University of Stuttgart
Institute for Modelling Hydraulic and Environmental Systems

Development of multi-physics models accounting for reversible flow at various subsurface energy storage sites

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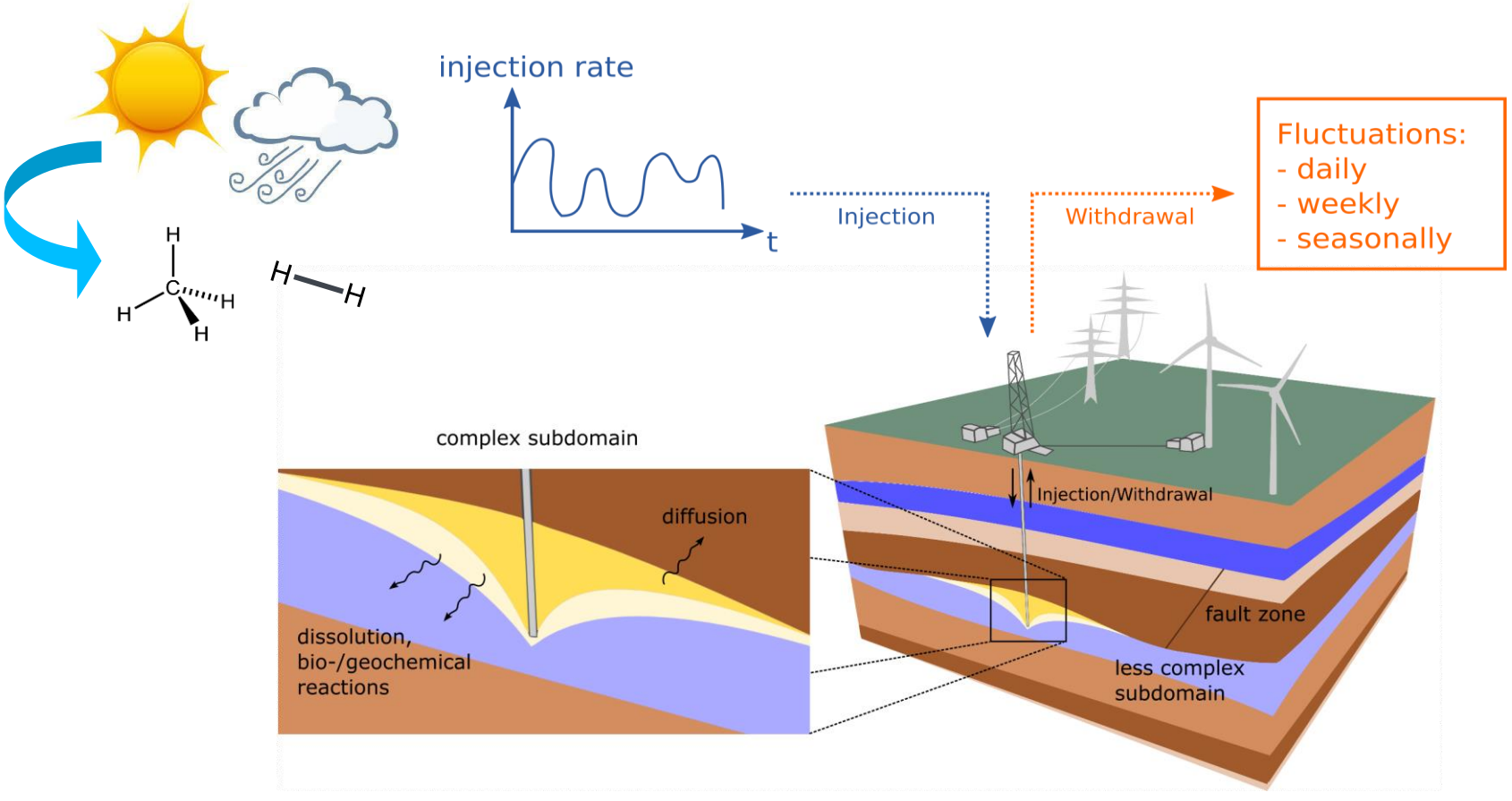
Interpore 2020

