Mondaic

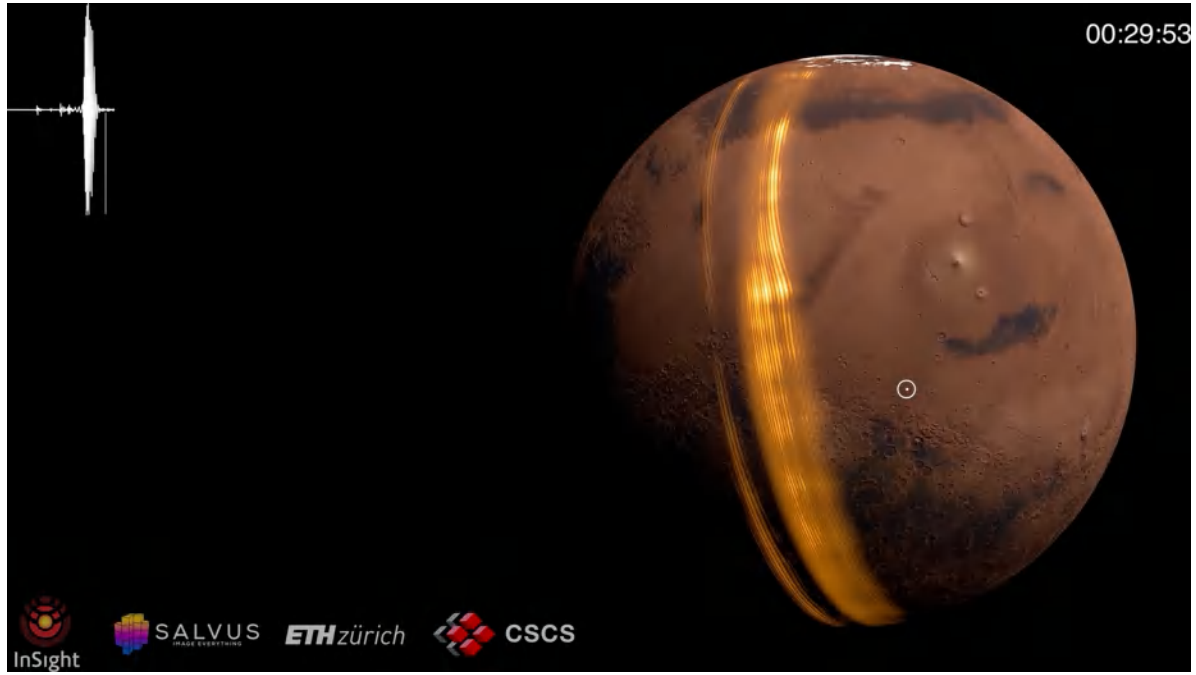
Outline

- Overview
- Components
- Applications
- Mondaic
- Tutorial (on Thursday)

