


(h)

Why DuMu^x?

1. TOUGH 2 (LBNL,Fortran, $\sim$ 2000€):
   $\Rightarrow$ Not built to handle incompressible system
2. MRST (Sintef, Matlab): (Windows 7, 32 bits)
   $\Rightarrow$ Limit of array size of operating system $\rightarrow$ limit of mesh size
   $\Rightarrow$ CPU time
3. DuMu^x (C^{++}, Open source on Linux): **CMWR conference, June 2014**
   - Incompressible, Immiscible flow:
     - Isothermal condition: TwoPModel (2p)
     - Non-Isothermal condition: TwoPNIModel (2pni)
   - Compressible, Miscible flow:
     - Isothermal condition:
       TwoPTwoCModel (2p (wetting, non wetting) - 2c (brine, CO_2))
     - Non-Isothermal condition: TwoPTwoCNIModel (2p2cni)

Geological storage of CO_2



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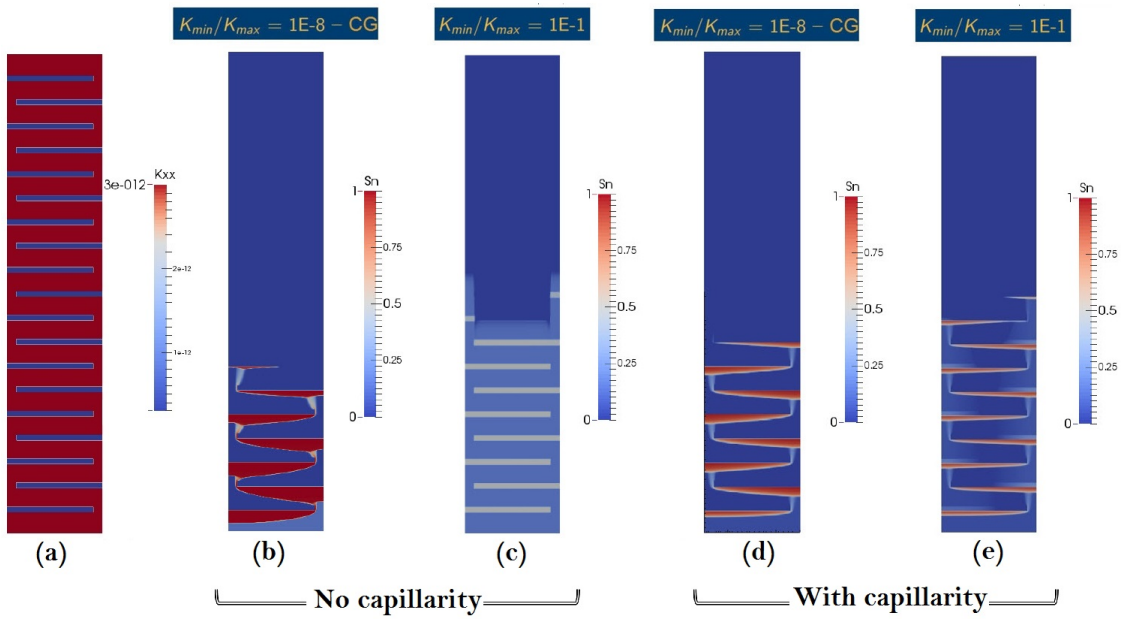

"Upscaling of gravity-driven two-phase flow CO_2 - brine a heterogeneous media"

⇒ Need of an efficient code for:

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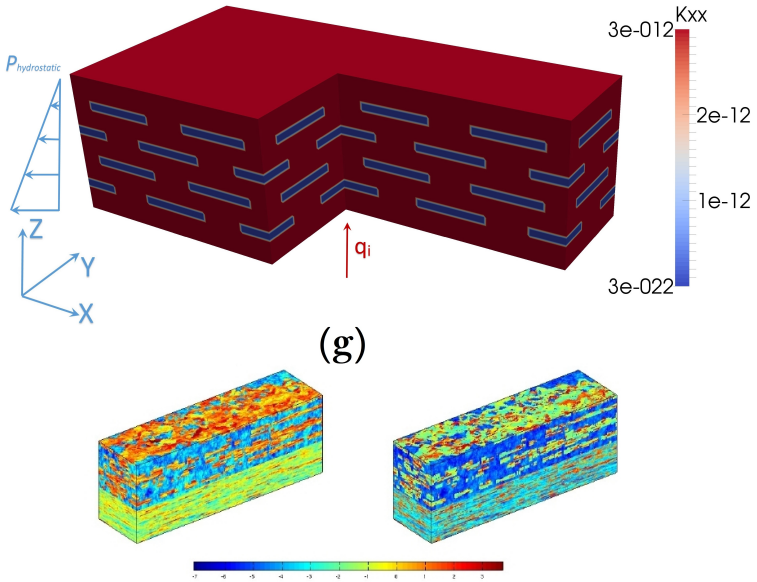
(ii) Simulation of CO_2 injection into a 3D realistic reservoir.



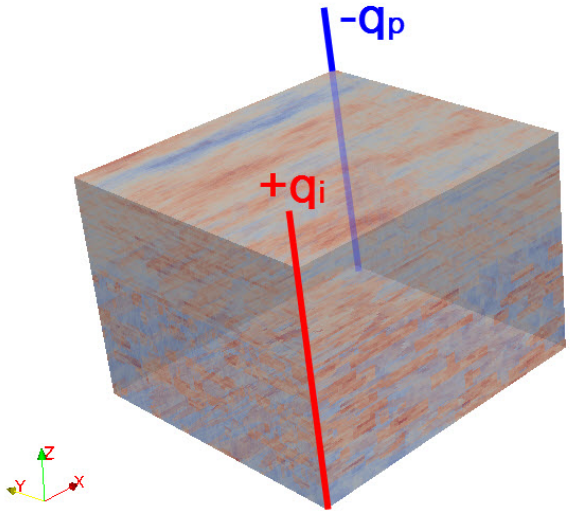
Outline

CO_2 injection into the SPE10 model $\sim$ 1.E6 elements

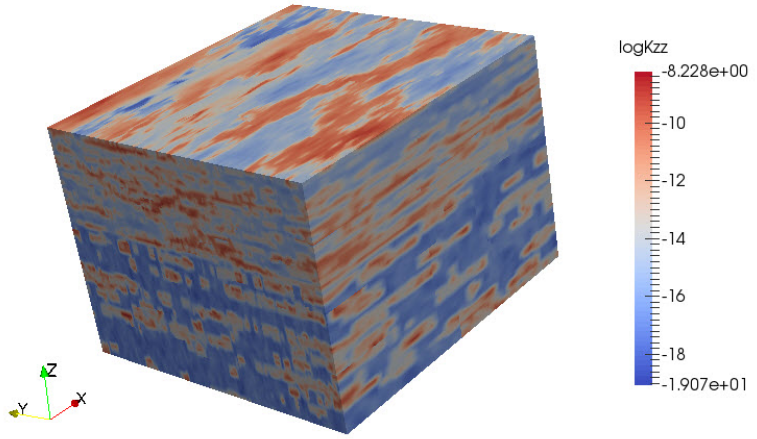
SPE10 original model: 360m x 660m x 51m

SPE10 modified model: 6400m x 8000m x 160m

** z-direction scaled by 50*



Wells



K_{zz}

Demands

Fine resolution of heterogeneous parameters

Fine resolution of fluid front

High number of grid cells/dof

$\Rightarrow$ Intractable CPU time

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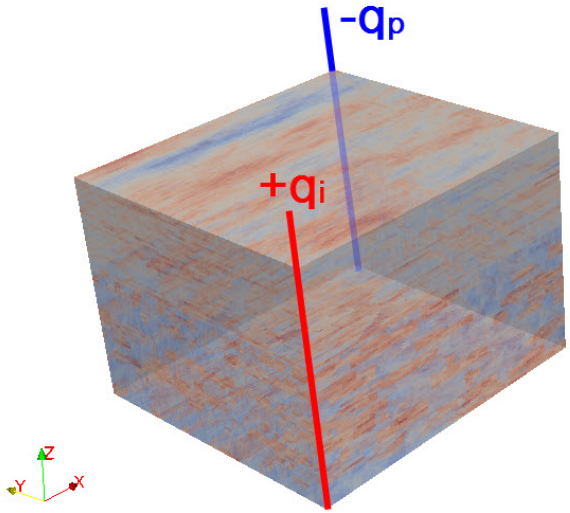

