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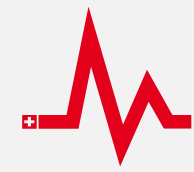
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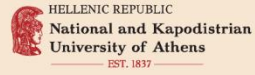
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Novel Bayesian inversion of dispersion and ellipticity curves intended for subsurface characterization

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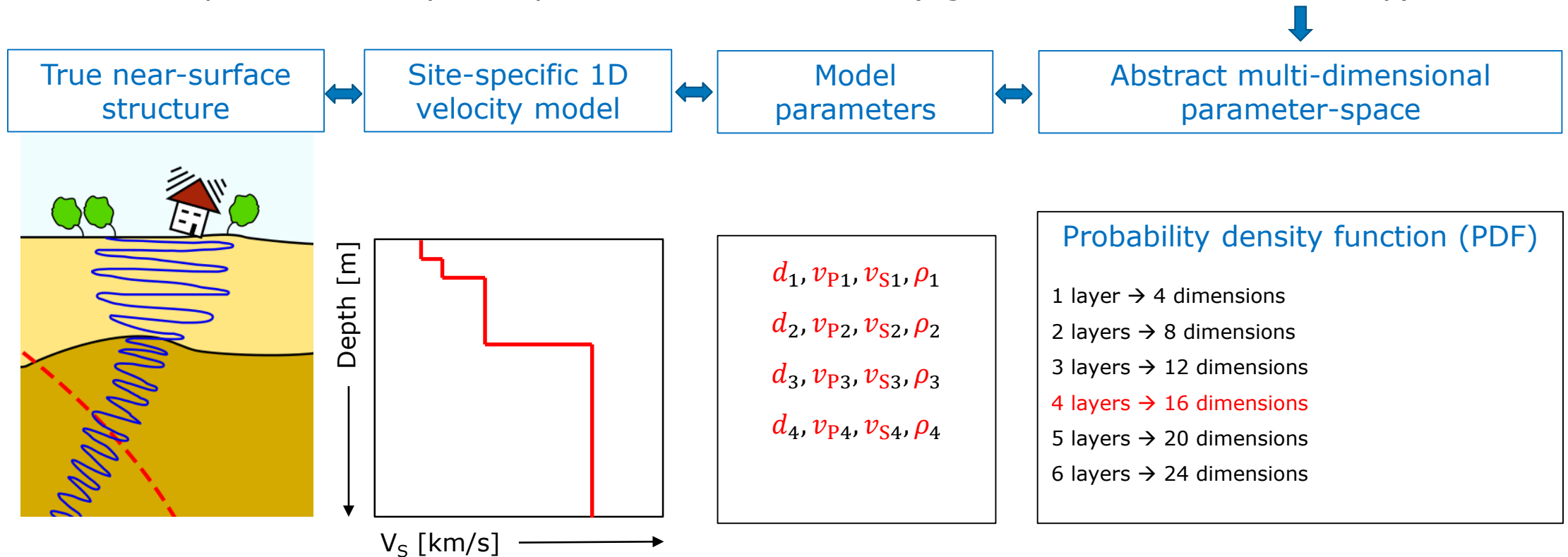
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Outline

- Introduction
- Inversion method
- Inversion tests with synthetic data
- Inversions of real data from Switzerland
- Summary

Introduction

- Input: Measured surface wave data (ambient seismic vibrations)
- Output: Velocity model (and its uncertainty)
- Inversion procedure: Bayesian probabilistic framework (rigorous work with uncertainty)



Inversion method – Overview

	Description	Reference
Parameterization	Voronoi nuclei	Bodin et al. (2012)
Bayesian	Probability density function (PDF) on the multi-dimensional parameter-space	Tarantola (2005)
Transdimensional	Variable data-driven number of layers	Green (1995)
Markov chain Monte-Carlo	Metropolis-Hastings algorithm	Metropolis et al. (1953) Hastings (1970)
Parallel Tempering	Multiple parallel Markov chains	Sambridge (2014)
Multizonal	Depth-dependent prior PDF	Hallo et al. (2021)

Inversion method – Bayesian

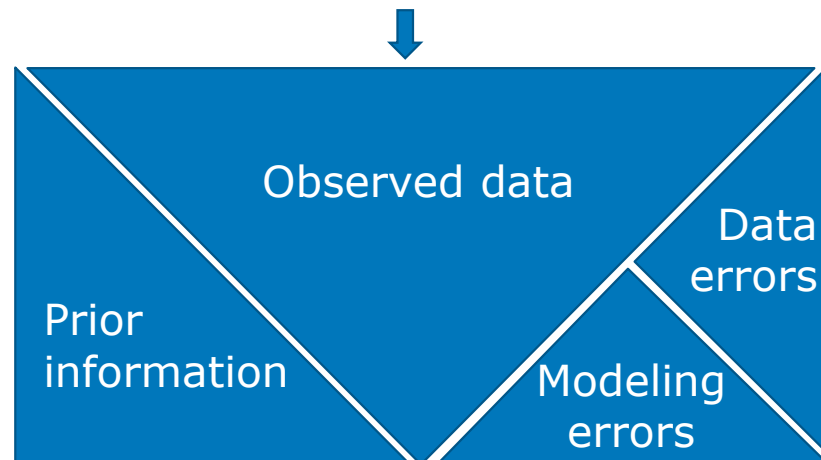
- Prior knowledge is given by a prior PDF
- Measured data are used in evaluation of the likelihood function
- The solution is given by conditional posterior PDF

$$p(\mathbf{m}|\mathbf{d}_{\text{obs}}) = c \cdot p(\mathbf{m}) \cdot \exp\left(-\frac{1}{2}(\mathbf{d}_{\text{obs}} - \mathbf{g}(\mathbf{m}))^T \mathbf{C}_D^{-1}(\mathbf{d}_{\text{obs}} - \mathbf{g}(\mathbf{m}))\right)$$