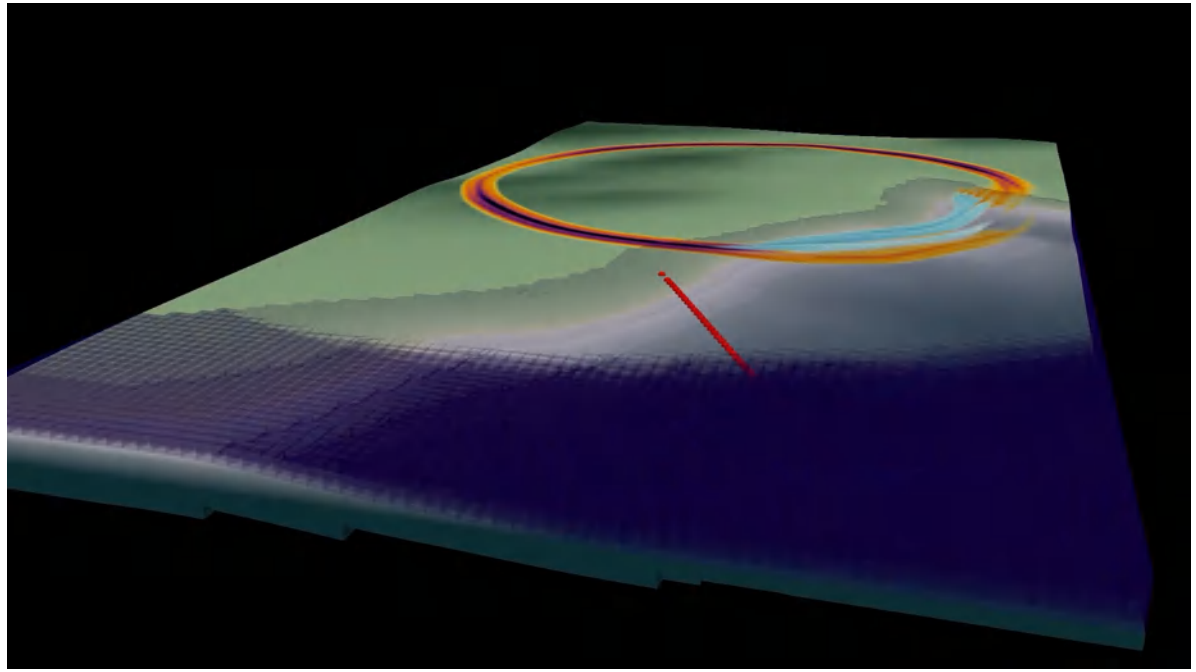
Salvus

Overview

Waveform modeling and inversion across the scales

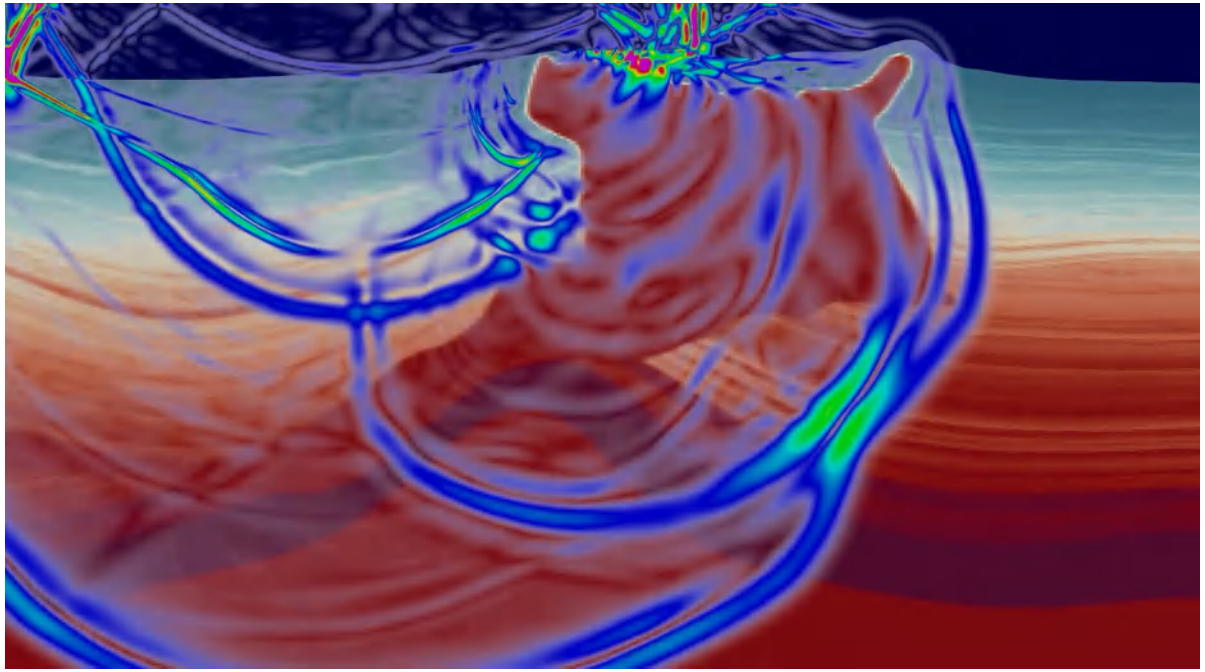


Global-scale Seismology

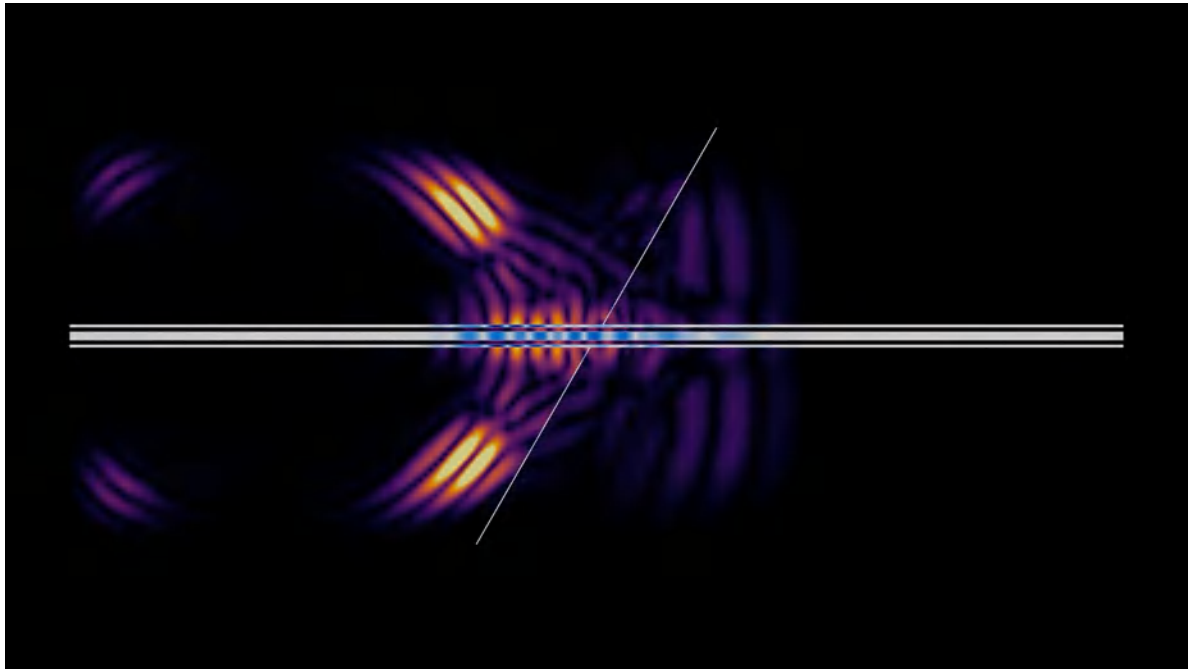


Regional-scale Seismology

Waveform modeling and inversion across the scales

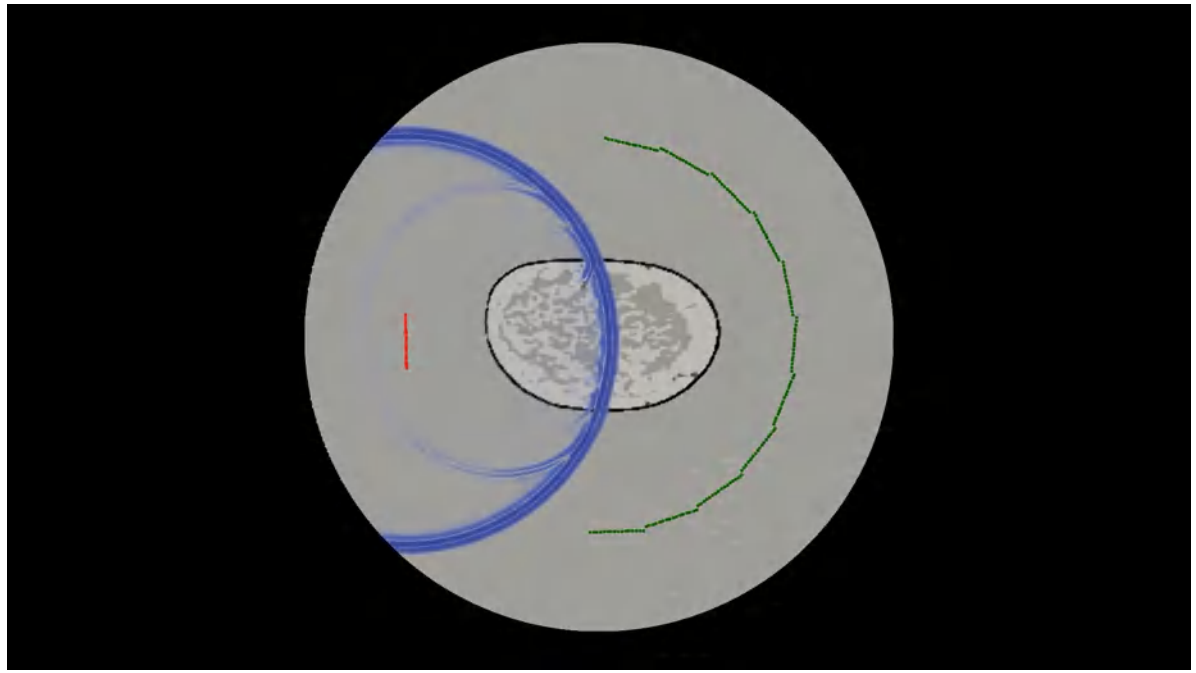


Exploration Geophysics

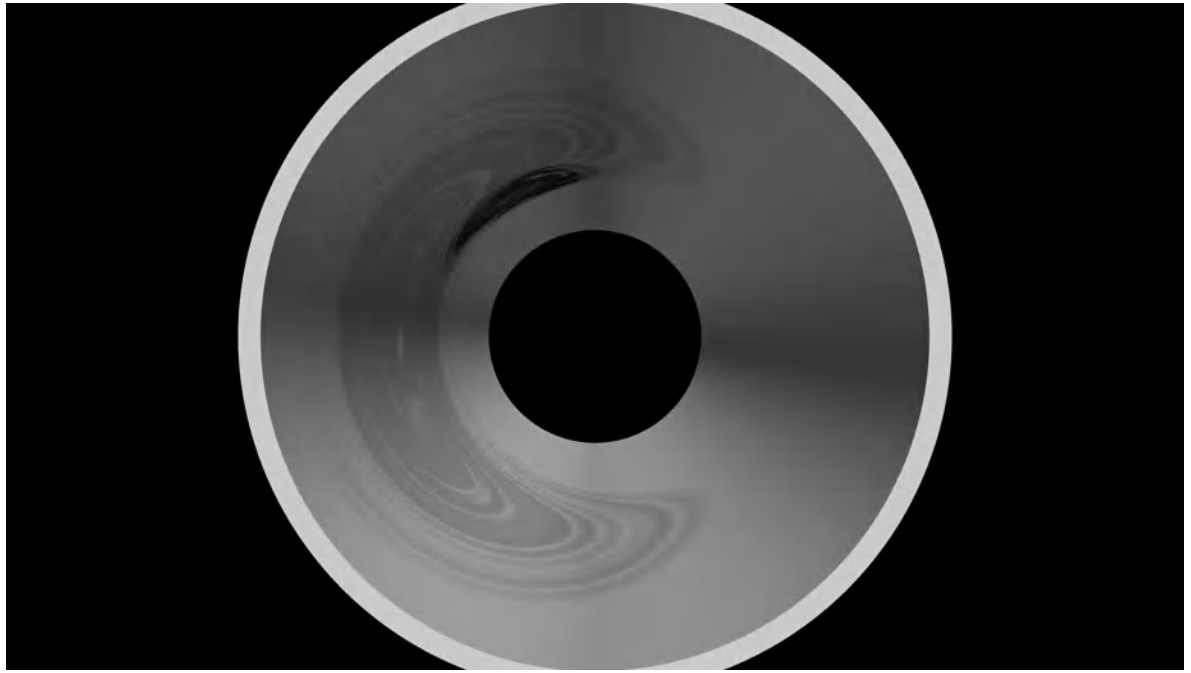


Borehole Acoustics

Waveform modeling and inversion across the scales



Medical imaging

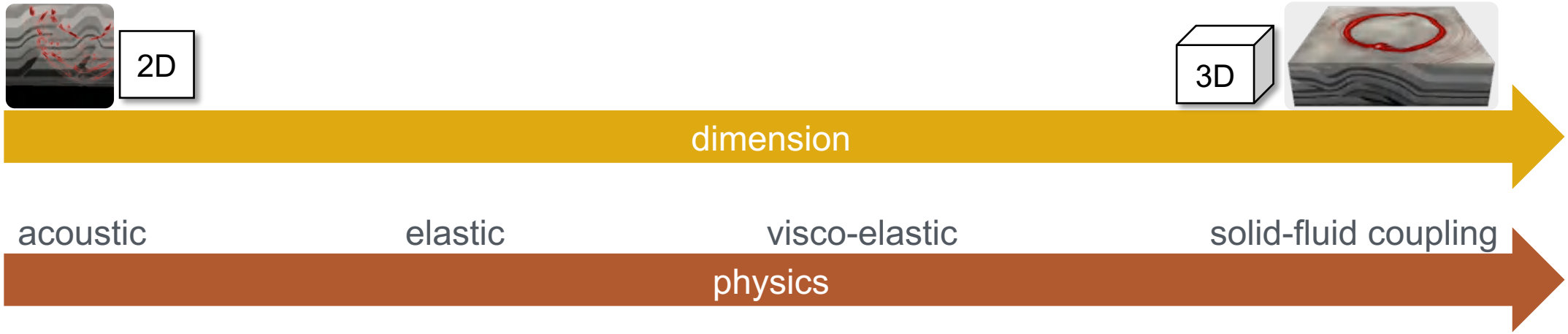


Nondestructive testing

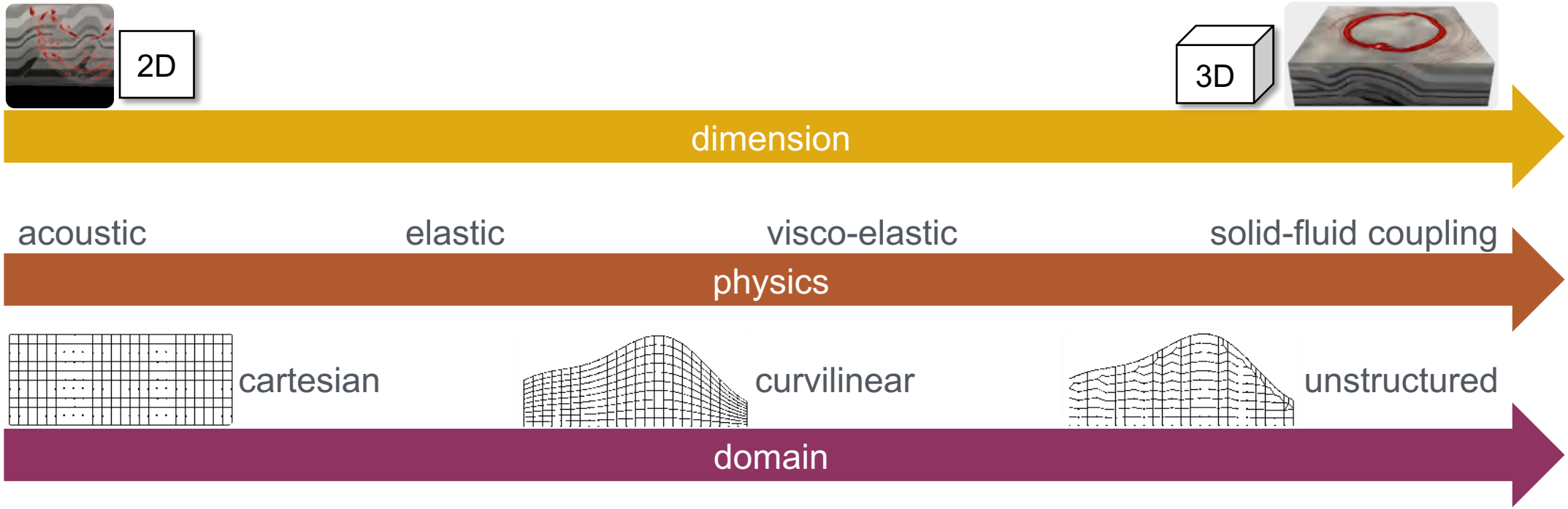
Solving problems across the scales

Solving problems across the scales

Solving problems across the scales



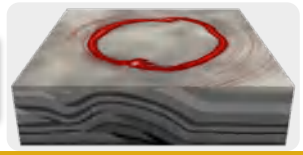
Solving problems across the scales



Solving problems across the scales

2D

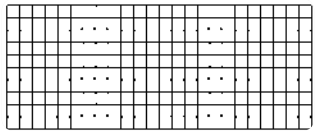
3D



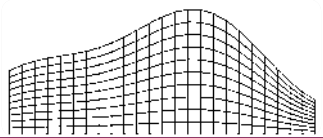
dimension

acoustic elastic visco-elastic solid-fluid coupling

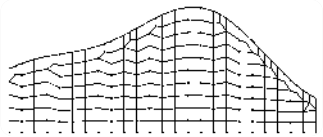
physics



cartesian

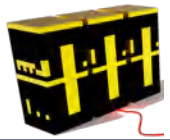


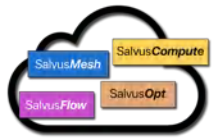
curvilinear



unstructured

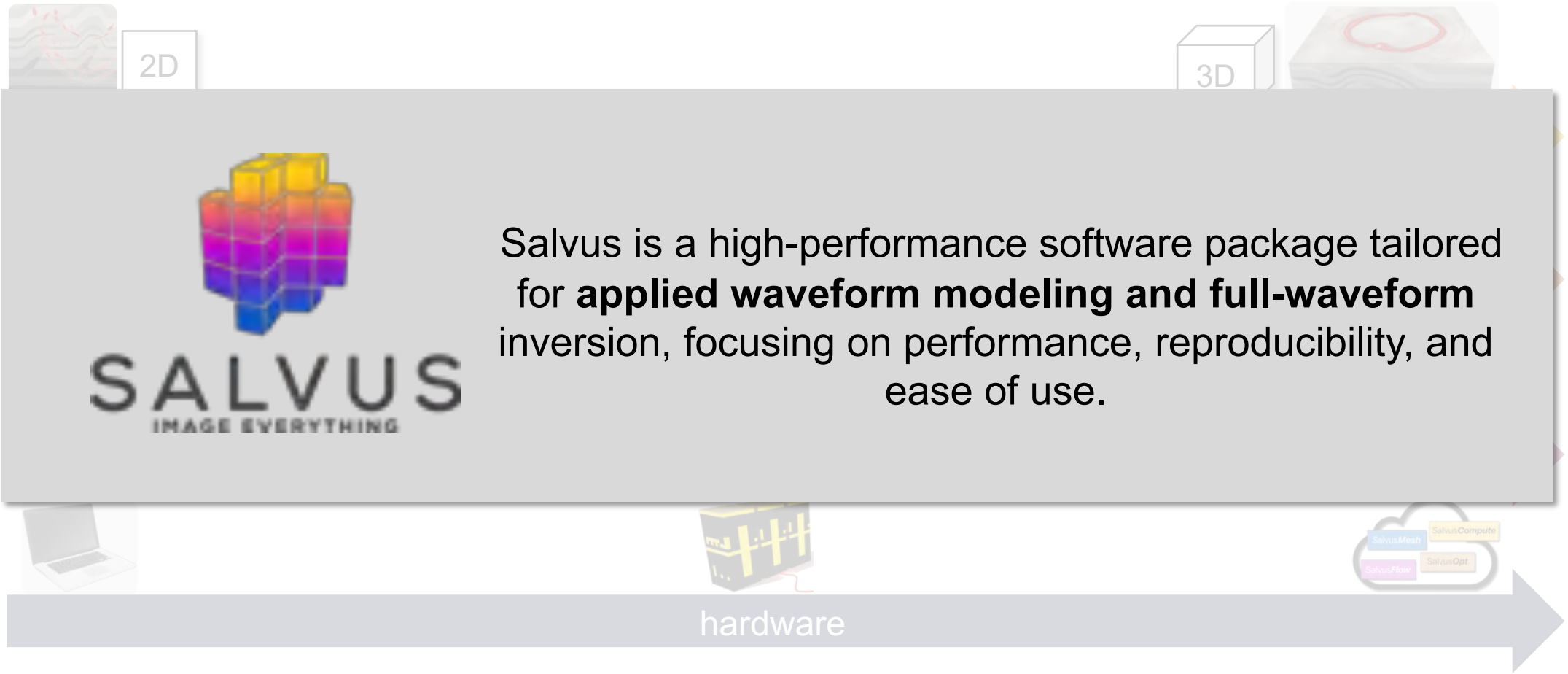
domain





hardware

Solving problems across the scales



Components

How does Salvus work?

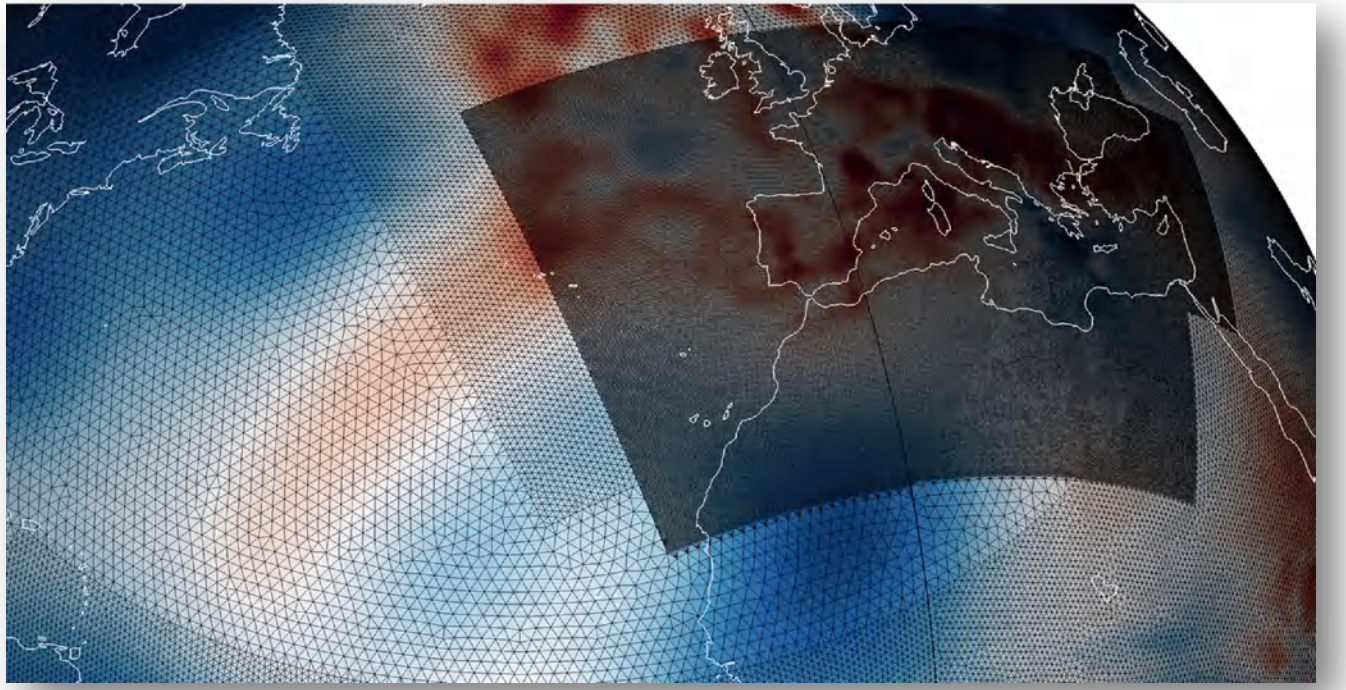
Components

Salvus***Compute*** | Salvus***Mesh*** | Salvus***Flow*** | Salvus***Opt*** | Salvus***Project***

SalvusCompute

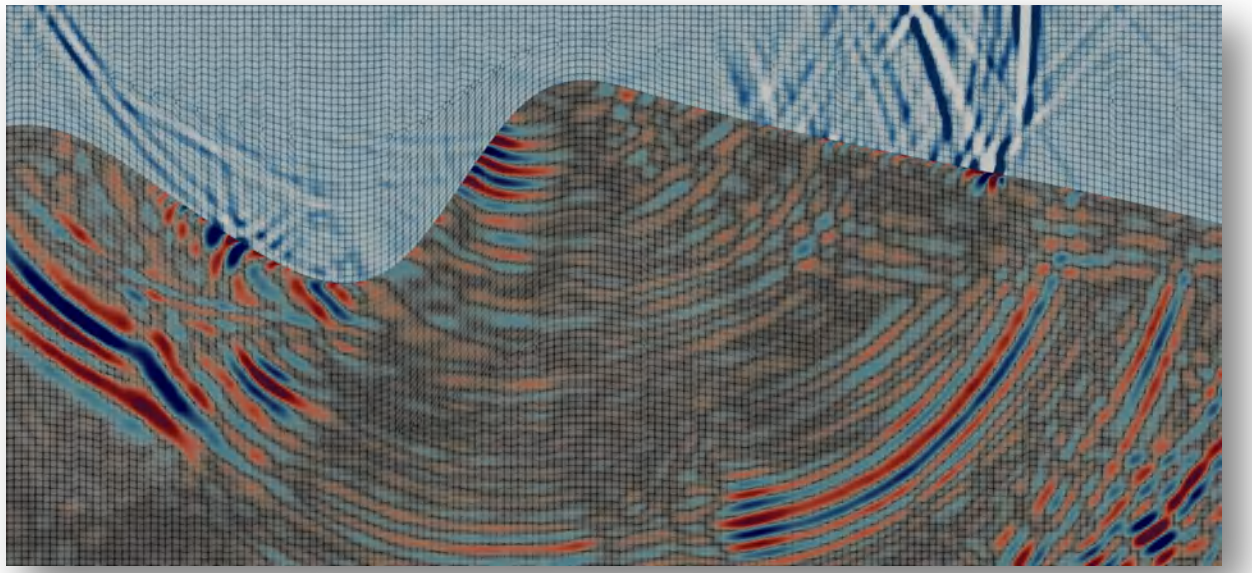
SalvusCompute

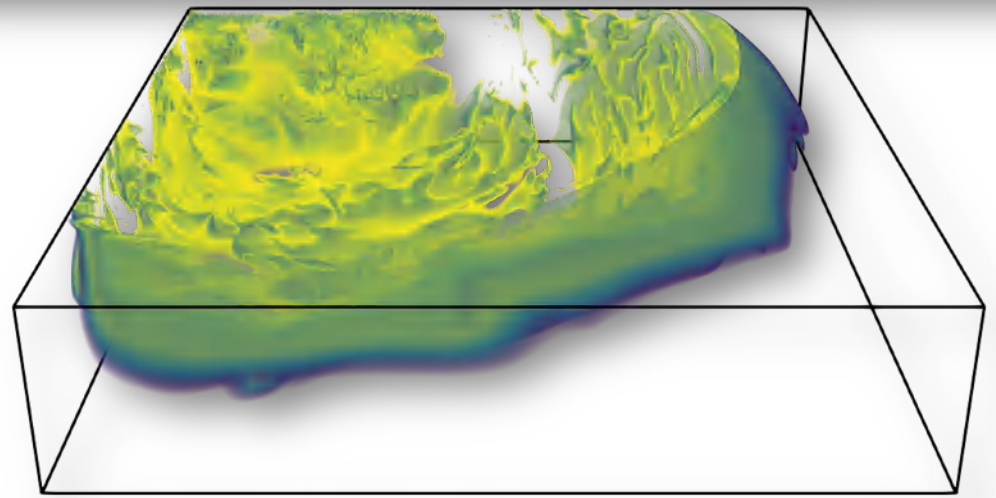
- Began development within the Collaborative Seismic Earth Model project at ETH Zurich



SalvusCompute

- Began development within the Collaborative Seismic Earth Model project at ETH Zurich
- Arbitrary-order Continuous-Galerkin spectral-element solver[1,2]
  - 2- and 3-dimensions
  - Coupled fluid / solid physics



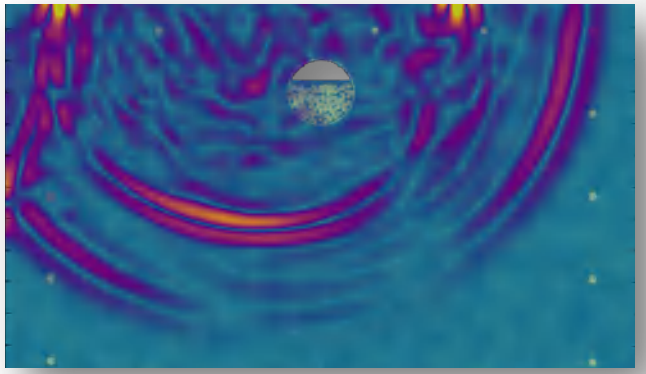


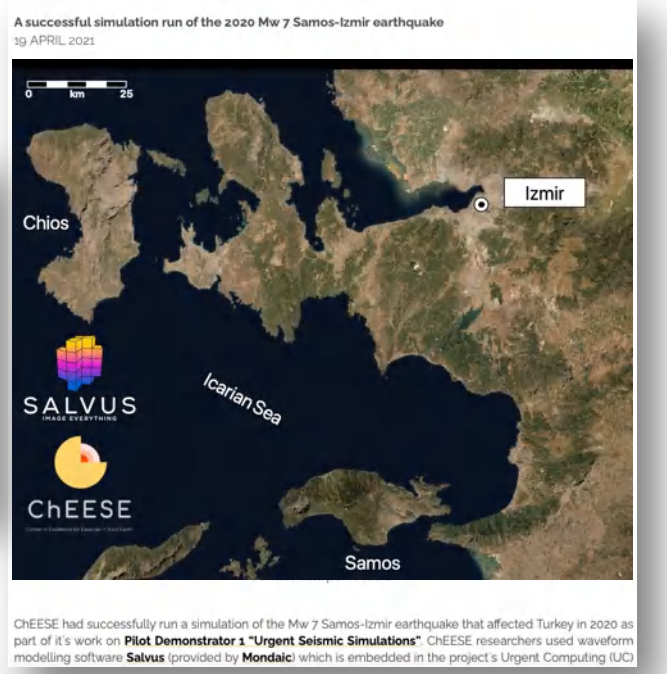
[1]Komatitsch and Tromp, Spectral-element simulations of global seismic wave propagation—I. Validation, *Geophysical Journal International*, Volume 149, Issue 2, May 2002

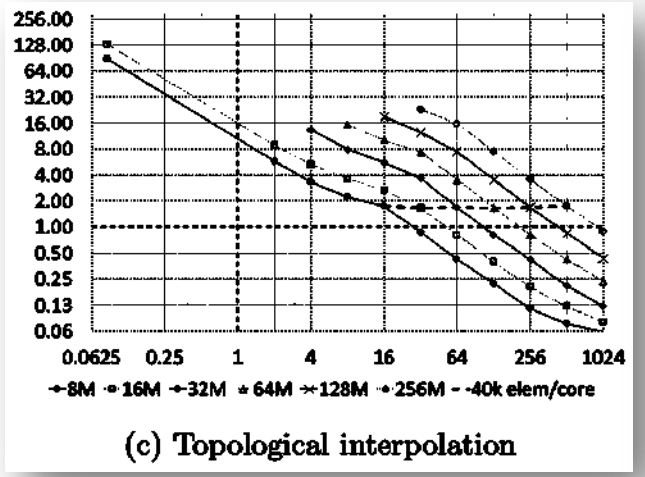
[2]Afanasiev et al., Modular and flexible spectral-element waveform modelling in two and three dimensions, *Geophysical Journal International*, Volume 216, Issue 3, 1 March 2019.

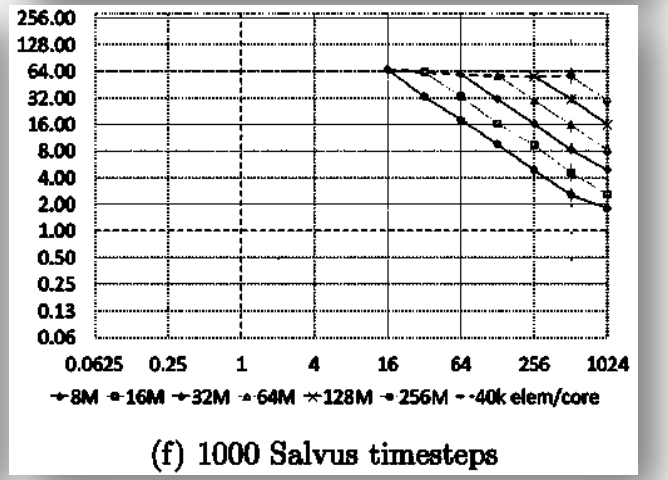
SalvusCompute

- Began development within the Collaborative Seismic Earth Model project at ETH Zurich
- Arbitrary-order Continuous-Galerkin spectral-element solver[1,2]
  - 2- and 3-dimensions
  - Coupled fluid / solid physics
- Run-time parallel mesh decomposition
  - PETSc DMPlex[3]
  - Scalable from laptops to supercomputers





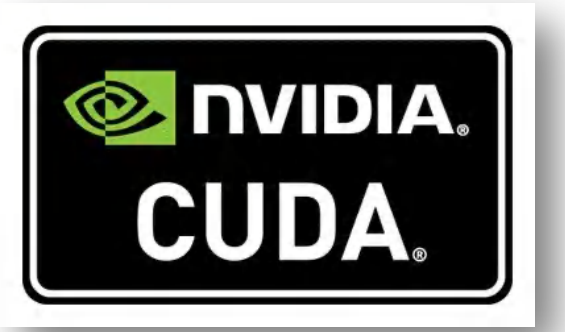




[1]Komatitsch and Tromp, Spectral-element simulations of global seismic wave propagation—I. Validation, *Geophysical Journal International*, Volume 149, Issue 2, May 2002
[2]Afanasiev et al., Modular and flexible spectral-element waveform modelling in two and three dimensions, *Geophysical Journal International*, Volume 216, Issue 3, 1 March 2019.
[3]Hapla et al., Fully parallel mesh I/O using PETSc DMPlex with an application to waveform modelling, *Accepted by SIAM SISC*, 2020.