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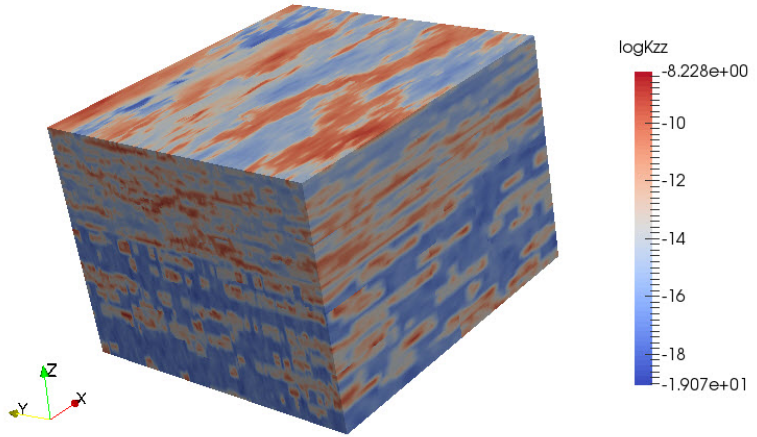

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- Adaptive Grid Refinement
- Massively parallel computing

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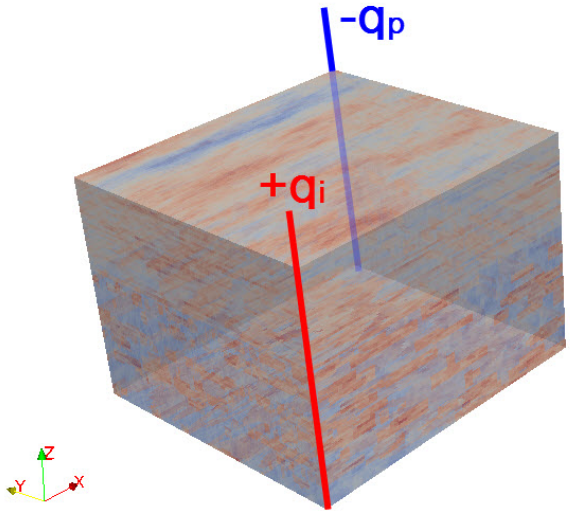

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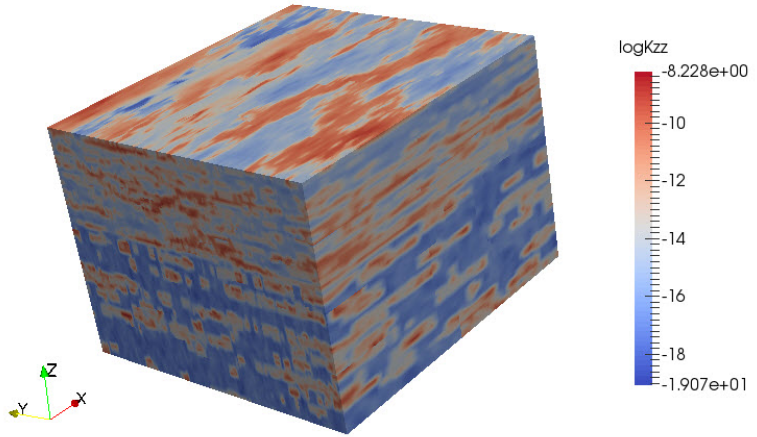

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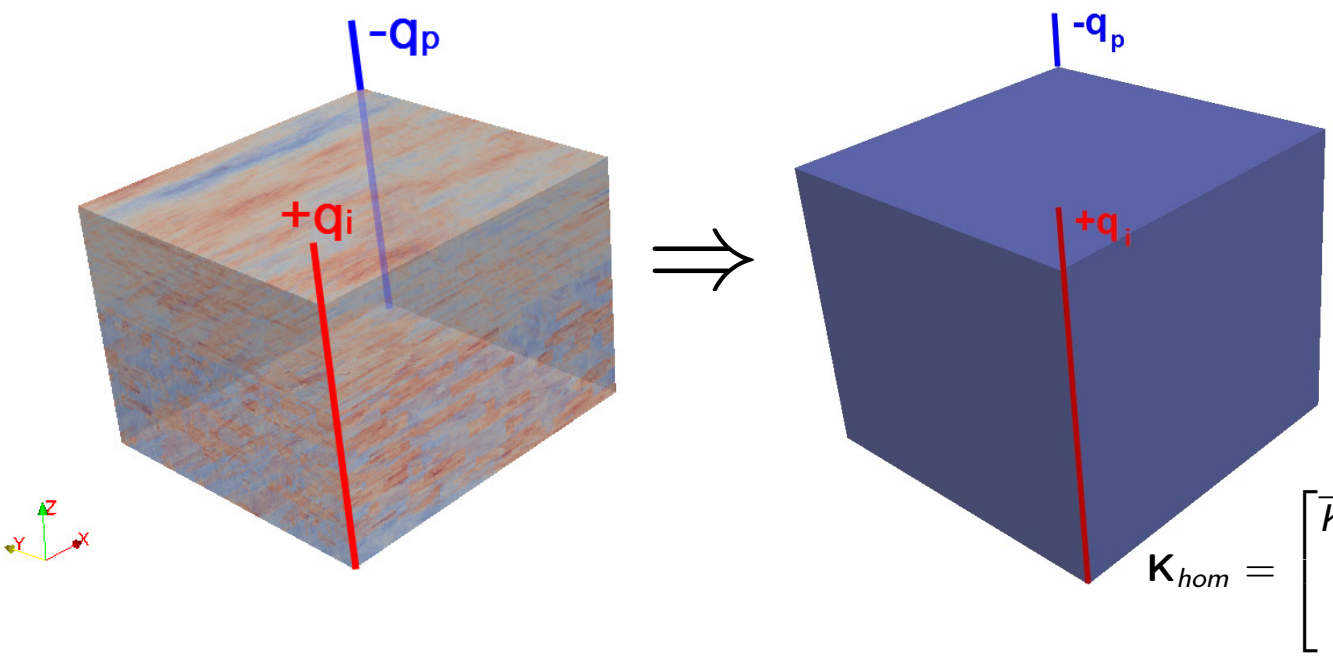


$$\mathbf{K}_{hom} = \begin{bmatrix} \overline{K}_{xx}^{har} & 0 & 0 \\ 0 & \overline{K}_{xx}^{har} & 0 \\ 0 & 0 & \overline{K}_{zz}^{har} \end{bmatrix}$$

- Massively parallel computing

$\Rightarrow$ How does Dumux behave when used on hundreds cores?

$\rightarrow$ Strong scaling (same problem with more and more processors)

2p model

Coupled system → Fully implicit (FI) method

- Darcy's law : $\mathbf{v}_\alpha = -\frac{k_{r,\alpha}}{\mu_\alpha}\mathbf{K}\left(\mathbf{grad}p_\alpha - \rho_\alpha \mathbf{g}\right)$
- Continuity equation : $\phi\frac{\partial S_\alpha}{\partial t} + \nabla.\mathbf{v}_\alpha = q_\alpha \; ; \alpha \in \{w, n\}$
- Capillary pressure: $p_c = p_n - p_w$

Reformulation → decoupled system: IMPES numerical scheme

- Pressure equation:

$$\nabla.[-\lambda_{tot}\mathbf{K}\nabla p_w - \lambda_{tot}\mathbf{K}\nabla p_c - (\lambda_w\rho_w + \lambda_n\rho_n)\mathbf{K}g\nabla z] = q_{tot}$$

- Transport equation:

$$\phi\frac{\partial S_w}{\partial t} + \nabla.\mathbf{v}_w = q_w$$

- Capillary pressure:

$$p_c = p_n - p_w$$

Numerical method for 2p model

Phase and Capillary potential

$\Phi_\alpha = p_\alpha + \rho_\alpha g z$, $\Phi_c = p_c + (\rho_n - \rho_w) g z$ with $\alpha \in [w, n]$

IMPES

$$\mathbf{A}_\Phi(\mathbf{S}_w^n)\mathbf{\Phi}_w^{n+1} + \mathbf{A}_c(\mathbf{S}_w^n)\mathbf{\Phi}_c(\mathbf{S}_w^n) = \mathbf{Q}_\Phi^{n+1}$$

$$\mathbf{M}\frac{\mathbf{S}_w^{n+1} - \mathbf{S}_w^n}{\Delta t^n} + \mathbf{A}_w(\mathbf{S}_w^n)\mathbf{\Phi}_w^{n+1} = \mathbf{Q}_w^{n+1}$$