Underground energy storage: Modeling challenges



- Large domains and limited data

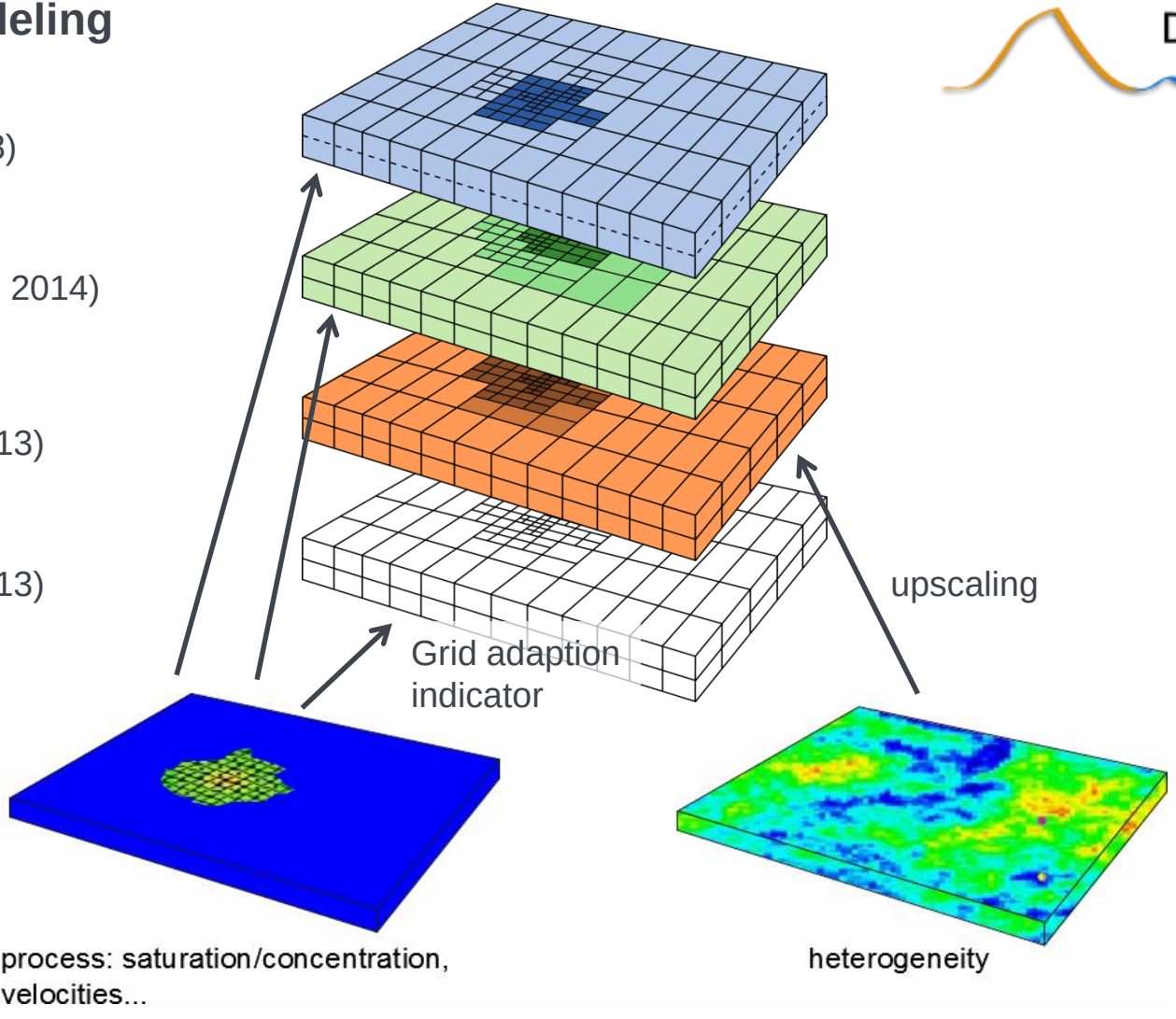
Adaptive modeling

Multi dimensions
(Becker et al. 2018)

Multi physics
(Faigle et al. 2013, 2014)

Multi scale
(M. Wolff, et al. 2013)

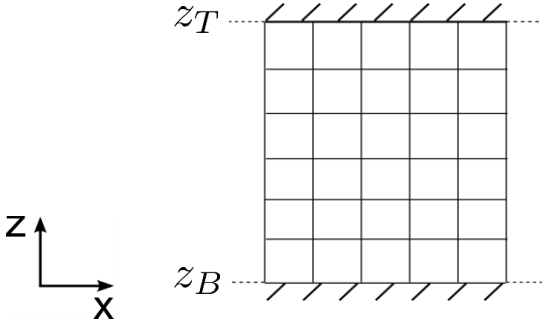
Adaptive grid
(M. Wolff, et al. 2013)



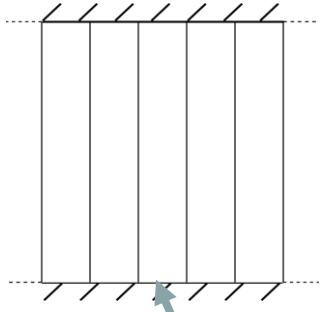
Vertical equilibrium model

Governing equations

2D



VE



$$\frac{\partial}{\partial t}(\varrho_\alpha \phi s_\alpha) + \nabla \cdot (\varrho_\alpha \mathbf{u}_\alpha) = \varrho_\alpha \mathbf{q}_\alpha$$

$$\mathbf{u}_\alpha = -\mathbf{k}\frac{\mathbf{k_{r,\alpha}}}{\mu_\alpha}(\nabla \mathbf{p}_\alpha - \varrho_\alpha \mathbf{g})$$