SalvusCompute

- Began development within the Collaborative Seismic Earth Model project at ETH Zurich
- Arbitrary-order Continuous-Galerkin spectral-element solver[1,2]
  - 2- and 3-dimensions
  - Coupled fluid / solid physics
- Run-time parallel mesh decomposition
  - PETSc DMPlex[3]
  - Scalable from laptops to supercomputers
- Modern C++ and CUDA

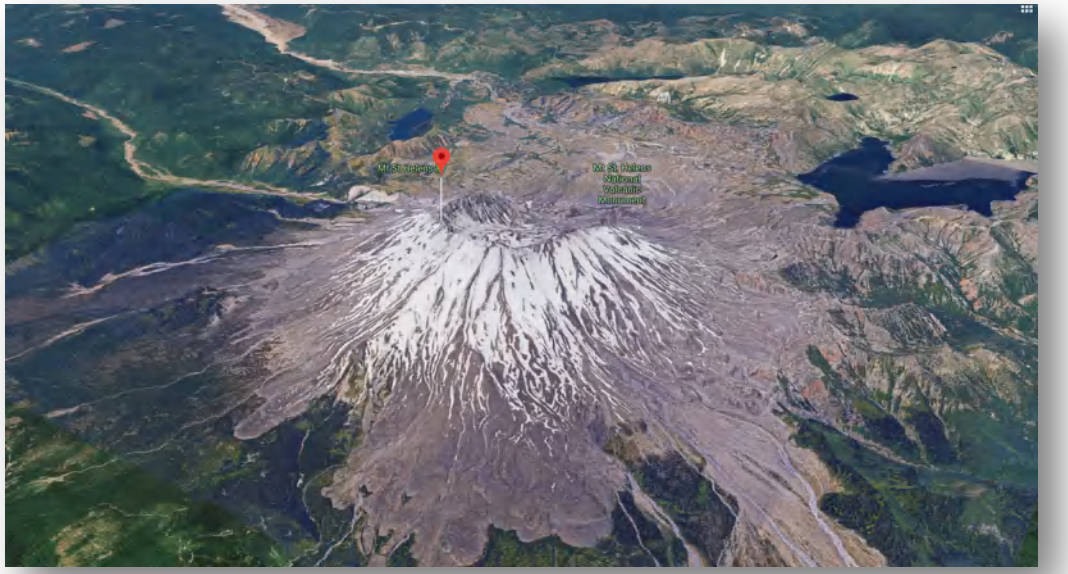


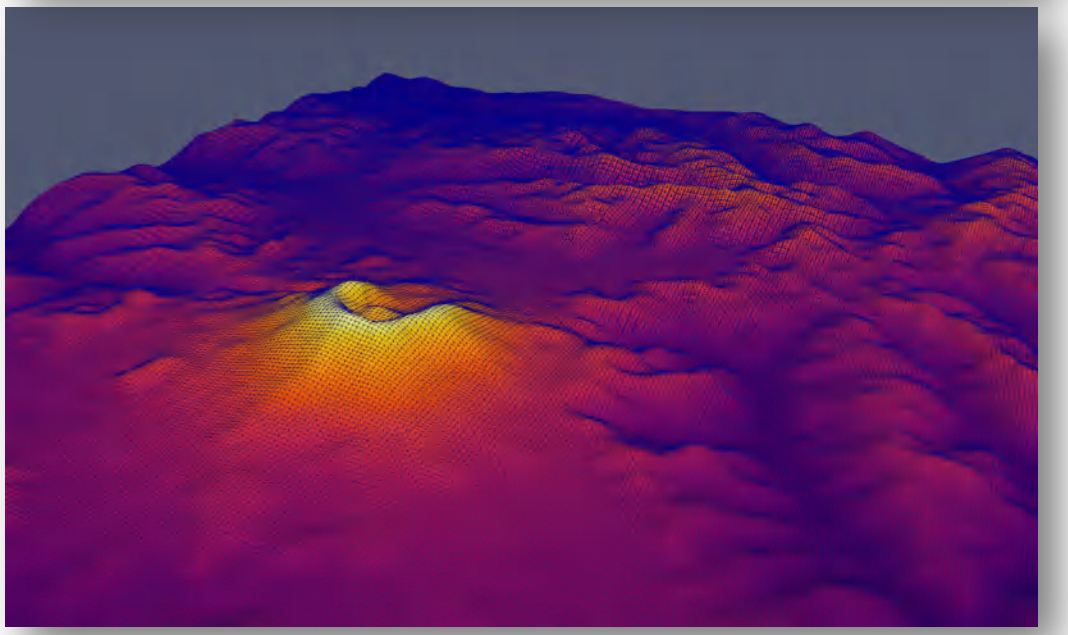
[1]Komatitsch and Tromp, Spectral-element simulations of global seismic wave propagation—I. Validation, *Geophysical Journal International*, Volume 149, Issue 2, May 2002
[2]Afanasiev et al., Modular and flexible spectral-element waveform modelling in two and three dimensions, *Geophysical Journal International*, Volume 216, Issue 3, 1 March 2019.
[3]Hapla et al., Fully parallel mesh I/O using PETSc DMPlex with an application to waveform modelling, *Accepted by SIAM SISC*, 2020.

SalvusMesh

SalvusMesh

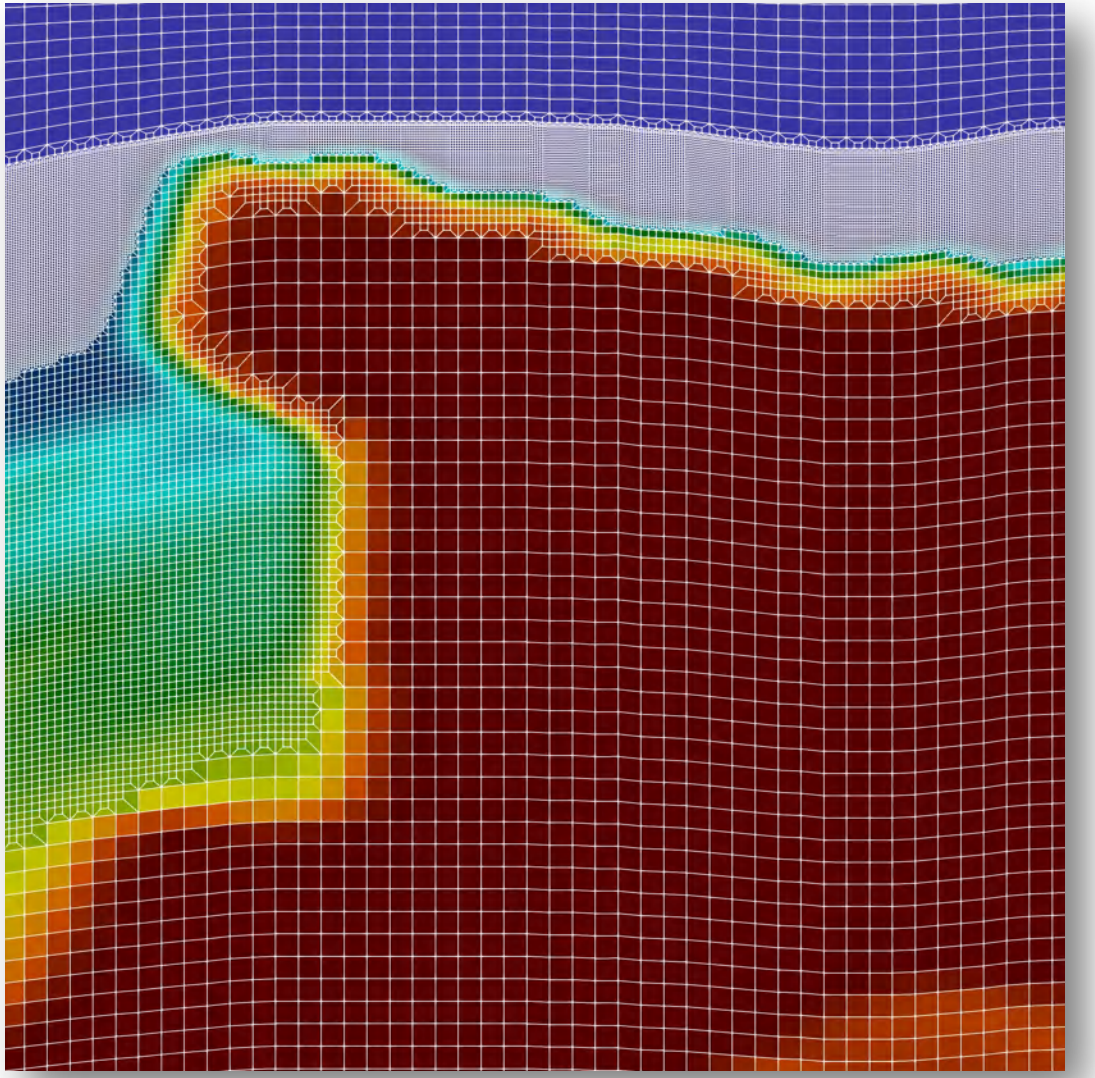
- Built for problems in geophysics
  - Variable velocity models
  - Automatic real-Earth topography





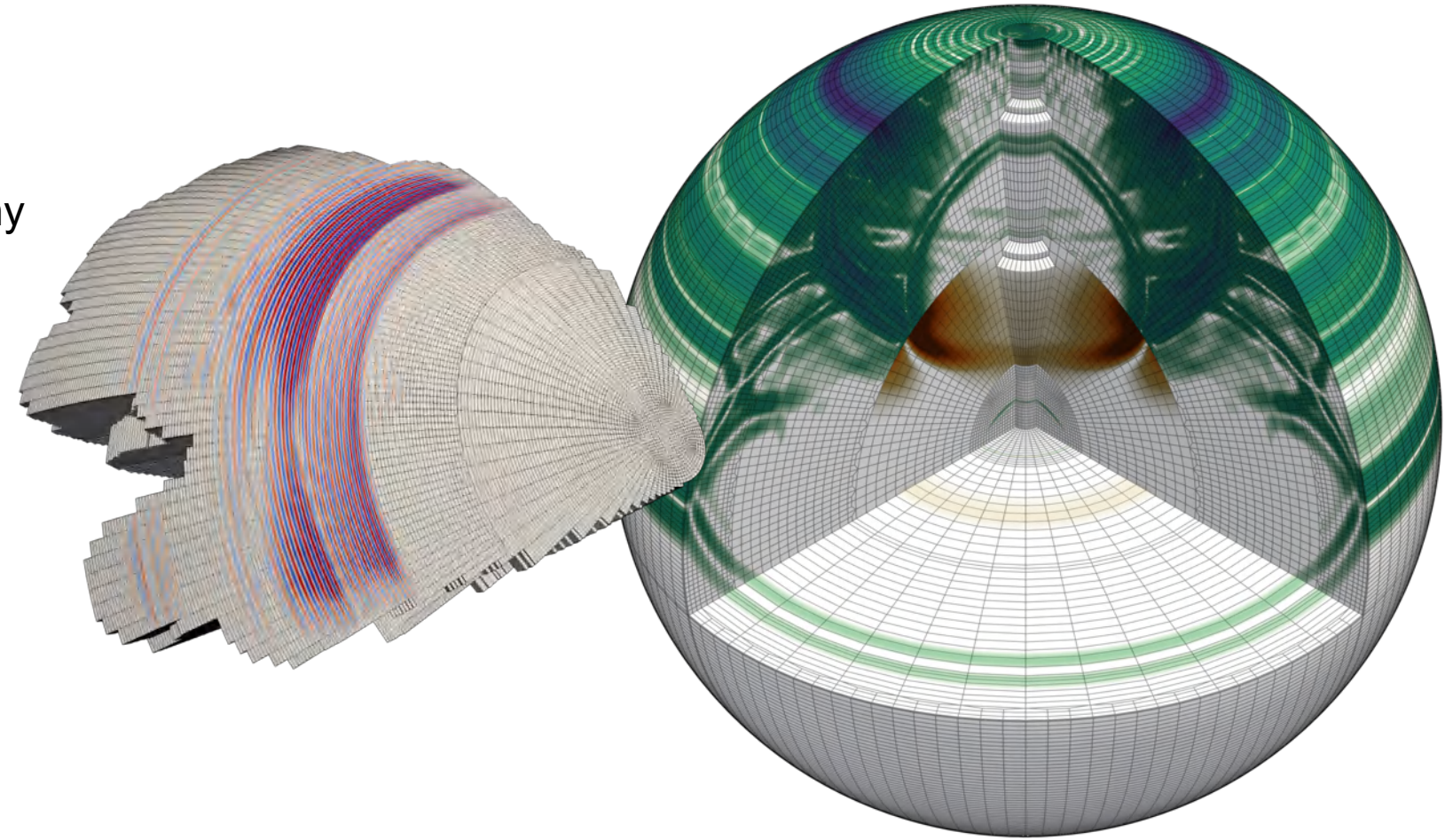
Salvus*Mesh*

- Built for problems in geophysics
  - Variable velocity models
  - Automatic real-Earth topography
- Conforming quad / hex elements
  - Automatic refinements



SalvusMesh

- Built for problems in geophysics
  - Variable velocity models
  - Automatic real-Earth topography
- Conforming quad / hex elements
  - Automatic refinements
- Target-oriented mesh design[1]
  - Data adaptive
  - Solution adaptive



[1]van Driel et al., Accelerating numerical wave propagation using wavefield adapted meshes. Part I: forward and adjoint modelling, *Geophysical Journal International*, Volume 221, Issue 3, June 2020

Salvus*Mesh*

- Built for problems in geophysics
  - Variable velocity models
  - Automatic real-Earth topography
- Conforming quad / hex elements
  - Automatic refinements
- Target-oriented mesh design[1]
  - Data adaptive
  - Solution adaptive
- Whole-earth topography and bathymetry
  - 3-D Fluid oceans
  - Interface to GMRT for local domains

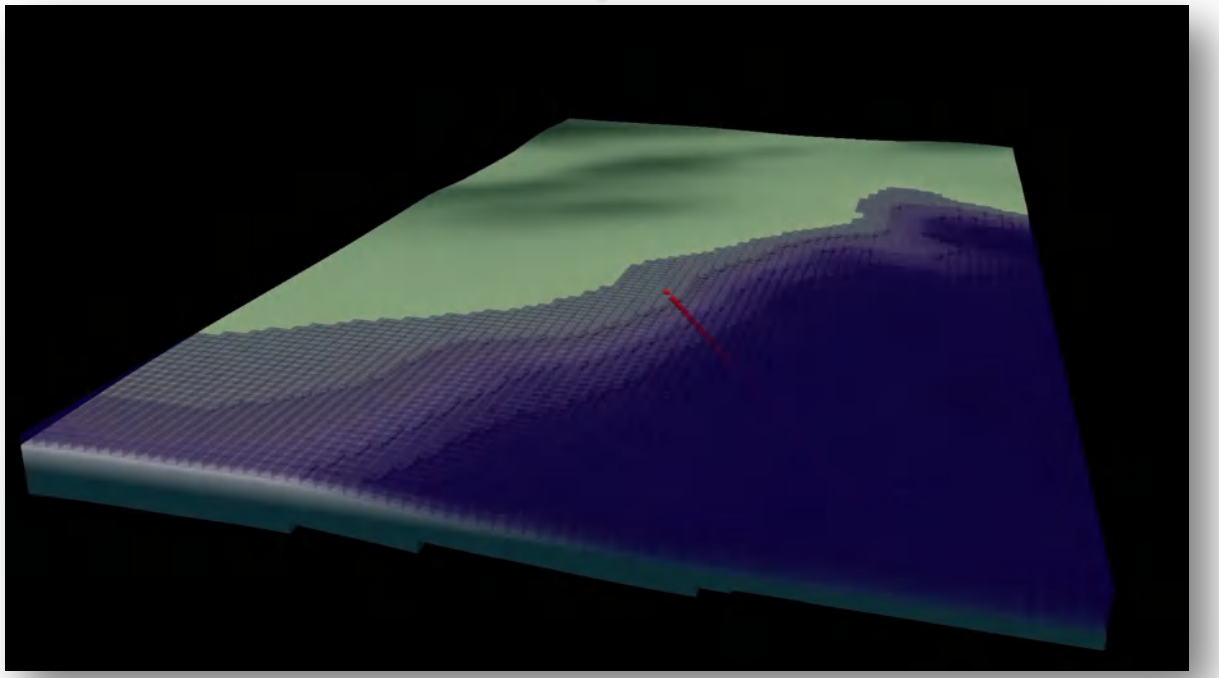
```
In [1]: import salvus.namespace as sn

        Define your spatial domain

In [2]: d = sn.domain.dim3.UtmDomain.from_spherical_chunk(
            min_latitude=36.6,
            max_latitude=37.0,
            min_longitude=-122.0,
            max_longitude=-121.0,
        )

        Download topography and bathymetry

In [3]: d.download_topography_and_bathymetry(
            filename="topo.nc", buffer_in_degrees=2.0, resolution="default"
        )
        Downloading topography: 2.88MiB [00:01, 1.65MiB/s]
```

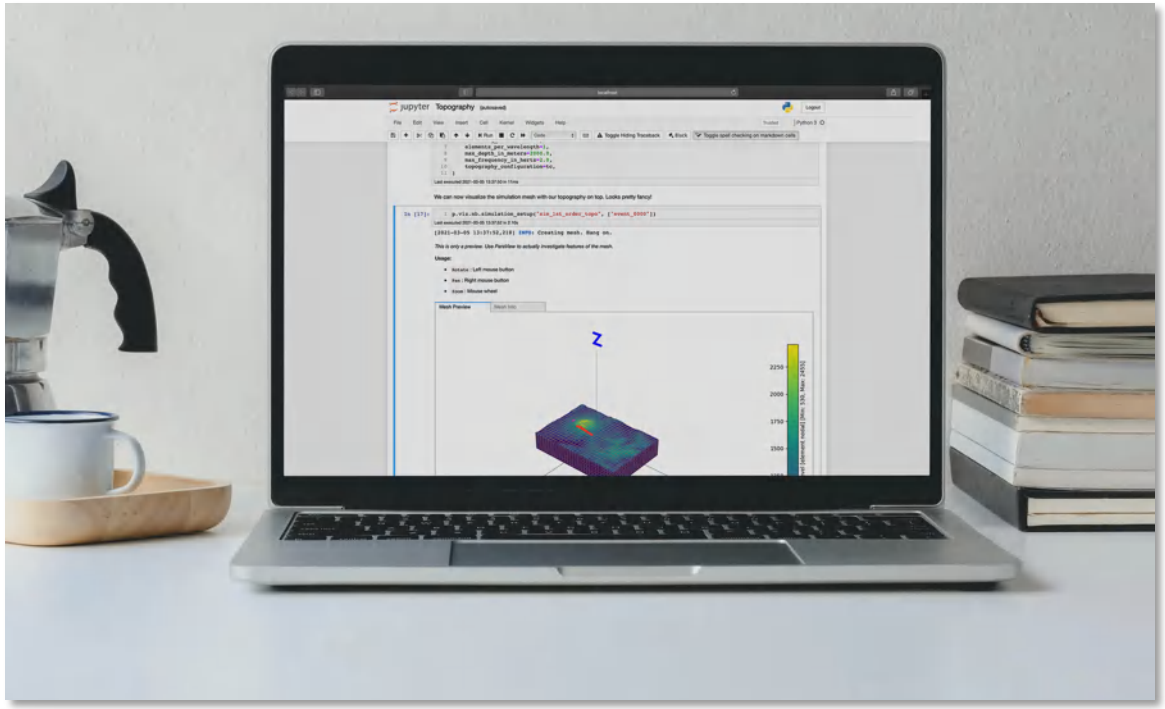


[1]van Driel et al., Accelerating numerical wave propagation using wavefield adapted meshes. Part I: forward and adjoint modelling, *Geophysical Journal International*, Volume 221, Issue 3, June 2020