Assumptions: equations are weakly coupled

Problems: CFL restrictions

FI

$$\mathbf{A}_\Phi(\mathbf{S}_w^{n+1})\mathbf{\Phi}_w^{n+1} + \mathbf{A}_c(\mathbf{S}_w^{n+1})\mathbf{\Phi}_c(\mathbf{S}_w^{n+1}) = \mathbf{Q}_\Phi^{n+1}$$

$$\mathbf{M}\frac{\mathbf{S}_w^{n+1} - \mathbf{S}_w^n}{\Delta t^n} + \mathbf{A}_w(\mathbf{S}_w^{n+1})\mathbf{\Phi}_w^{n+1} = \mathbf{Q}_w^{n+1}$$

Assumptions: no

Problems: convergence of solver

(R. Helmig, MSPM 2014)

2p2c model

Coupled system

$$v_\alpha = -\frac{k_{r,\alpha}}{\mu_\alpha}\mathbf{K}\left(\mathbf{grad}p_\alpha - \rho_\alpha \mathbf{g}\right)$$

$$\phi\frac{\partial \sum_\alpha \rho_\alpha \frac{M^\kappa}{M_\alpha} x_\alpha^\kappa \alpha S_\alpha}{\partial t} - \sum_\alpha div\left\{\rho_\alpha \frac{M^\kappa}{M_\alpha} x_\alpha^\kappa \frac{k_{r,\alpha}}{\mu_\alpha}\mathbf{K}\left(\mathbf{grad}p_\alpha - \rho_\alpha \mathbf{g}\right)\right\}$$

$$-\sum_\alpha div\left\{D_{\alpha,pm}^\kappa \rho_\alpha \frac{M^k}{M_\alpha}\mathbf{grad}x_\alpha^\kappa\right\} - q_\alpha^\kappa = 0\ ;\alpha \in \{w,n\}\ ;\kappa \in \{w, CO_2\}$$

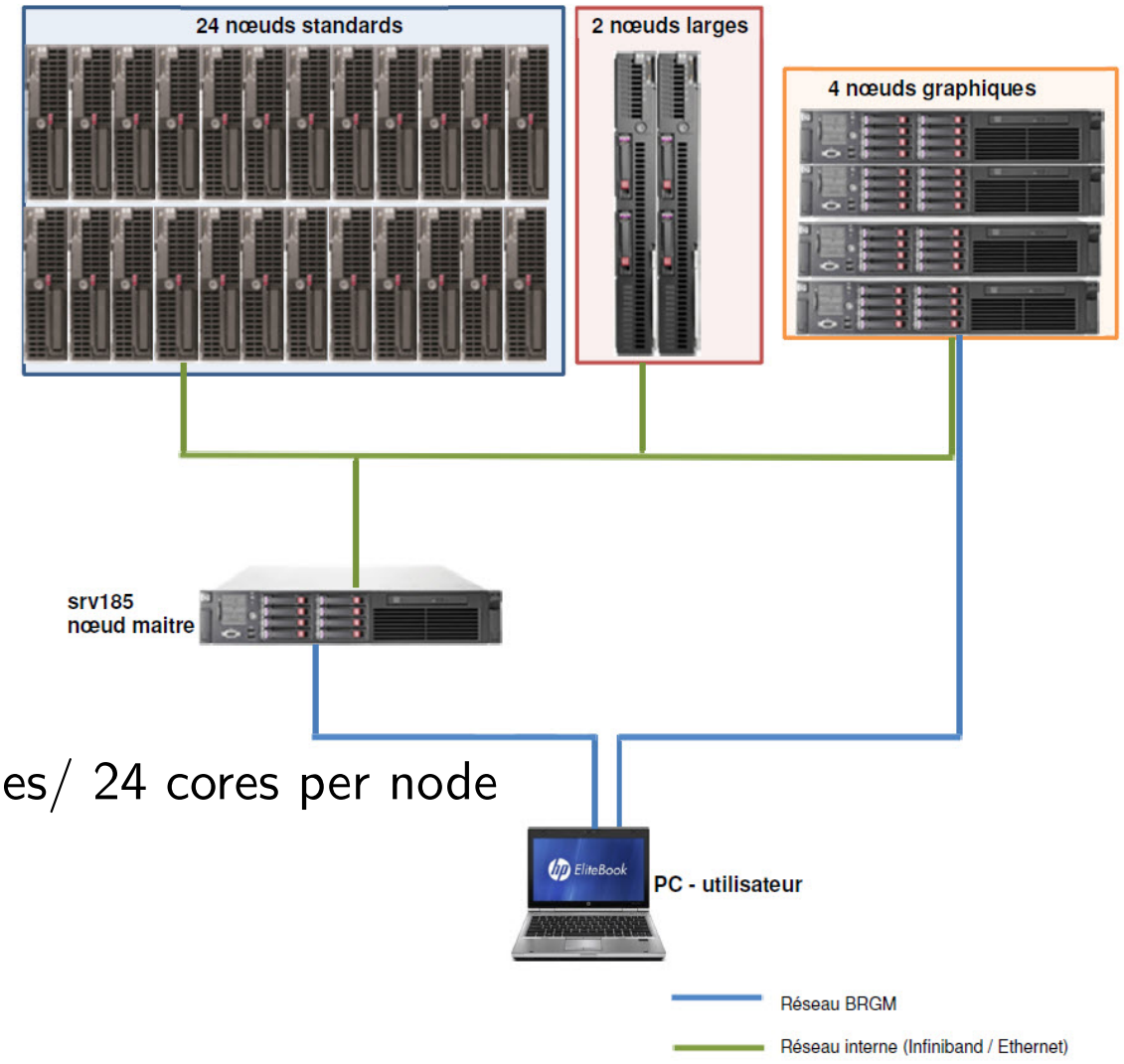
Decoupled system - IMPES-like model

$$c_{tot}\frac{\partial p}{\partial t} + \sum_\kappa \frac{\partial \mathbf{v}_{tot}}{\partial C^\kappa}\nabla.\left(\sum_\alpha X_\alpha^\kappa \rho_\alpha \mathbf{v}_\alpha\right) = \sum_\kappa \frac{\partial \mathbf{v}_{tot}}{\partial C^\kappa} q^\kappa$$

$$\frac{\partial C^\kappa}{\partial t} = -\nabla.\left(\sum_\kappa X_\alpha^\kappa \rho_\alpha \mathbf{v}_\alpha\right) + q^\kappa$$