posterior PDF

prior PDF

likelihood function



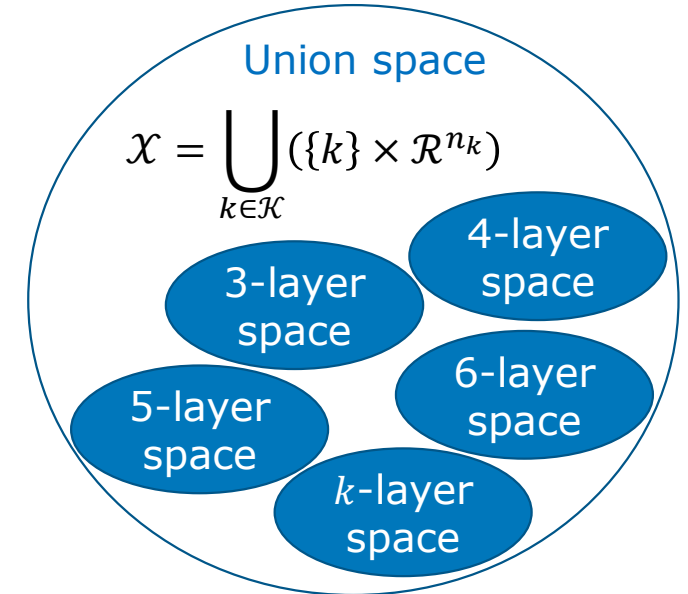
$p(\cdot)$ – probability density function
 c – normalization constant
 \mathbf{m} – model parameters
 \mathbf{d}_{obs} – observed data
 $\mathbf{g}(\cdot)$ – forward problem
 \mathbf{C}_D – data covariance matrix

(e.g. Tarantola 2005)

Inversion method – Transdimensional

- Number of parameters is subject of inversion (Green 1995)
- Union space consists of multiple parameter-spaces
- Variable number of layers (e.g., Bodin et al. 2012)
- Occam's razor where sampling models has as few layers as possible, but not less then required by the observed data:

$$p(k) \propto k^{-1} \text{ (Hallo \& Gallovi\c{c} 2020)}$$



$$p(k, \mathbf{w}_k | \mathbf{d}_{\text{obs}}) = c \cdot p(k) \cdot p(\mathbf{w}_k | k) \cdot \exp\left(-\frac{1}{2}(\mathbf{d}_{\text{obs}} - \mathbf{g}(k, \mathbf{w}_k))^T \mathbf{C}_D^{-1}(\mathbf{d}_{\text{obs}} - \mathbf{g}(k, \mathbf{w}_k))\right)$$

posterior PDF

prior PDF

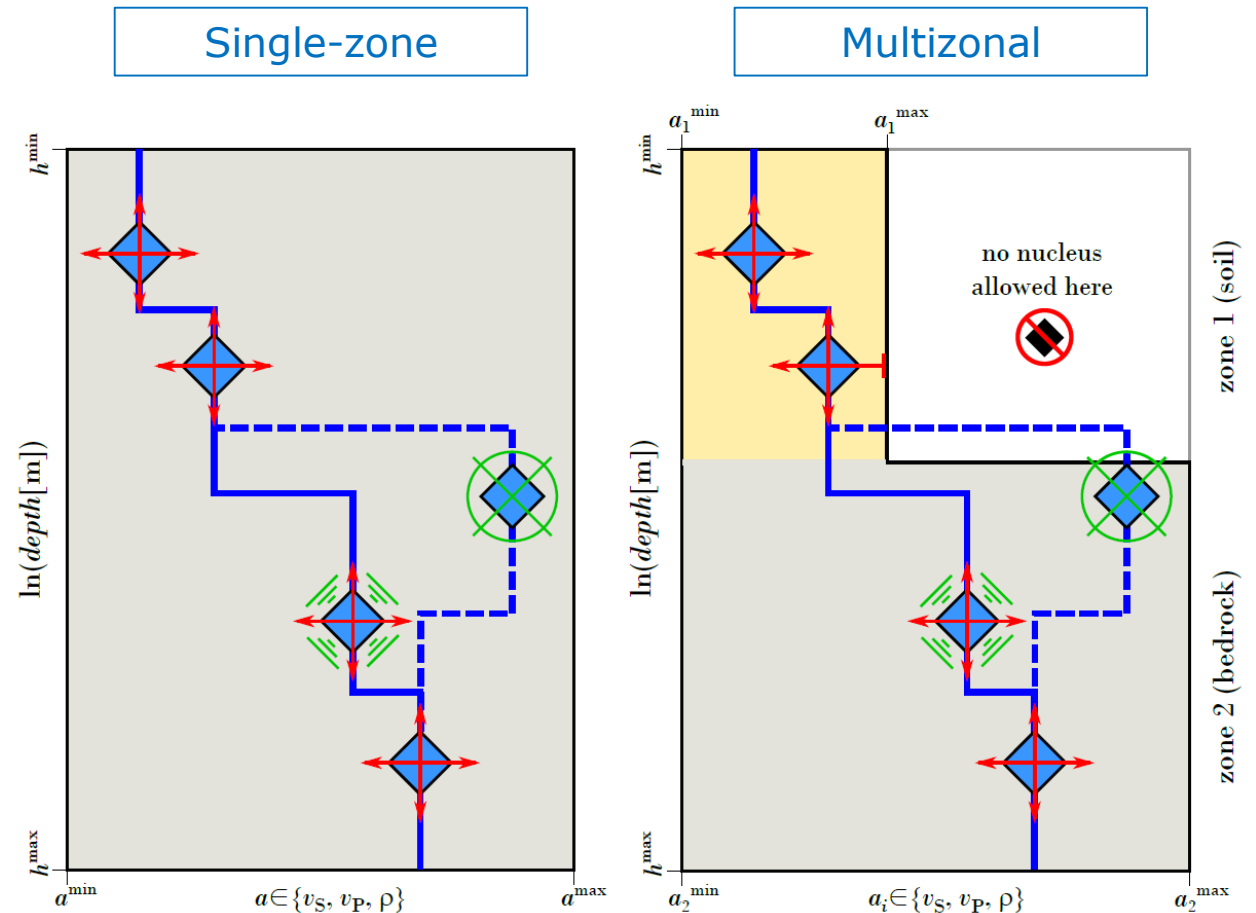
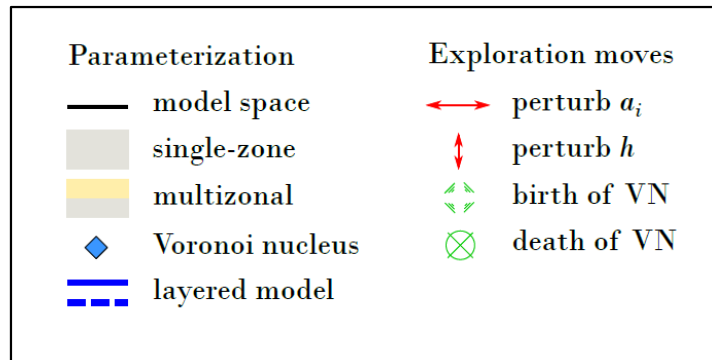
likelihood function