SalvusFlow

Salvus*Flow*

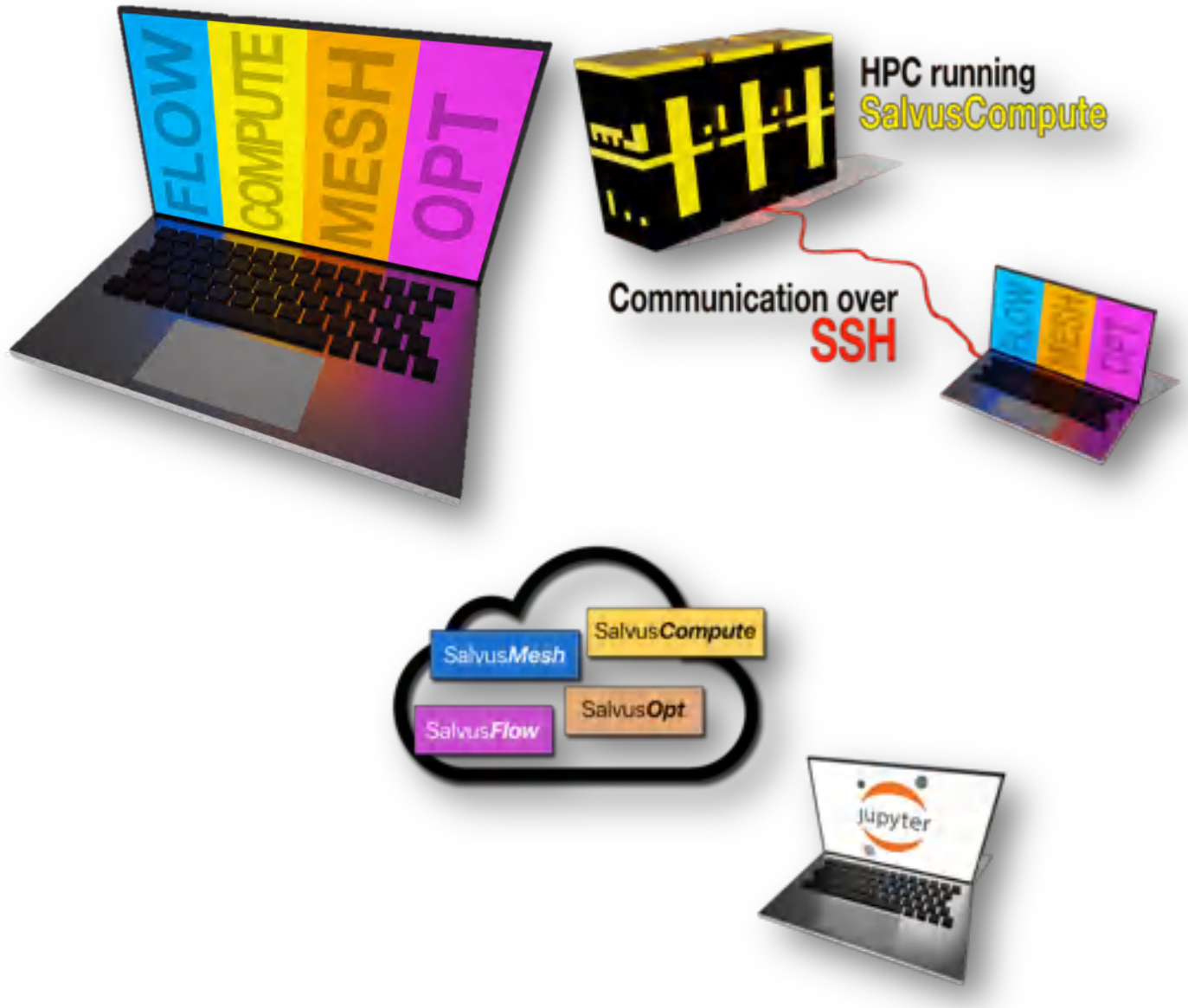
- How the user interacts with Salvus
  - Python interface
  - Scripts or Jupyter notebooks



```python
# Create the simulation object and combine all the information.
w = simple_config.simulation.Waveform(mesh=m.create_mesh())
# Sources and receivers will be placed exactly relative to the
# local mesh surface. Please refer to the sources and receivers
# documentation for more details.
w.add_sources(source)
w.add_receivers(
    simple_config.receiver.seismology.parse(
        inv, dimensions=3, fields=["displacement"]
    )
)
```

SalvusFlow

- How the user interacts with Salvus
  - Python interface
  - Scripts or Jupyter notebooks
- Job execution on local and remote sites



Salvus*Flow*

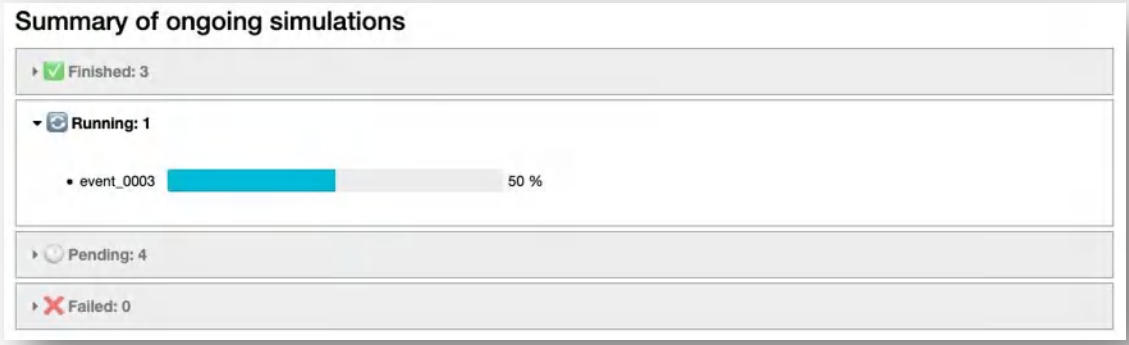
- How the user interacts with Salvus
  - Python interface
  - Scripts or Jupyter notebooks
- Job execution on local and remote sites
- Uploading / downloading of input / output files
  - Input file validation
  - Queue monitoring

```
In [10]: import salvus

In [11]: w = salvus.namespace.simple_config.simulation.Waveform()

In [12]: w.output.volume_data.fields = ["stran", "displacement"]
```

```
ValueError: `item` must be one of: "displacement", "velocity", "ac
celeration", "fem-ku-acoustic", "inverse-mass-matrix-acoustic", "f
em-ku-elastic", "inverse-mass-matrix-elastic", "gradient-of-displa
cement", "stress-tensor", "stress", "strain", "phi", "phi_t", "phi
_tt", "gradient-of-phi", "m1-times-gradient-of-phi", "absorbing-ga
```



SalvusFlow

- How the user interacts with Salvus
  - Python interface
  - Scripts or Jupyter notebooks
- Job execution on local and remote sites
- Uploading / downloading of input / output files
  - Input file validation
  - Queue monitoring
- “Abstracts away” the compute resources

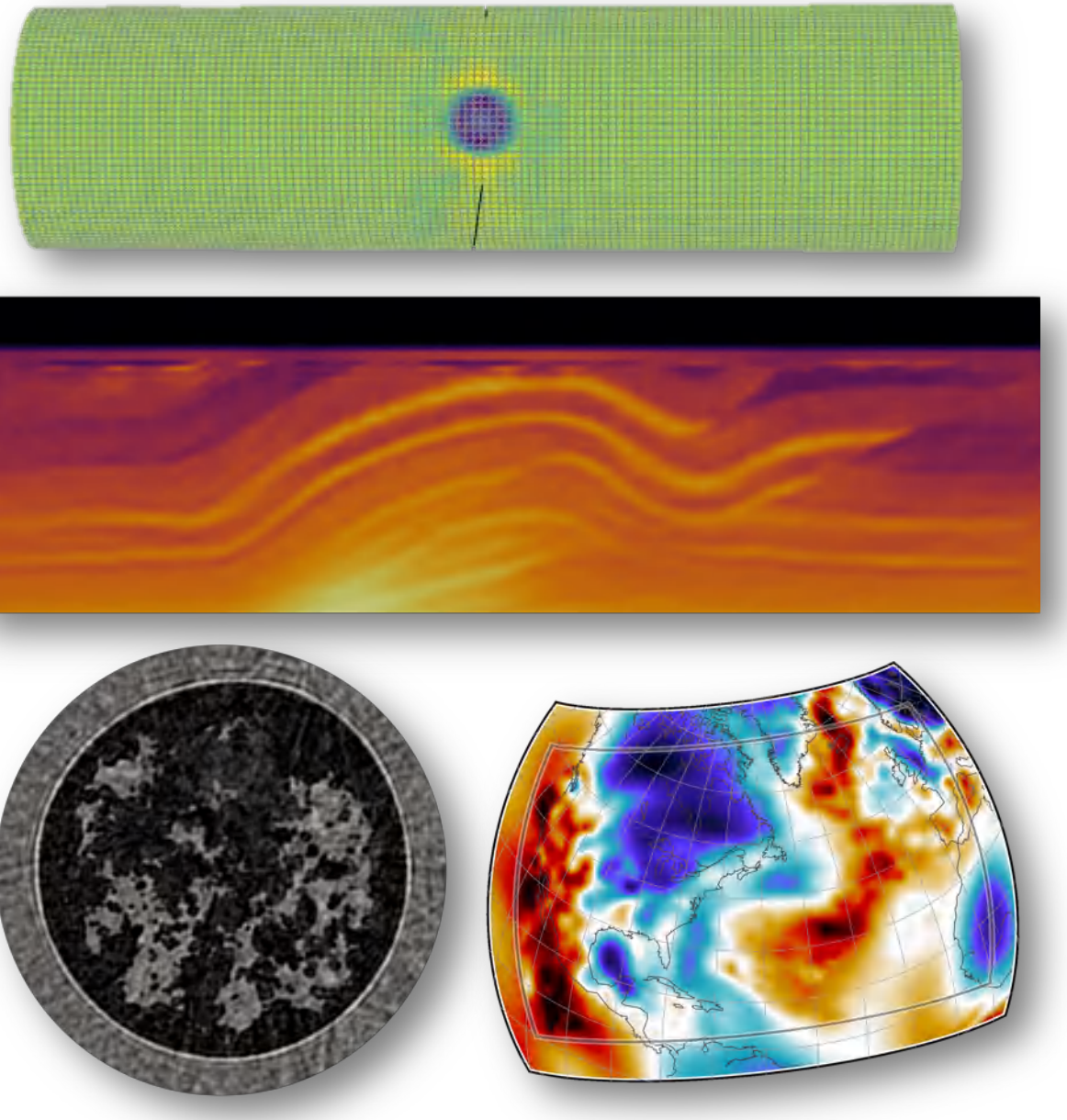
```
(salvus_0.11) ~ salvus-flow init-site tiny_gpu
Successfully initialized site:

> Name: tiny_gpu
    Site Type: ssh
    Default Ranks: 2
    Max Ranks: 24
    Salvus Binary: /home/mafanasiev/Development/salvus/build/release_single_clang/bin/salvus
    Run Directory: /home/mafanasiev/Data/salvus_flow/run
    Temp Directory: /mnt/data/salvus_flow
    Update Interval in Seconds: 1.0
    Use License Tokens: False
    Use CUDA Capable GPUs: True
    SSH Settings:
        Hostname: tiny
        Username: mafanasiev
    Site information:
      Salvus version: 0.11.16-30-g74ce34c6-dirty
      Floating point size: 32
      Available GLL orders: [1, 2, 4]
      Available shape mapping orders: [1, 2, 4]
      Available numbers of linear solids: [5]
      Last updated: just now (Configuration did not change since last update)
```

SalvusOpt

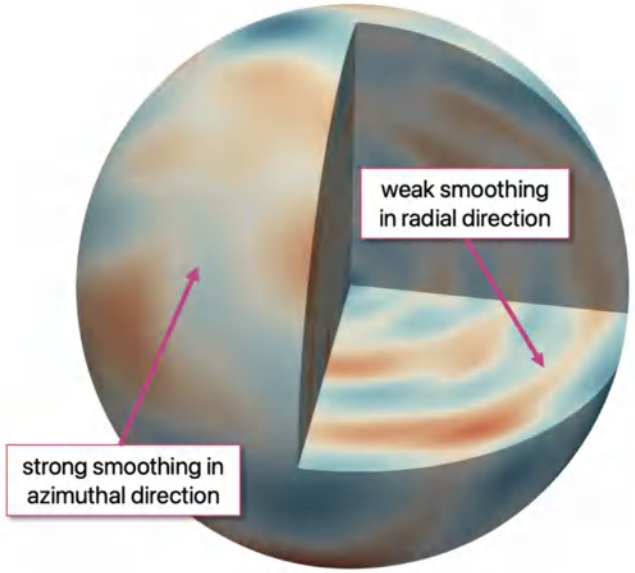
SalvusOpt

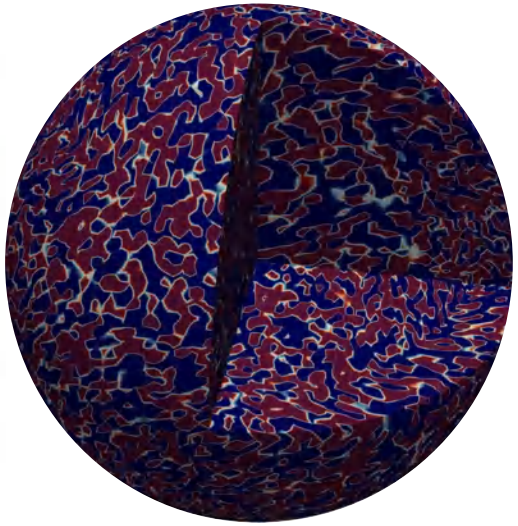
- Nonlinear optimization framework[1]
  - Built specifically for full-waveform inversion

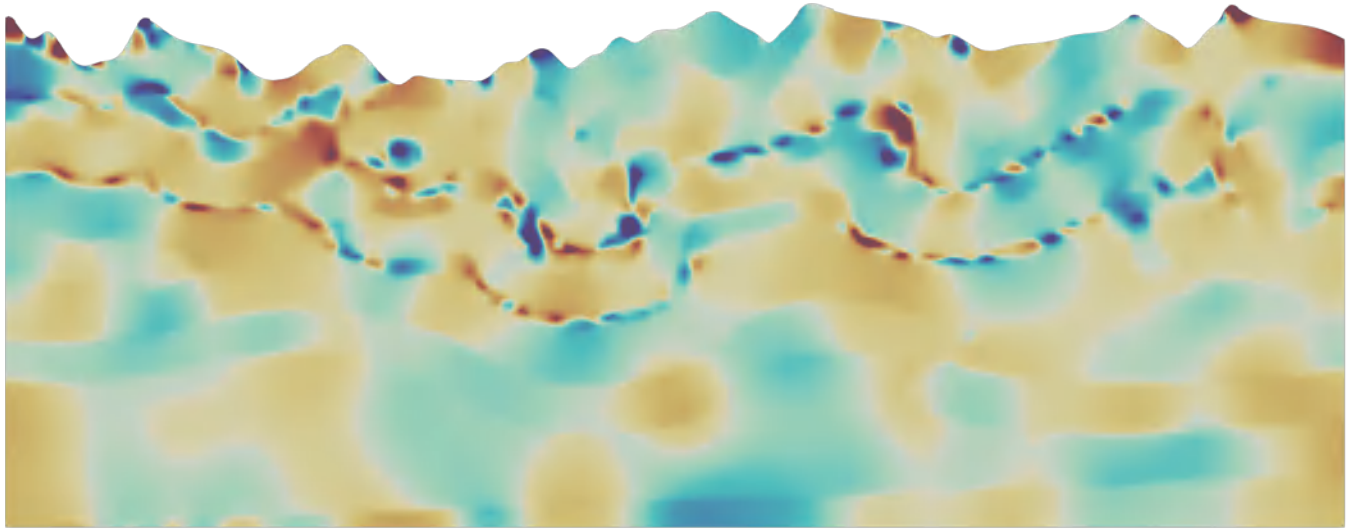


SalvusOpt

- Nonlinear optimization framework[1]
  - Built specifically for full-waveform inversion
- Regularization on unstructured grids
  - Wavelength and direction-dependent smoothing operators

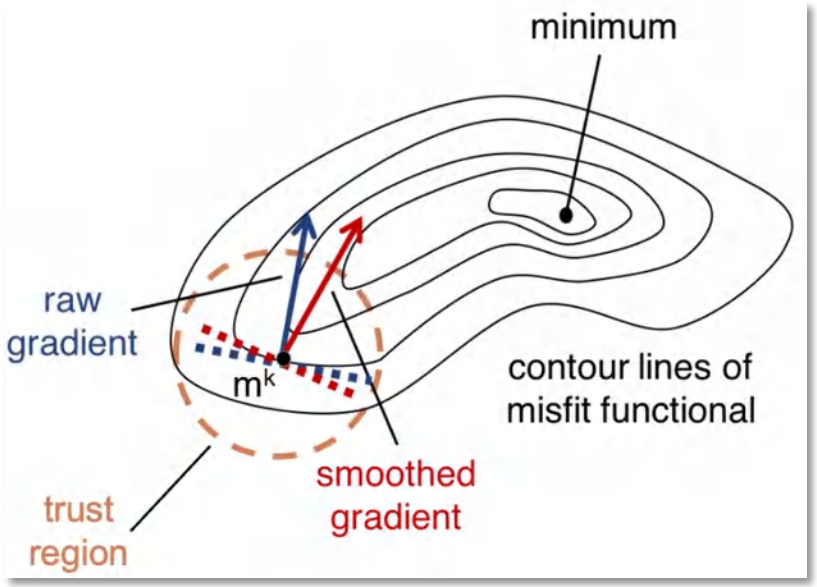


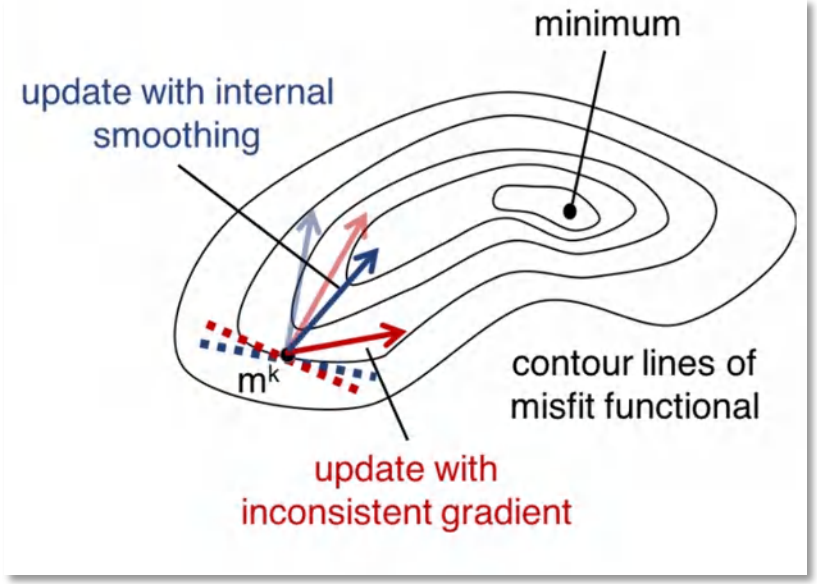




SalvusOpt

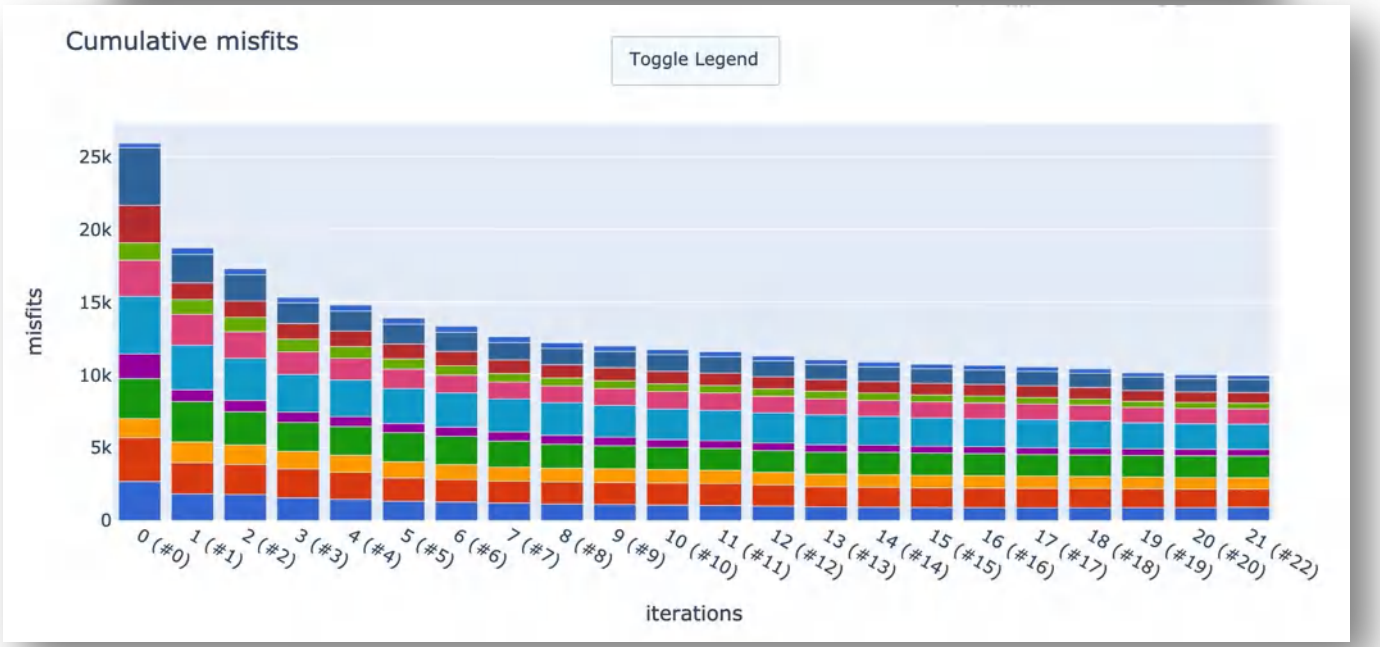
- Nonlinear optimization framework[1]
  - Built specifically for full-waveform inversion
- Regularization on unstructured grids
  - Wavelength and direction-dependent smoothing operators
- Trust-region Newton type methods
  - Automatic step-length determination
  - Custom or built-in parameter mappings