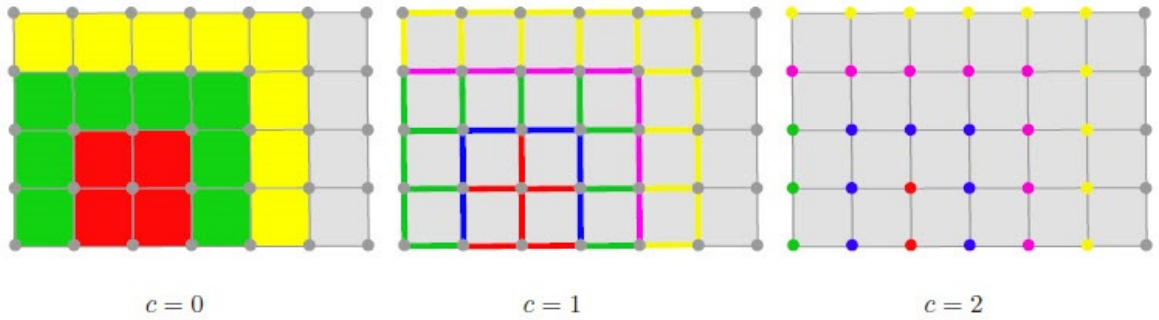
Outline

BRGM's cluster

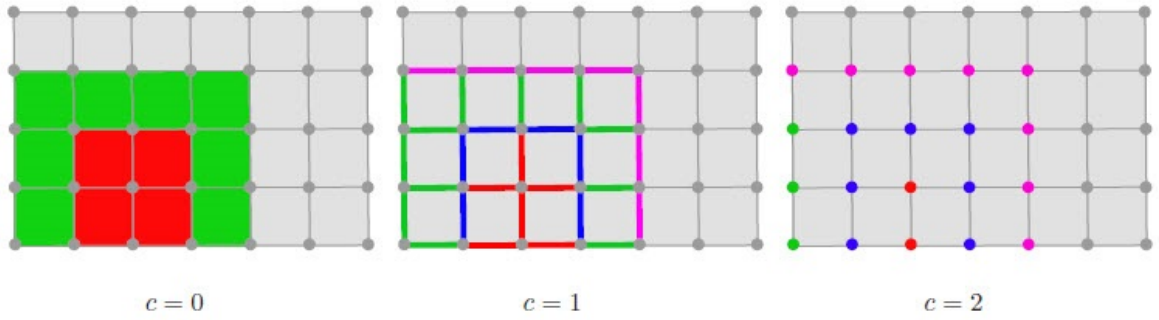


24 standard nodes/ 24 cores per node
$\rightarrow$ 576 cores

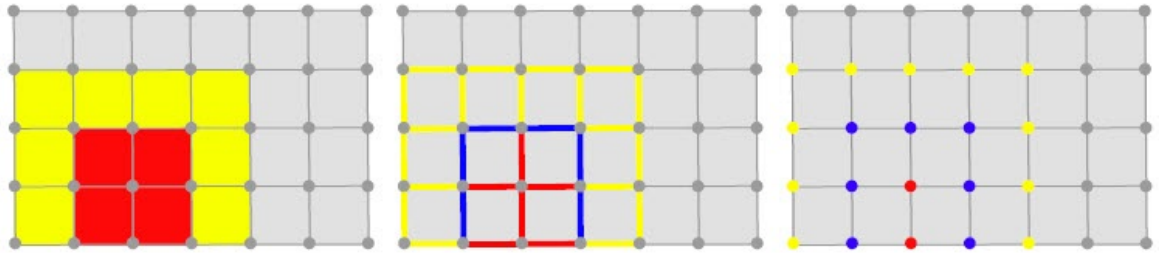
Data decomposition



YaspGrid



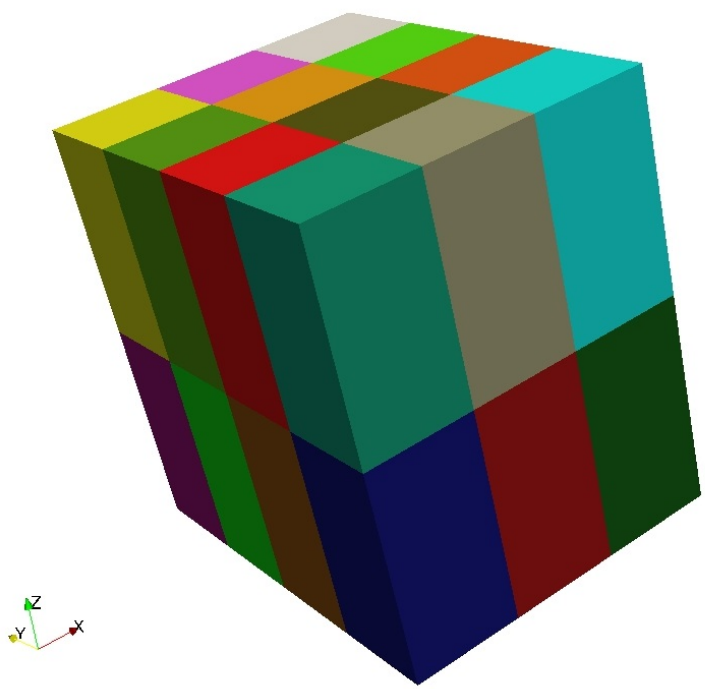
ALUGrid



Entity located in	Partition Type value
$B_i = \overline{\partial\Omega_i \setminus \partial\Omega}$	*border*
$\overline{\Omega_i \setminus B_i}$	*interior*
$F_i = \overline{\partial\hat{\Omega}_i \setminus \partial\Omega \setminus B_i}$	*front*
$\overline{\hat{\Omega}_i \setminus (B_i \cup F_i)}$	*overlap*
Rest	*ghost*

(https://www.dune-project.org/)

Partitioning - shared by 24 cores (reference)



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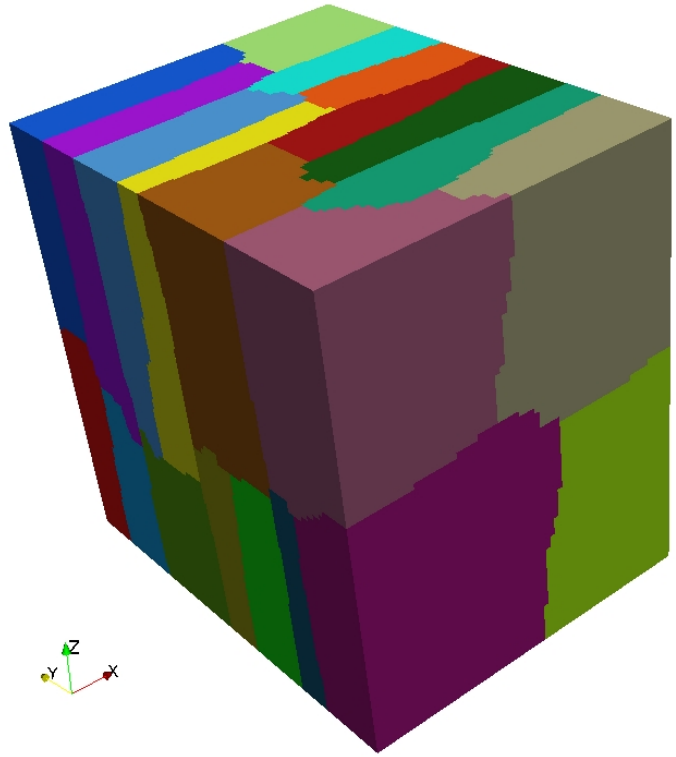


ALUGrid

- Partitioning with Metis/ParMetis
- Simulation run with 24, 48, 96, 192, 384 cores using OpenMPI

Summary of simulations using DuMu^x

$\Rightarrow$ Influence of physical model on parallel performance
Influence of numerical scheme on parallel performance
Choice of grid type and linear solver

1. 2p model
   - Coupled model
     - ▷ YaspGrid
     - ▷ ALUGrid
   - Decoupled model
     - ▷ ALUGrid
2. 2p2c model
   - Coupled model
     - ▷ ALUGrid

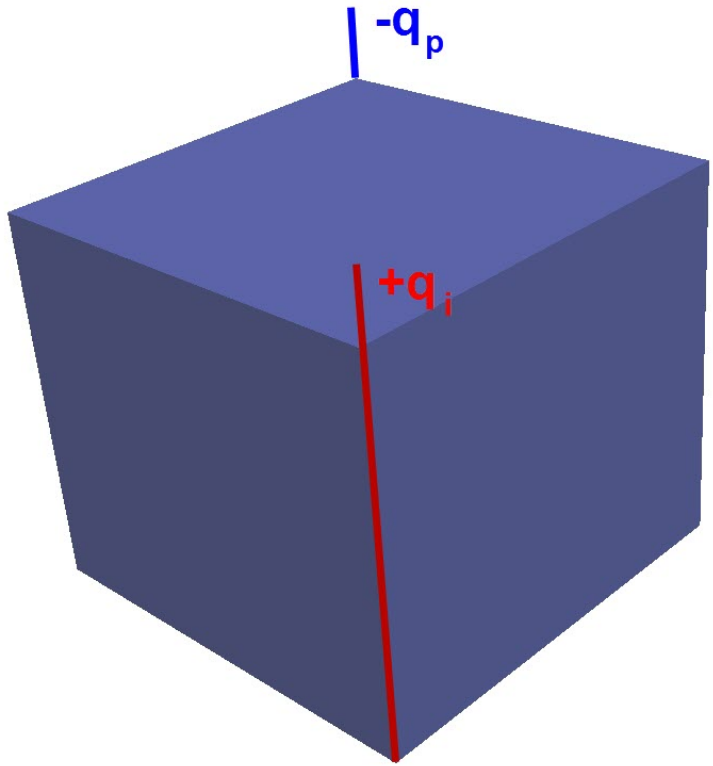
- Implicit models: Cell-centered finite-volume discretization scheme, implicit Euler time scheme with adaptative time step procedure

