University of Stuttgart
Institute for Modelling Hydraulic and
Environmental Systems

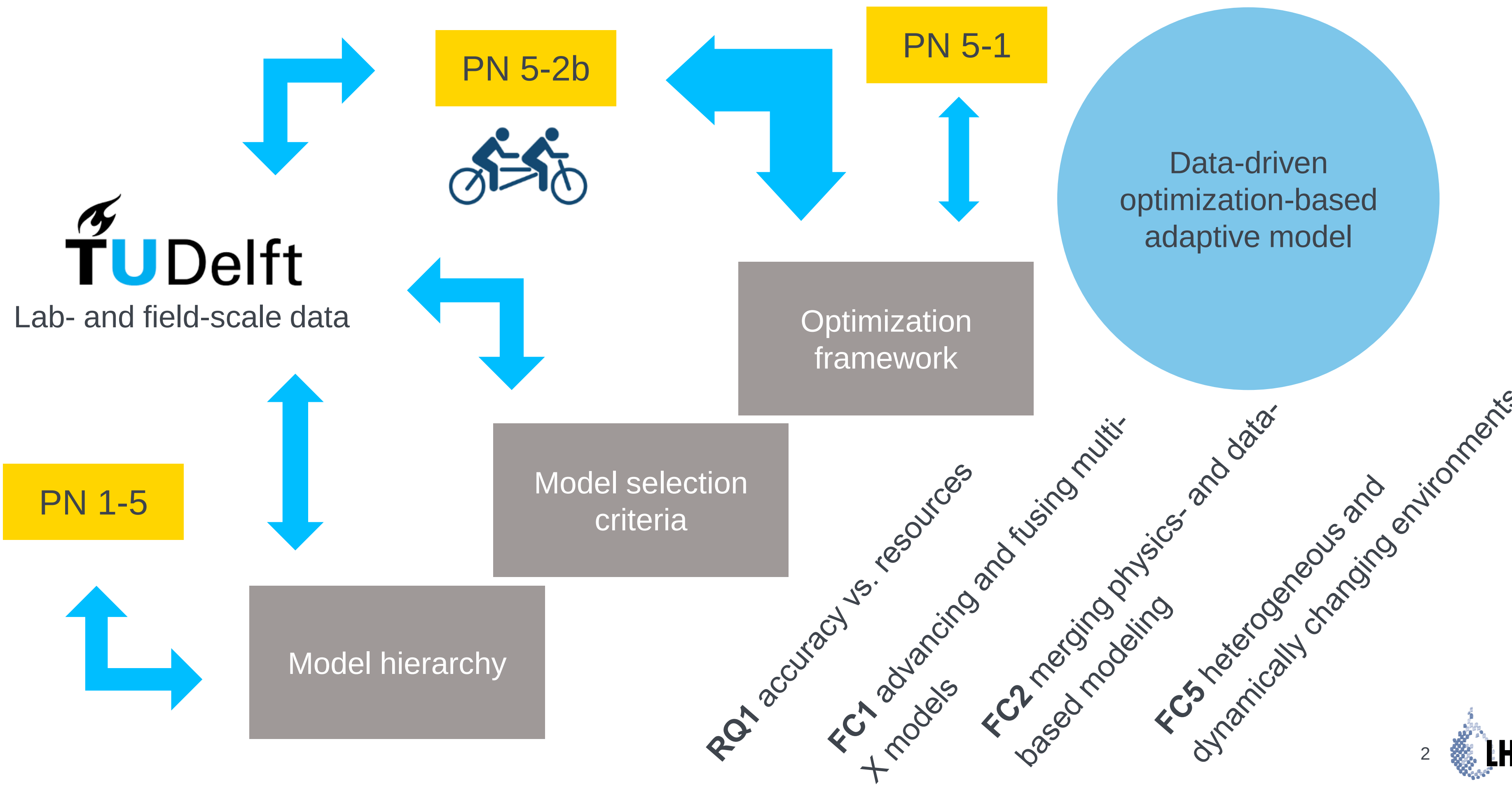
An adaptive hybrid model for the simulation of underground gas storage