SalvusOpt

- Nonlinear optimization framework[1]
  - Built specifically for full-waveform inversion
- Regularization on unstructured grids
  - Wavelength and direction-dependent smoothing operators
- Trust-region Newton type methods
  - Automatic step-length determination
  - Custom or built-in parameter mappings
- Interactive visual feedback
  - Model update magnitudes
  - Trust-region accuracy



[1]Boehm et al., Time-domain spectral-element ultrasound waveform tomography using a stochastic quasi-Newton method, *Proceedings Volume 10580, Medical Imaging 2018*, 105800H (2018)

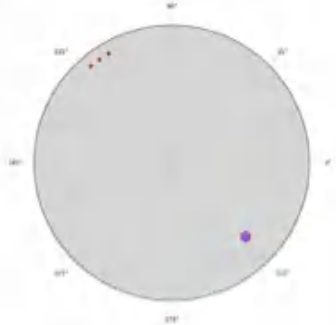
SalvusProject

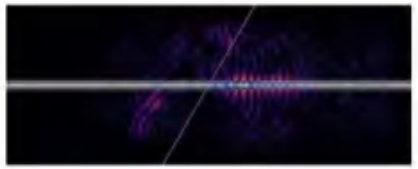
SalvusProject

Built for…

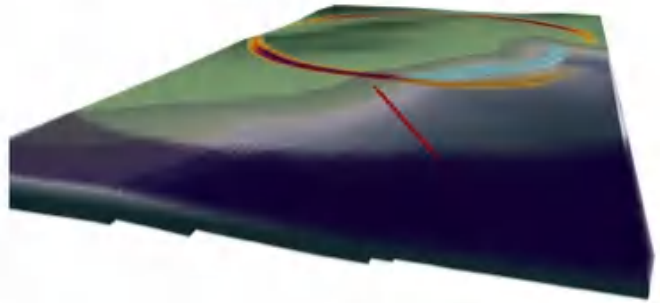
- Reproducibility
- Data management
- Visualization and QC

dim2.CircularDomain



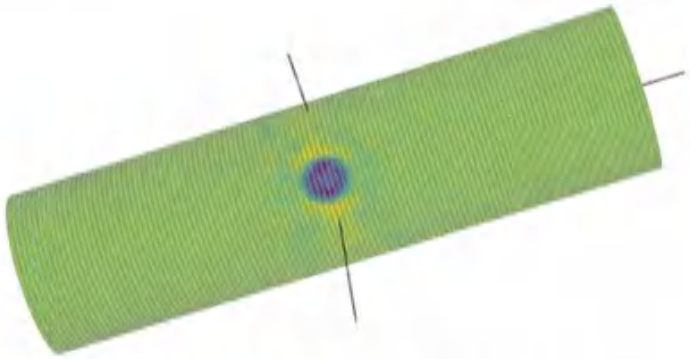


dim3.UtmDomain



dim2.BoxDomain

dim3.SphericalGlobeDomain

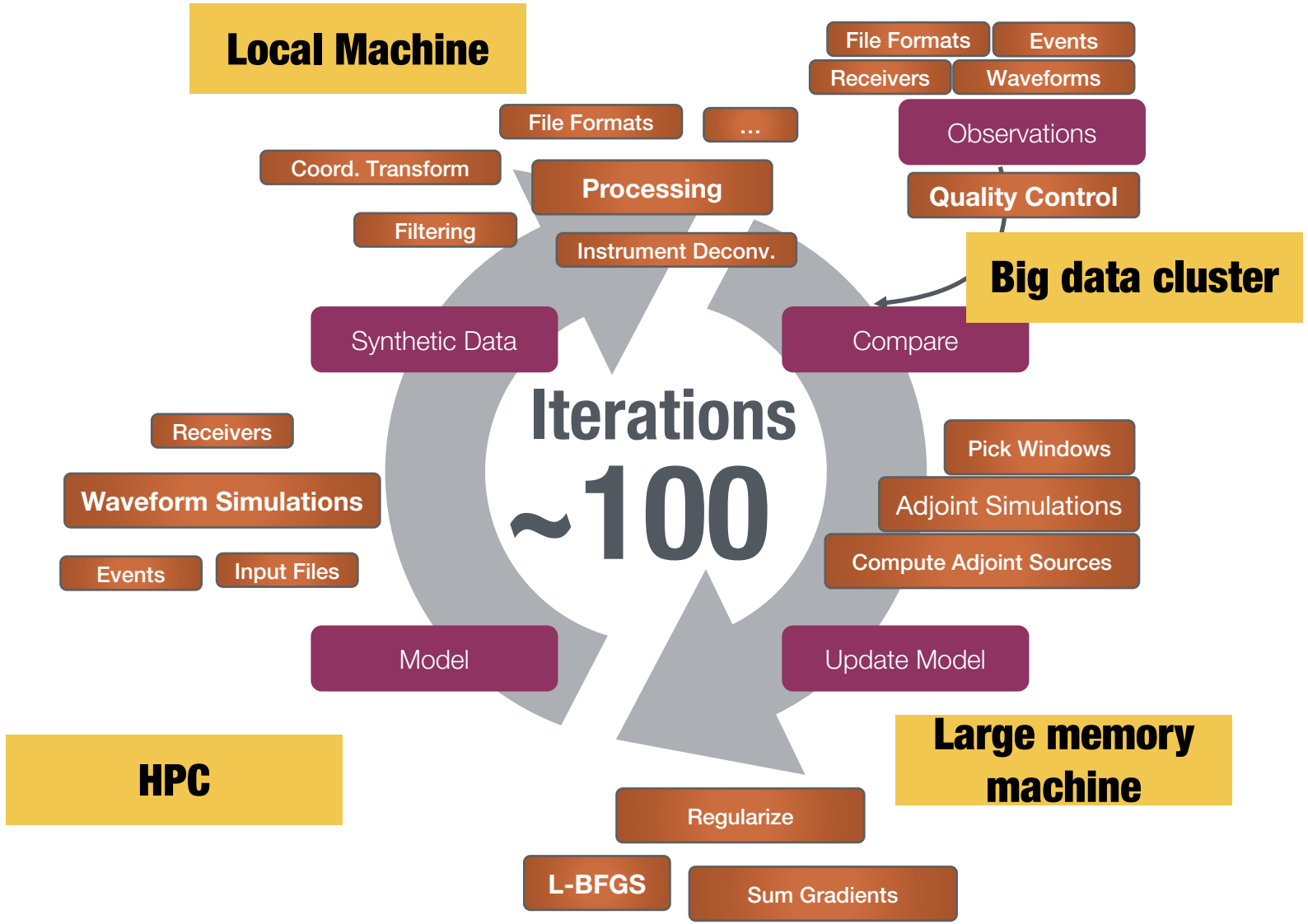


dim3.BoxDomain
with custom mesh

SalvusProject

Built for…
- Reproducibility
- Data management
- Visualization and QC

…and enables you to
- Organize results
- Pick up where you left off
- Share work with colleagues

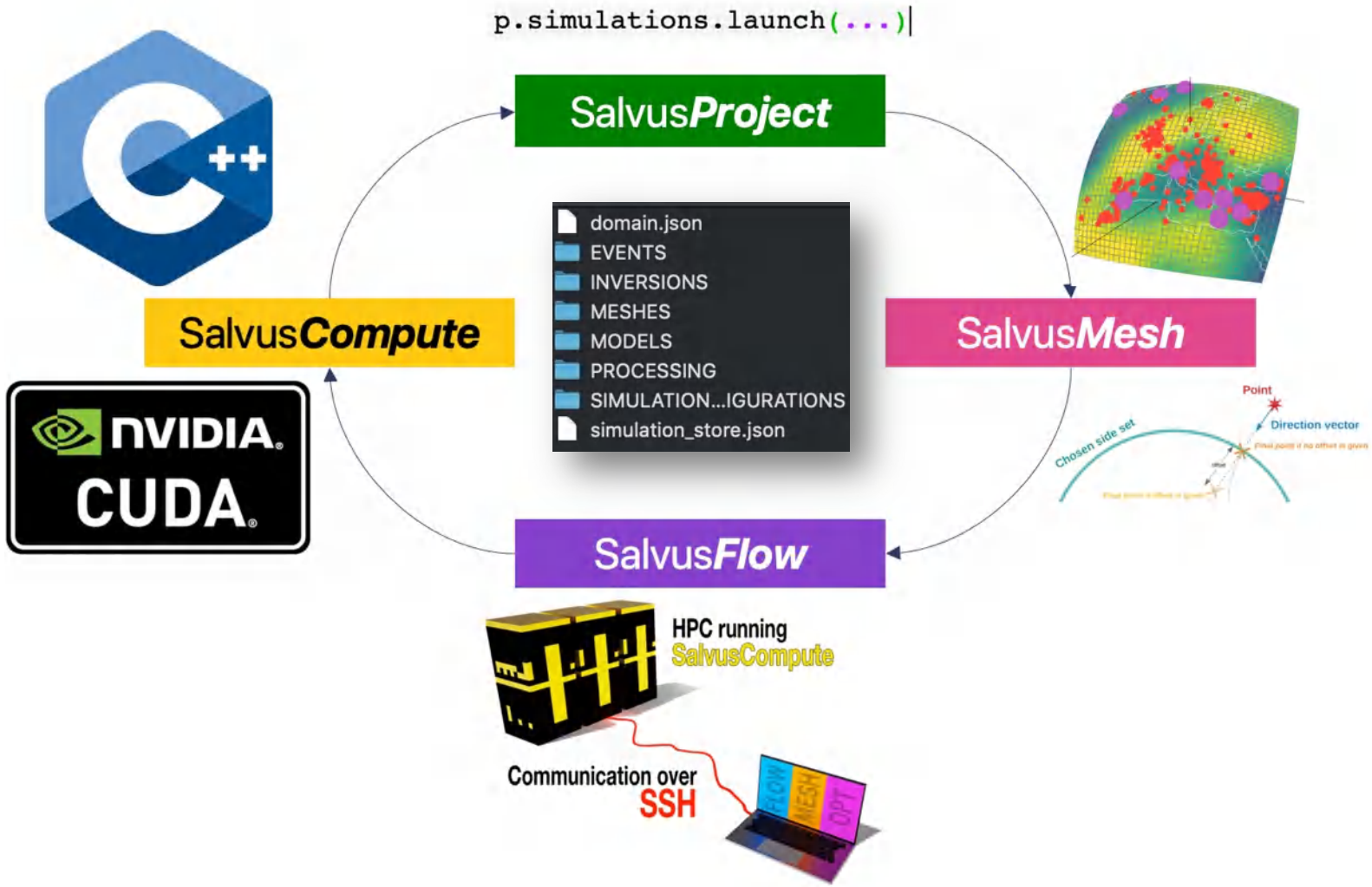


SalvusProject

Built for…
- Reproducibility
- Data management
- Visualization and QC

…and enables you to
- Organize results
- Pick up where you left off
- Share work with colleagues

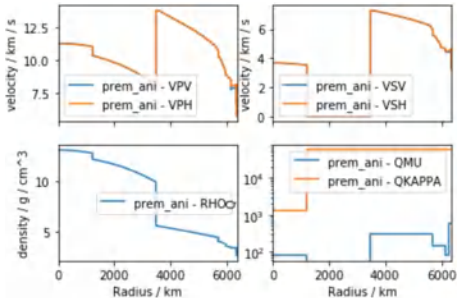
…by keeping a **serialized, and state-aware database** on your local machine.

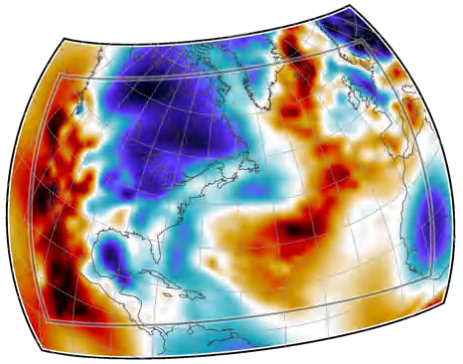


SalvusProject

SalvusProject

- Models, meshes, simulation parameters, etc, are given unique “hashes”





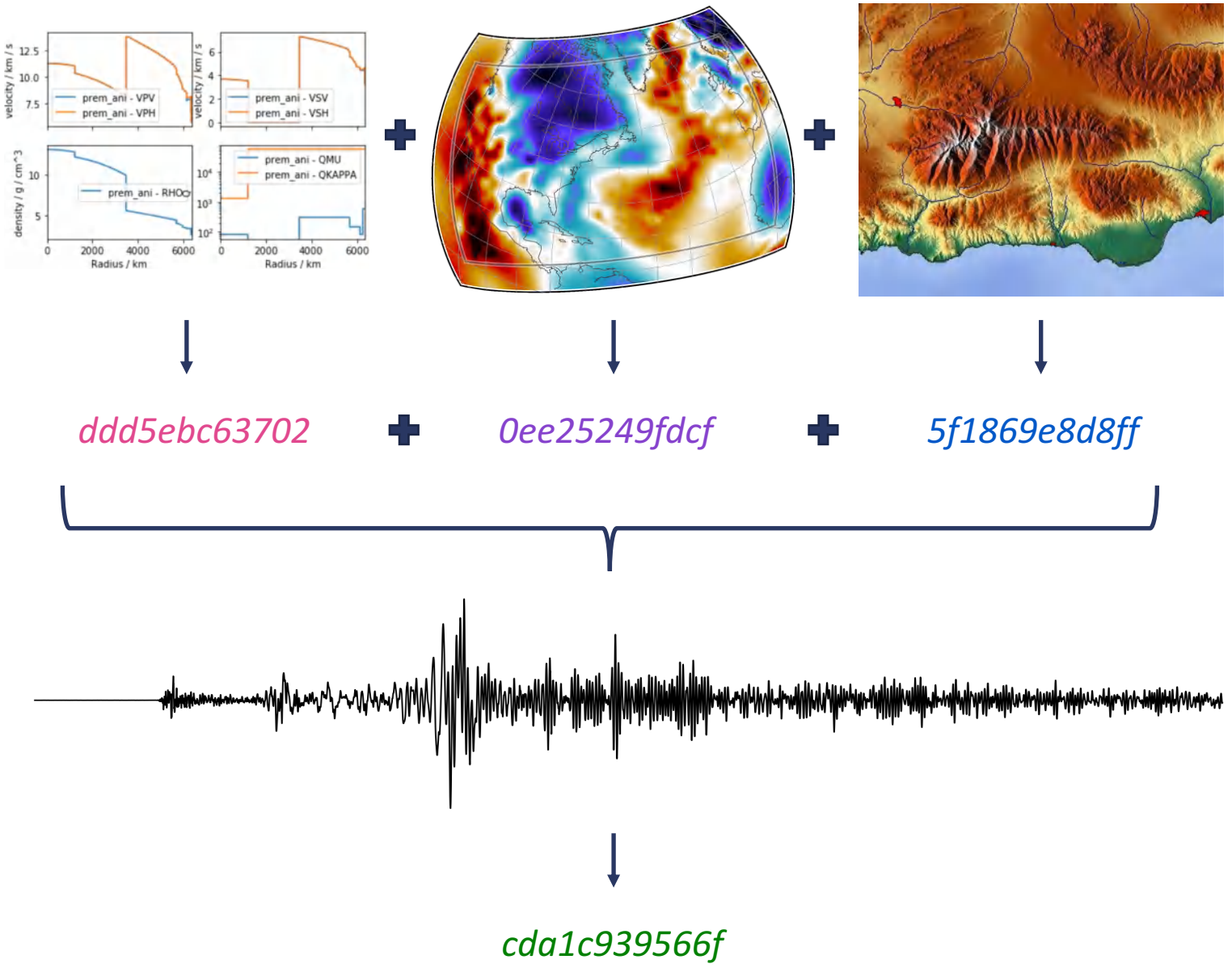
ddd5ebc63702

0ee25249fdcf

5f1869e8d8ff

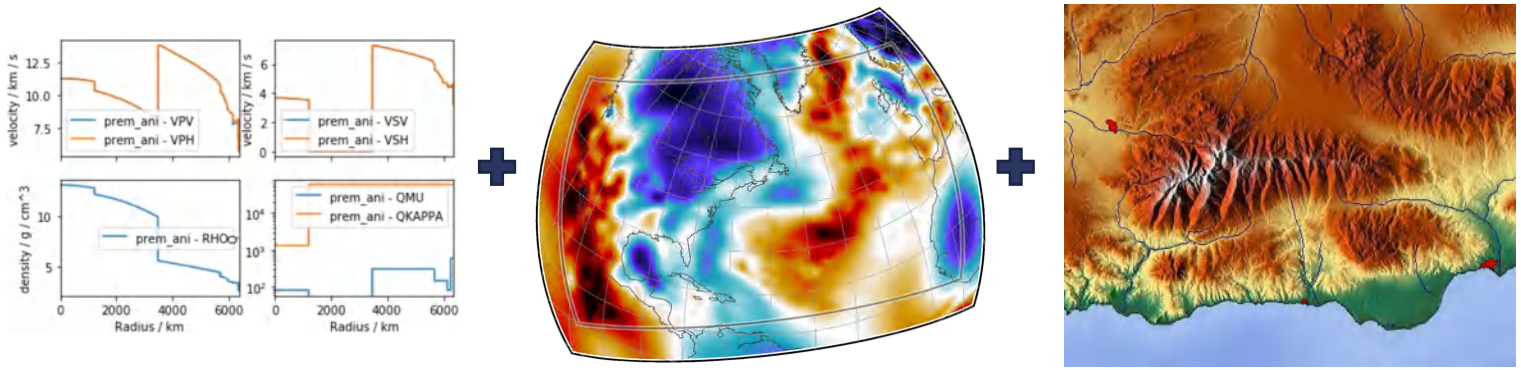
SalvusProject

- Models, meshes, simulation parameters, etc, are given unique “hashes”
- Hashes are combined to uniquely refer to intermediate results



SalvusProject

- Models, meshes, simulation parameters, etc, are given unique “hashes”
- Hashes are combined to uniquely refer to intermediate results
- If a hash:
  - Has no associated data, compute it!
  - Has associated data, just open it!

