Muography Simulations for Carbon Capture and Storage Monitoring

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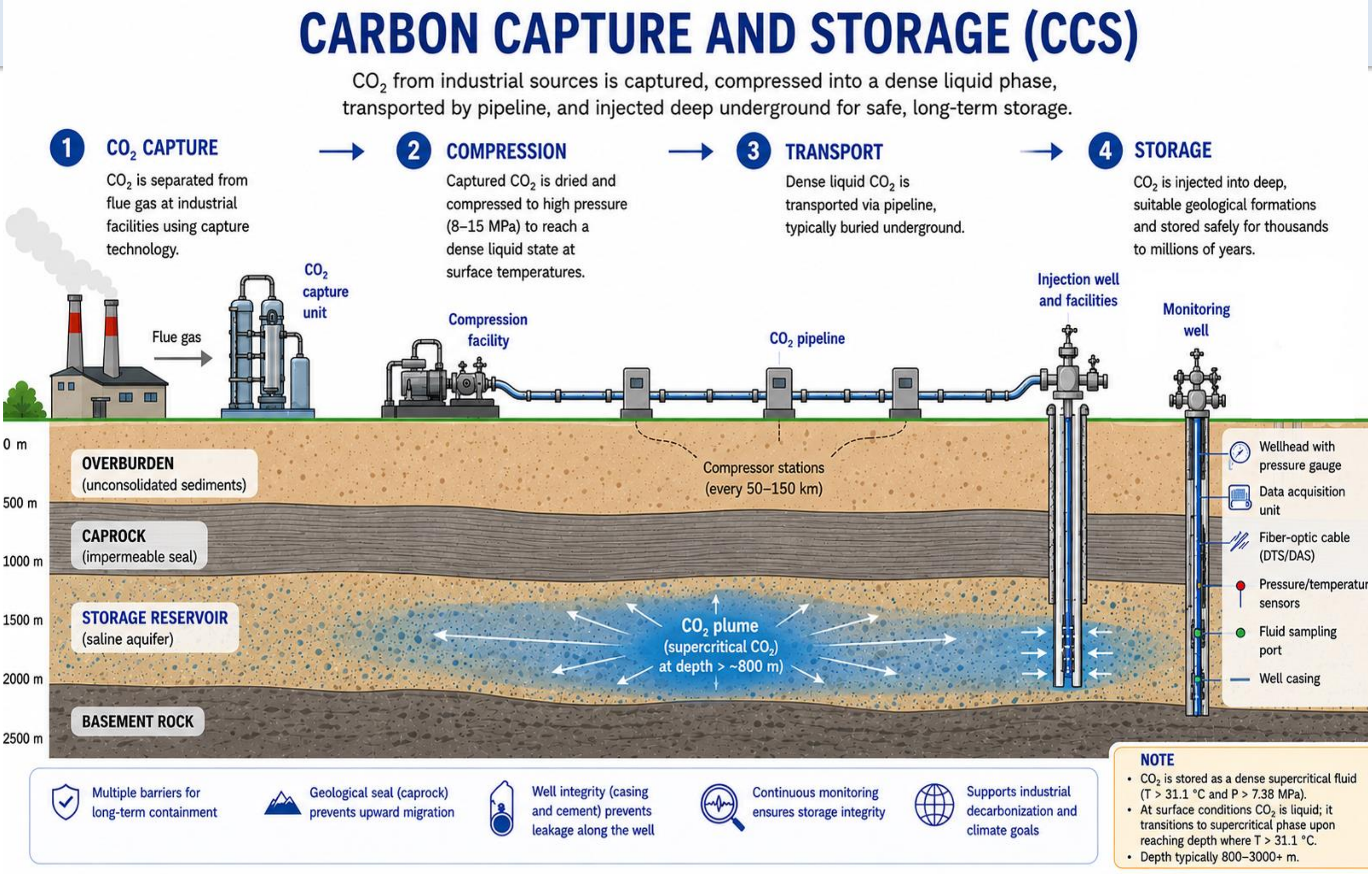


CARBON CAPTURE AND STORAGE (CCS)

CO_2 from industrial sources is captured, compressed into a dense liquid phase, transported by pipeline, and injected deep underground for safe, long-term storage.

1 CO_2 CAPTURE
CO_2 is separated from flue gas at industrial facilities using capture technology.

2 COMPRESSION
Captured CO_2 is dried and compressed to high pressure (8–15 MPa) to reach a dense liquid state at surface temperatures.

3 TRANSPORT
Dense liquid CO_2 is transported via pipeline, typically buried underground.

4 STORAGE
CO_2 is injected into deep, suitable geological formations and stored safely for thousands to millions of years.

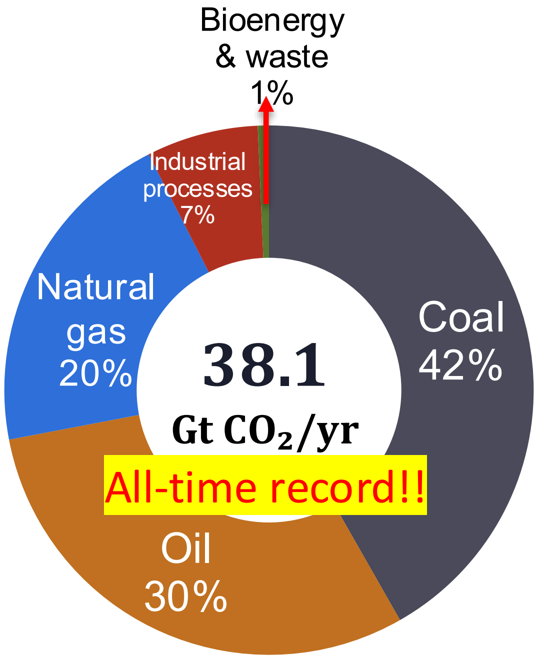
- Multiple barriers for long-term containment
- Geological seal (caprock) prevents upward migration
- Well integrity (casing and cement) prevents leakage along the well
- Continuous monitoring ensures storage integrity
- Supports industrial decarbonization and climate goals

NOTE
- CO_2 is stored as a dense supercritical fluid ($T > 31.1$ °C and $P > 7.38$ MPa).
- At surface conditions CO_2 is liquid; it transitions to supercritical phase upon reaching depth where $T > 31.1$ °C.
- Depth typically 800–3000+ m.

Created using ChatGPT/DALL-E (OpenAI) and modified by the author.

Why does CCS matter and CCS deployment status

CO_2 Emissions



International Energy Agency (IEA) Global Energy Review 2026, Table p.44

~69% of emissions (coal + gas + industrial processes) come from large point sources where CCS is technically applicable, yet only **0.03%** is currently stored.

CCS — GEOLOGICAL STORAGE (IEA CCUS Projects Database 2026)

Operational today	Under construction	Planned pipeline
23 facilities	30 projects mostly 2026–2029	322 projects announced only
11.3 **Mt CO_2/yr**	**31.7** **Mt CO_2/yr**	**360** **Mt CO_2/yr** *~×29 increase if all built*

Note: this is only CCS and we have CCUS sites as well!

Every CCS site needs long-term storage verification.

Emissions: IEA Global Energy Review 2026, p.44 (Apr 2026). CCS figures: IEA CCUS Projects Database 2026 (Feb 2026), fate = 'Dedicated storage', phase 1. GCCSI Global Status of CCS 2025 (Oct 2025).

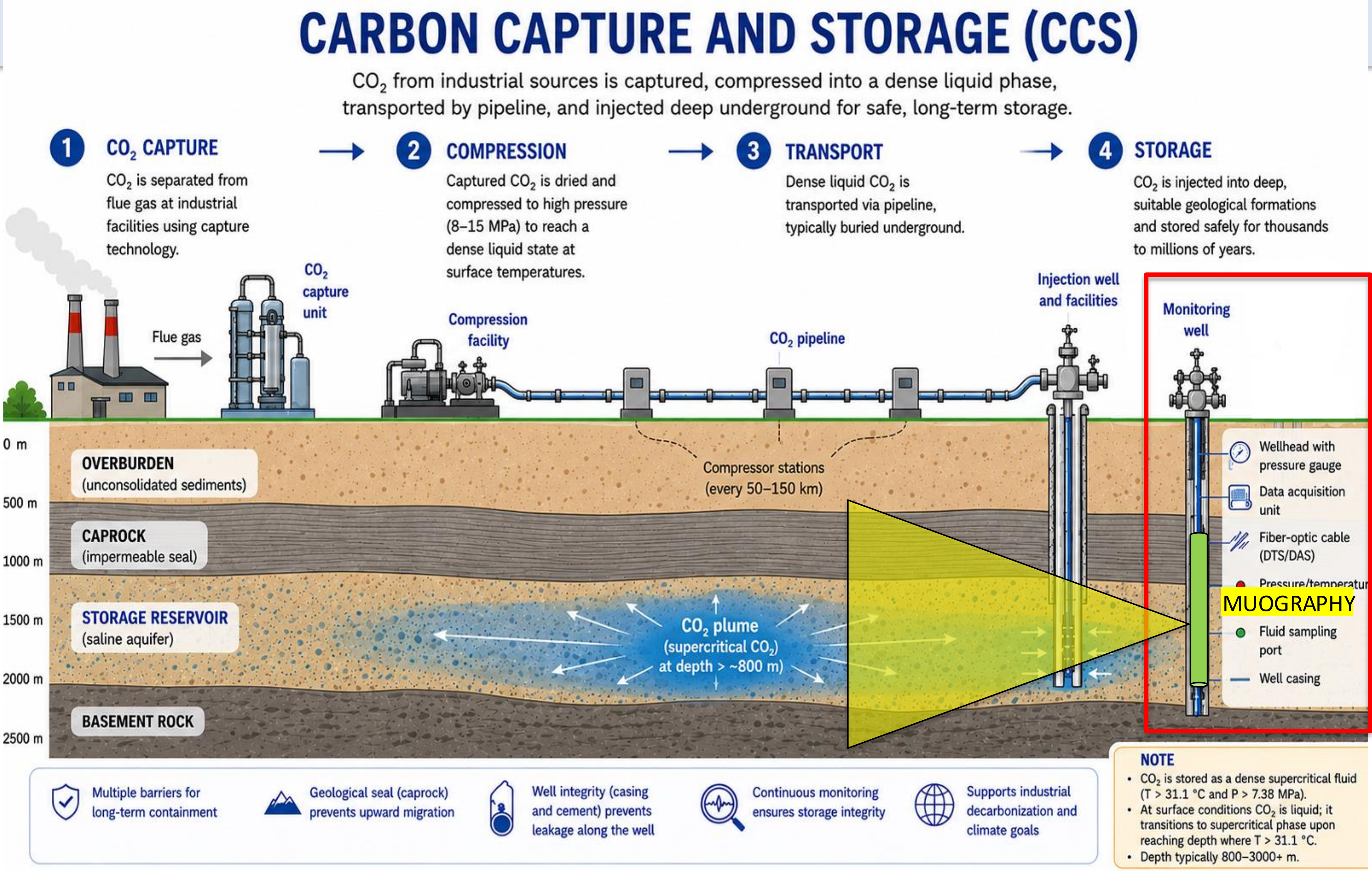
CCS Monitoring Technologies

- Seismic, electromagnetics, gravity, satellite-based deformation, and geochemistry have all been used for CCS monitoring purposes.