k – number of layers

\mathbf{w}_k – model parameters given number of layers k

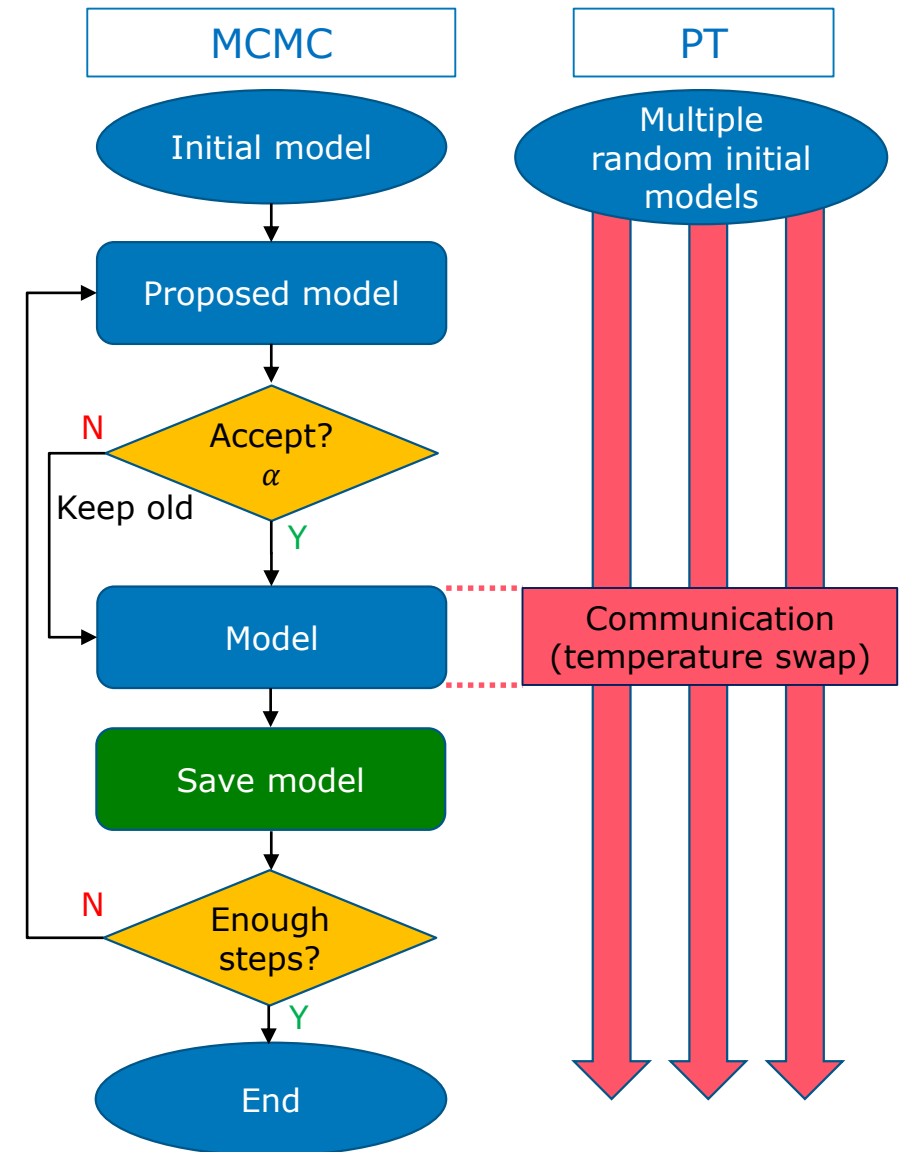
Inversion method – Multizonal

- Novel approach (Hallo et al. 2021)
- Possibility to include additional prior knowledge in the inversion:
 - groundwater level
 - standard penetration test
 - well-log data
 - geological mapping
- Depth-dependent prior PDF