- Non-linearities : Newton iteration method

- Linear solver : AMG Backend

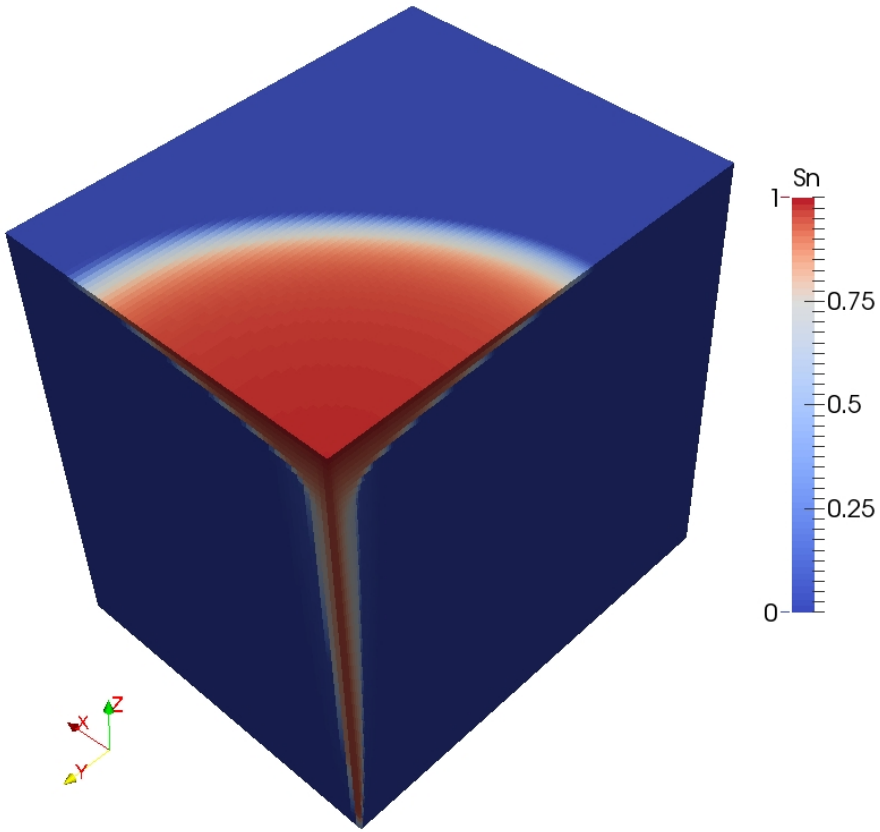
Parameters - 2p model

- $q_{i,CO_2} = 15 kg/s \sim 0.4734 Mt/year$
- Producer borehole pressure
  $p_{bhp} = 200 bar$
- Densities:
  $\rho_{CO_2} = 710 kg/m^3$
  $\rho_{brine} = 1050 kg/m^3$
- Viscosities:
  $\mu_{CO_2} = 0.08 cP =$ 8.E-5 $Pa.s$
  $\mu_{brine} = 0.8 cP =$ 8.E-4 $Pa.s$
- Reservoir initially saturated with brine
- No flux Neumann BC for all of domain bounds
- Capillary pressure is neglected

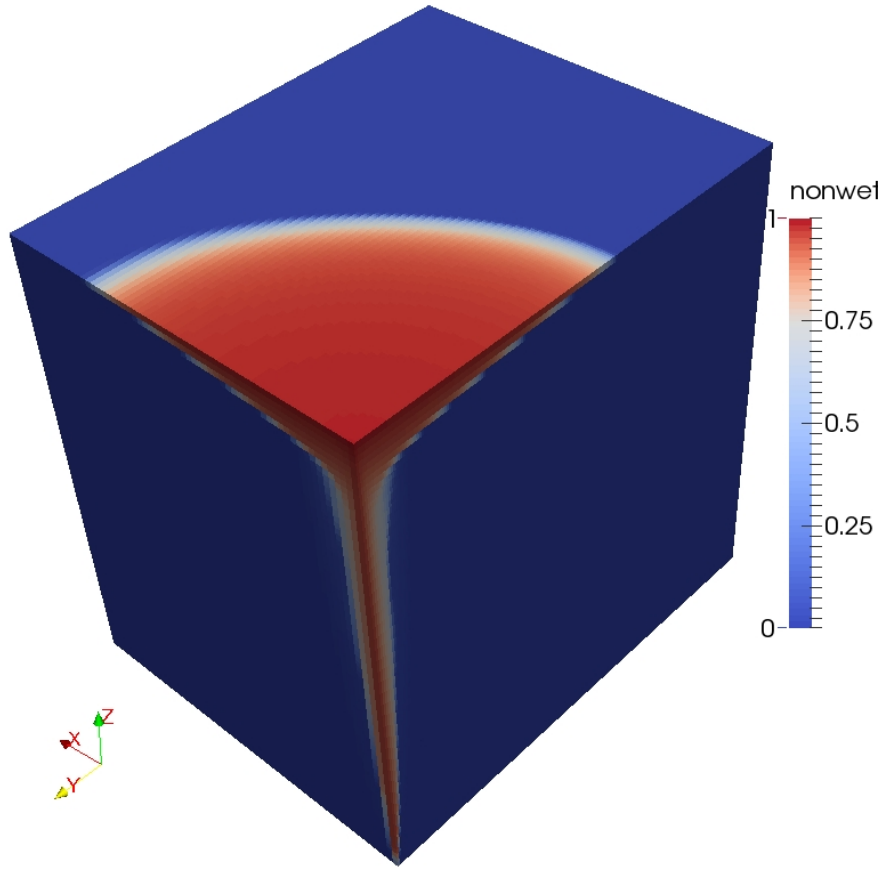


Simulation results - 2p model : 20 years of injection

Similar results, more numerical diffusion with Implicit than with IMPES



Coupled (Implicit)



Decoupled (IMPES)

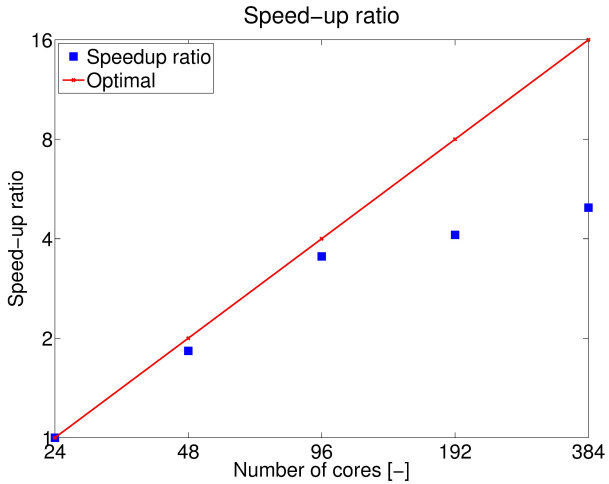
Simulation results - 2p model : Influence of numerical schemes on parallel performance

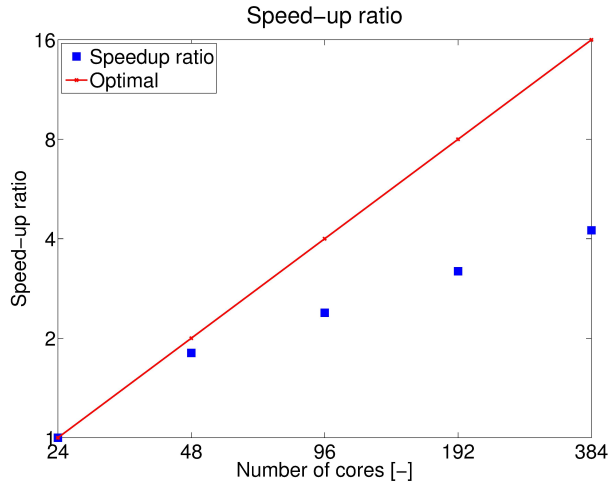
	Implicit-ALUGrid		IMPES-ALUGrid	
	CPU Time [s]	Time step	CPU Time [s]	Time step
24 cores	4587.27	76	26655.2	6037
48 cores	2503.85	73	14765.7	6037
96 cores	1296.53	76	11156.3	6037
192 cores	1116.46	73	8358.32	6037
384 cores	923.626	73	6283.65	6037