- *Seismic is the gold standard for plume imaging and spatial coverage, but it is* ***expensive****,* ***periodic****, and its sensitivity to CO_2 saturation is* ***strongly nonlinear*** *and effectively saturates above a few tens of percent, making quantitative saturation estimation unreliable. It also cannot resolve bulk density independently from velocity without additional constraints.*

Gap: No single method can independently quantify bulk density and CO_2 saturation with continuous coverage.

Muography using borehole detectors directly measures bulk density continuously and passively!



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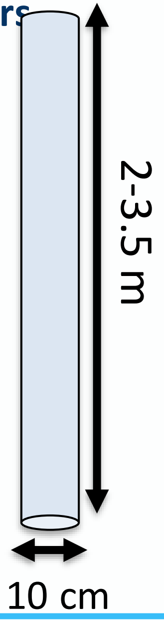
The Problems

Computational Challenges

Limited Detection Area in Area in borehole detectors



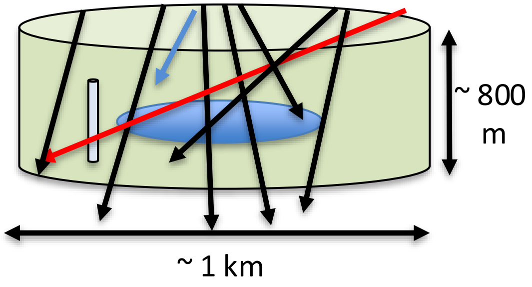
Poor Simulation Efficiency Efficiency

Muons generated over a large surface must be transported through ~1 km km of overburden, because because of **energy** and **direction** only a tiny fraction fraction can reach the detector!

For example, for a 30 m of of rock, modelling muons muons less than 16 GeV is is waste of CPU calculation calculation time.

Homogeneity Assumption Assumption

Codes like **MUSIC** and **PROPOSAL** are fast but assume homogeneous material and they cannot cannot model complex detector geometry or heterogeneous structures. structures.



Result: Achieving adequate statistics for underground muography requires generating an impractically impractically large number of primary muons which is computationally prohibitive even on HPC on HPC clusters.

Solution 1

Two-Step Transport

Divide simulation into two physically-motivated stages

Step 1

Surface → Near Detector

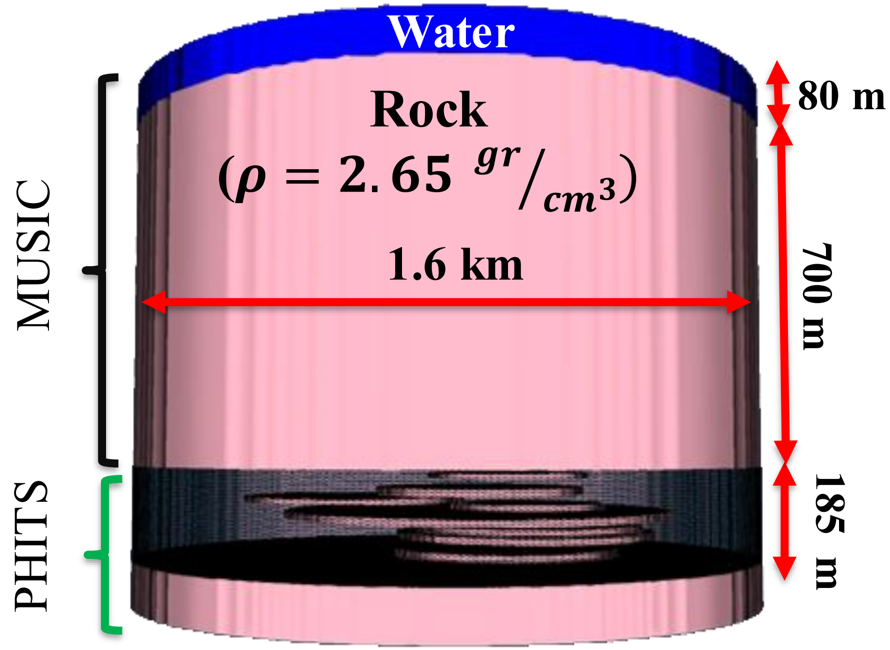
Using muon transport codes such as such as MUSIC → Fast muon propagation through **large homogeneous** rock/water overburden thicknesses.

Energy, Position, Direction

Step 2

Detector Region + ROI

Full particle physics in PHITS, Geant4, FLUKA : detector geometry, secondary particles, and **material heterogeneity** only where it matters.



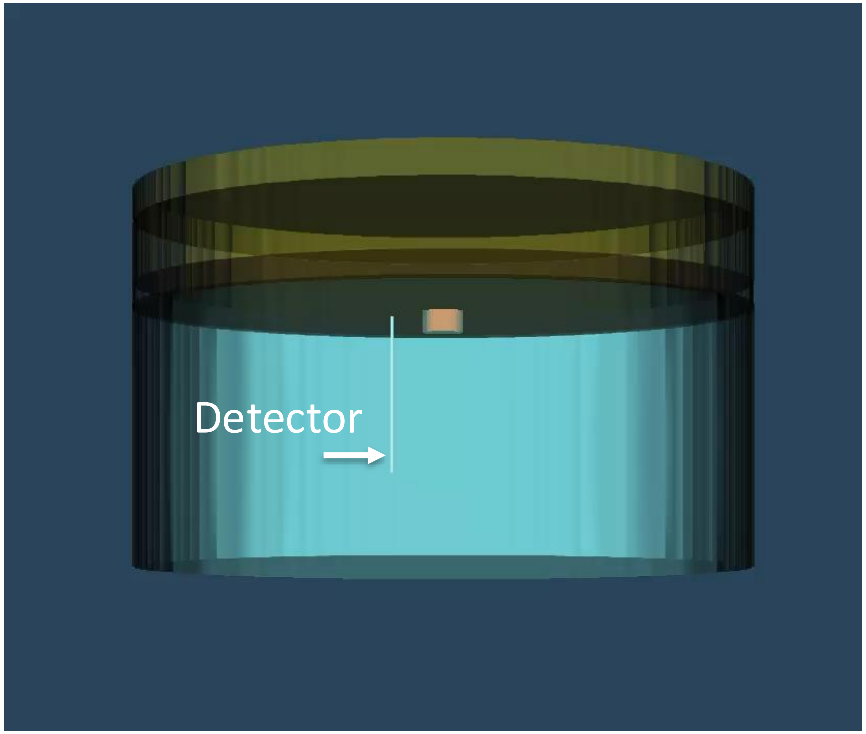
Sleipner CCS

[Basiri et al. (2026) Int. J. Greenhouse Gas Control 154, 104683]

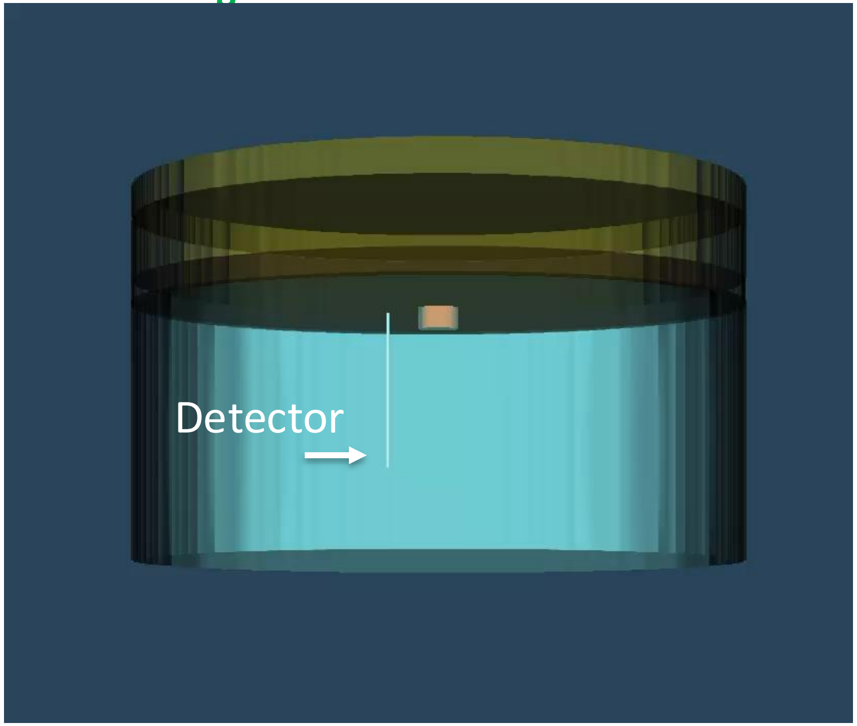
✓ The key advantage: we don't waste CPU time transporting muons through hundreds of meters of rock or water.