Beatrix Becker

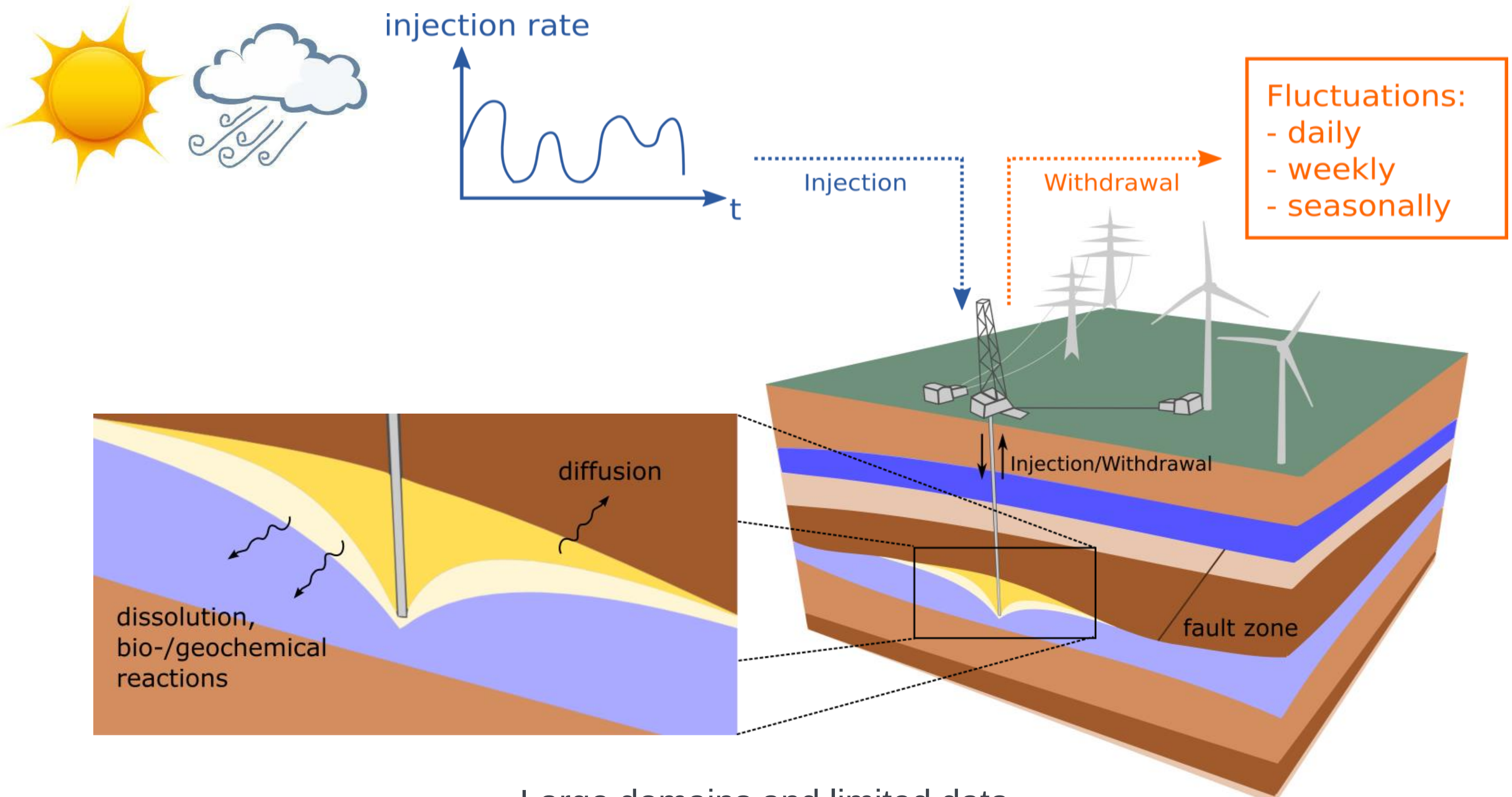
PN 5-2a
SimTech Status Seminar 2019

Introduction to PN 5-2a and integration in SimTech

Data-driven optimization algorithms for local dynamic model adaptivity



Gas storage: Modeling challenges



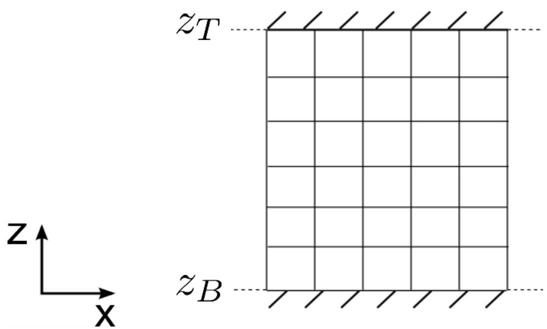
- Large domains and limited data

Vertical equilibrium model

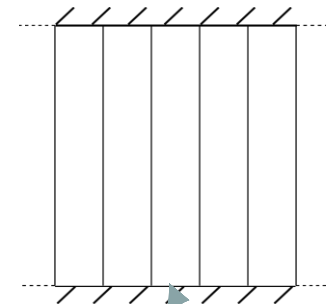
Governing equations

VE assumption:
hydrostatic pressure
in vertical direction

Full D



VE



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

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