$$\frac{\partial}{\partial t}(\varrho_\alpha \Phi S_\alpha) + \nabla_{||} \cdot (\varrho_\alpha \mathbf{U}_\alpha) = \varrho_\alpha \mathbf{Q}_\alpha$$

$$\mathbf{U}_\alpha = -\mathbf{K}\frac{\mathbf{K_{r,\alpha}}}{\mu_\alpha}(\nabla_{||} \mathbf{P}_\alpha - \varrho_\alpha \mathbf{G})$$

$$\int_{z_B}^{z_T} \ldots \, \mathrm{dz}$$

$$P_c(S_\alpha)$$

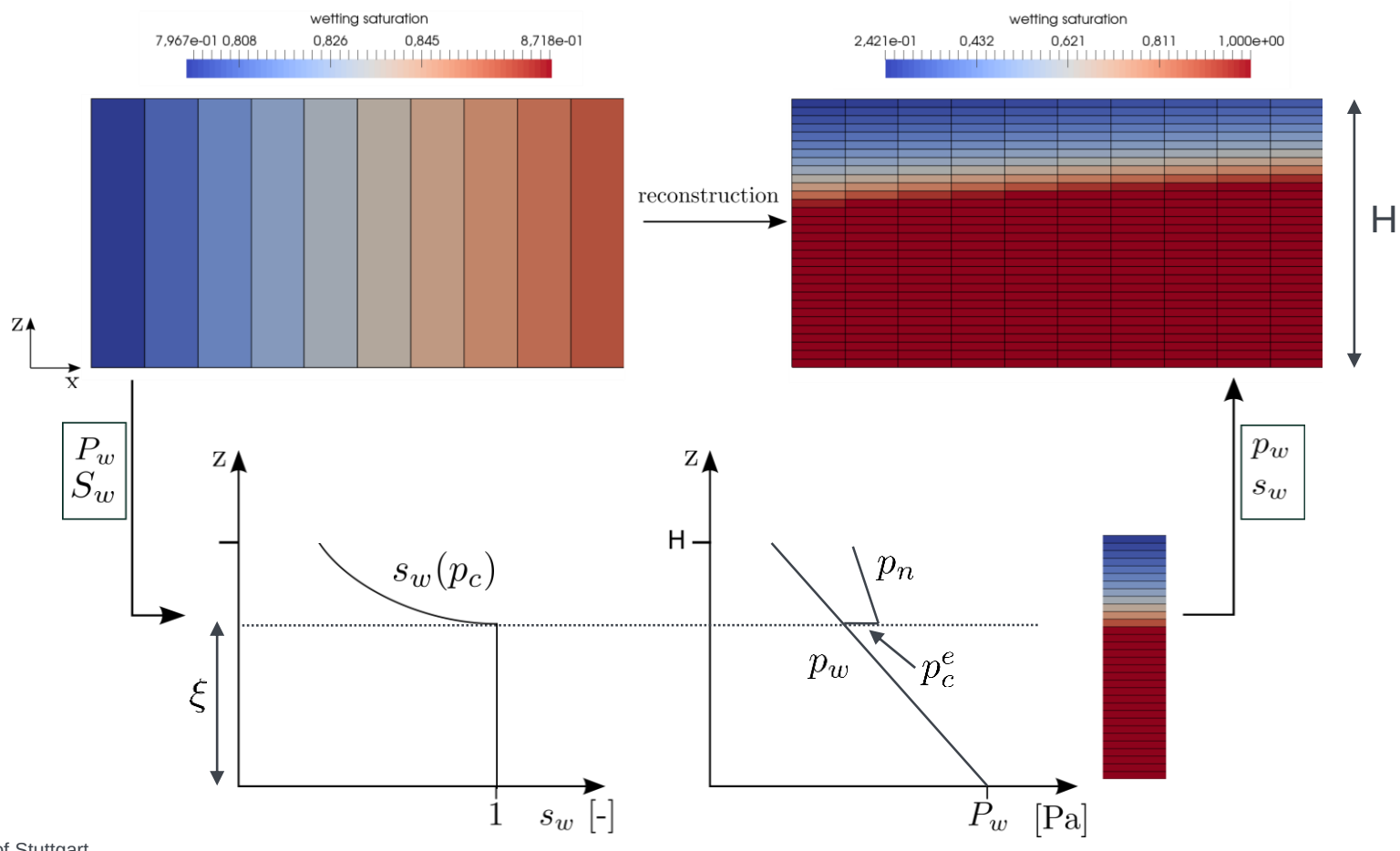
$$\sum S_\alpha = 1$$

$$S_\alpha, \; P_\alpha$$

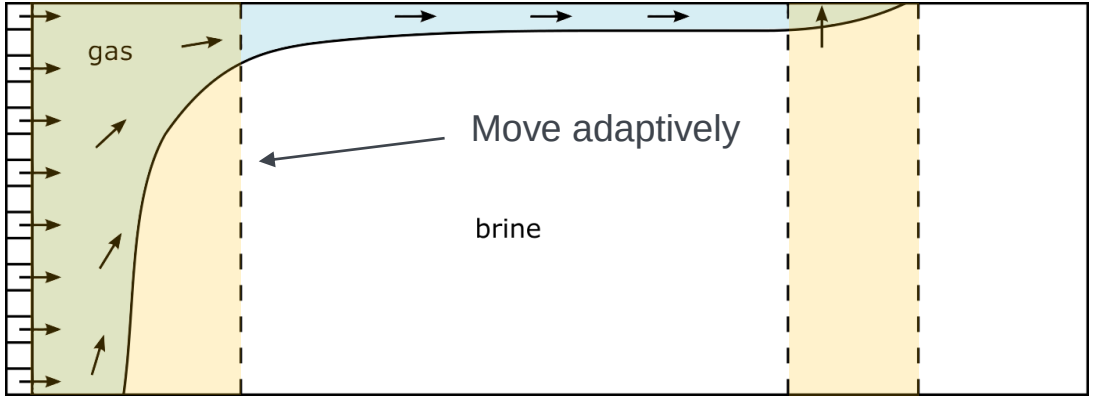
(Nordbotten & Celia, 2012)

Vertical equilibrium model

Reconstruction of fine scale solution



Multiphysics (hybrid) model



More complex area,
Horizontal and vertical flow

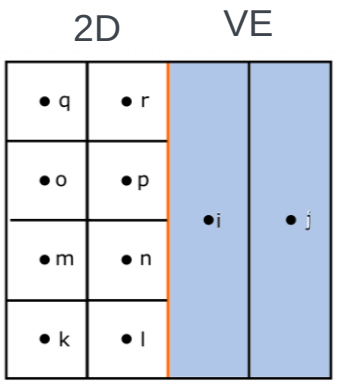