Solution 2 Geometric and energy threshold filtering

❌ 1000 muons without filtering



✅ 1000 selected muons with filtering filtering



Vast CPU time wasted transporting muons that muons that miss the detector by **orders of of magnitude**.

Only geometrically viable muons are transported. transported. **same physics**, fraction of the CPU CPU cost.

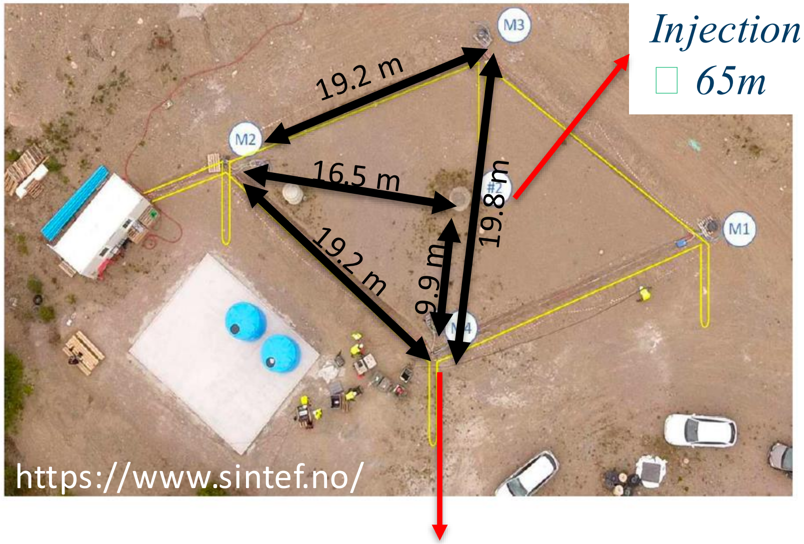
Net efficiency rate: **0.02% without filtering**

Svelvik CO_2 Field Lab

Site Overview

- *It is a testbed lab enabling repeatable, controlled CO_2 injection experiments with simultaneous monitoring facilities.*
- **Location:** ~50 km south of Oslo, Norway.
- SINTEF-owned

Well Configuration



https://www.sintef.no/

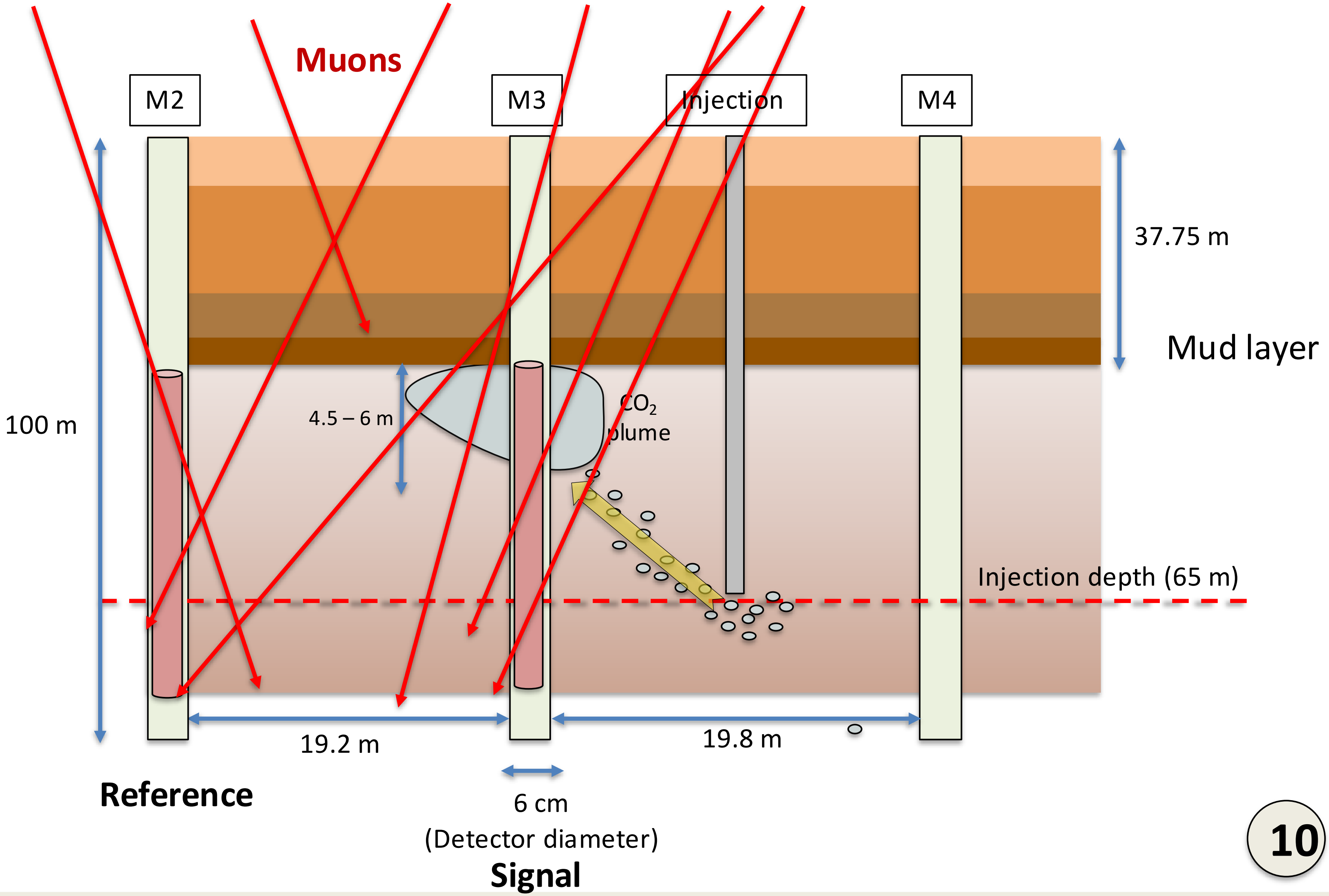
Injection well
☐ *65m*

- *M1, M2, M3, M4 are observation wells 100m*

Oct–Nov 2023 campaign: 3,687.7 kg CO_2 injected over 30 days· Muography detected ~5% flux increase in plume zone (performed by Geoptic company)·

Injection rate is about 8 kg/hour (around 200 kg/day).

Svelvik CO_2 Field Lab after injection

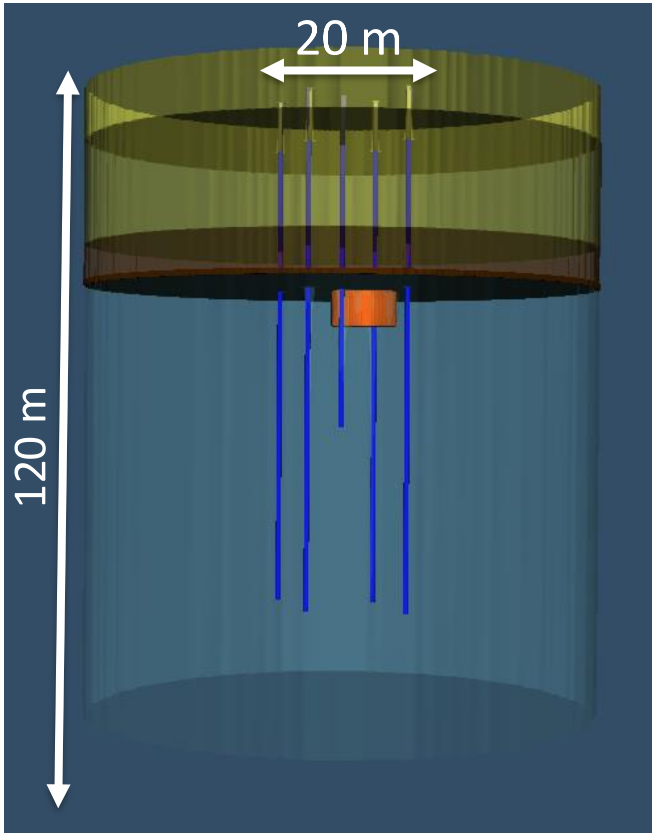


Svelvik PHITS simulations

Source type: Filtered cosmic-ray muon source/ normal source using PARMA model in PHITS

Simulation Scenarios

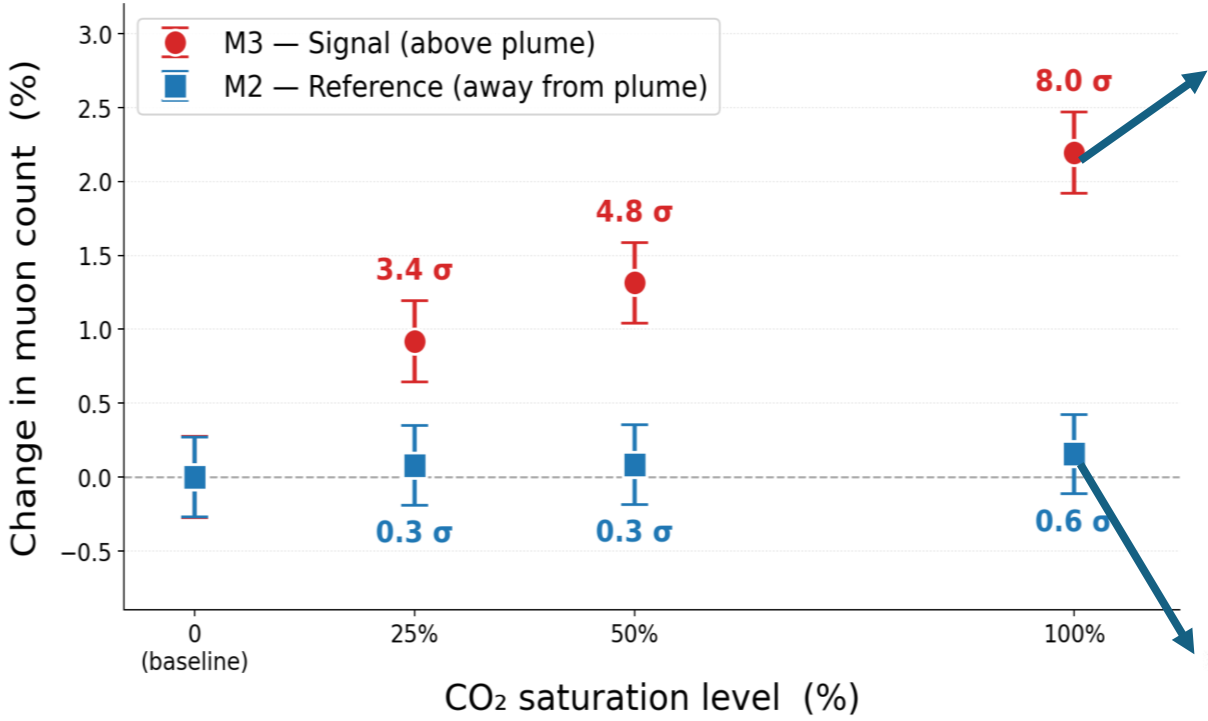
- Baseline Reservoir (plume density: 1.66 g/cm³)
- 25%, 50%, 100% CO_2 Saturation (Plume density: 1.51, 1.36, 1.06 g/cm³)