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

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

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

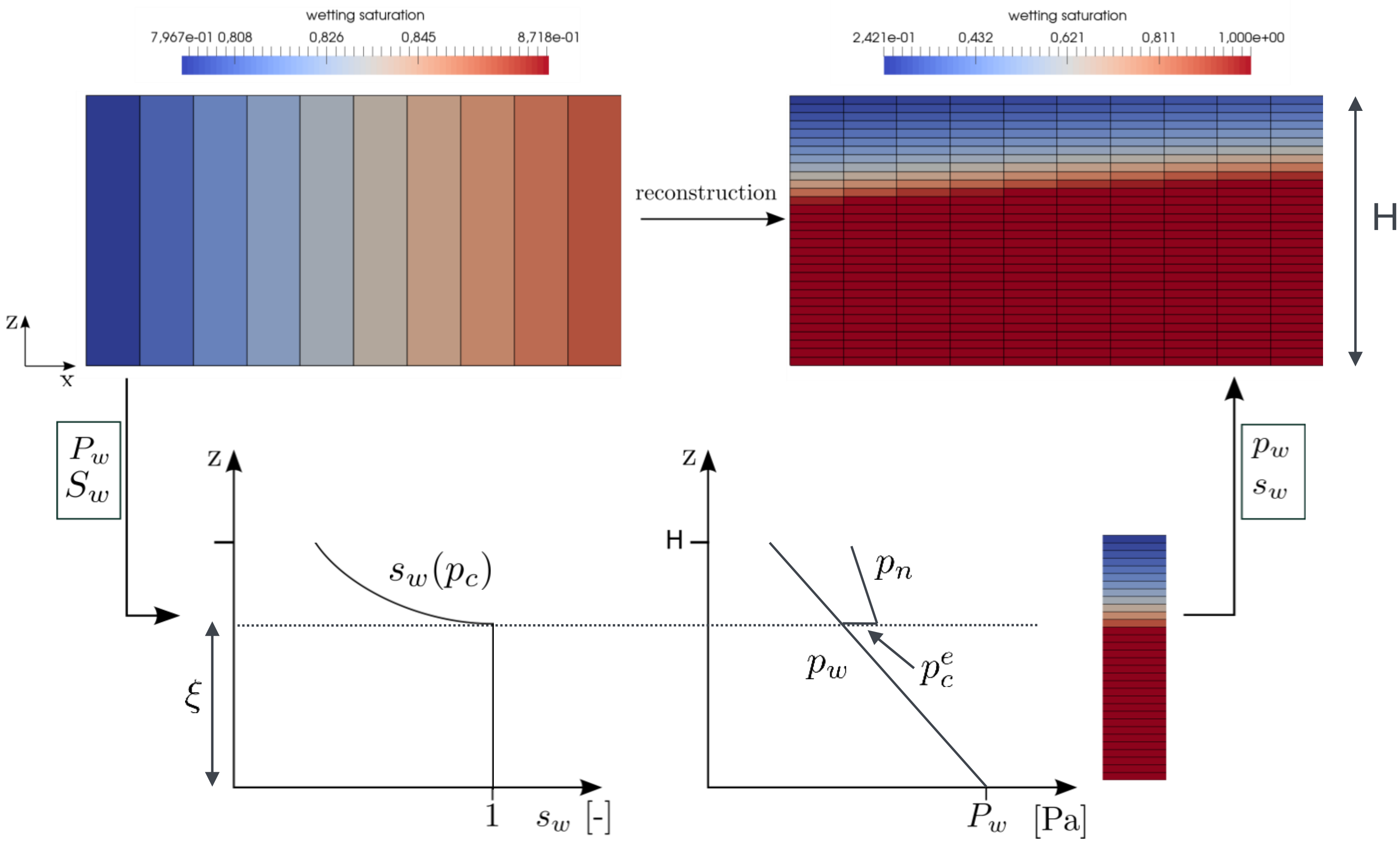
$$P_c(S_\alpha)$$
$$\sum S_\alpha = 1$$

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

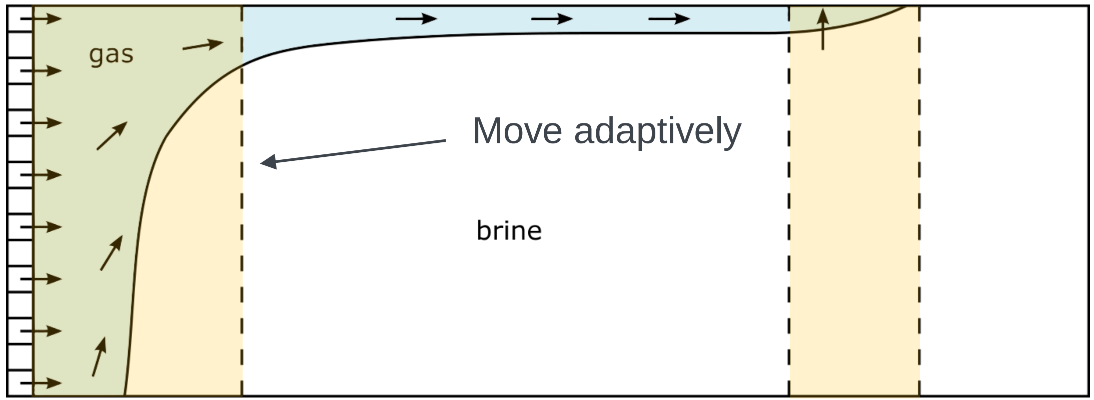
(Nordbotten & Celia, 2012)

Vertical equilibrium model

Reconstruction of fine scale solution



Multiphysics (hybrid) model



More complex area,
Horizontal and vertical flow

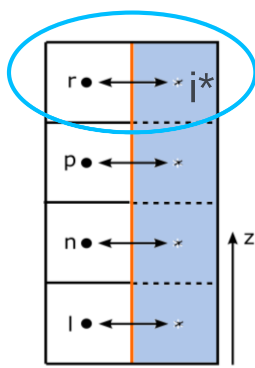
Full multidimensional model

Less complex area,
Horizontal flow,