Full multidimensional model

Less complex area,
Horizontal flow,
Segregation of phases

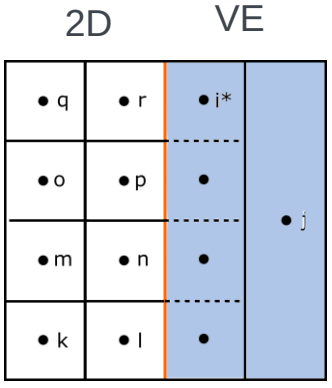
Vertical Equilibrium model

2D-VE coupling

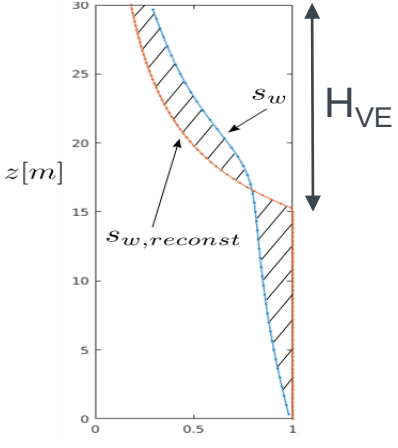
- Fluxes over boundary between subdomains



Introduce ghost cells



- Switch criterion based on column profiles



$$c_{sat} = \frac{\int_0^H |s_w - s_{w,reconst}| \mathrm{dz}}{H_{VE}}$$

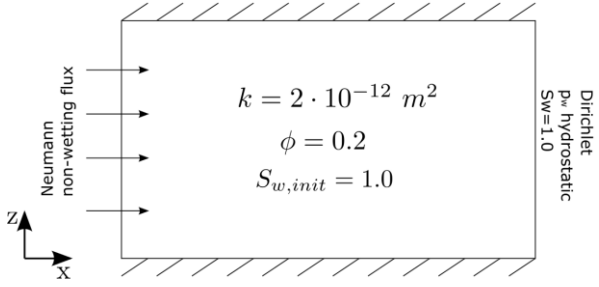
$$c_{relPerm} = \frac{\int_0^H |k_{rw} - k_{rw,reconst}| \mathrm{dz}}{H_{VE}}$$

$$c_{crit} < \epsilon_{crit}$$

Turn column into VE column

Results 2D-VE coupling

Adaptive coupling



Brooks-Corey cap. pressure:

$\lambda = 2.0$, $p_e = 1\ bar$

Phase properties (CH_4, water):