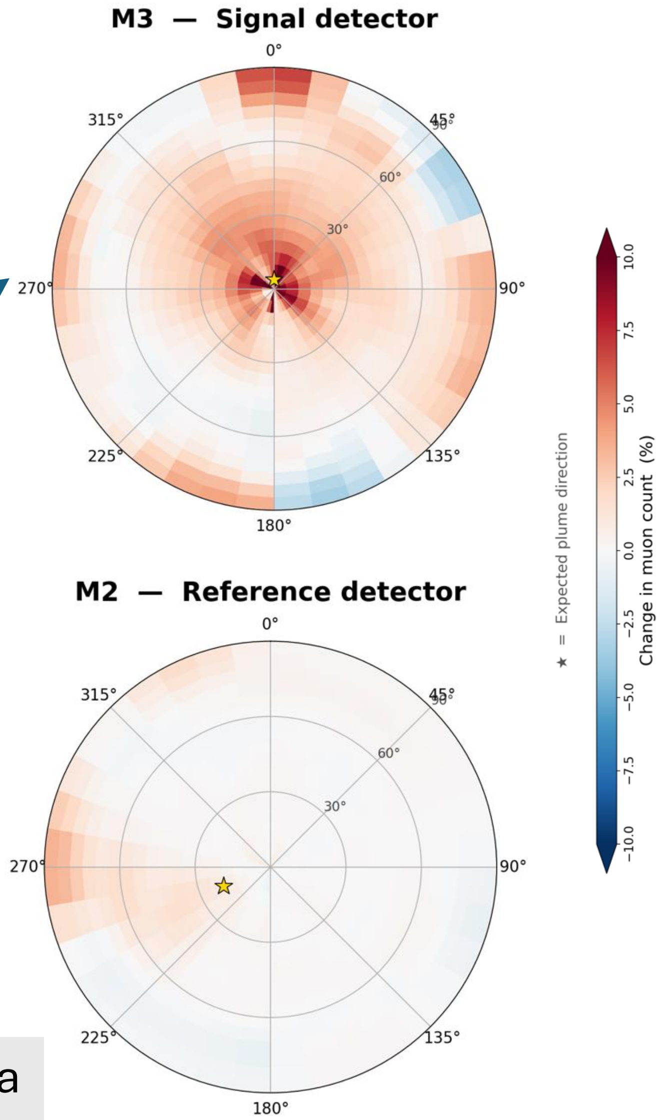


Calculation speed comparison

Simulation mode	Total histories	Detector hits	CPU calculation time
Normal source	100 M	3500	48 hours
Filtered source	10 M selected Equivalent to 171 B	65,000 (18x higher)	22 hours (2x faster)

Preliminary results using 50 M selected muons





M3 shows a red region concentrated near the center, extra muons arriving from almost directly overhead where the plume sits.

UCMuon *(UCLouvain Cosmic Muon simulation suite)*

UCMuon (**You See Muon!**) is an open-source cosmic muon simulation suite with **a browser-based graphical interface**, deployable locally or as command-line executables.

Streamlit GUI (5 tabs)

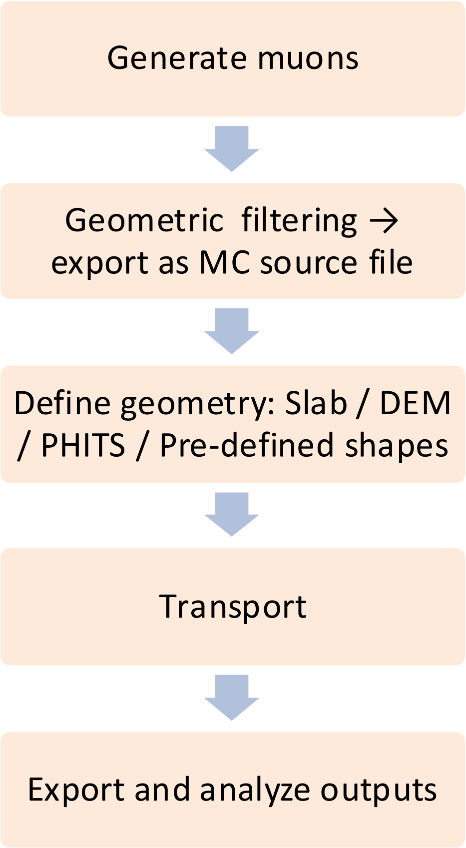
Generator
(Spectra, shapes, angular modes, detector filter, Guaranteed-hit mode)

Transport
(5 engines including MUISC, PROPOSAL, slab, density modes)

Terrain
(Reads DEM / Pre-defined shapes / PHITS geometry and transports using the engines)

Results
Config (Session autosave)

Workflow



Generate muons

Geometric filtering → export as MC source file

Define geometry: Slab / DEM / PHITS / Pre-defined shapes

Transport

Export and analyze outputs

Applications

Muon source for MC
Surface population → PHITS, Geant4, or MUSIC for muography and detector simulation

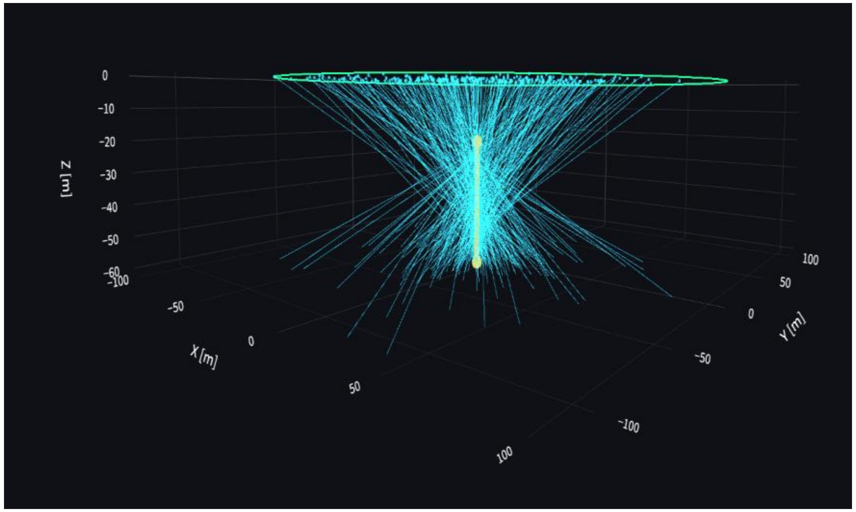
Subsurface muography
Large-scale fast muon transport

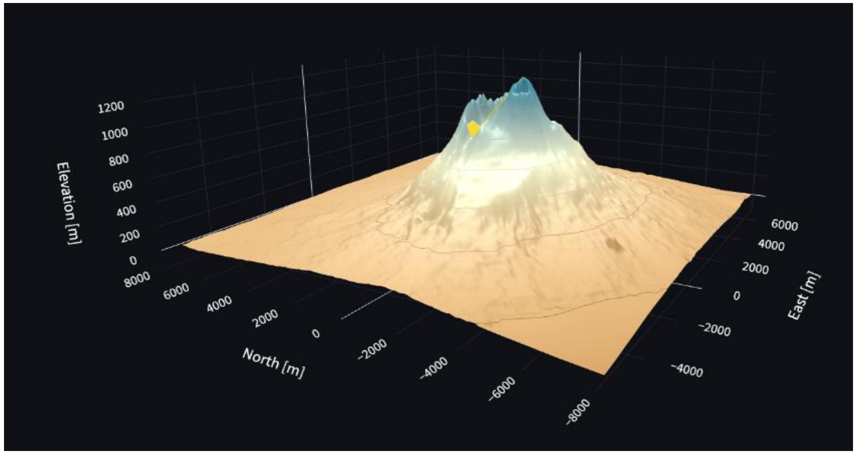
Volcano imaging
Real-site DEM topography
Field-deployed muography

Glacier
Directional flux through ice and subglacial surveys

Selected helpers & tools

- ✓ Geant4 and PHITS source file export
- ✓ **Source geometry sizing guide**
- ✓ Minimum energy threshold estimator
- ✓ **Equivalent real measurement time estimator**
- ✓ **Effective solid angle calculator**
- ✓ DEM download, validation and detector position check
- ✓ **Interactive 3D terrain view with ray directions**
- ✓ On-the-fly results analysis
- ✓ Directional surface flux estimator





Summary

What was demonstrated

Hybrid two-stage transport (MUSIC + PHITS)

Stage 1: MUSIC propagates muons through homogeneous overburden.

Stage 2: PHITS handles heterogeneous reservoir + detector region.
Validated at Sleipner (780 m water + rock overburden).

Geometric filtering (UCMuon)

Select only energy and geometrically viable muons before transport.

18× more detector hits · 2× faster CPU · equivalent to 171 billion histories.

Validated at Svelvik CO_2 Field Lab.

UCMuon suite is under development to meet the needs!

Using combined methods reduce simulation time by orders of magnitude while fully preserving muon physics and statistical validity.

If you want
to go fast,
go alone;

If you want
to go far,
go together.

AFRICAN PROVERB

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THANK YOU!