Segregation of phases

Vertical Equilibrium model

2D-VE coupling

- Fluxes over boundary between subdomains



$$v_{tot,i^*r} = -k\lambda_{tot}\left(\frac{p_{wr}-p^*_{wi}}{\Delta x} + f_n \frac{p_{cr}-p^*_{ci}}{\Delta x}\right)$$

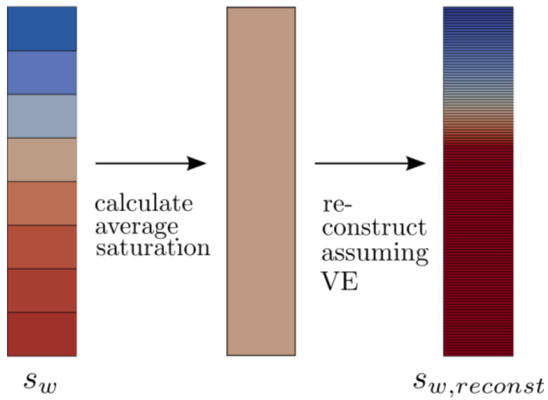
$$p^*_{wi} = P_{wi} - \varrho_w g z$$

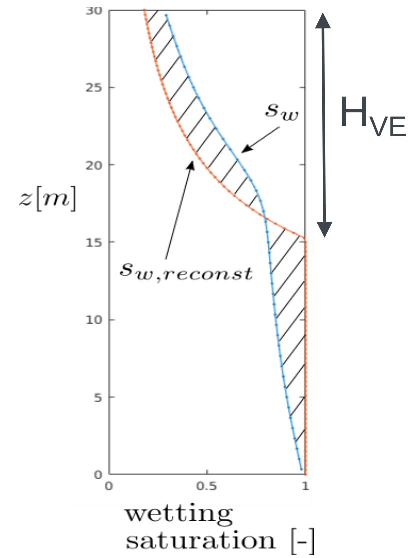
$$p^*_{ci} = p_c(s^*_w)$$

$$\lambda_{tot}, f_n \quad \text{all depending on } \bar{s}^*_w$$

2D-VE coupling

- Switch criterion based on column profiles





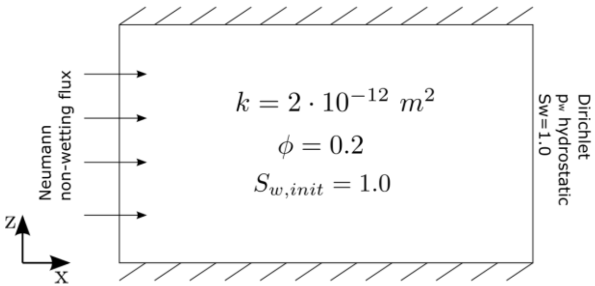
$$c_{sat} = \frac{\int_0^H |s_w - s_{w,reconst}| \mathrm{dz}}{H_{VE}}$$