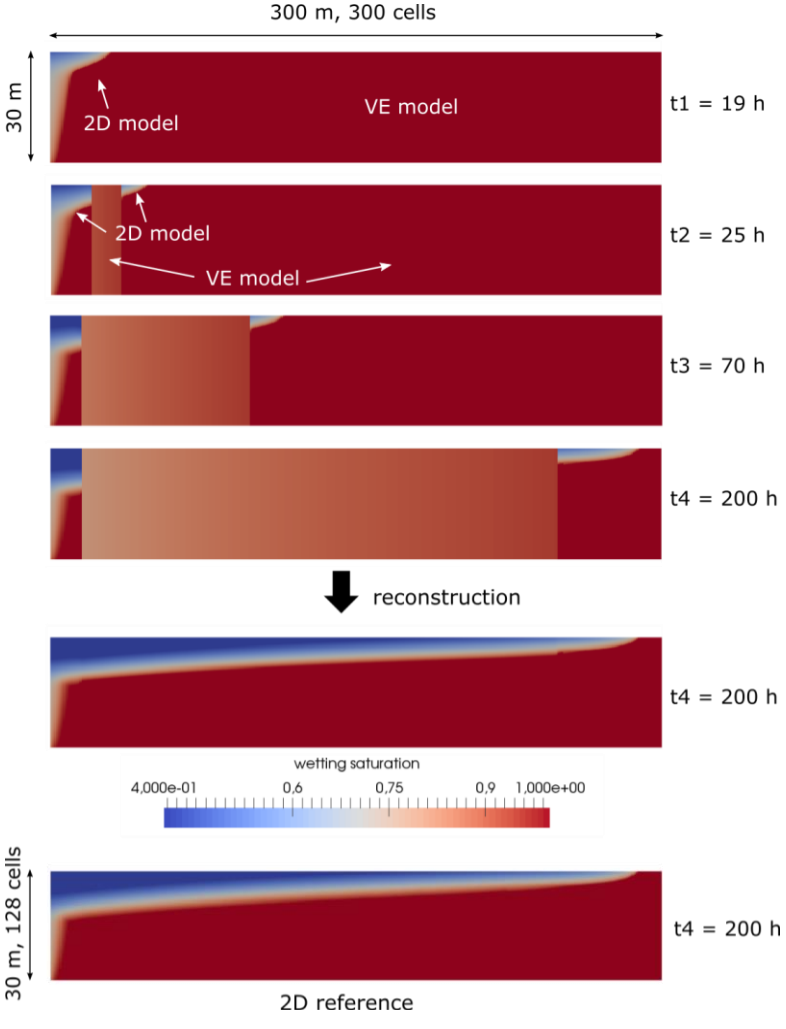
$\varrho_n = 59.2\ kg/m^3$

$\varrho_w = 991\ kg/m^3$

$\mu_n = 1.2 \cdot 10^{-5}\ Pa\,s$

$\mu_w = 5.2 \cdot 10^{-4}\ Pa\,s$

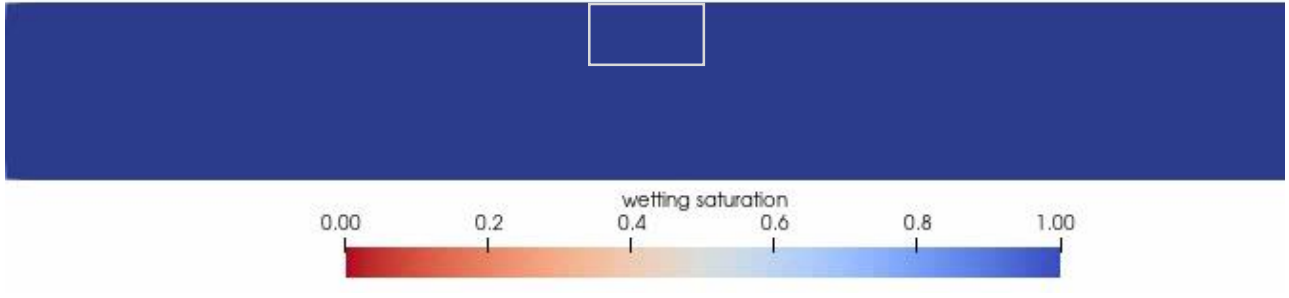
Injection rate: $Q_{nw} = 552\ t/m/a$



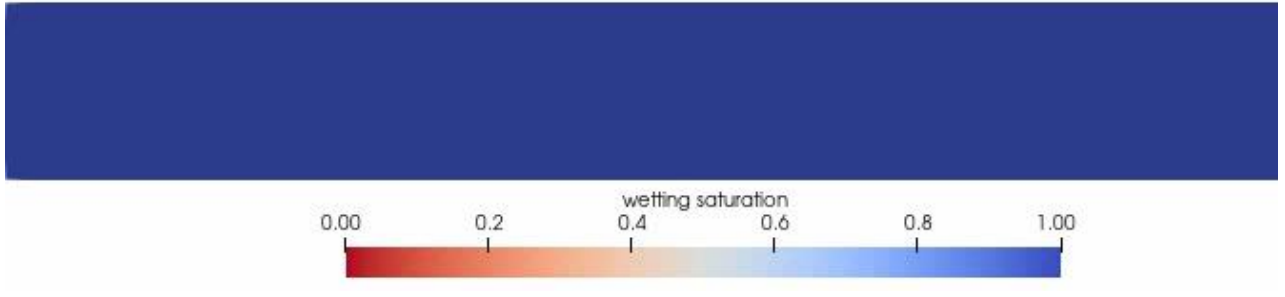
Results coupling 2D and vertical equilibrium