Backup slides

Current CCS Monitoring Technologies

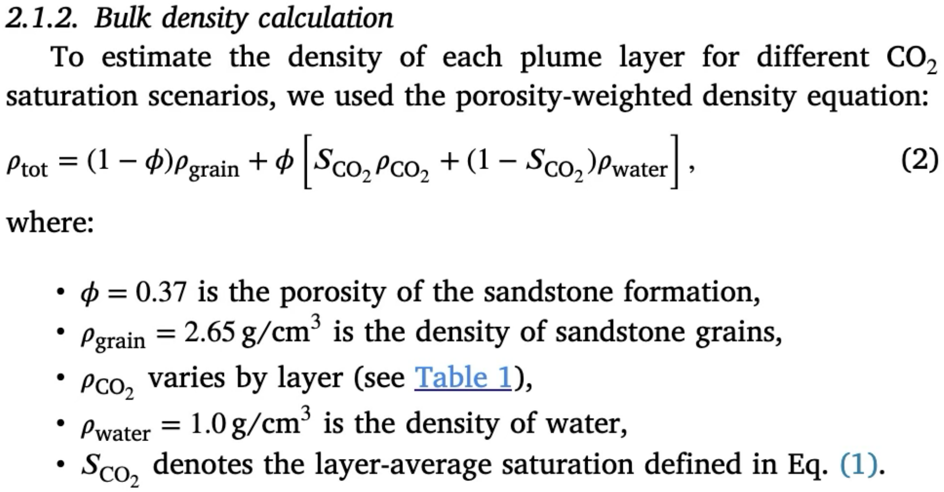
Seismic
Plume imaging, wide coverage; non-unique (saturation vs pressure); periodic surveys

Electromagnetics
Sensitive to resistivity changes; operational complexity

Gravity
Sensitive to density and mass change; small signals, strict repeatability

Satellite-based deformation (InSAR/GNSS)
Constrains pressure and geomechanics; indirect for saturation

Geochemistry and environmental monitoring
Leakage detection and compliance; limited for plume geometry at depth



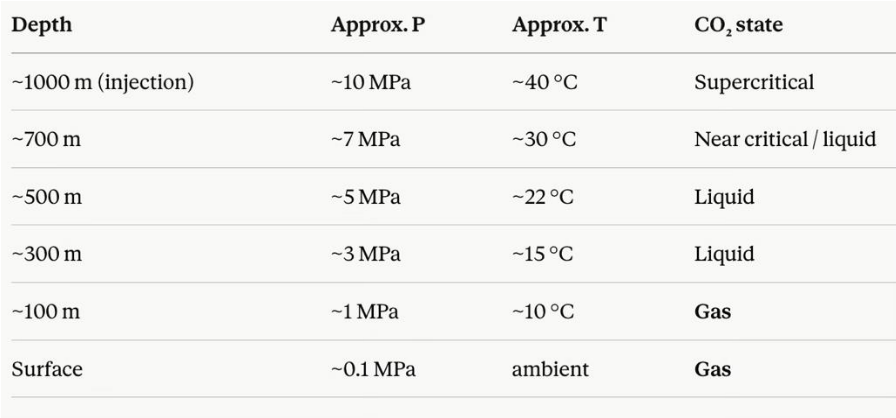
2.1.2. Bulk density calculation

To estimate the density of each plume layer for different CO_2 saturation scenarios, we used the porosity-weighted density equation:

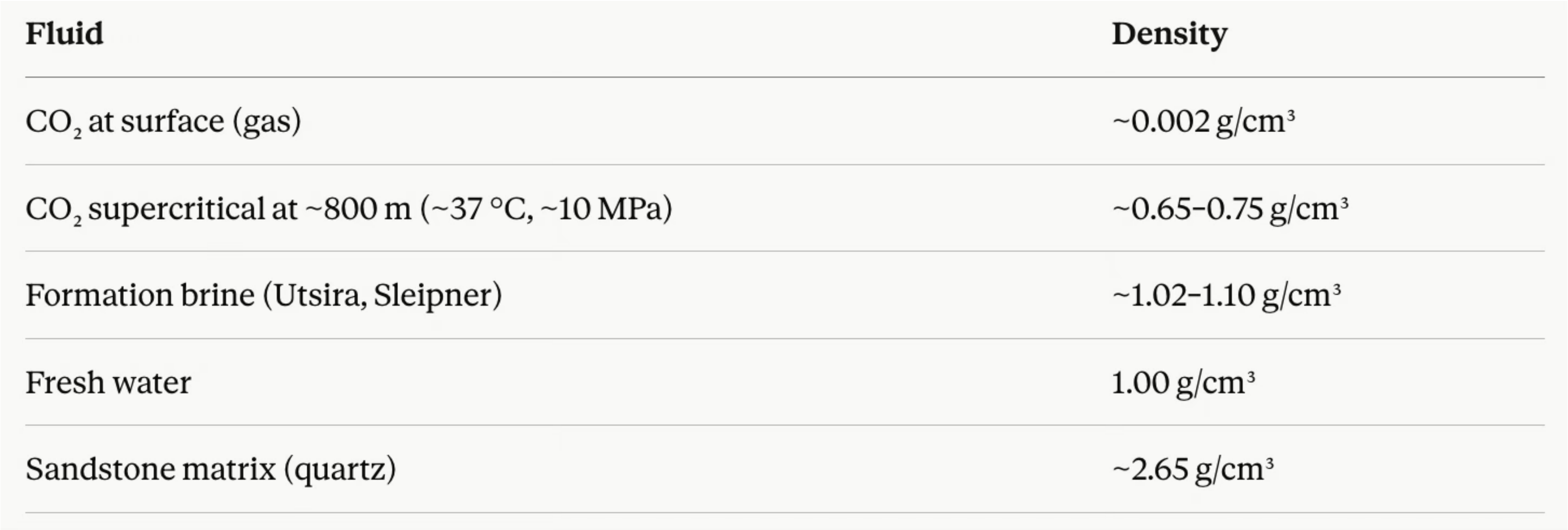
$$\rho_{\mathrm{tot}} = (1-\phi)\rho_{\mathrm{grain}} + \phi\left[S_{\mathrm{CO_2}}\rho_{\mathrm{CO_2}} + (1-S_{\mathrm{CO_2}})\rho_{\mathrm{water}}\right], \quad (2)$$

where:

- $\phi = 0.37$ is the porosity of the sandstone formation,
- $\rho_{\mathrm{grain}} = 2.65\,\mathrm{g/cm^3}$ is the density of sandstone grains,
- $\rho_{\mathrm{CO_2}}$ varies by layer (see Table 1),
- $\rho_{\mathrm{water}} = 1.0\,\mathrm{g/cm^3}$ is the density of water,
- $S_{\mathrm{CO_2}}$ denotes the layer-average saturation defined in Eq. (1).



Depth	Approx. P	Approx. T	CO_2 state
~1000 m (injection)	~10 MPa	~40 °C	Supercritical
~700 m	~7 MPa	~30 °C	Near critical / liquid
~500 m	~5 MPa	~22 °C	Liquid
~300 m	~3 MPa	~15 °C	Liquid
~100 m	~1 MPa	~10 °C	**Gas**
Surface	~0.1 MPa	ambient	**Gas**

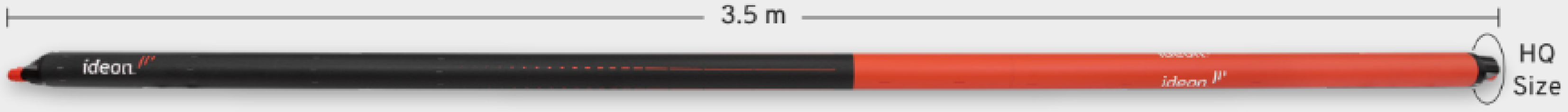


Fluid	Density
CO_2 at surface (gas)	~0.002 g/cm³
CO_2 supercritical at ~800 m (~37 °C, ~10 MPa)	~0.65–0.75 g/cm³
Formation brine (Utsira, Sleipner)	~1.02–1.10 g/cm³
Fresh water	1.00 g/cm³
Sandstone matrix (quartz)	~2.65 g/cm³