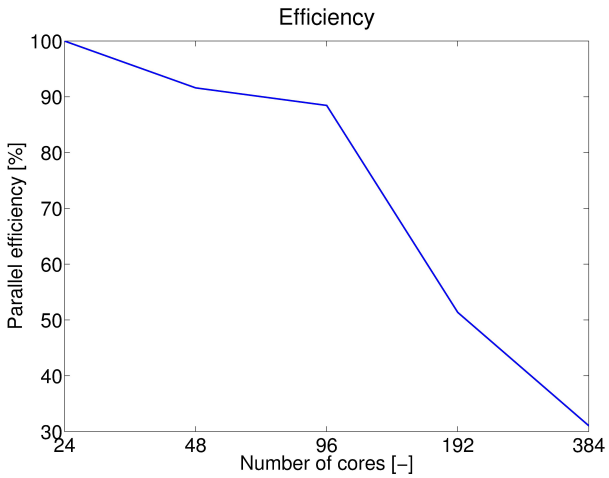
CPU Time and Time step count

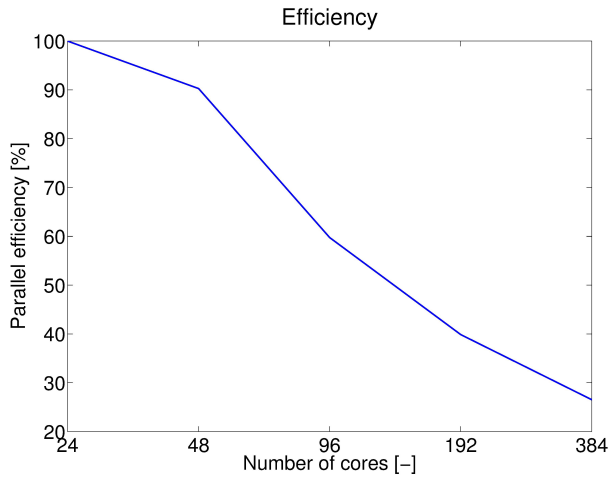
Simulation results - 2p model - Influence of numerical schemes on parallel performance

Speedup $\sigma_n = \frac{T_{24}}{T_n}$; Parallel efficiency $\epsilon_n = \frac{24}{n}\sigma_n$









Implicit-ALUGrid

IMPES-ALUGrid

Simulation results - 2p model : Influence of grid type on parallel performance

	Implicit-YaspGrid		Implicit-ALUGrid	
	CPU Time [s]	Time step	CPU Time [s]	Time step
24 cores	3934.94	76	4587.27	73
48 cores	2175.51	73	2503.85	73
96 cores	1668.16	76	1296.53	73
192 cores	1169.24	73	1116.46	79
384 cores	981.37	73	923.626	75

CPU Time and Time step count

Simulation results - 2p model : Influence of grid type on parallel performance

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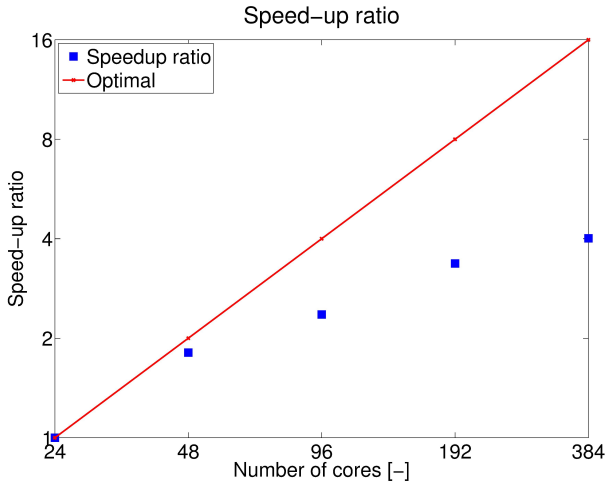
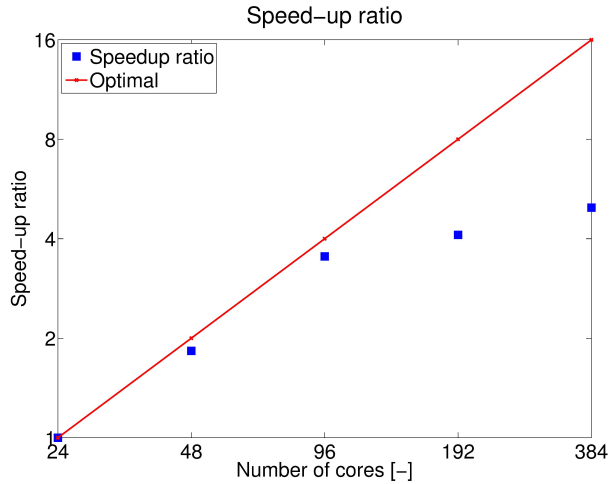
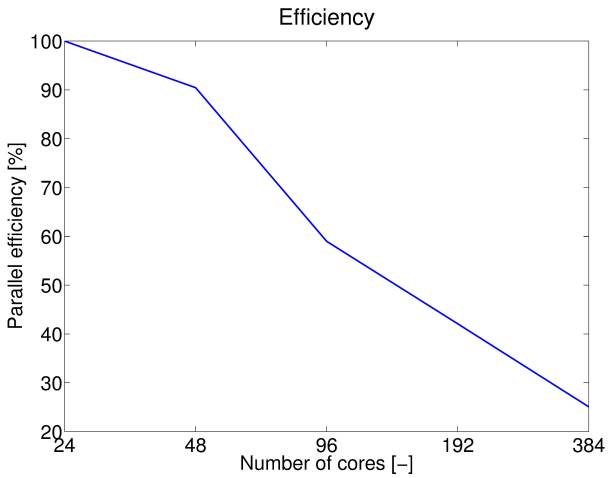
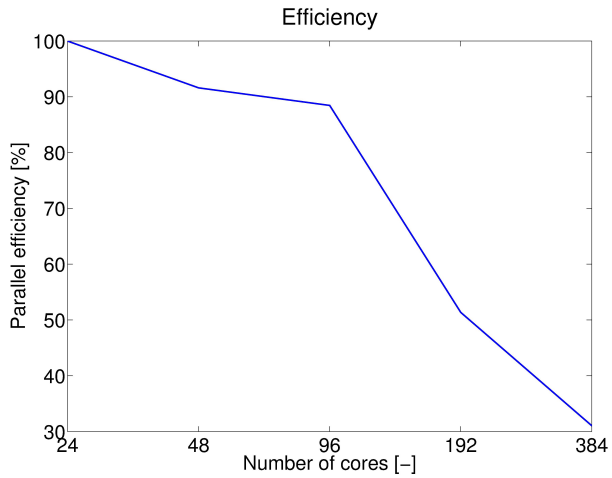