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

$$c_{crit} < \epsilon_{crit}$$ ➡ 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):

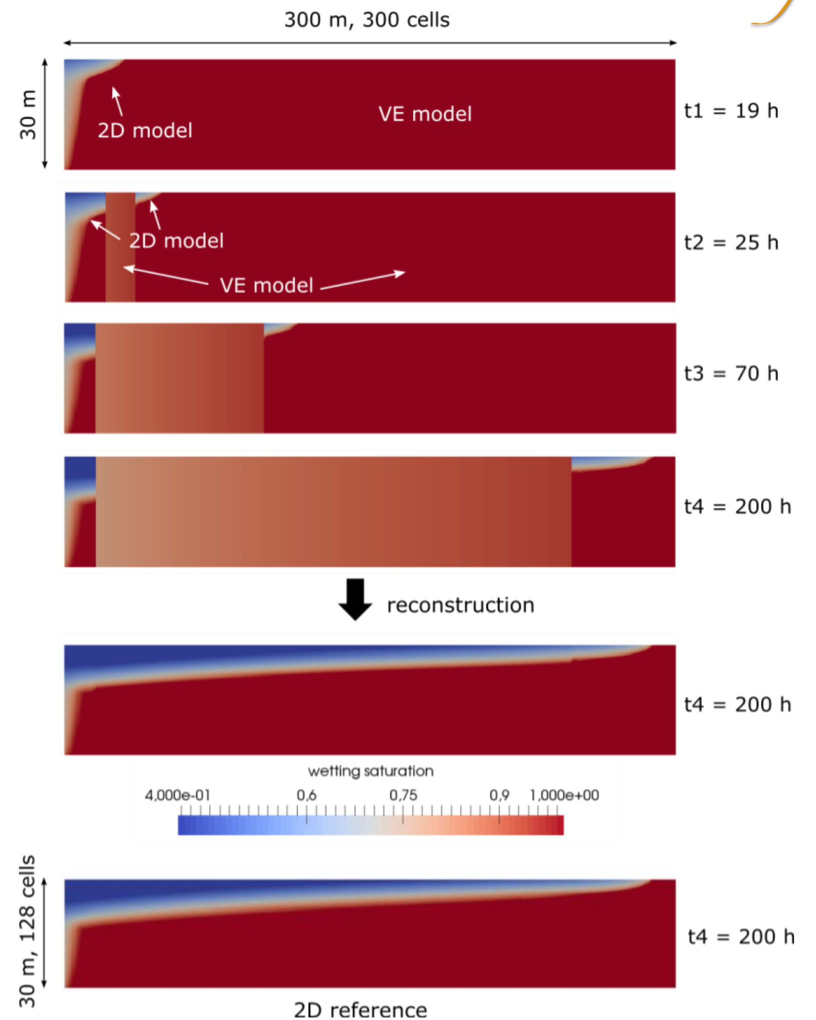
$\varrho_n = 59.2\ kg/m^3$

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

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

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

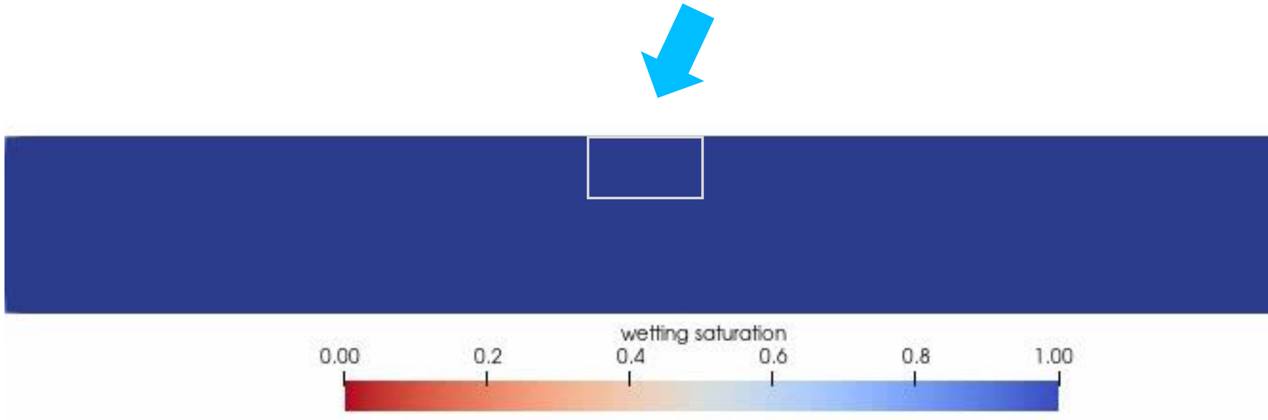
Injection rate: $Q_{nw} = 552\ t/m/a$



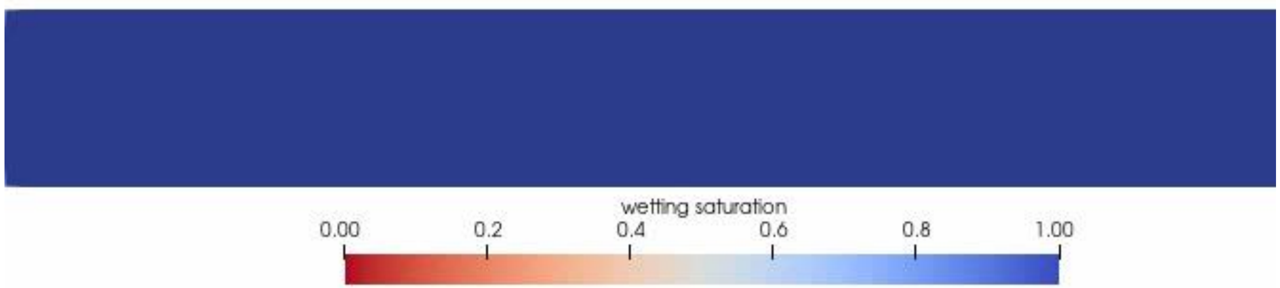
Results coupling 2D and vertical equilibrium