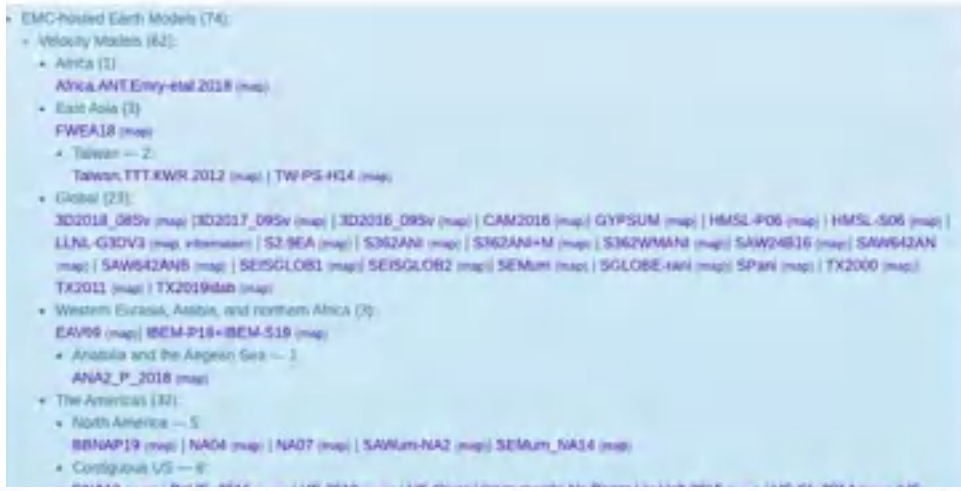


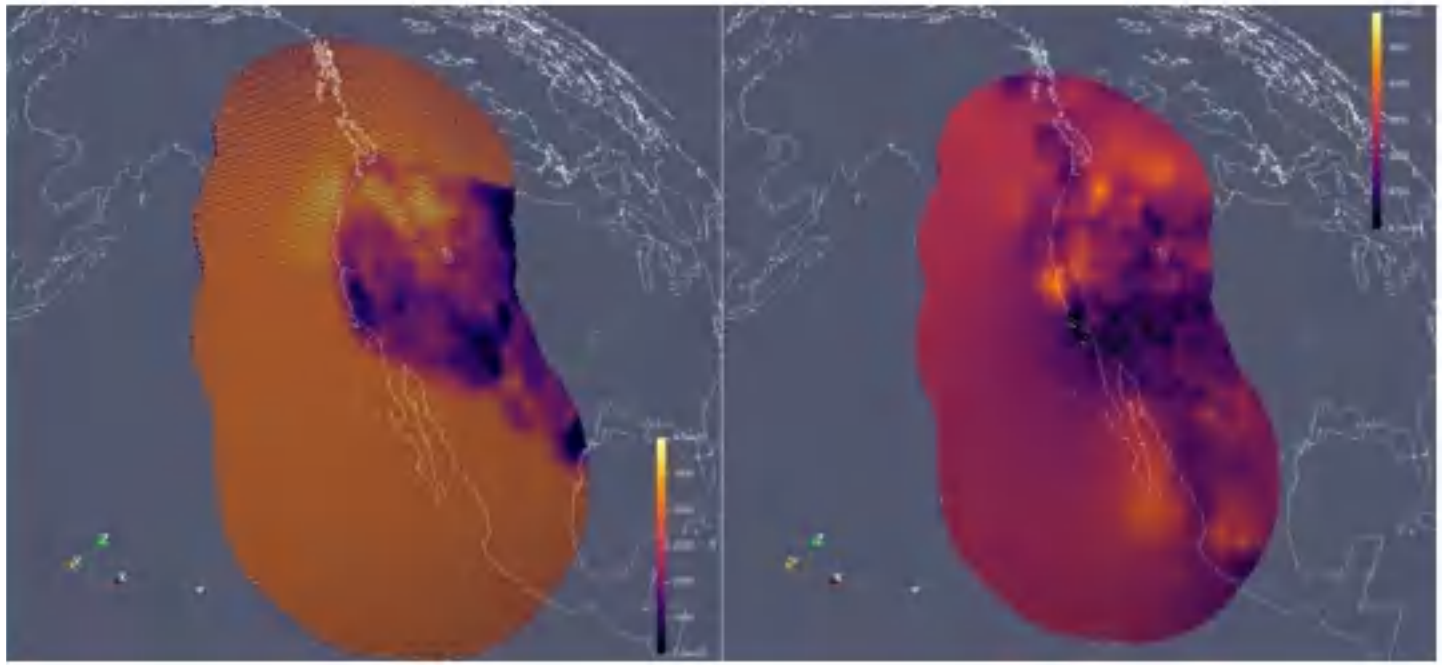
ddd5ebc63702 + *0ee25249fdcf* + *5f1869e8d8ff*

cda1c939566f

SalvusProject

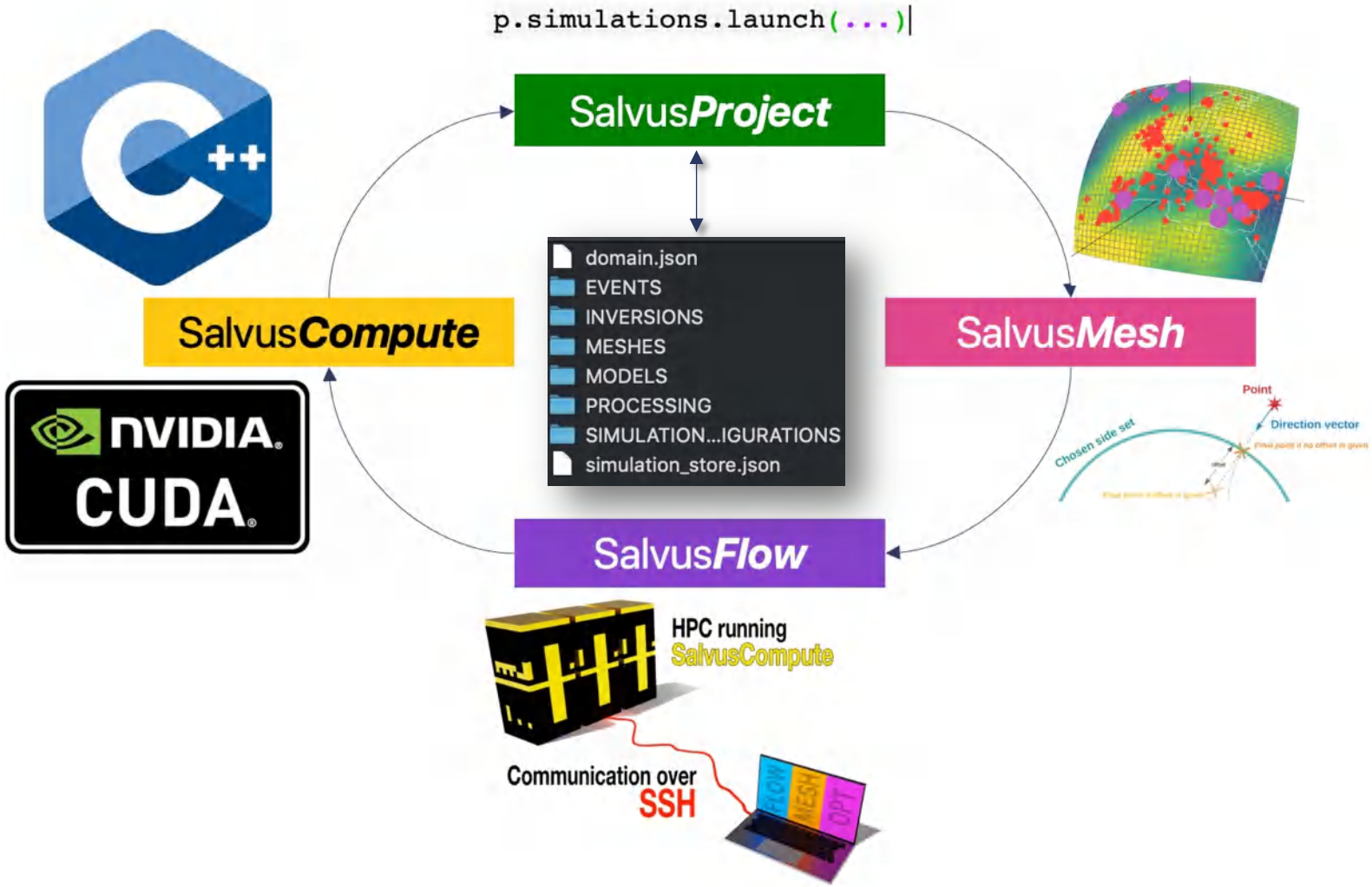
- Models, meshes, simulation parameters, etc, are given unique “hashes”
- Hashes are combined to uniquely refer to intermediate results
- If a hash:
  - Has no associated data, compute it!
  - Has associated data, just open it!
- Hashes are lightweight and persistent on disk
  - Share projects and models with colleagues





SalvusProject

- Models, meshes, simulation parameters, etc, are given unique “hashes”
- Hashes are combined to uniquely refer to intermediate results
- If a hash:
  - Has no associated data, compute it!
  - Has associated data, just open it!
- Hashes are lightweight and persistent on disk
  - Share projects and models with colleagues
- All of this happens automatically: pay as much or as little attention as you like

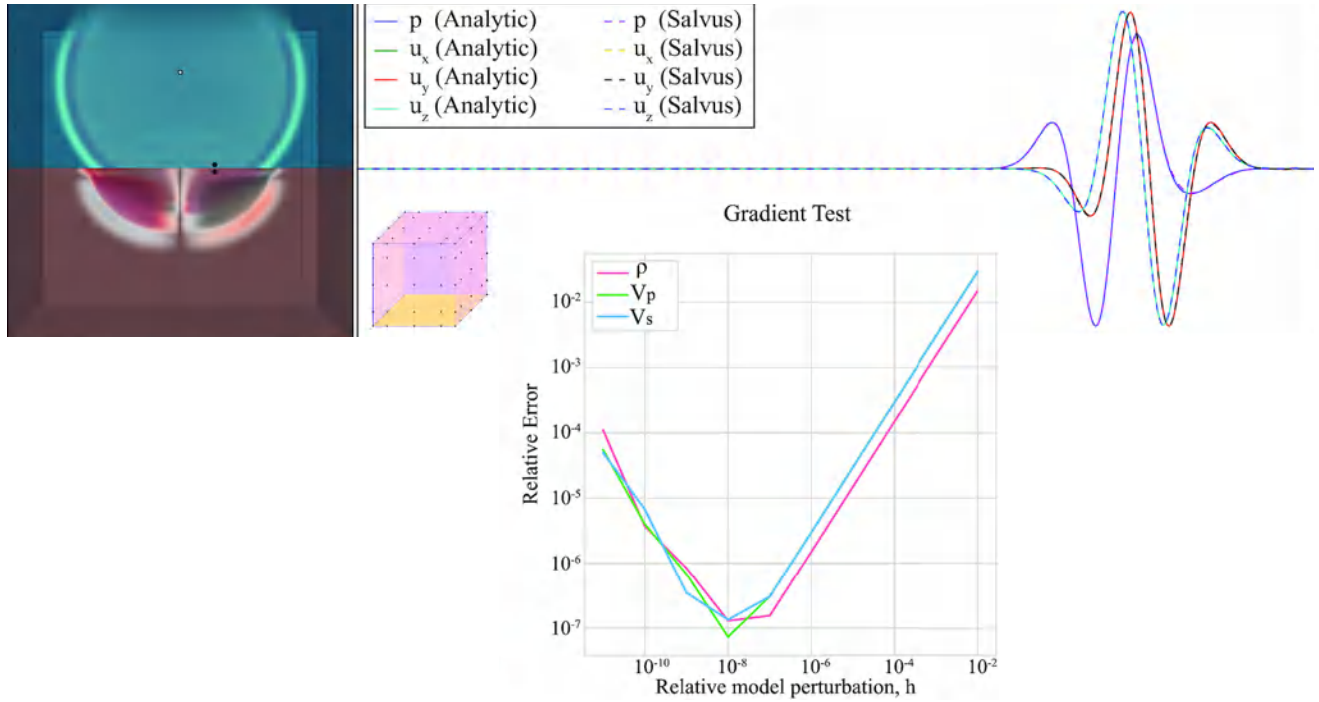


SalvusProject

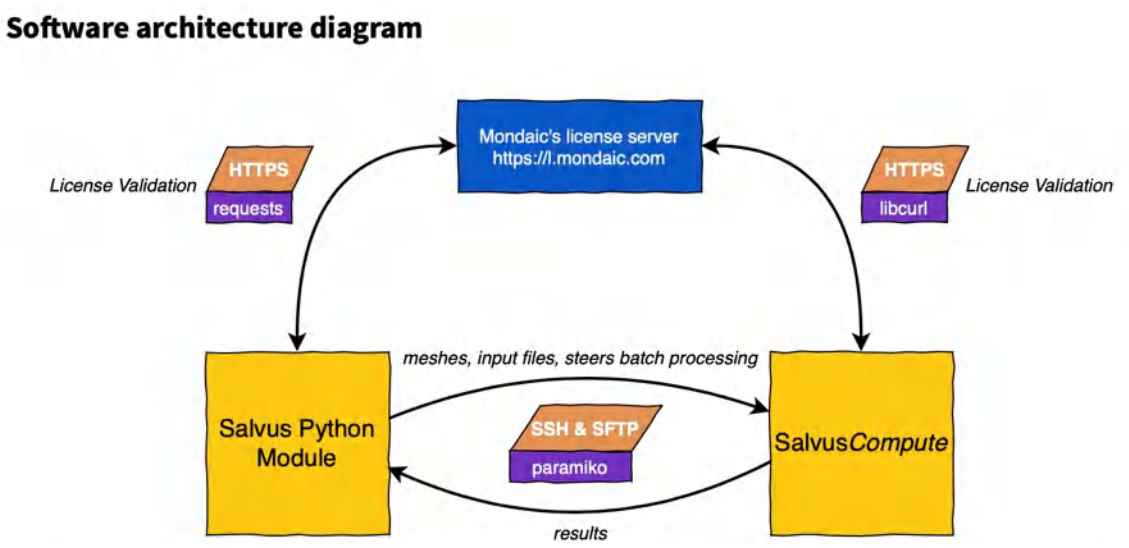
- Models, meshes, simulation parameters, etc, are given unique “hashes”
- Hashes are combined to uniquely refer to intermediate results
- If a hash:
  - Has no associated data, compute it!
  - Has associated data, just open it!
- Hashes are lightweight and persistent on disk
  - Share projects and models with colleagues
- All of this happens automatically: pay as much or as little attention as you like

Quality control: Validation, verification and security

Extensive continuous integration pipelines.
Benchmark solutions for semi-analytic problems.



Static application security
for SANS Top 25 vulnerabilities.



Continuous integration and testing ensure validity, integrity and security of the software.

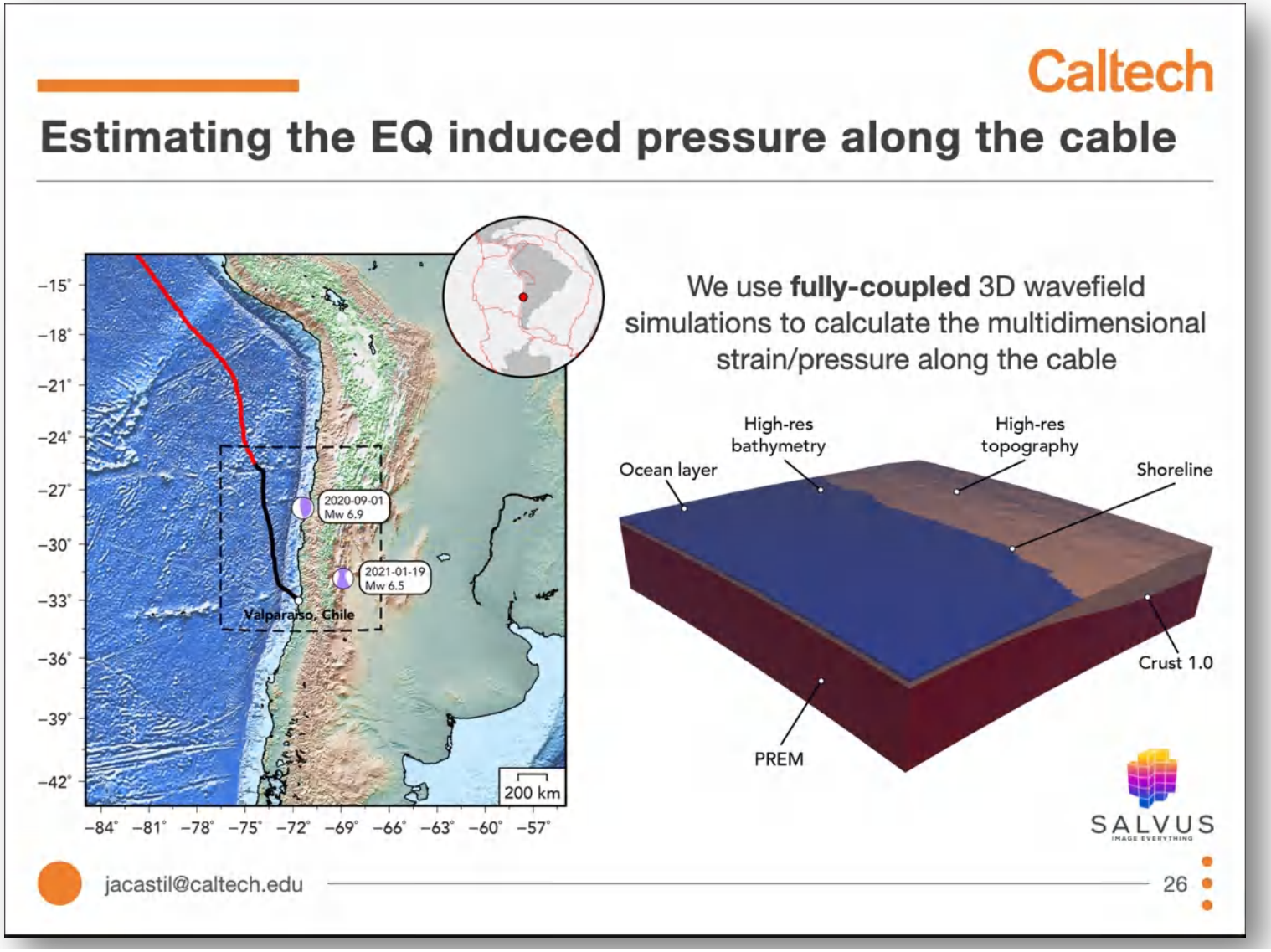
Case Studies

A variety of applications supported by Salvus

Jorge Castellanos

Simulating strain recordings along transoceanic cables

J. Castellanos et al. (2021). **On the Sensitivity of Optical Polarization Transoceanic Cables to Seismic and Water Waves**. SSA Annual meeting, April 19-23, 2021.