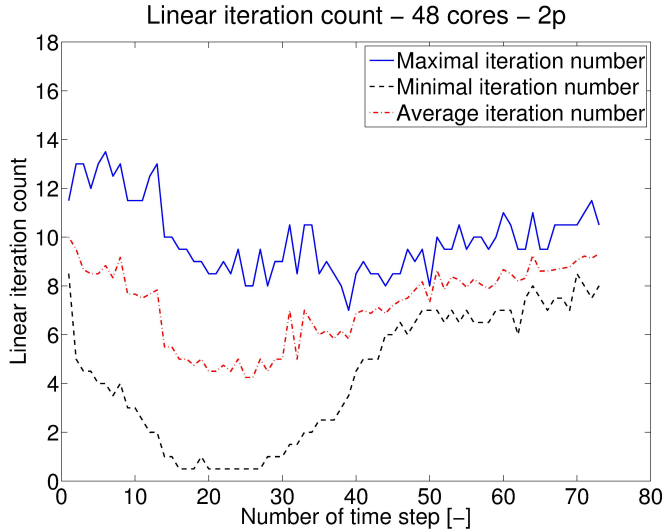


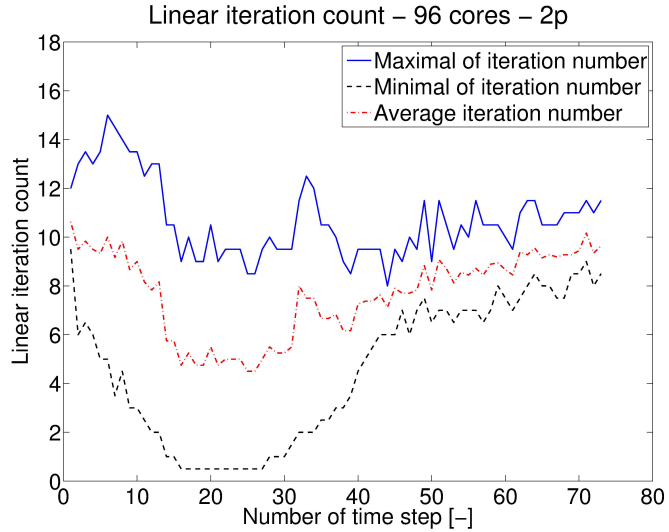
Implicit-YaspGrid

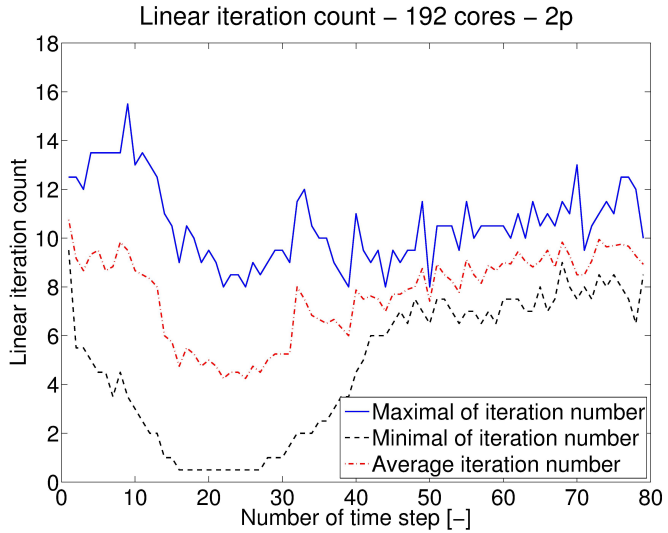
Implicit-ALUGrid

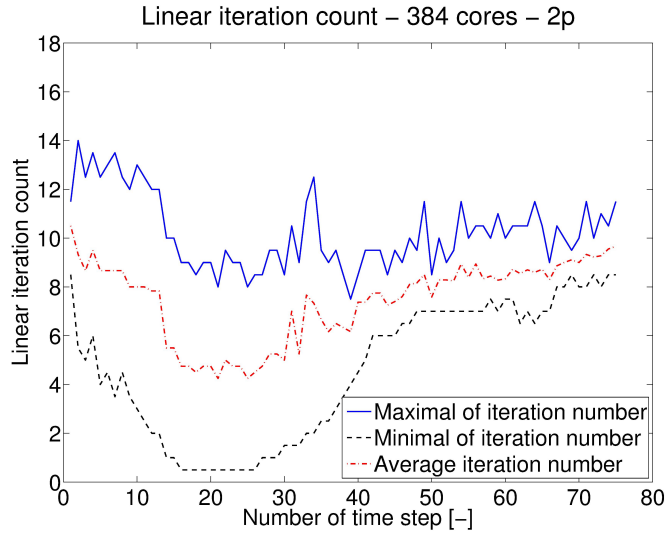
2p Implicit - ALU: AMGBackEnd Linear solver