Adaptive coupling, example with low-permeability lens

Simulation result



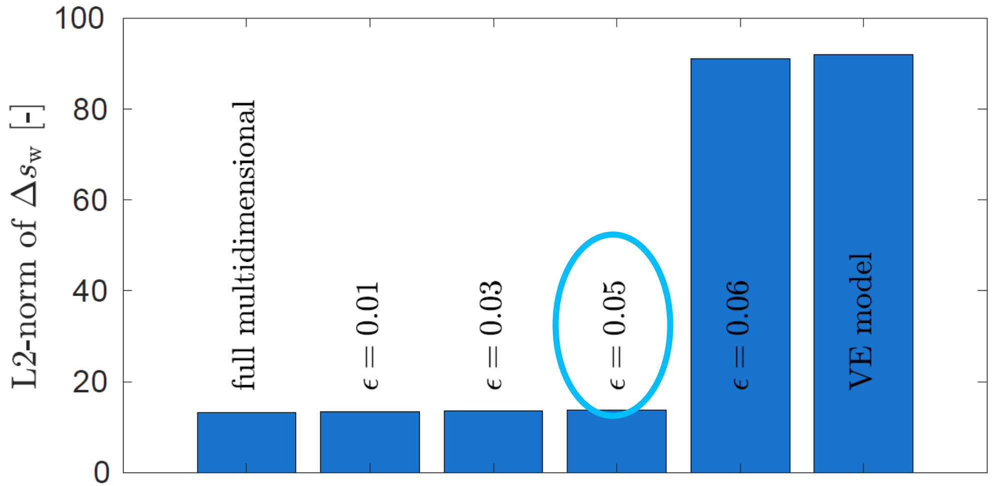
Reconstruction



Efficiency of the multiphysics model

Efficiency:
Speed ✖ Accuracy

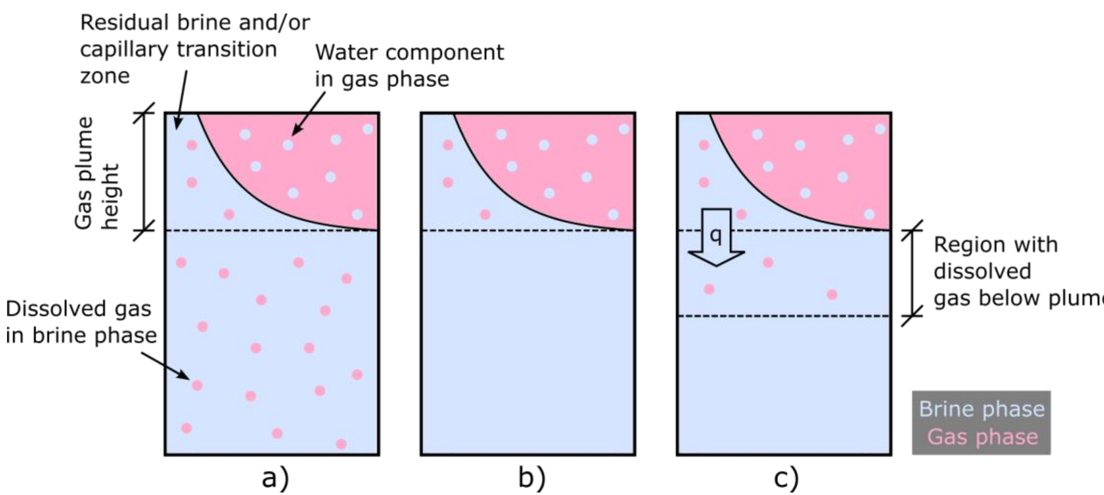
Model	relative average number of cells [-]	relative CPU time [-]
Full VE	0.008	0.003
Multiphysics $\epsilon_{\mathrm{relPerm}} = 0.06$	0.04	0.02
Multiphysics $\epsilon_{\mathrm{relPerm}} = 0.05$	0.11	0.05
Multiphysics $\epsilon_{\mathrm{relPerm}} = 0.04$	0.12	0.06
Multiphysics $\epsilon_{\mathrm{relPerm}}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



(Becker et al., 2018)

Outlook

- Extend model hierarchy
  - compositional models for full multidimensions and vertical equilibrium ➡ see poster!
  - using field/lab data
  - couple models
- New model selection criteria (data- and model-based)



References

- Becker, B., Guo, B., Bandilla, K., Celia, M., Flemisch, B., Helmig, R. (2018). An adaptive multiphysics model coupling vertical equilibrium and full multidimensions for multiphase flow in porous media, Water Resources Research, 54(7), 4347-4360.
- Guo, B., Bandilla, K. W., Doster, F., Keilegavlen, E. and Celia, M. A. (2014). A vertically integrated model with vertical dynamics for CO2 storage, Water Ressources Research, 50.
- Guo, B., Bandilla, K. W., Nordbotten, J. M., Celia, M. A., Keilegavlen, E., Doster, F. (2016). A multiscale multilayer vertically integrated model with vertical dynamics for CO2 sequestration in layered geological formations, Water Resources Research.
- Nordbotten, J. M., Celia, M. A. (2012): Geological Storage of CO2: Modeling Approaches for Large-Scale Simulation. John Wiley & Sons.

University of Stuttgart

Thank you!

Beatrix Becker

e-mail Beatrix.becker@iws.uni-stuttgart.de

University of Stuttgart
Institute for Modelling Hydraulic and
Environmental Systems
Pfaffenwaldring 61
D-70569 Stuttgart, Germany