Inversion method – MCMC & Parallel Tempering

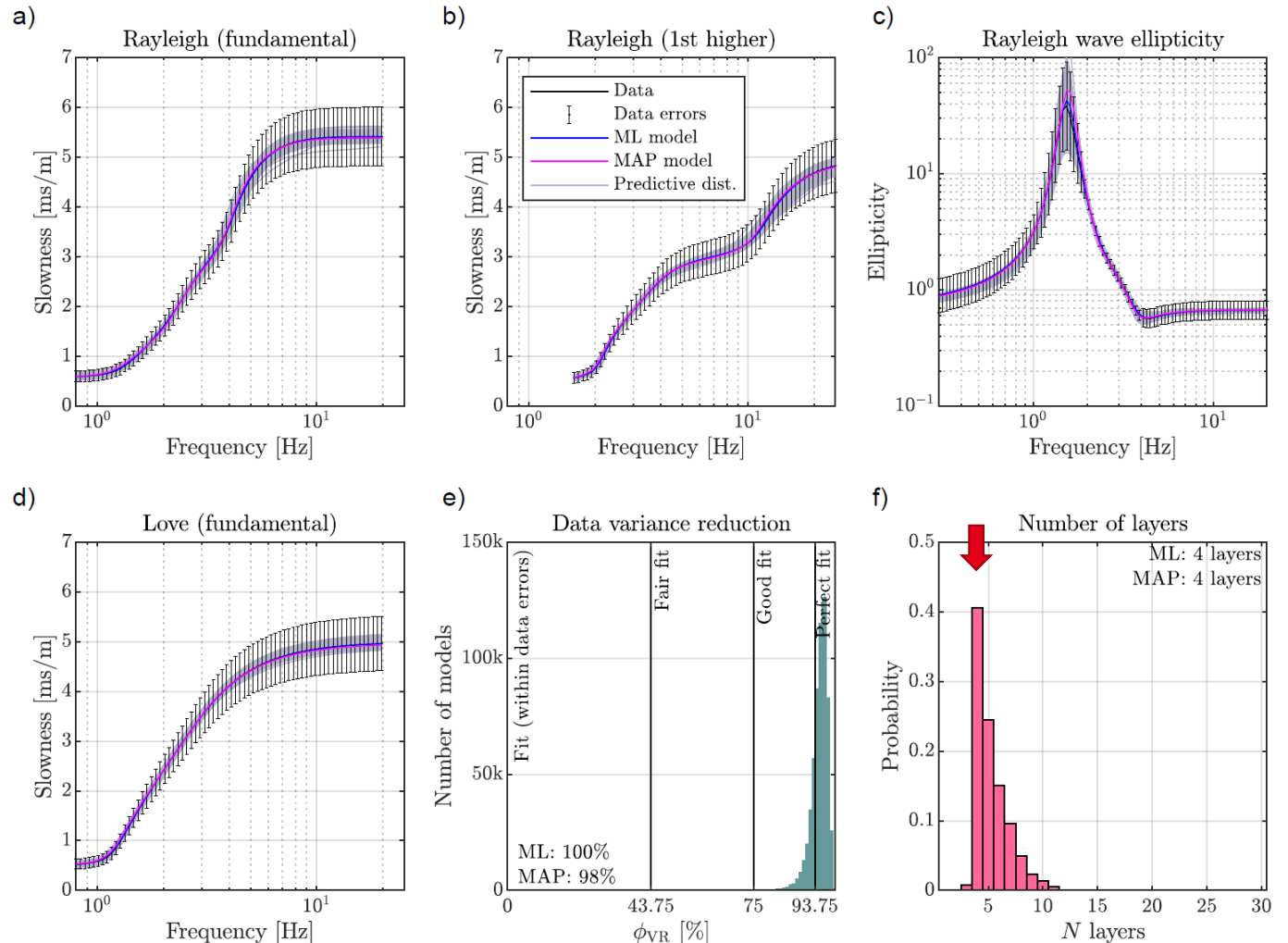
- Markov chain Monte-Carlo (MCMC) exploration of the parameter space (Metropolis et al. 1953, Hastings 1970)
- Parallel Tempering (PT) following Sambridge (2014)
- The acceptance probability α ensures that saved models are discrete approximation of the **posterior PDF** $p(k, \mathbf{w}_k | \mathbf{d}_{\text{obs}})$
- The acceptance probability α for the multizonal transdimensional case was derived analytically by Hallo et al. (2021)



Inversion tests with synthetic data

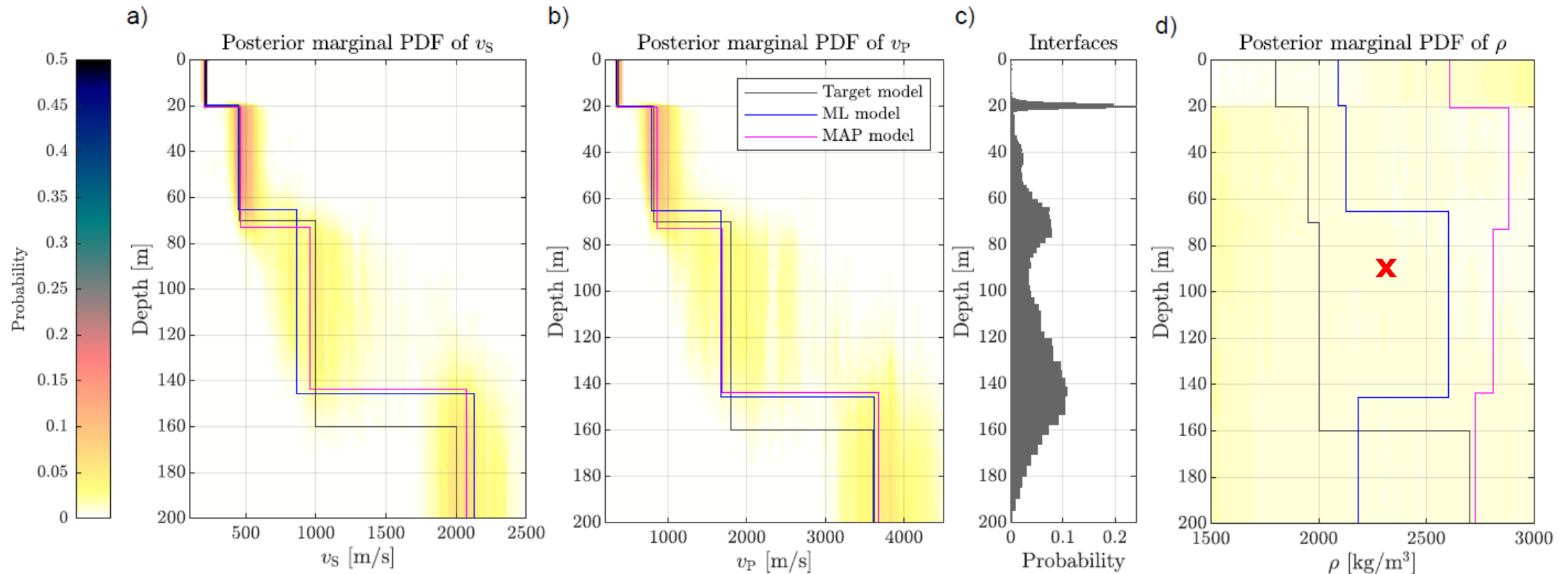
Inversion of synthetic data – Simple subsurface structure