Linear iteration count



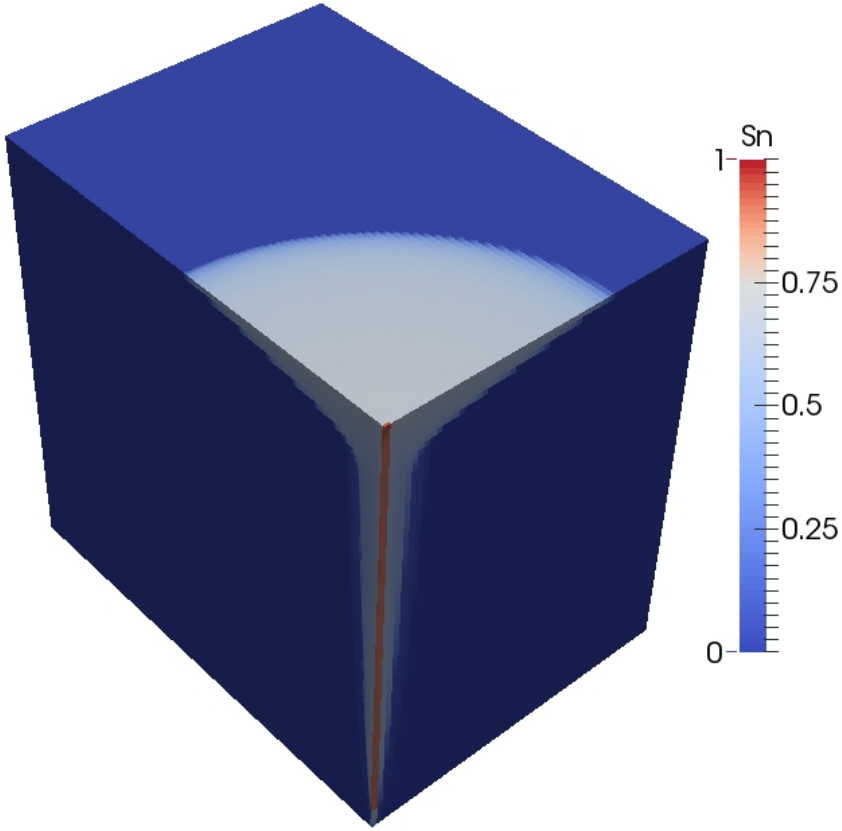


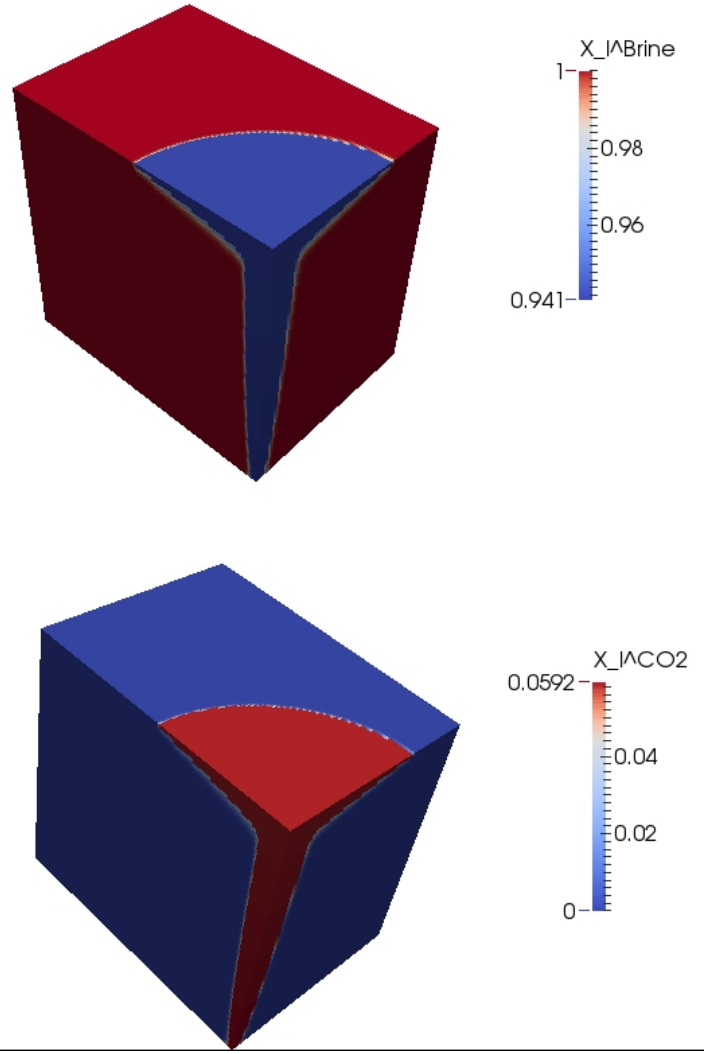




Simulation results - 2p2c implicit model

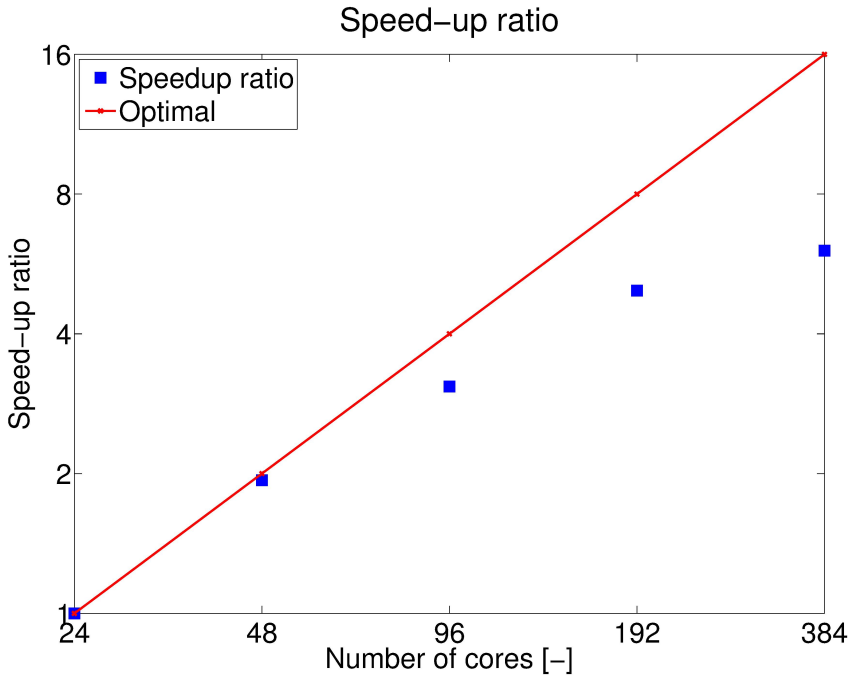
20 years of injection

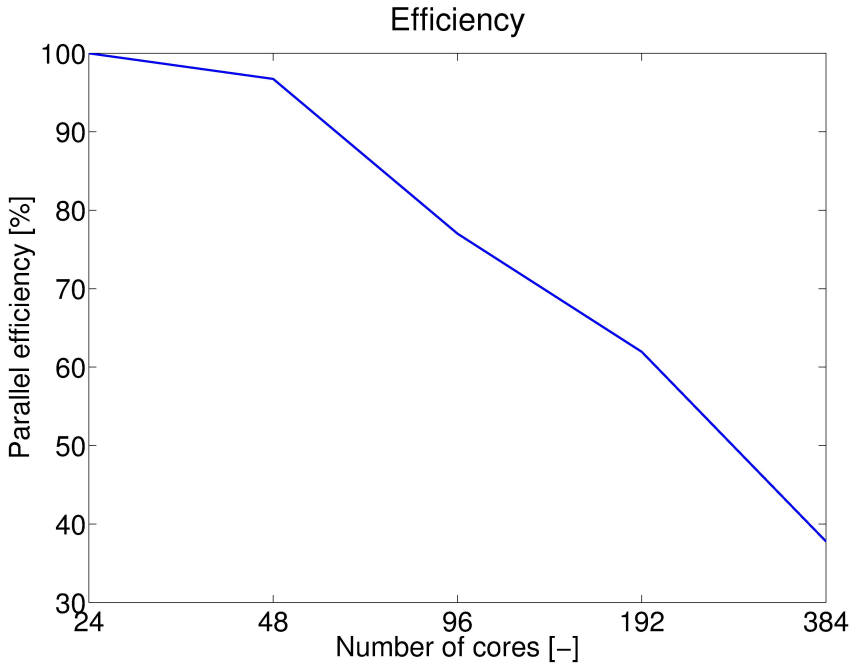




Simulation results - 2p2c implicit model

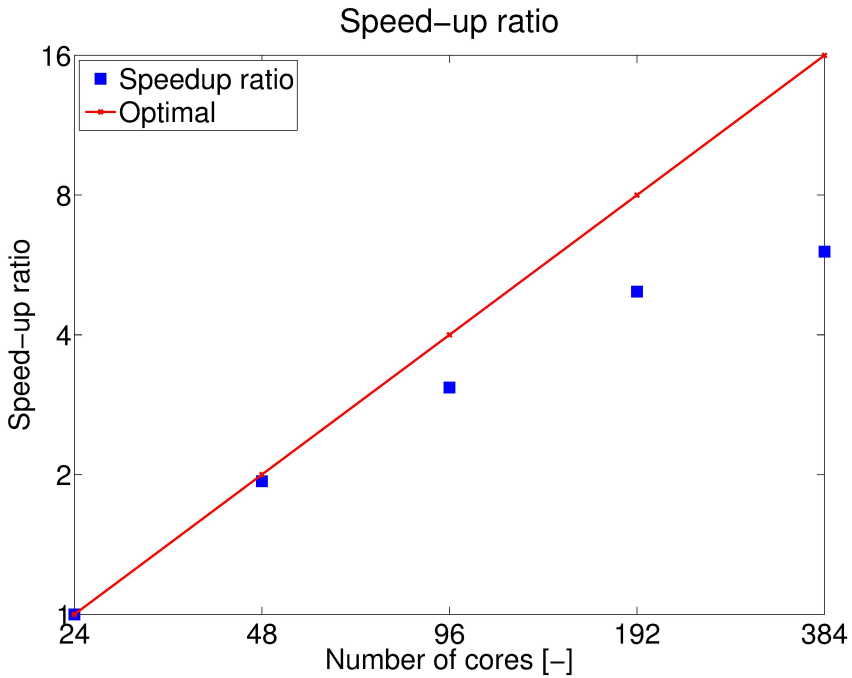
Speedup $\sigma_n = \frac{T_{24}}{T_n}$; Parallel efficiency $\epsilon_n = \frac{24}{n}\sigma_n$



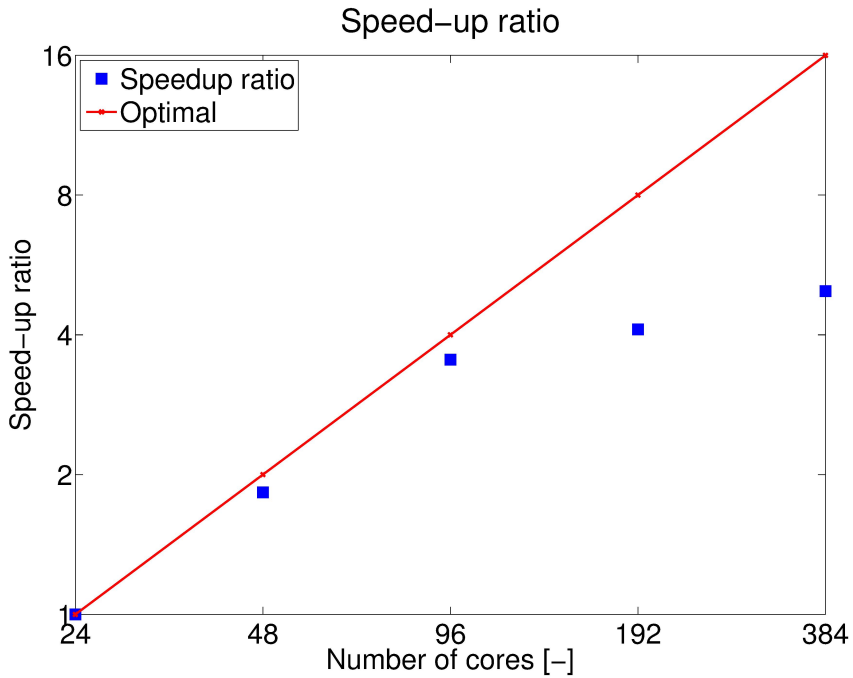


Simulation results - 2p2c implicit model

Speedup $\sigma_n = \frac{T_{24}}{T_n}$; Parallel efficiency $\epsilon_n = \frac{24}{n}\sigma_n$



2p2c-Implicit-ALU



2p-Implicit-ALU

Outline

Conclusion and Perspectives

Conclusion:

- ALUGrid and AMGBackEnd for massively parallel simulations.
- DuMu^x exhibits a fairly good parallel performance for acceleration (strong scaling) with numbers of processors < 100.
- For simulation with numbers of processors > 100, a better speedup is expected.
- Nevertheless, the DuMu^x's ability for parallel computation allows to perform simulations for long-term scenarios of CO_2 storage in space scale range from ten to hundred kilometers square.

Future works:

- Parallel simulation in heterogeneous media
- Include capillary pressure
- Combination of parallel numerical algorithms and grid adaptive refinement $\rightarrow$ *Problem between MPFAL-method and grid partitioning*
- Investigate others physical models (non-isothermal models 2pni, 2p2c ni)

Thank you for your attention!