University of Stuttgart

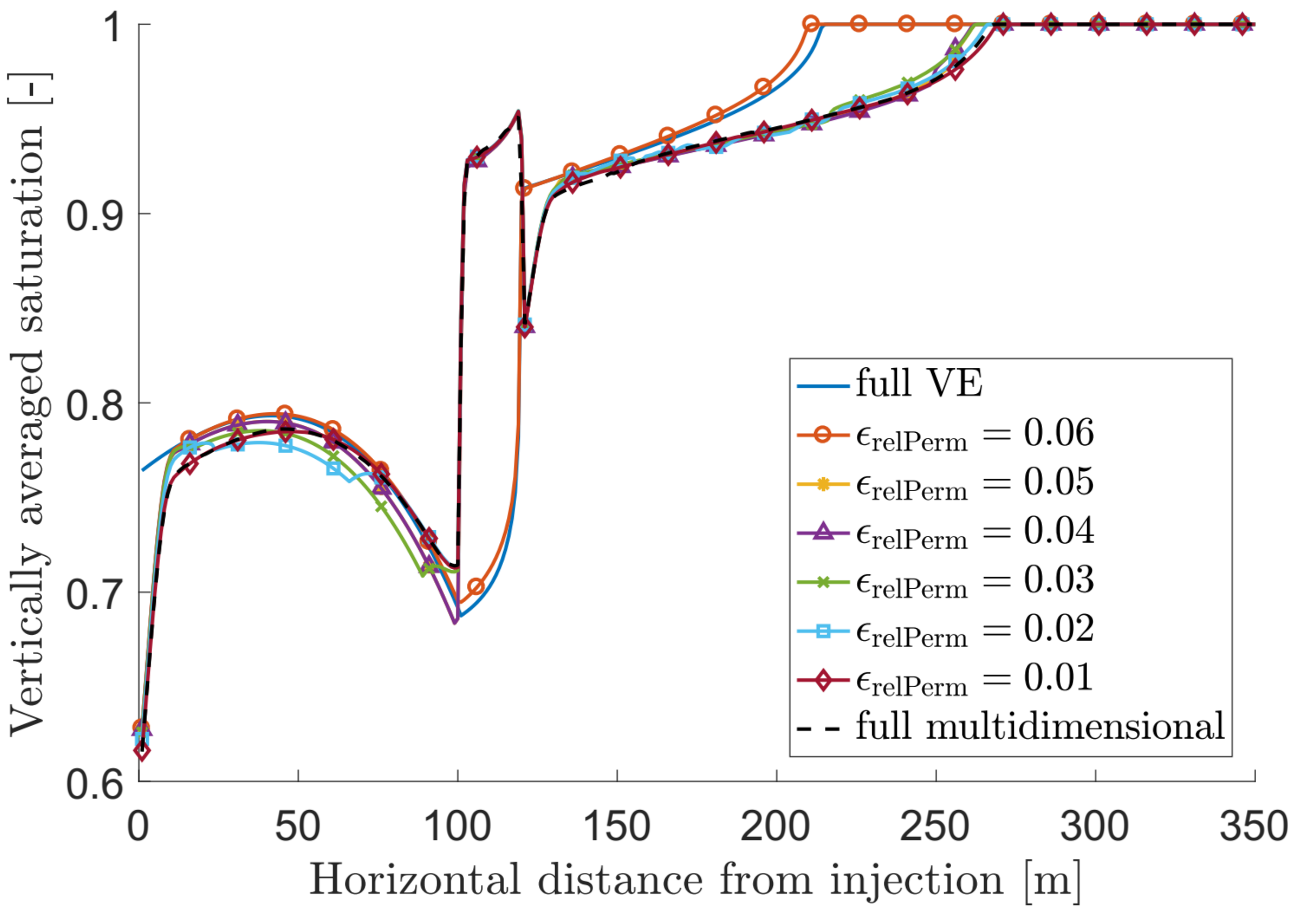
Thank you!

Beatrix Becker

e-mail Beatrix.becker@iws.uni-stuttgart.de

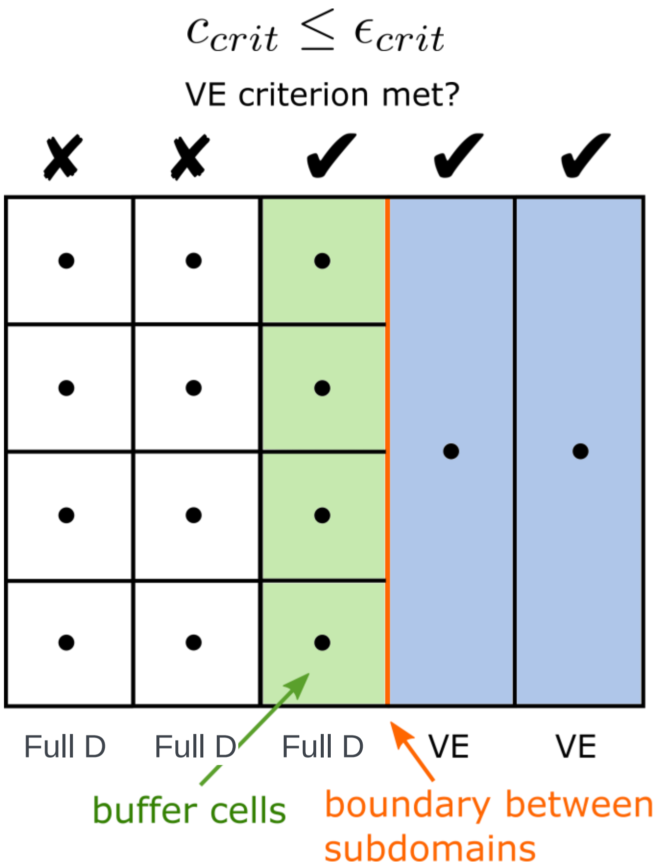
University of Stuttgart
Institute for Modelling Hydraulic and
Environmental Systems
Pfaffenwaldring 61
D-70569 Stuttgart, Germany

Choice of threshold value for VE-criterion



(Becker et al., 2018)

Buffer columns



- A column stays a full-D column when the criterion is not met.
- A column is turned into a VE column when the criterion is met and the column is not a direct neighbor of a column where the criterion is not met.
- Buffer columns ensure that VE columns are turned back to full-D columns when necessary.