- Forward problem by Geopsy
- Synthetic data computed in the known 1D model of 4 layers
- Rayleigh wave fundamental and 1st higher modes
- Love wave fundamental mode
- Rayleigh wave ellipticity
- Inversion results:
 - Perfect fit to all data
 - Highest posterior probability for 4 layers (the correct value)



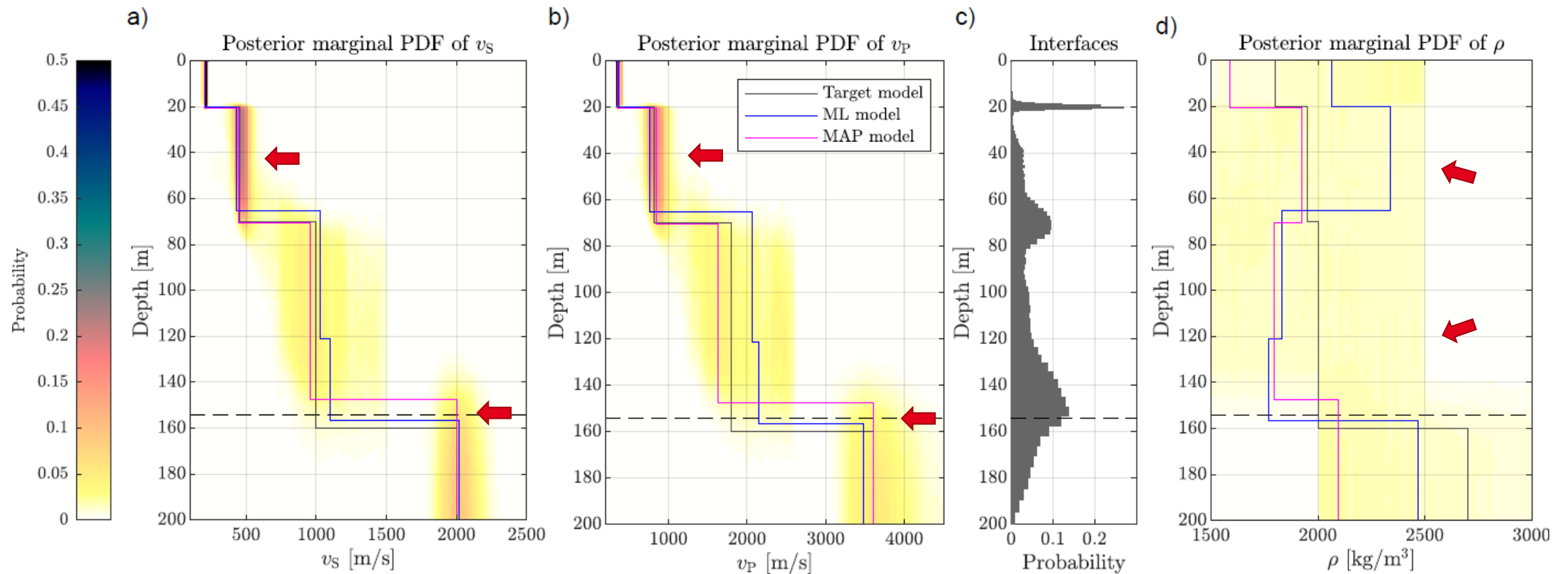
Inversion of synthetic data – Simple subsurface structure (single-zone)

- Inversion results (v_p, v_s) match the known “target” model
- It is not possible to retrieve the mass density from such a data



Inversion of synthetic data – Simple subsurface structure (multizonal)