Muography Borehole Detector

Ideon

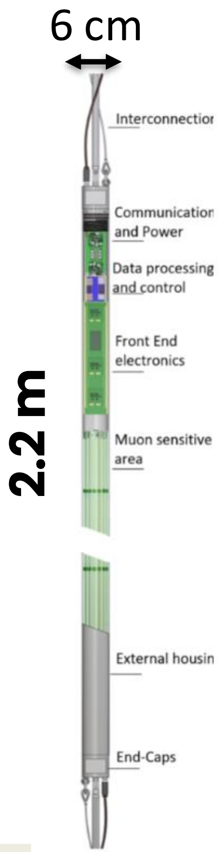
https://ideon.ai/

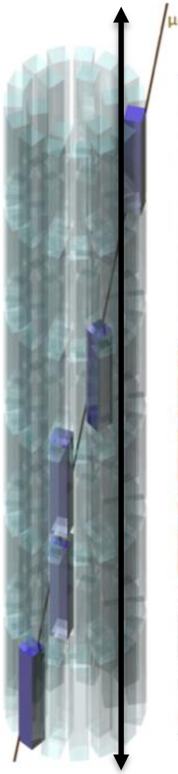


9 cm

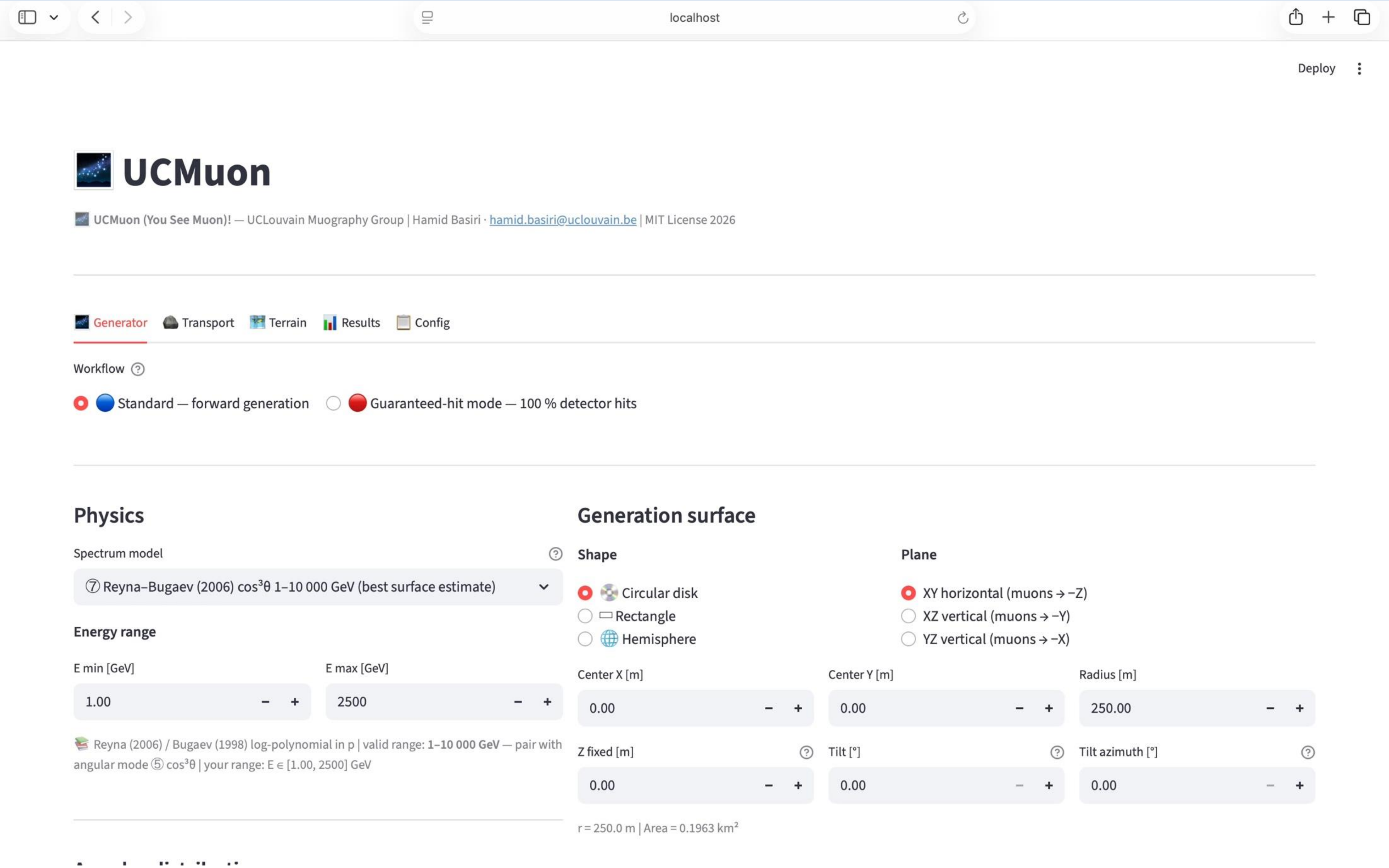
Ideon used borehole-format muon-tracking detectors deployed from surface, with an angular resolution of approximately 25 milliradians.

Geoptic





https://geoptic.co.uk/



UCMuon

UCMuon (You See Muon)! — UCLouvain Muography Group | Hamid Basiri · hamid.basiri@uclouvain.be | MIT License 2026

Workflow

● 🔵 Standard — forward generation ○ 🔴 Guaranteed-hit mode — 100 % detector hits

Physics

Spectrum model: ⑦ Reyna–Bugaev (2006) $\cos^3\theta$ 1–10 000 GeV (best surface estimate)

Energy range

E min [GeV]: 1.00

E max [GeV]: 2500

Reyna (2006) / Bugaev (1998) log-polynomial in p | valid range: **1–10 000 GeV** — pair with angular mode ⑤ $\cos^3\theta$ | your range: E ∈ [1.00, 2500] GeV

Generation surface

Shape

- ● Circular disk
- ○ ▭ Rectangle
- ○ 🌐 Hemisphere

Plane

- ● XY horizontal (muons → −Z)
- ○ XZ vertical (muons → −Y)
- ○ YZ vertical (muons → −X)