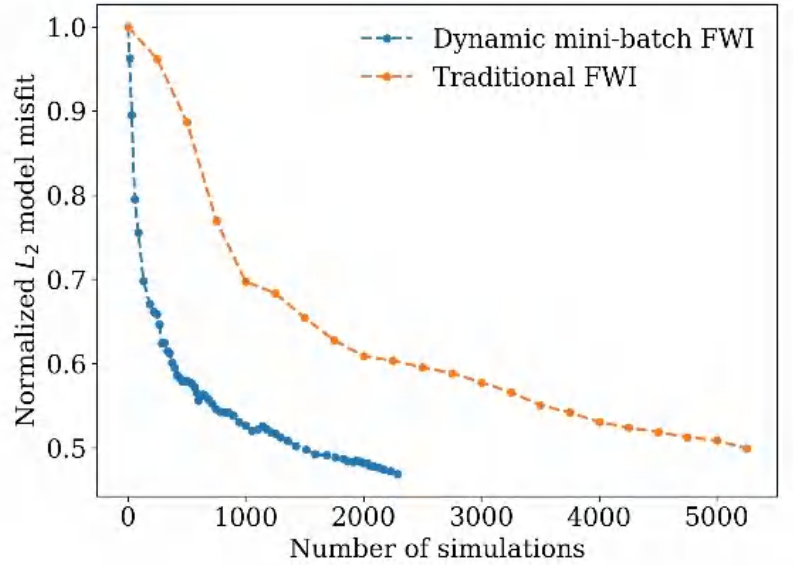


Dirk-Philip van Herwaarden

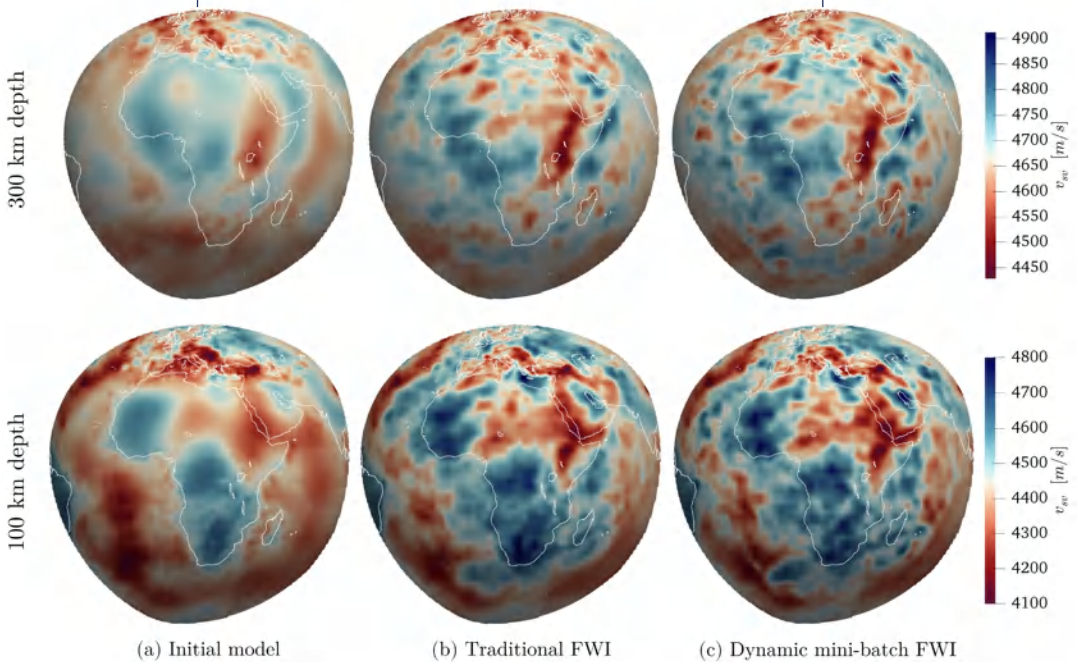
Reducing the number of simulations required for full-waveform inversion through optimized quasi-random event selection

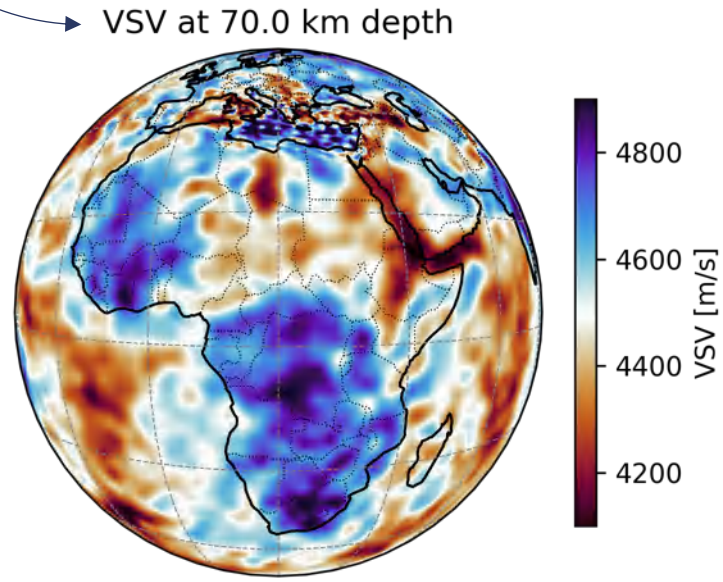
van Herwaarden, et al., Accelerated full-waveform inversion using dynamic mini-batches, *Geophysical Journal International*, Volume 221, Issue 2, May 2020
van Herwaarden et al., Evolutionary full-waveform inversion, *Geophysical Journal International*, September 2020, *in press*.

Reduction in total number of required simulations



Comparison of models using traditional or mini-batch FWI

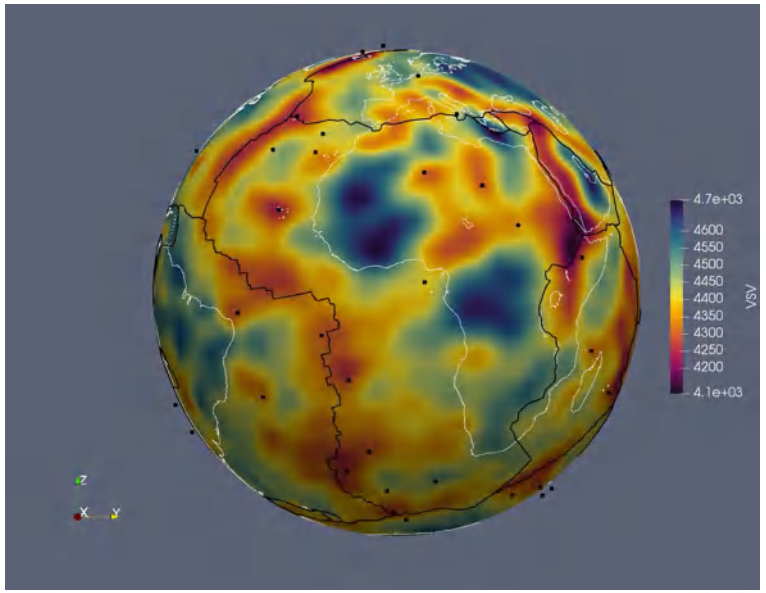




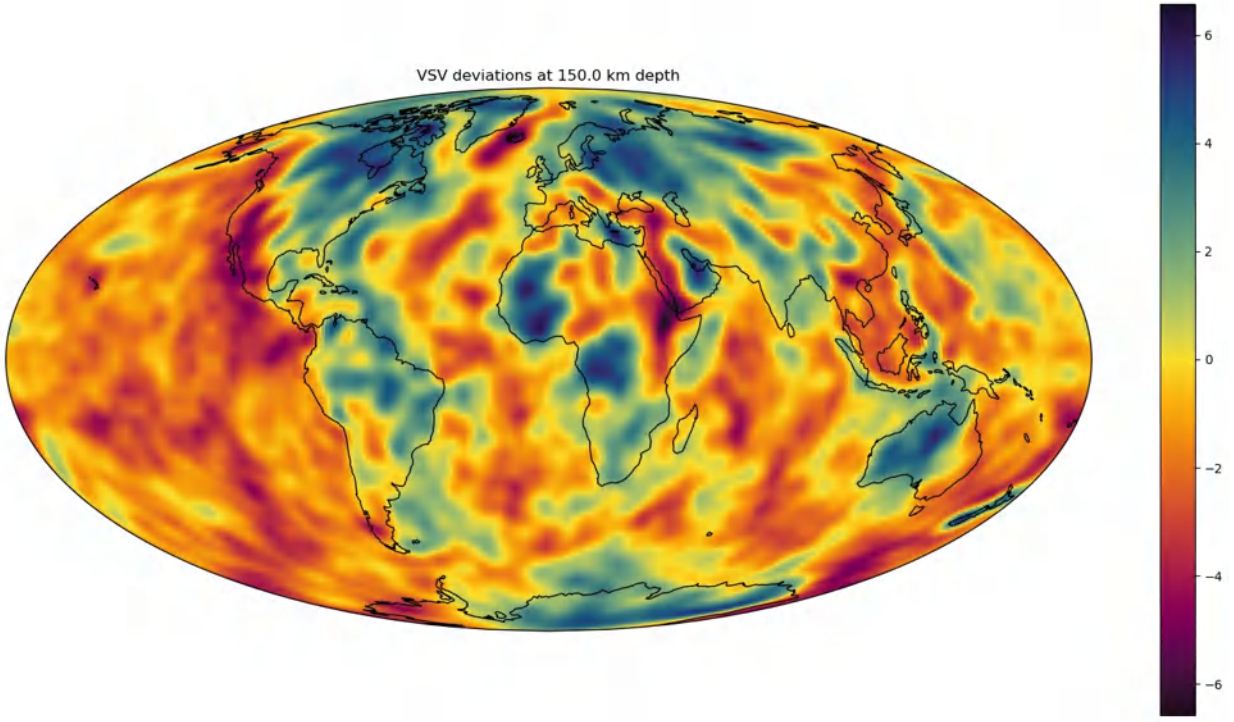
Sölvi Thrastarson

Increasing the efficiency of global-scale full-waveform inversion through the use of optimized event-specific meshes

Thrastarson et al., Accelerating numerical wave propagation by wavefield adapted meshes. Part II: full-waveform inversion, *Geophysical Journal International*, Volume 221, Issue 3, June 2020



3-D full-waveform Earth model
Quantity: VSV, 150km depth
Starting model: PREM



Laura Cobden

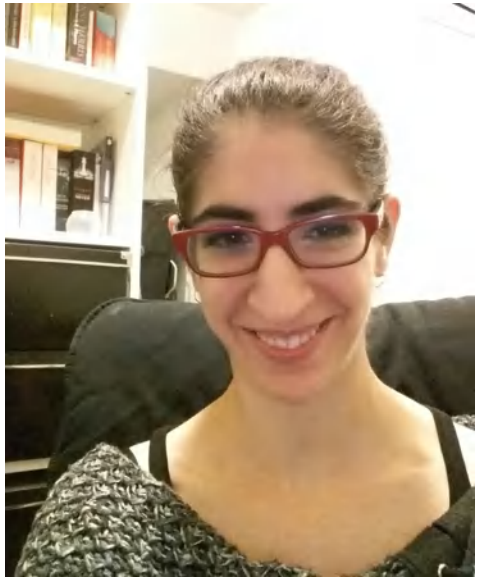
Investigating the effect of mantle plumes on high-frequency seismic signals

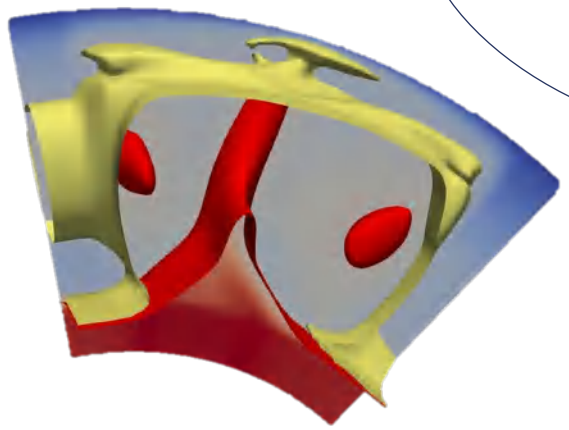
Cobden, Deschamps, Rost, Thomas, Tackley, et al., *Probing mantle plumes using seismic* arrays, *ongoing*.

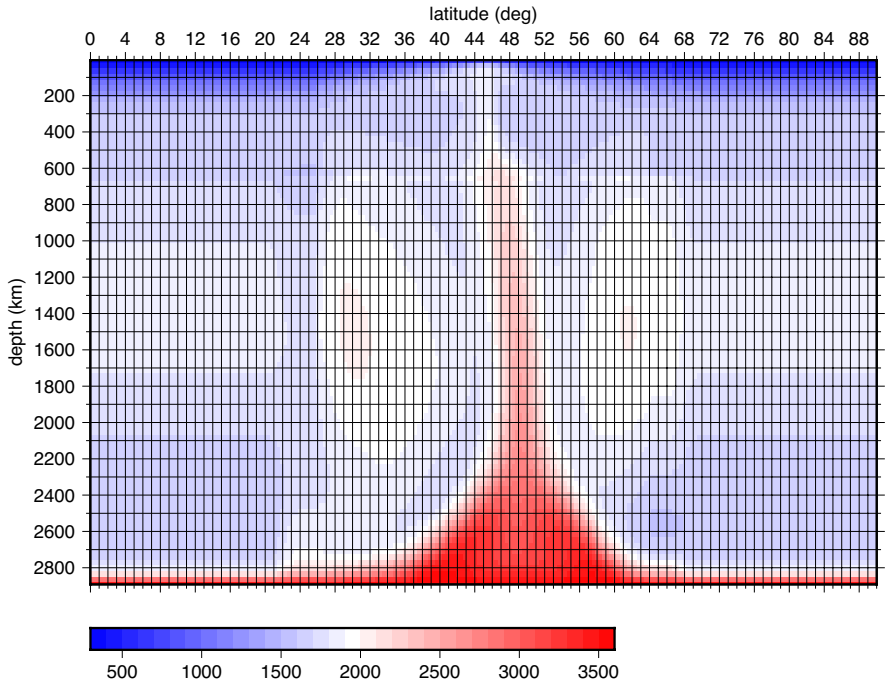
Wavefield simulations and array analysis

Viscoelastic properties

Geodynamic Plume models



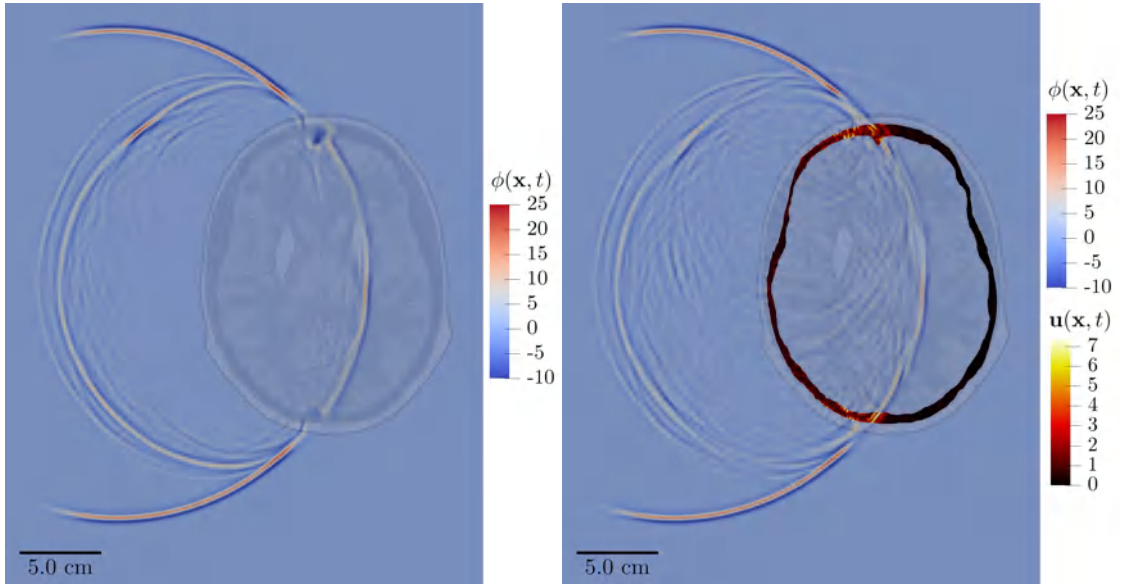




Patrick Marty

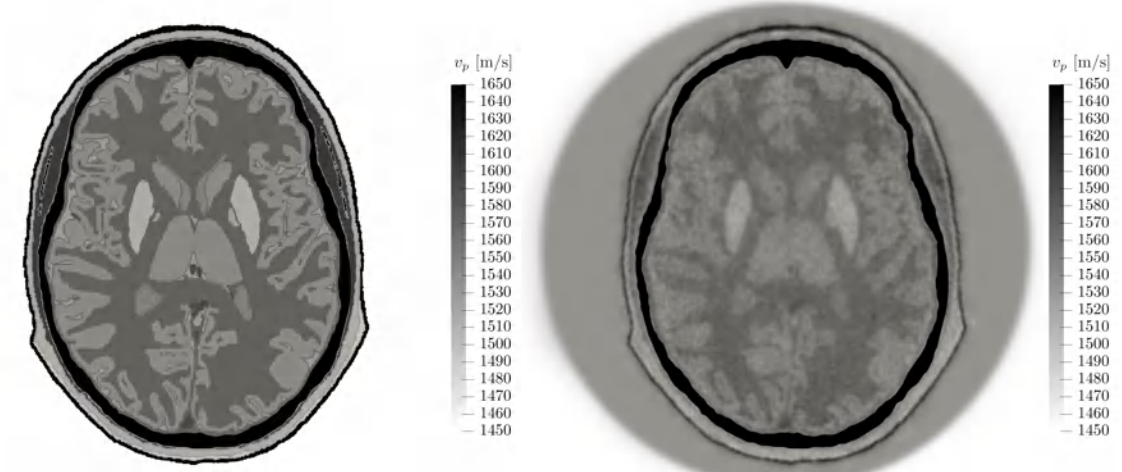
Full-waveform inversion for medical imaging and early cancer detection

Marty et al., Acoustoelastic full-waveform inversion for transcranial ultrasound computed tomography, *accepted at SPIE Medical Imaging*, February 2021.



Acoustic Skull

Elastic Skull



Target brain model

Imaging result after FWI

Mondaic

Why does it say “Spinoff”?

Mondaic

Mondaic

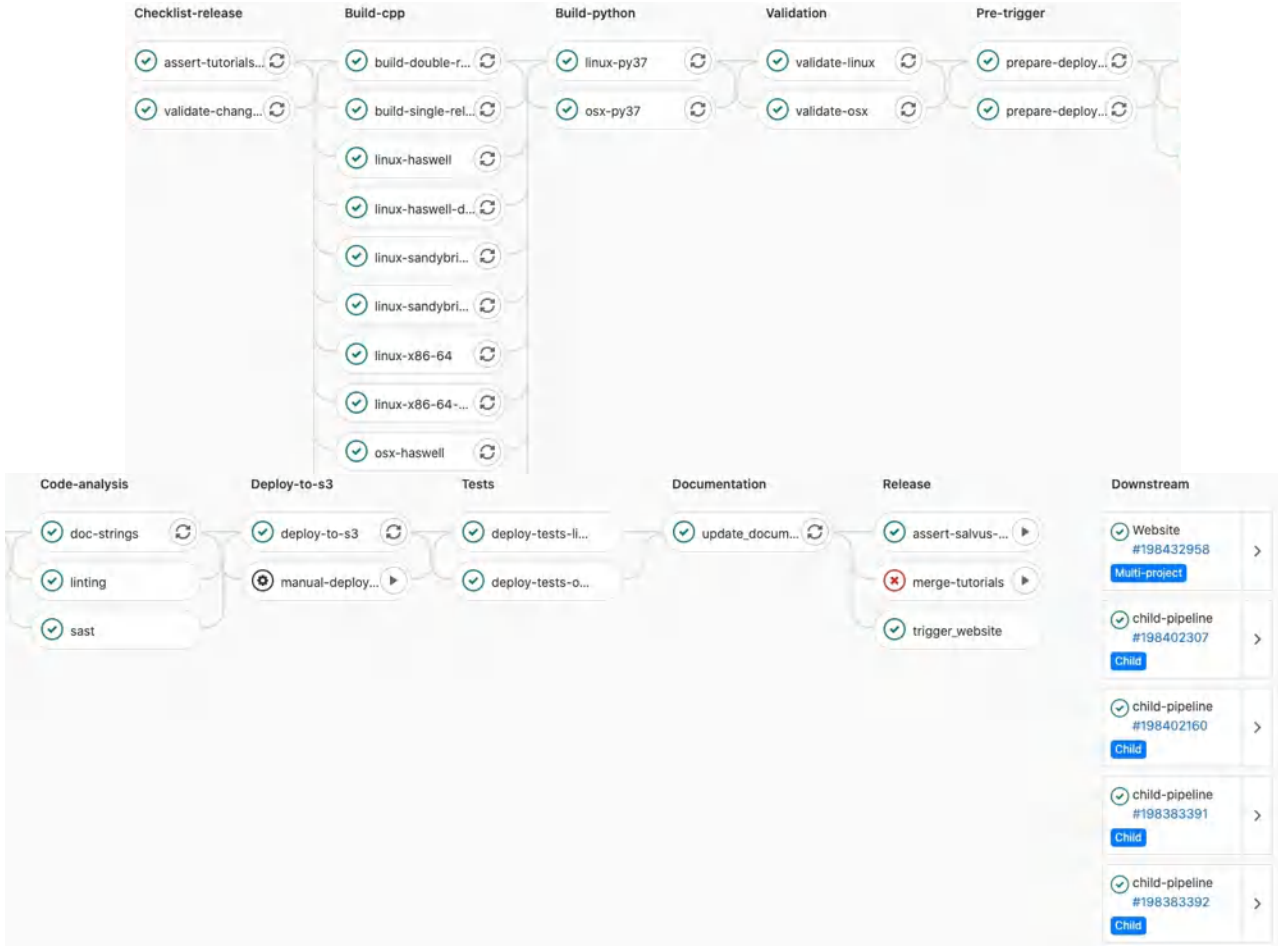
- Salvus was originally conceived and developed during its developers' time at ETH

Mondaic

- Salvus was originally conceived and developed during its developers' time at ETH
- Official spinoff founded in 2018, looking towards Salvus' long-term maintenance and growth