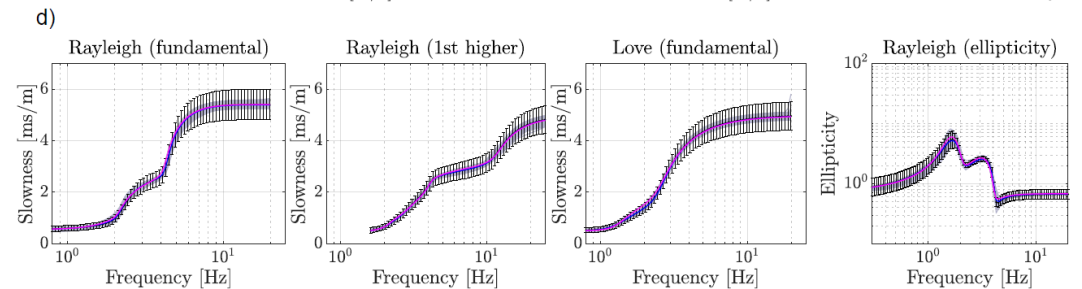
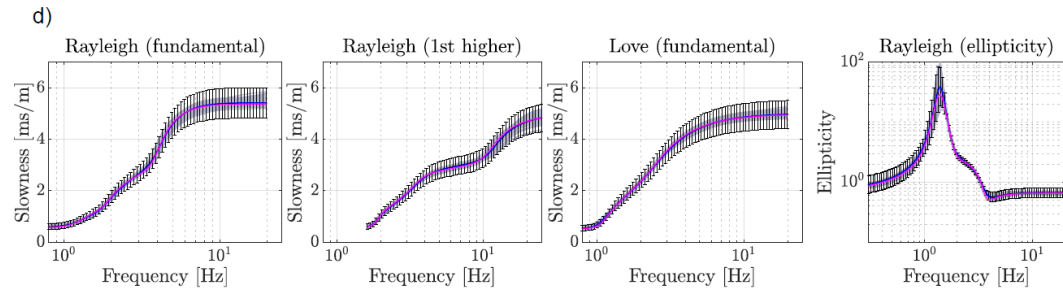
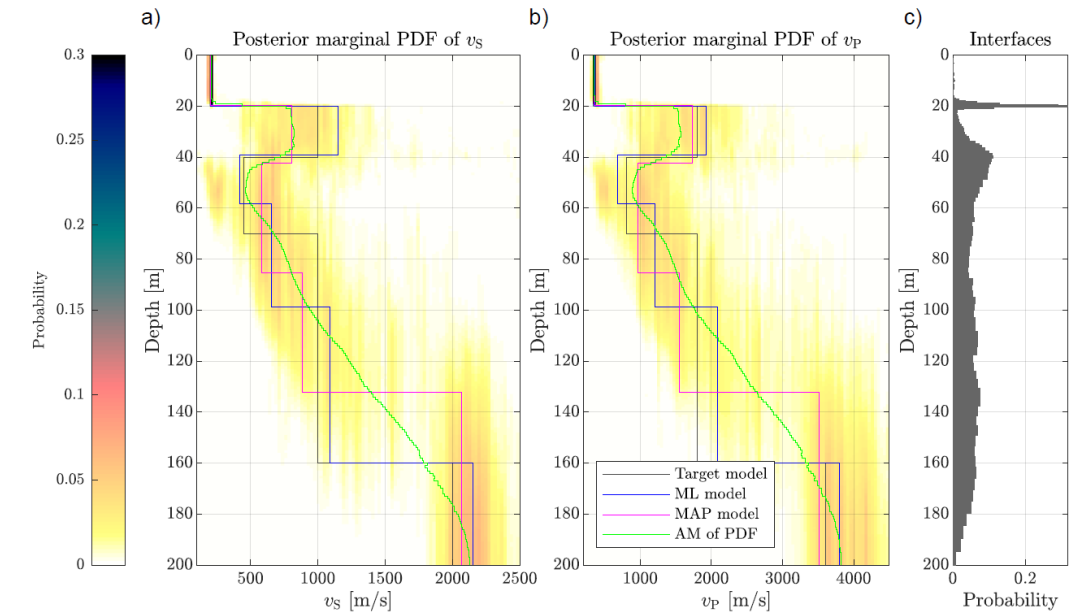
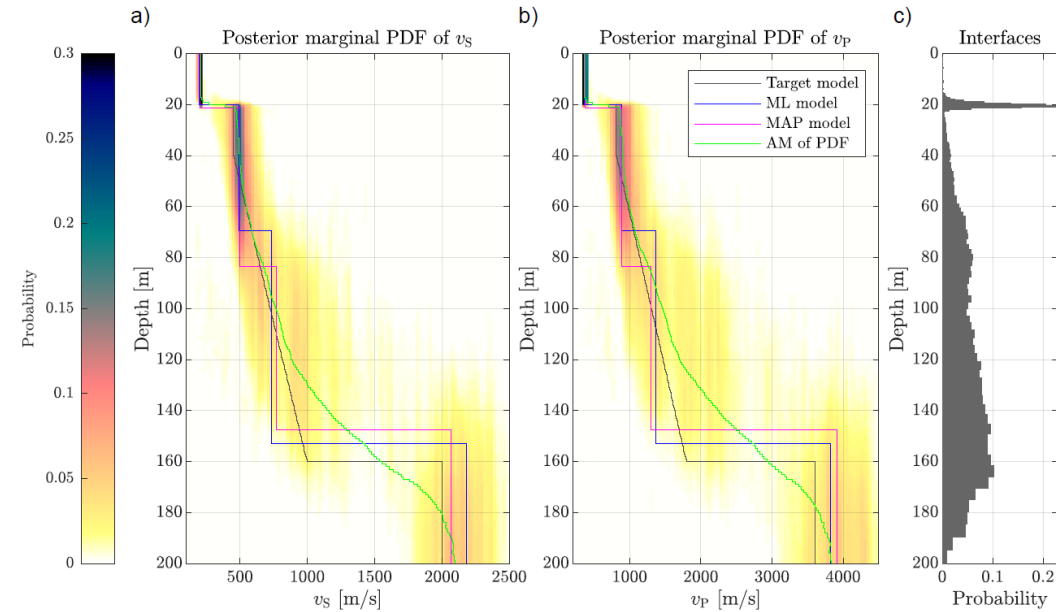
- Multizonal prior PDF (two depth-zones: 0-154 m and >154 m)
- There is an improvement in the posterior PDF