Center X [m]: 0.00

Center Y [m]: 0.00

Radius [m]: 250.00

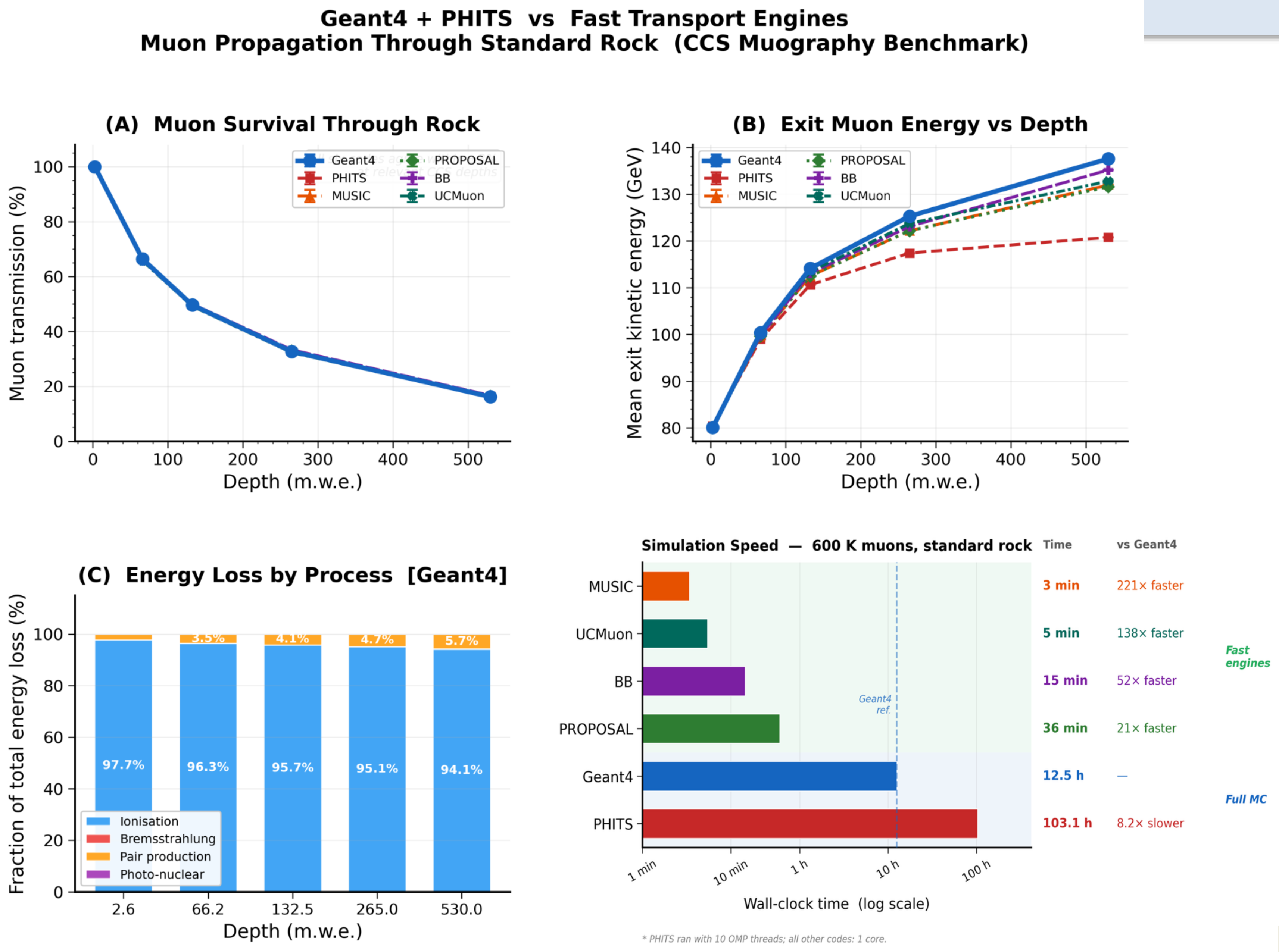
Z fixed [m]: 0.00

Tilt [°]: 0.00

Tilt azimuth [°]: 0.00

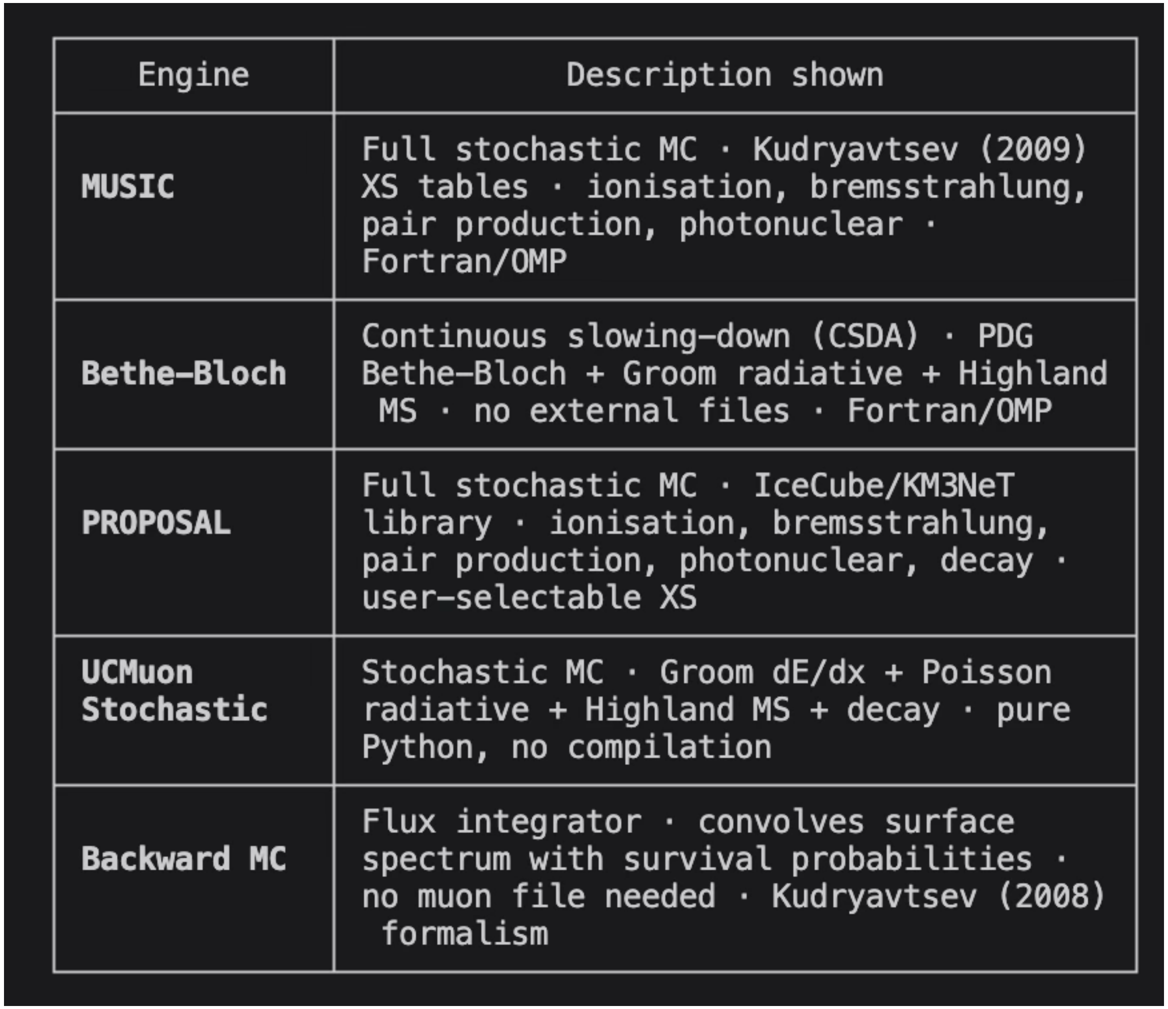
r = 250.0 m | Area = 0.1963 km²

Benchmark in rock slab using multi-energy vertical muon source



Geant4 + PHITS vs Fast Transport Engines
Muon Propagation Through Standard Rock (CCS Muography Benchmark)

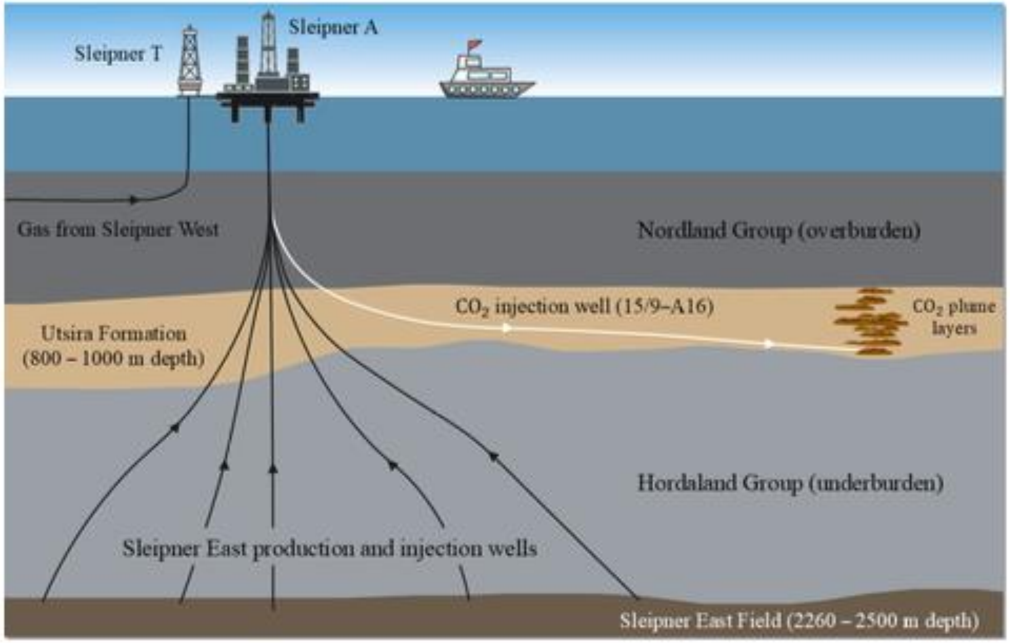
* PHITS ran with 10 OMP threads; all other codes: 1 core.



Engine	Description shown
MUSIC	Full stochastic MC · Kudryavtsev (2009) XS tables · ionisation, bremsstrahlung, pair production, photonuclear · Fortran/OMP
Bethe–Bloch	Continuous slowing–down (CSDA) · PDG Bethe–Bloch + Groom radiative + Highland MS · no external files · Fortran/OMP
PROPOSAL	Full stochastic MC · IceCube/KM3NeT library · ionisation, bremsstrahlung, pair production, photonuclear, decay · user–selectable XS
UCMuon Stochastic	Stochastic MC · Groom dE/dx + Poisson radiative + Highland MS + decay · pure Python, no compilation
Backward MC	Flux integrator · convolves surface spectrum with survival probabilities · no muon file needed · Kudryavtsev (2008) formalism

Sleipner CCS Project

- **Natural gas field** located in the North Sea, off the coast of Norway.
- Pioneering **carbon capture and storage (CCS)** technology.
- CO2 injection rate of about *1 million tons per annum (Mtpa).*
- Approximately **20 Mt CO2** has been stored.
- Can we (i) detect stacked Sleipner plumes and (ii) discriminate 25%, 50%, 100% layer-average saturation?

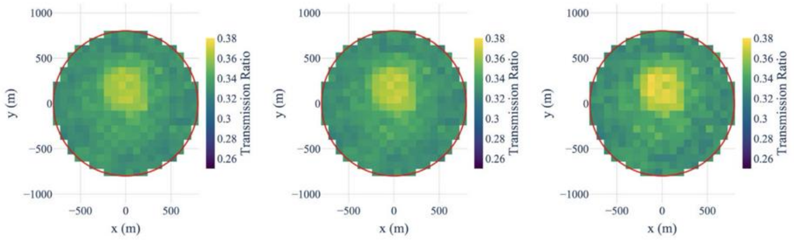


- Simplified geometry: seawater + overburden + reservoir with nine plume layers
- Vertical muons used for feasibility and runtime control
- Idealized large detection plane
- Muons with an energy of 500-2500 GeV
- 3 saturation levels of 25%, 50% and 100% (1.7 to 2.1 gr/cm3)

Basiri et al. (2026) Int. J. Greenhouse Gas Control 154, 104683

Physical Sensitivity to CO_2 Saturation: Key Results

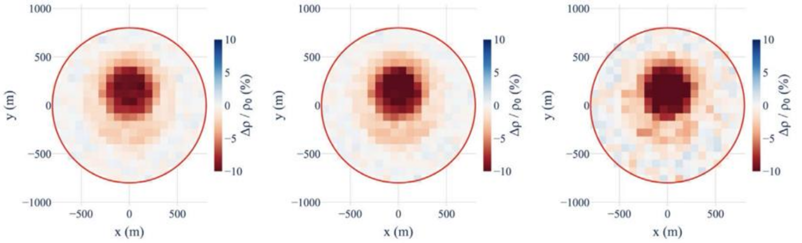
Muon Transmission Maps



(a) 25% CO_2 saturation (b) 50% CO_2 saturation (c) 100% CO_2 saturation

Transmission increases monotonically with $S^{c}O_2$; core enhancement +5.5% → +6.8%

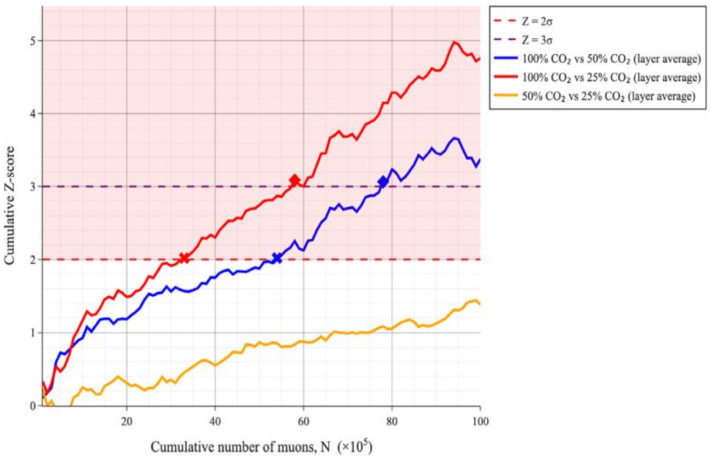
Path-Averaged Density-Deficit Maps (Δρ/ρ0)



(a) 25% CO_2 saturation (b) 50% CO_2 saturation (c) 100% CO_2 saturation

9-layer plume geometry spatially recovered; deficit grows monotonically with saturation