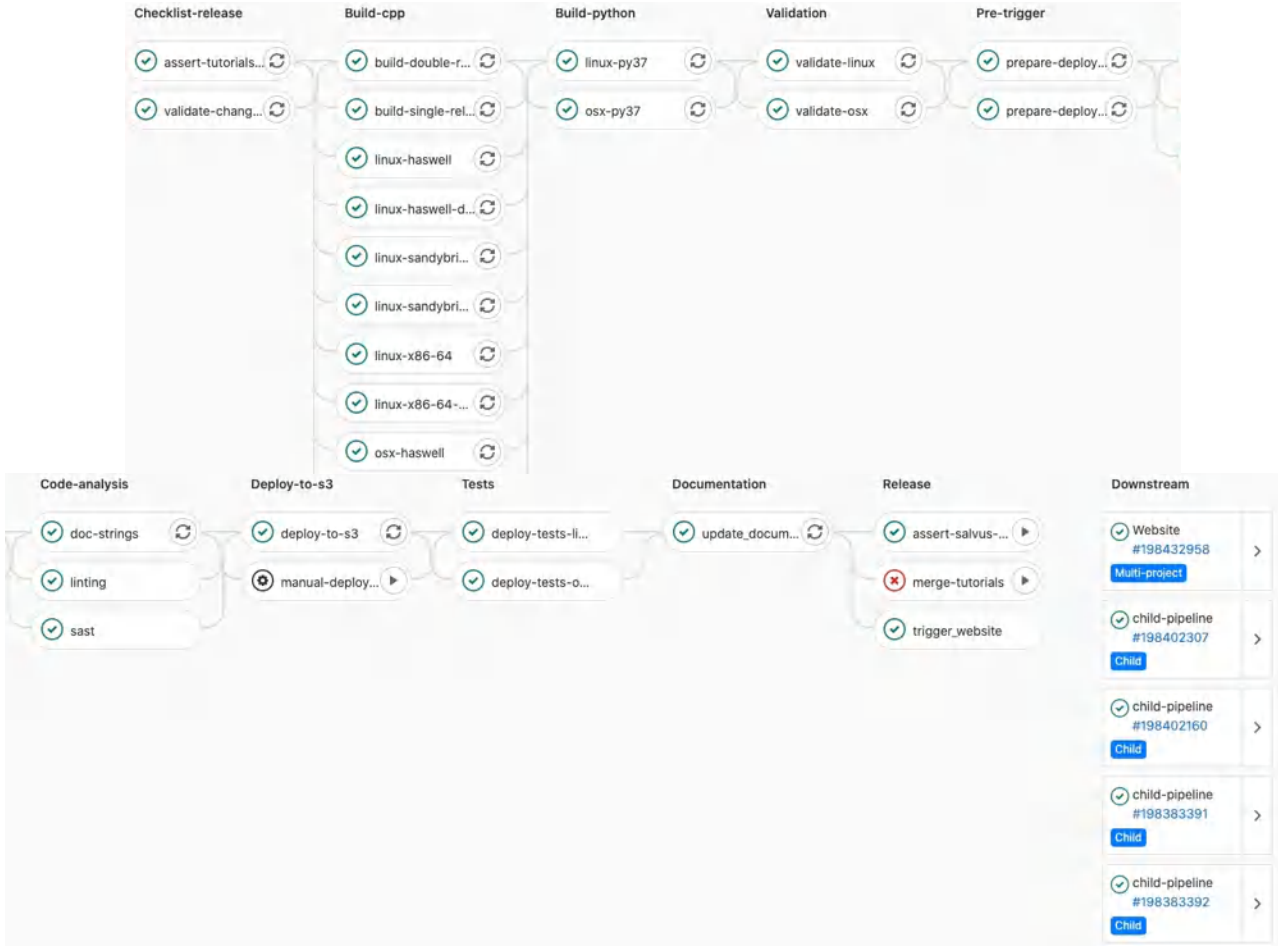
Mondaic

- Salvus was originally conceived and developed during its developers' time at ETH
- Official spinoff founded in 2018, looking towards Salvus' long-term maintenance and growth
- Behind-the-scenes engineering and continuous deployment



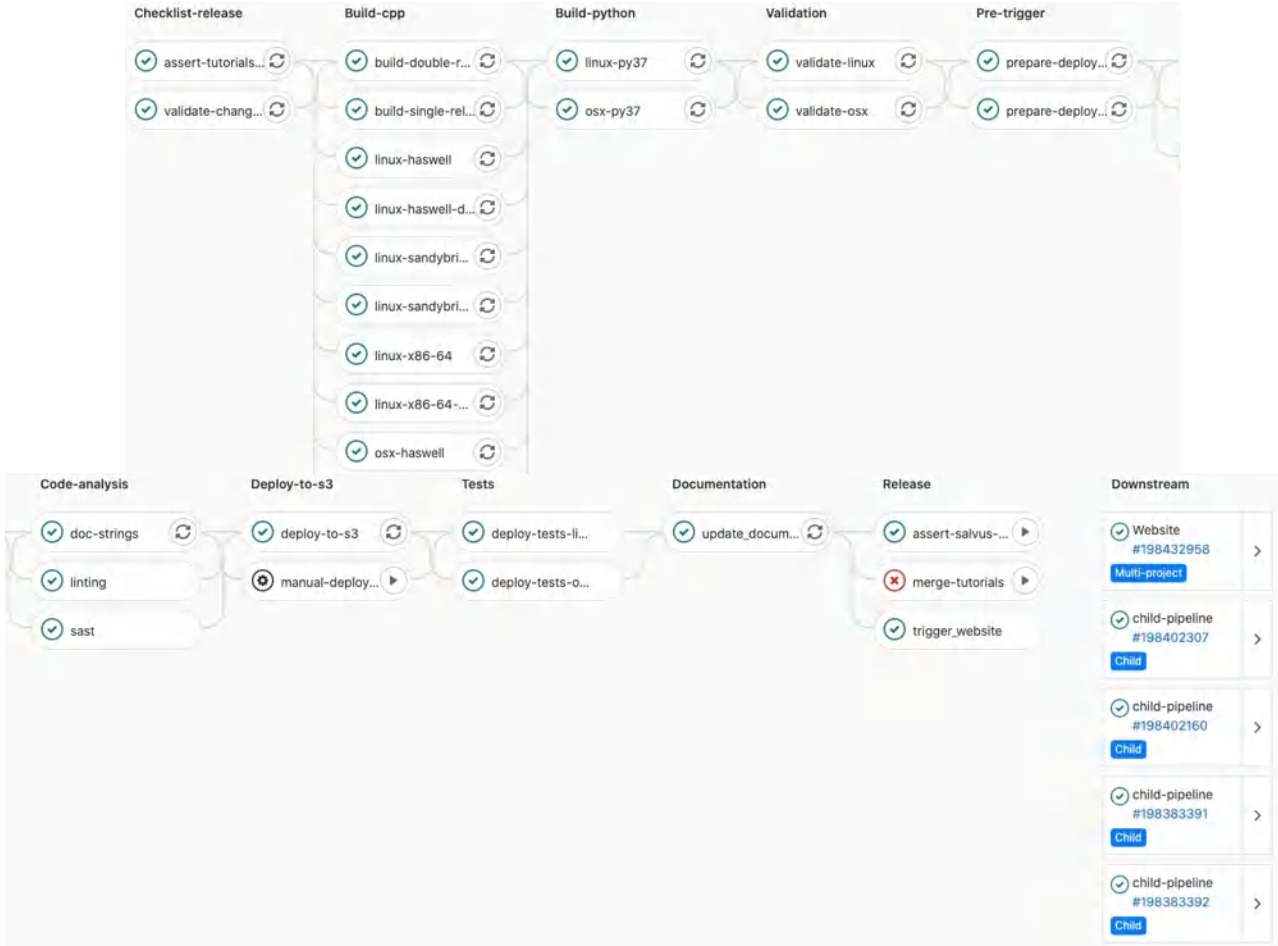
Mondaic

- Salvus was originally conceived and developed during its developers' time at ETH
- Official spinoff founded in 2018, looking towards Salvus' long-term maintenance and growth
- Behind-the-scenes engineering and continuous deployment
- Hope to support and enable research in the Earth science community through the provision of professional and robust software



Mondaic

- Salvus was originally conceived and developed during its developers' time at ETH
- Official spinoff founded in 2018, looking towards Salvus' long-term maintenance and growth
- Behind-the-scenes engineering and continuous deployment
- Hope to support and enable research in the Earth science community through the provision of professional and robust software
- Flexible academic pricing



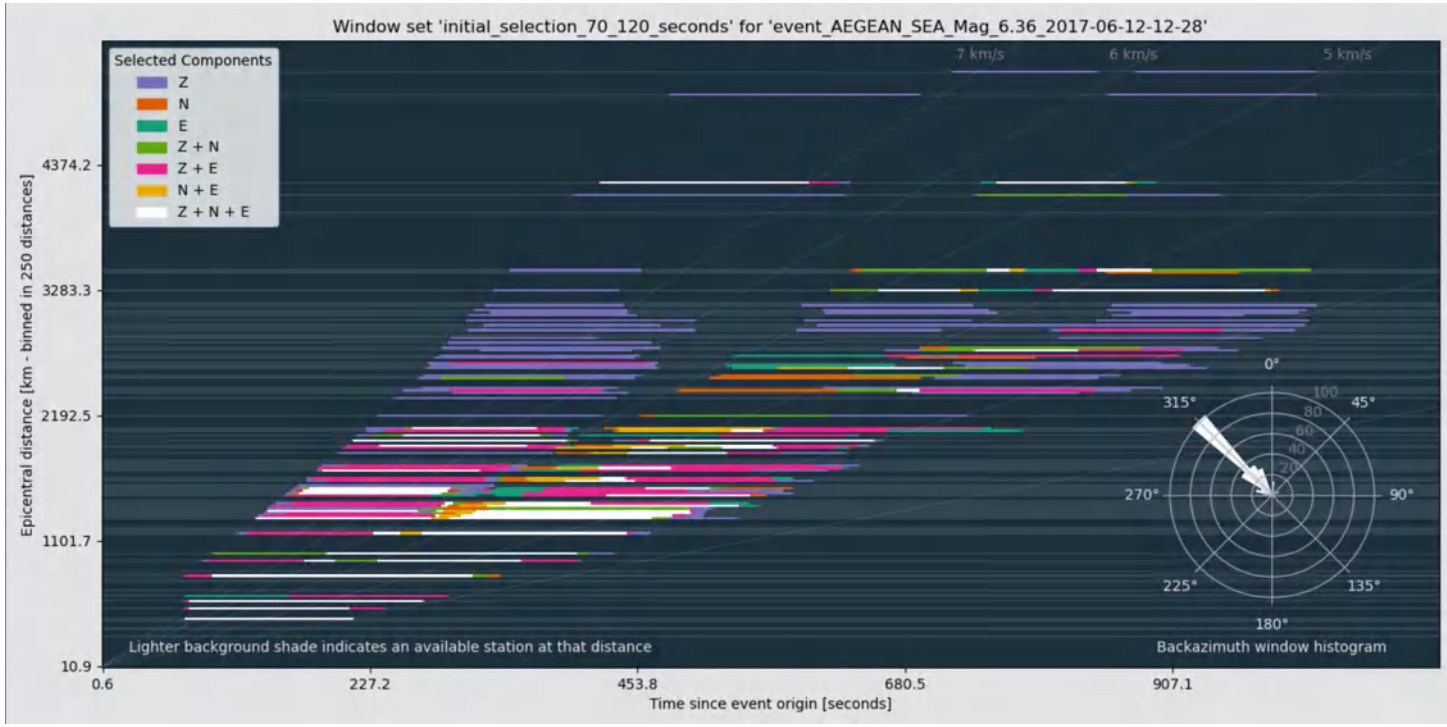
Tutorial

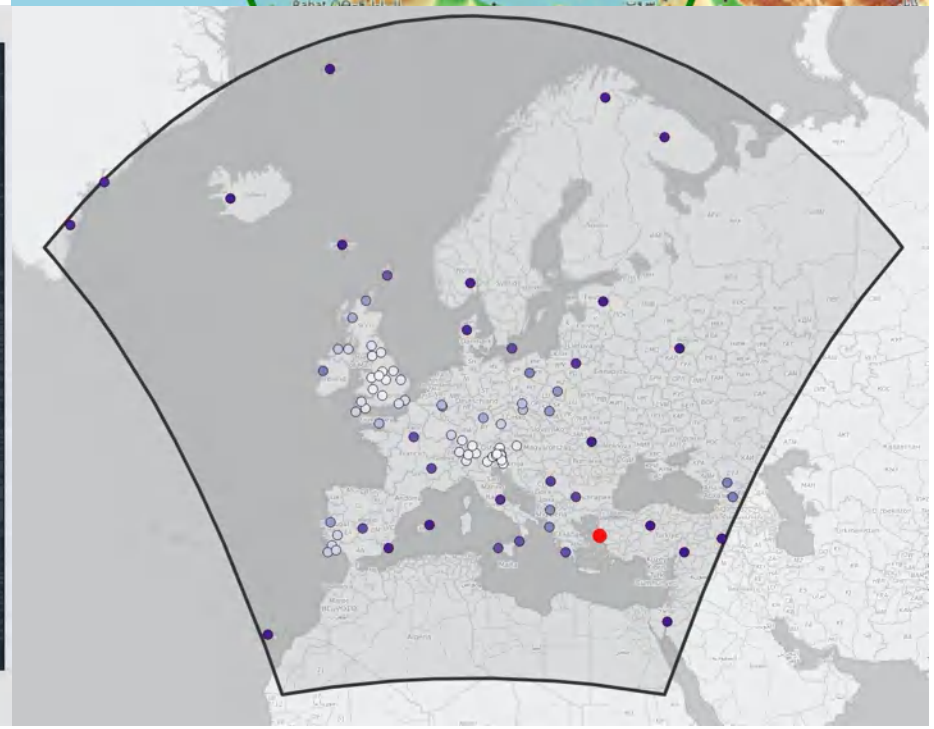
What will we do on Friday?

Continental-scale full-waveform inversion

Continental-scale full-waveform inversion

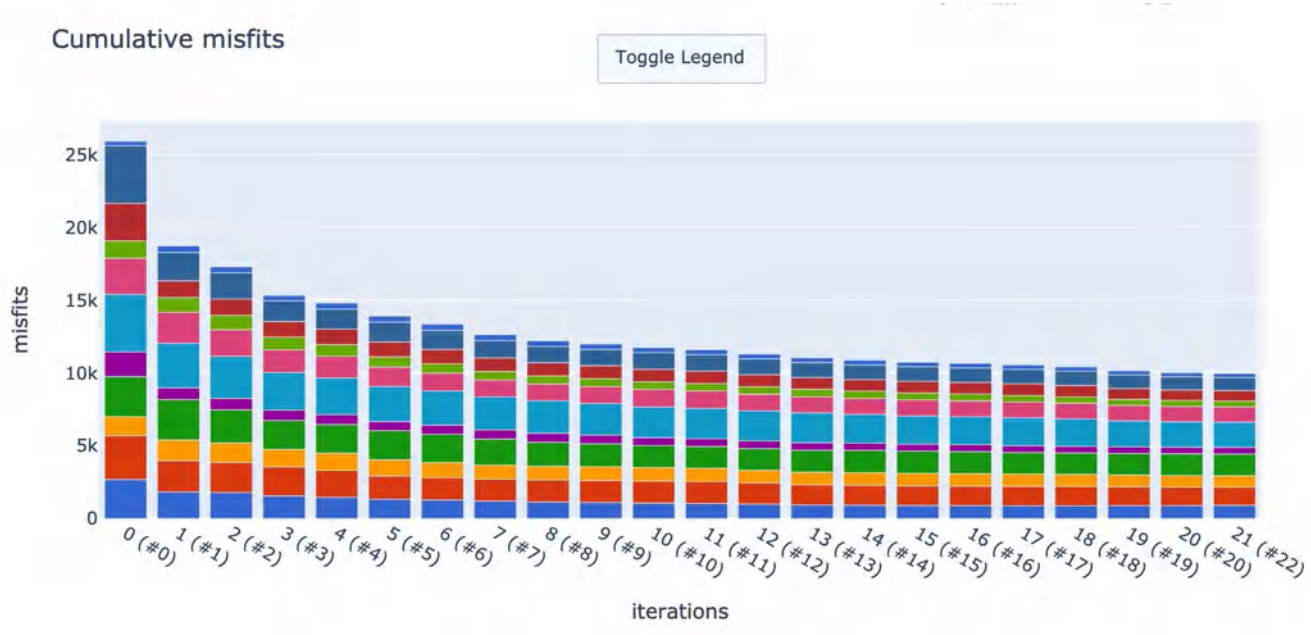
- “From scratch” using real data

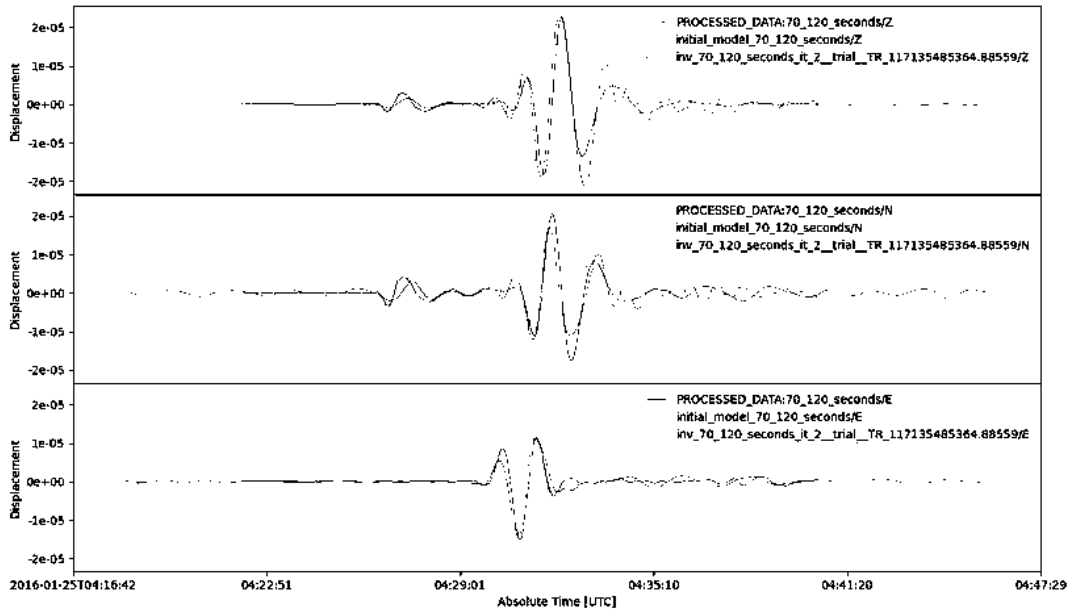




Continental-scale full-waveform inversion

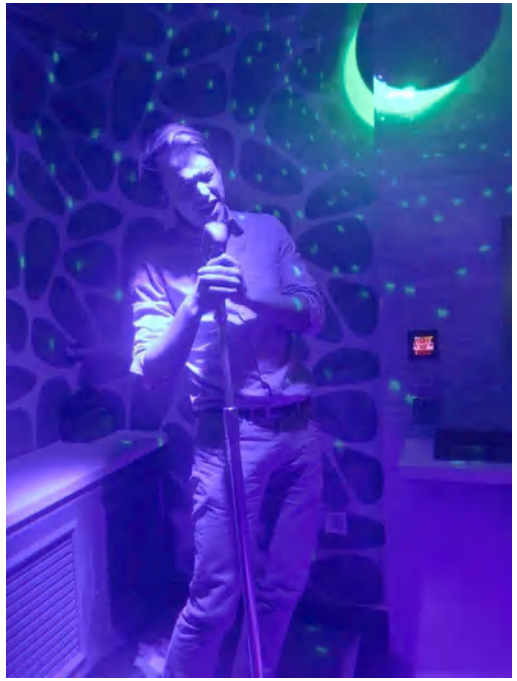
- “From scratch” using real data
- Learn the steps involved with a practical example
  - Inspect data, compute misfits, and iteratively update the model





Instructors

Christian Böhm



Lion Krischer

Michael Afanasiev

Thanks for listening