Inversion of synthetic data – Complicated subsurface structures

Velocity gradient

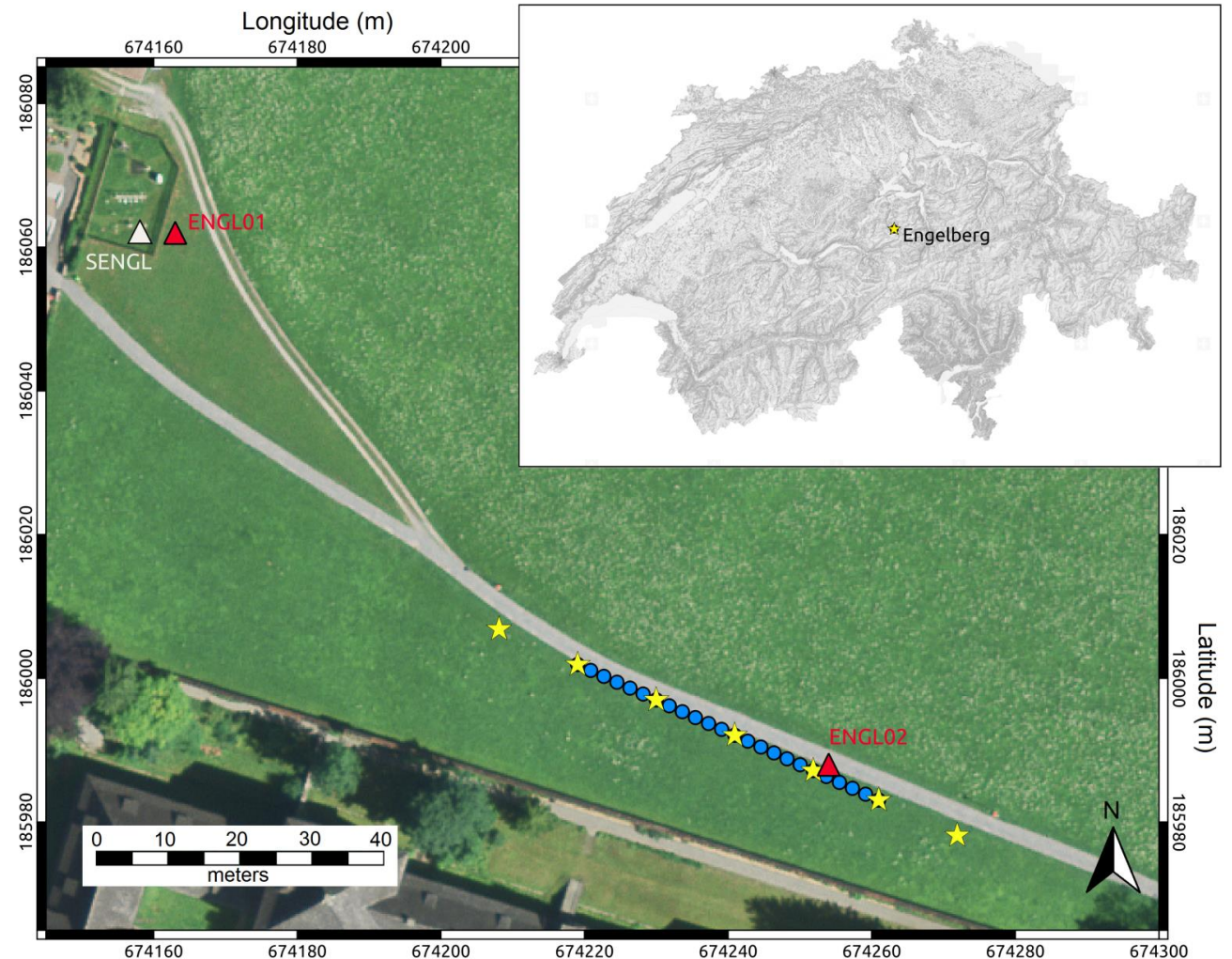
Low-velocity zone



Real data inversion

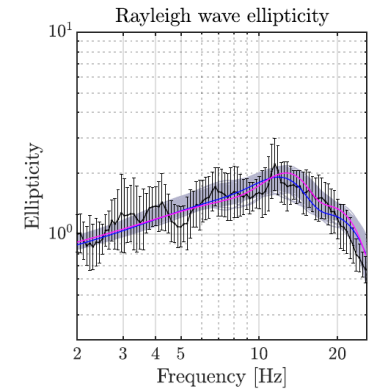
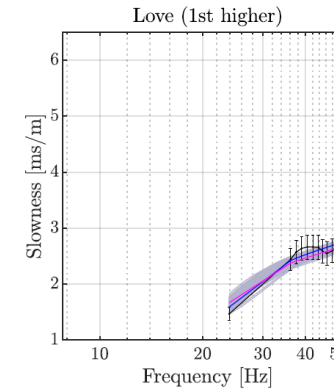
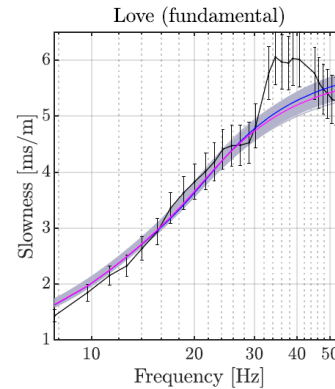
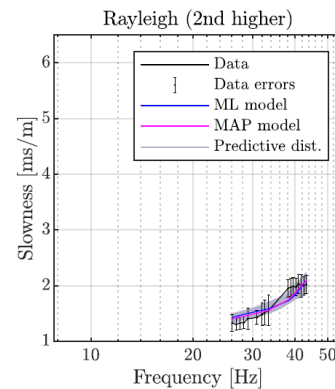
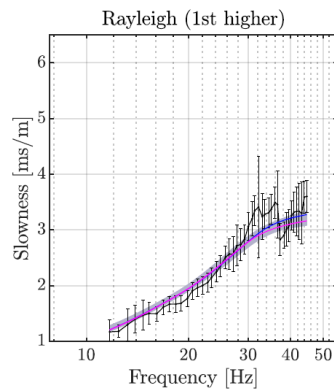
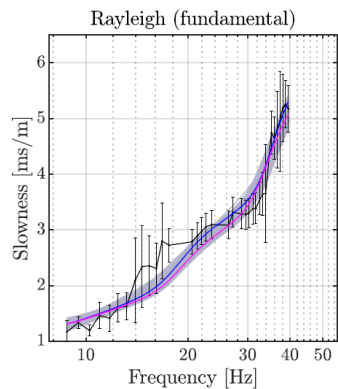
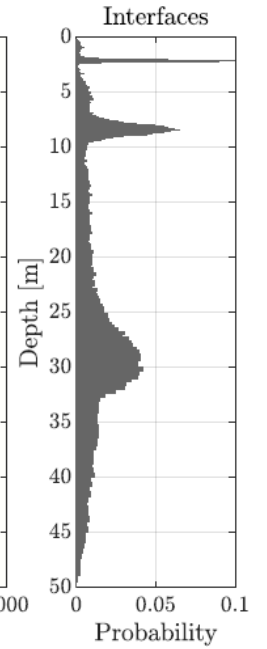
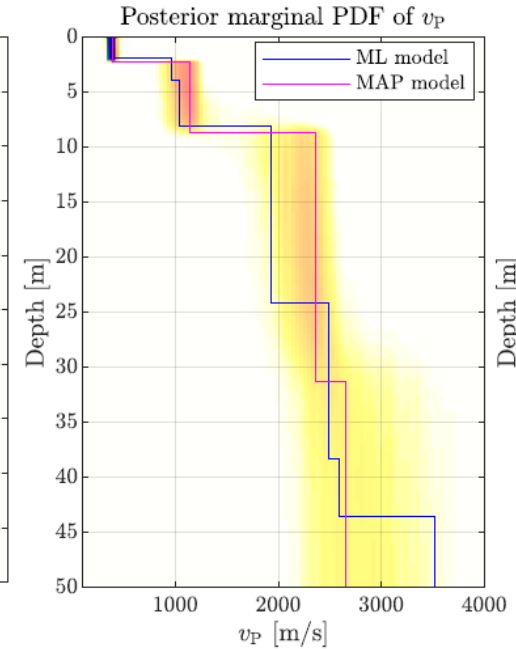
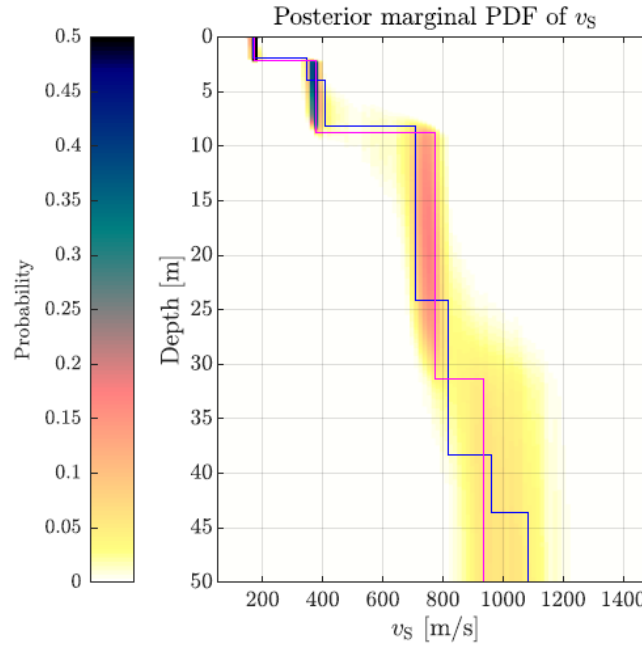
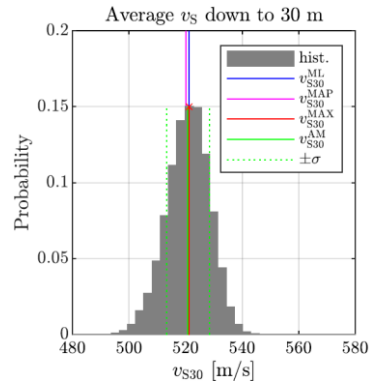
Real data inversion