Adaptive coupling, example with low-permeability lens

Simulation result



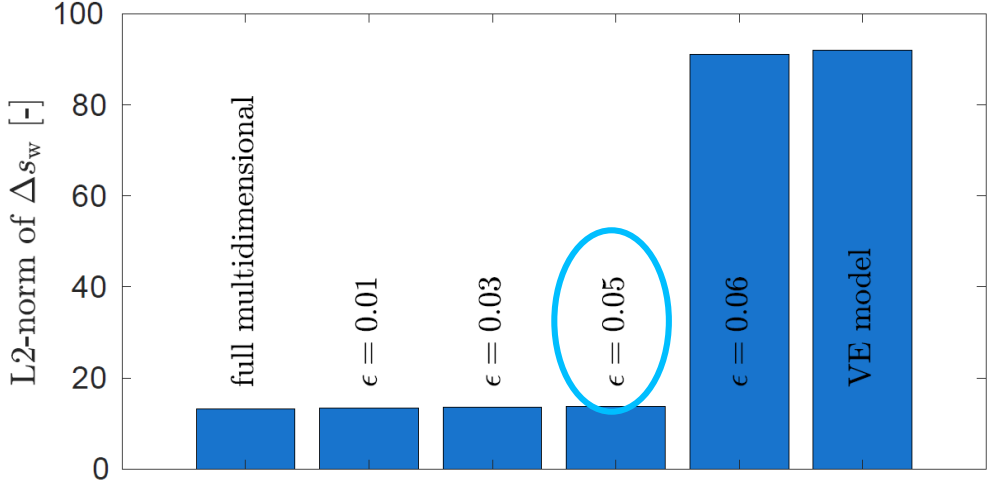
Reconstruction



Efficiency of the multiphysics model

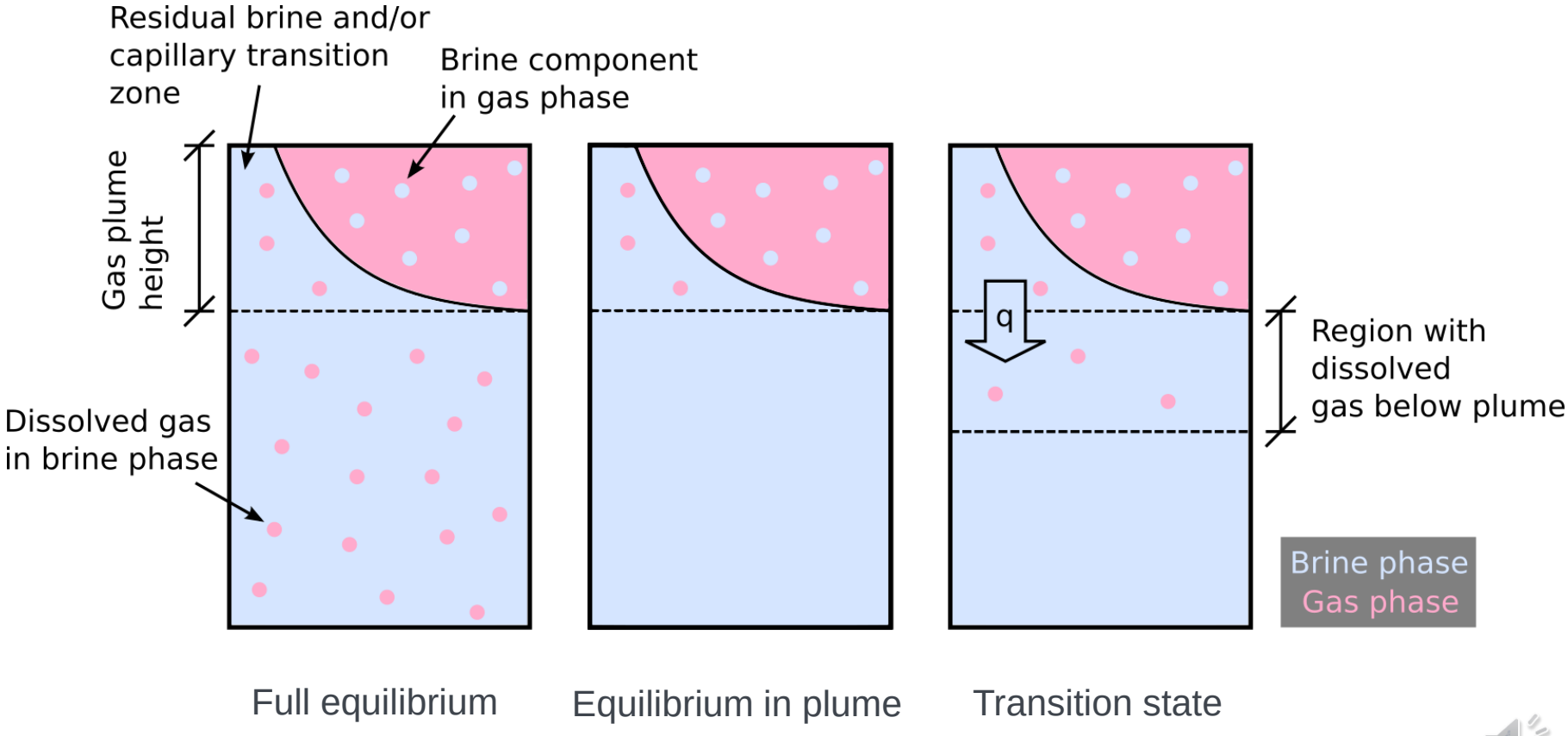
Efficiency:
Speed ✖ Accuracy

Model	relative average number of cells [-]	relative CPU time [-]
Full VE	0.008	0.003
Multiphysics $\epsilon_{\text{relPerm}} = 0.06$	0.04	0.03
Multiphysics $\epsilon_{\text{relPerm}} = 0.05$	0.11	0.05