- Surface waves data from ambient seismic vibration measurements:
 - Passive array methods
 - Active methods
 - Single station methods
 - RayDec (Hobiger et al. 2009)
 - MASW (Park et al. 1999)
- SENGL (Engelberg) data:
 - SSMNet
 - Alpine valley in central Switzerland
 - active and passive measurements
 - MASW and RayDec processing
 - Panzera et al. (2020)



Real data inversion – Results

- Fair fit to all data
- Resultant velocity profiles in agreement with local geology
- v_{S30} histogram



Summary

1. Solution uncertainty (posterior PDF)
2. Number of layers is automatic and data-driven (transdimensional)
3. Suppressed dependency on the initial model (parallel tempering)
4. Possibility to include additional prior knowledge (multizonal)

Perspectives

- Easy to change forward problem solver (Rayleigh \rightarrow Scholte waves)
- Inversion of single station data (Rayleigh wave ellipticity on Mars)
- Theoretical local spectral amplification functions including uncertainty

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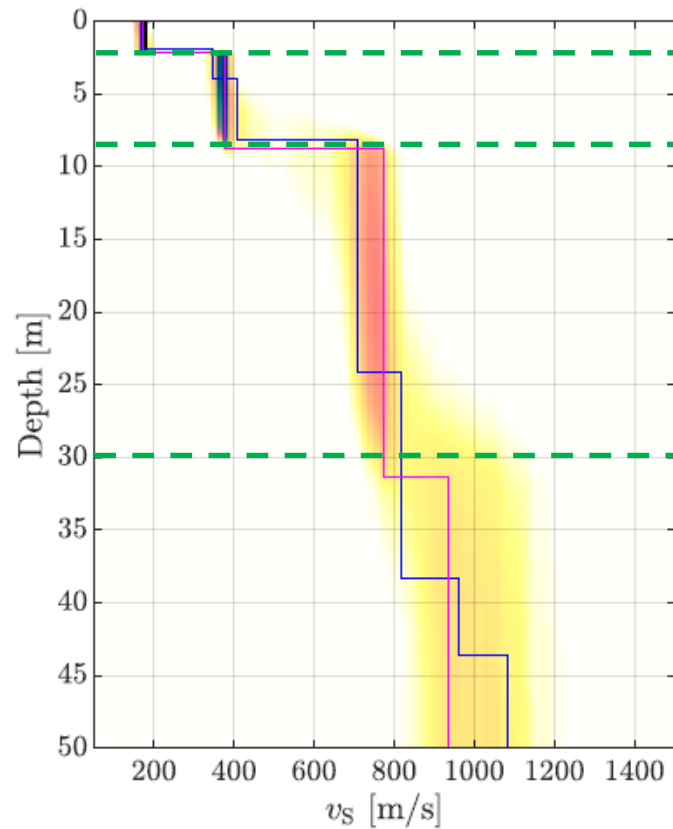
Acknowledgments

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Inversion of Rayleigh wave ellipticity – SENGL site

- Challenging test with data from single station measurement

Inversion of all available surface wave data



Inversion of Rayleigh wave ellipticity only