Multiphysics $\epsilon_{\text{relPerm}} = 0.04$	0.12	0.06
Multiphysics $\epsilon_{\text{relPerm}} = 0.03$	0.19	0.12
Multiphysics $\epsilon_{\text{relPerm}} = 0.02$	0.3	0.18
Multiphysics $\epsilon_{\text{relPerm}} = 0.01$	0.41	0.22
Full multidimensional	1	1



(Becker et al., 2018)

Outlook: Compositional VE (2 phases, 2 components)

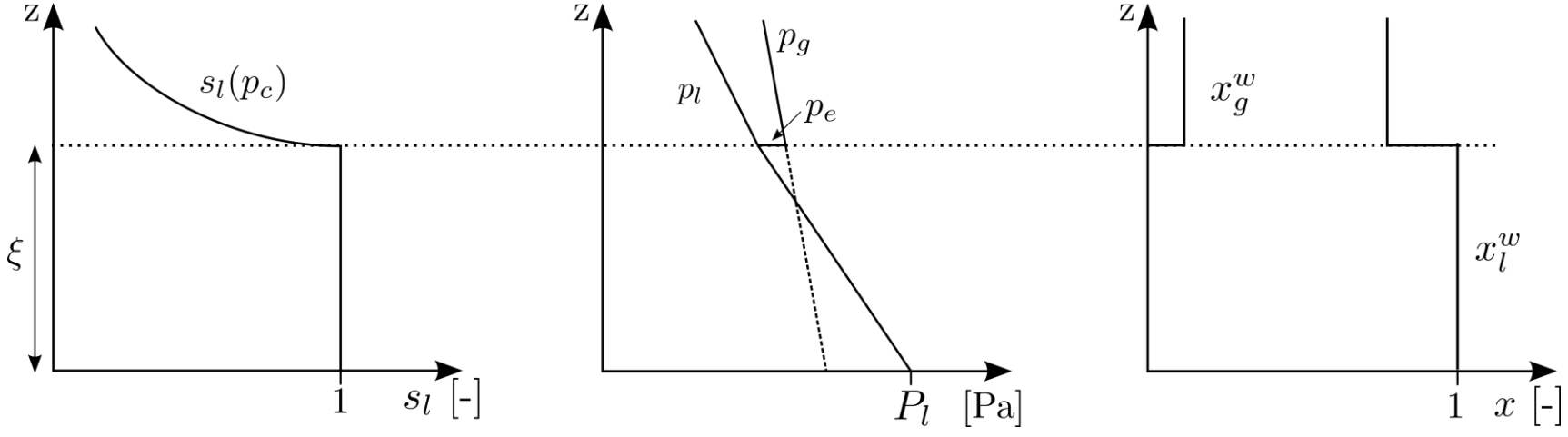


Assumptions for vertical profiles

Saturation:

Pressure:

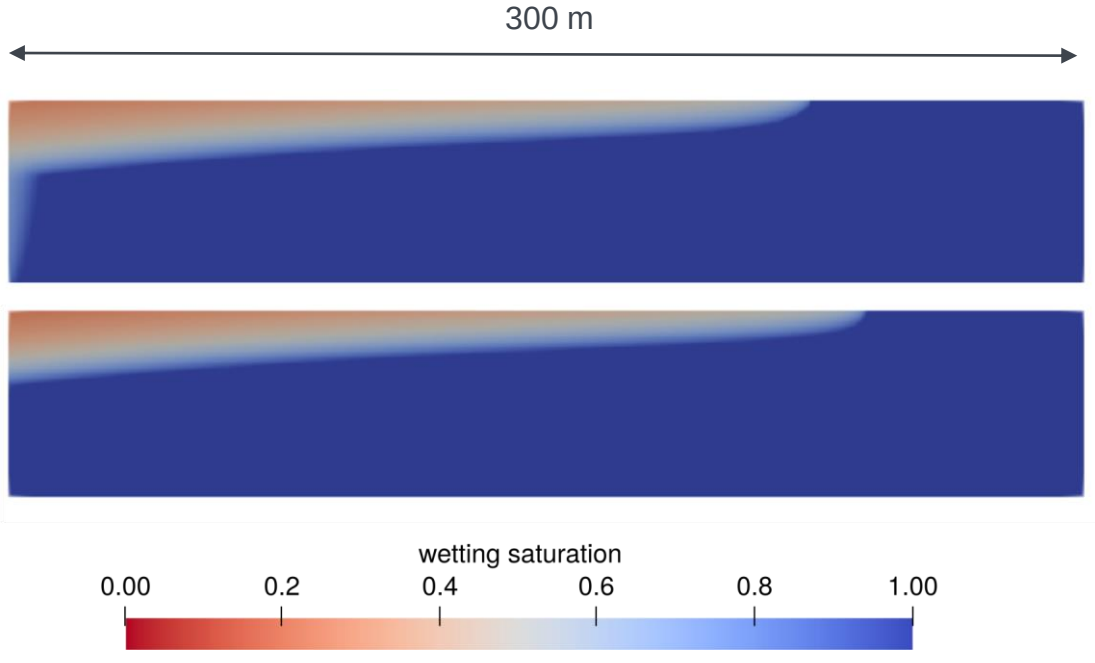
Mass/mole fraction:



Preliminary results: compositional VE

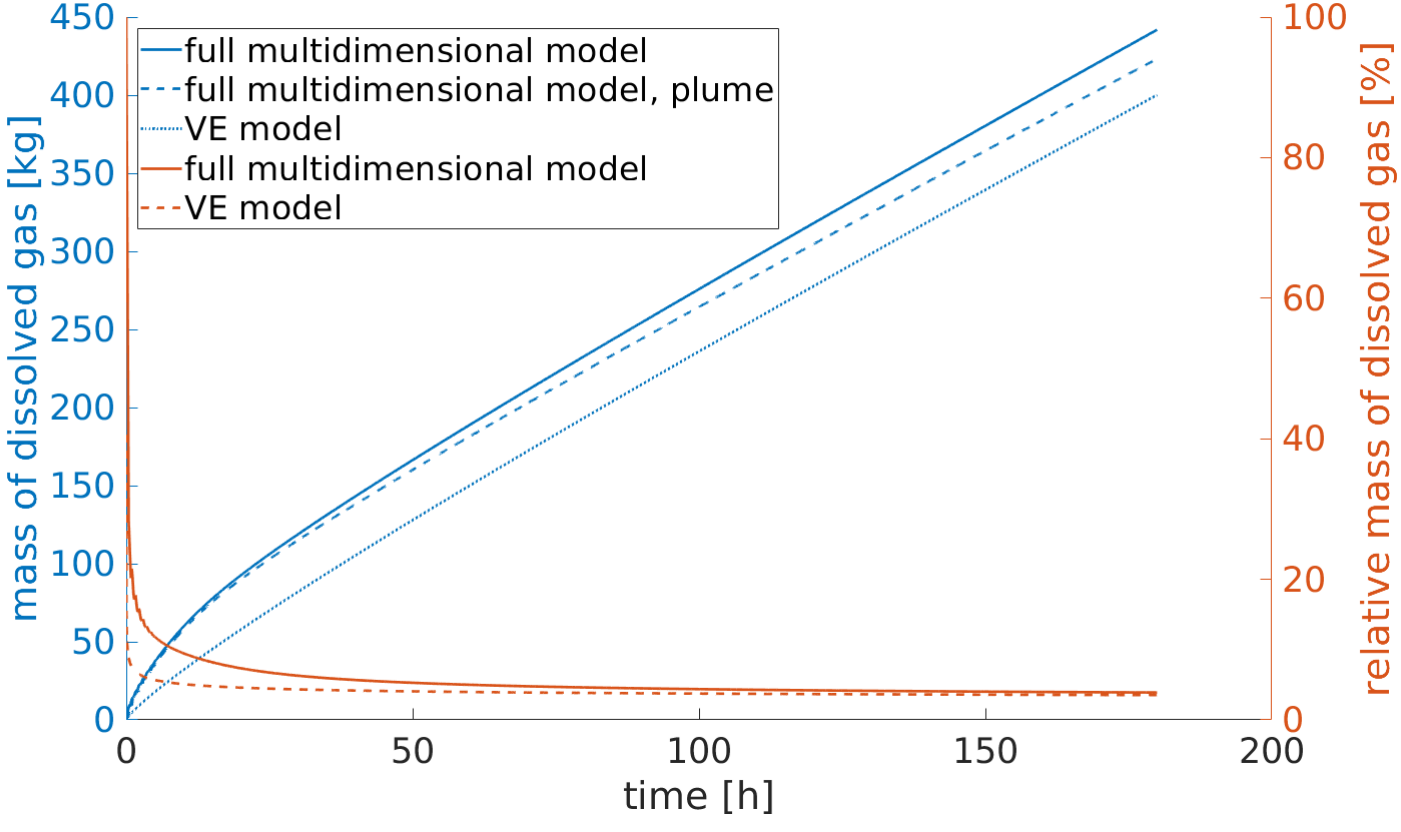
Full multidimensional reference

Compositional VE reconstruction



Time: 180 h

Preliminary results: dissolved gas



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Thank you!

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