Cumulative Z-Score vs. Accumulated Muons



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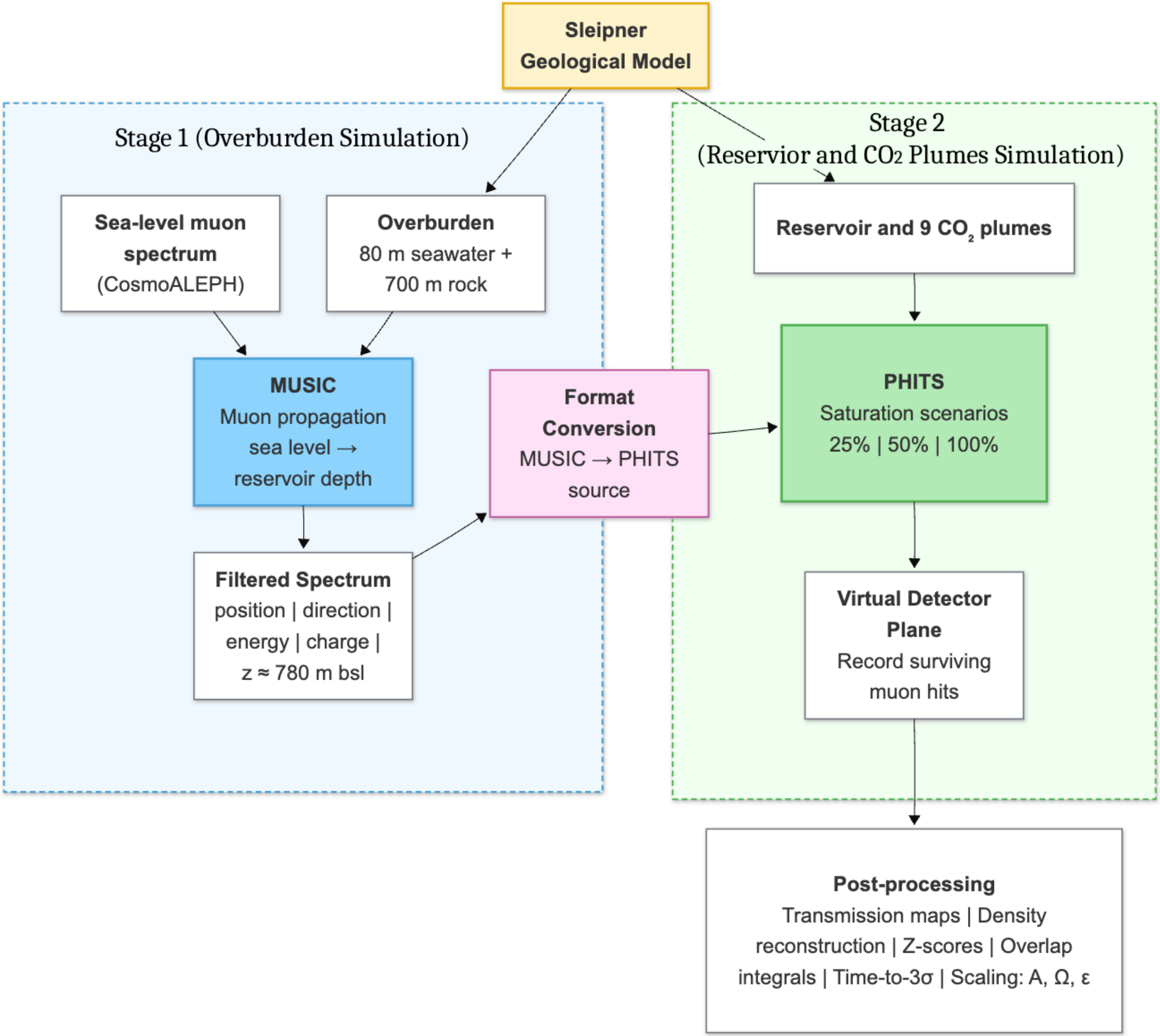
Statistical Discriminability Summary

Comparison	Z-score	Misclassif.
100% vs. 50%	**≥ 3σ**	1.7%
100% vs. 25%	**≫ 3σ**	0.1%
50% vs. 25%	**< 2σ**	**33%**

Key takeaway: 100% vs. 50% separated at ≥ 3σ with 10^7 muons. Discriminating 50% vs. 25% needs ~4× more muons. All results conditional on idealized simulation assumptions.



Sleipner Geological Model

Stage 1 (Overburden Simulation)

Sea-level muon spectrum (CosmoALEPH)

Overburden 80 m seawater + 700 m rock

MUSIC Muon propagation sea level → reservoir depth

Filtered Spectrum position | direction | energy | charge | $z \approx 780$ m bsl

Format Conversion MUSIC → PHITS source

Stage 2 (Reservior and CO_2 Plumes Simulation)

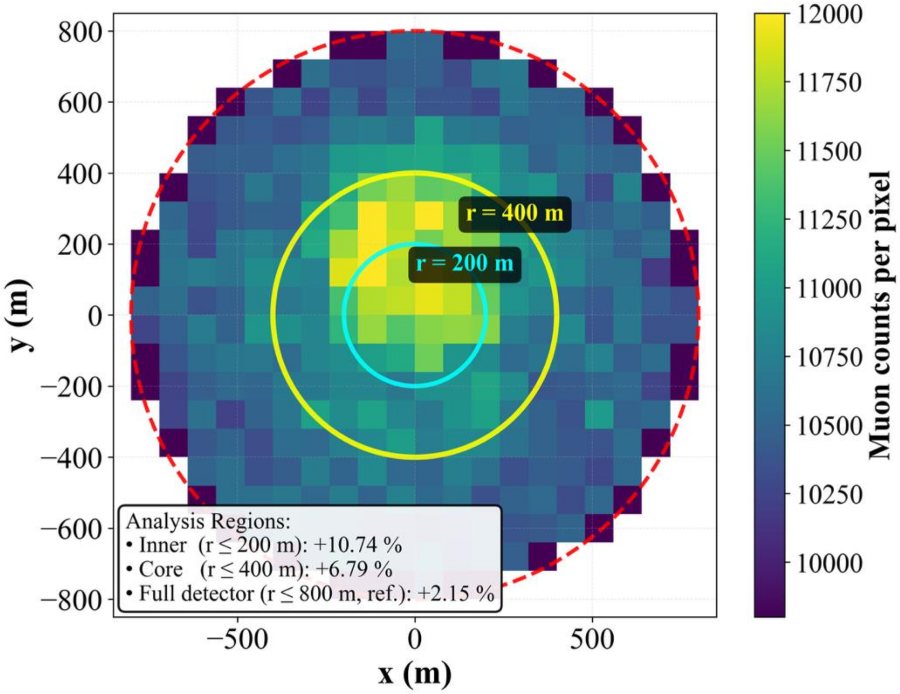
Reservoir and 9 CO_2 plumes

PHITS Saturation scenarios 25% | 50% | 100%

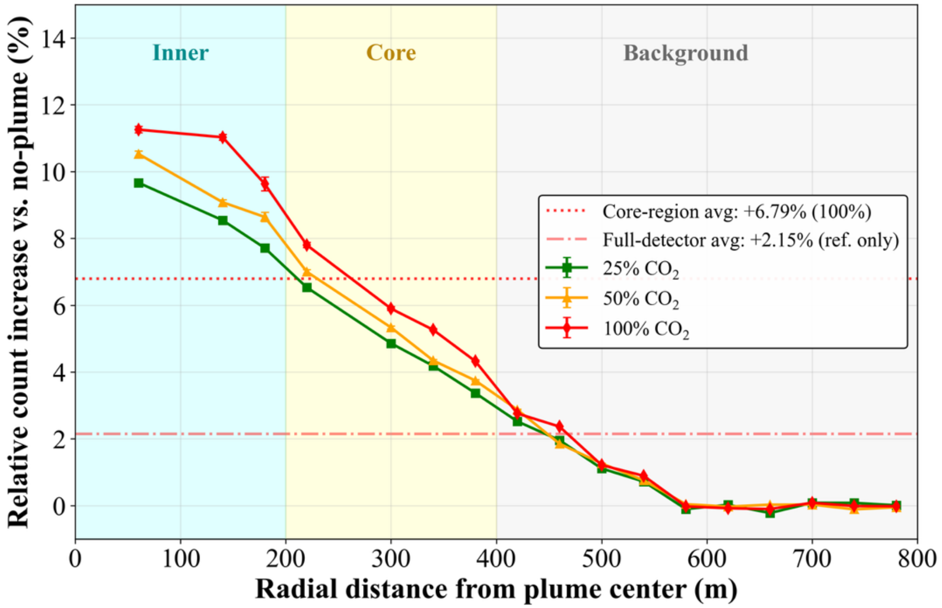
Virtual Detector Plane Record surviving muon hits

Post-processing Transmission maps | Density reconstruction | Z-scores | Overlap integrals | Time-to-3σ | Scaling: A, Ω, ε

Spatial distribution and radial dependence of the plume detection signal



(a) Muon count map for 100% CO_2 saturation with inner (cyan, $r \leq 200$ m), core (yellow, $r \leq 400$ m), and full-detector reference (red dashed, $r \leq 800$ m) regions overlaid.



(b) Relative count increase vs. radial distance for three saturation levels. Dotted line: core-region average (+6.79%). Dash-dot line: full-detector average (+2.15%, reference only). Signal decays beyond $r \approx 600$ m.

Svelvik CO_2 Field Lab

Small-Scale Open-Access CCS Monitoring Testbed · Norway

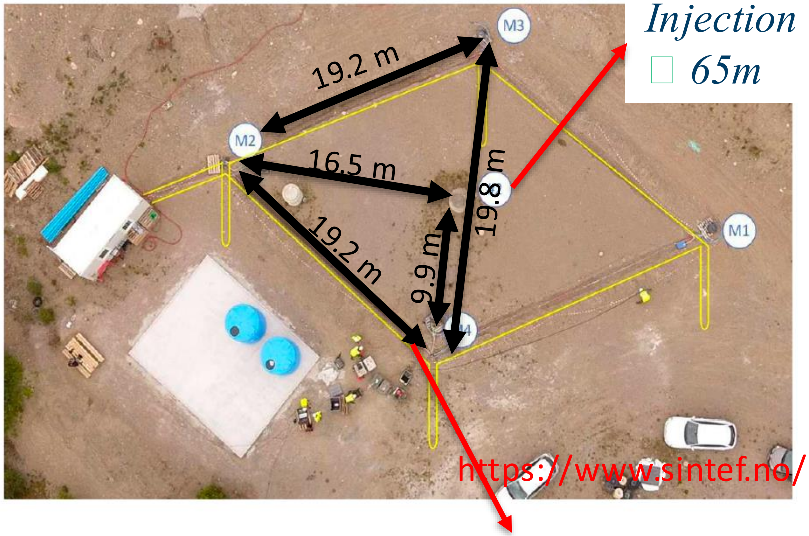
Site Overview

- *Svelvik CO_2 Field Lab is a unique multi-method testbed enabling repeatable, controlled CO_2 injection experiments with simultaneous seismic, electrical, fibre-optic monitoring.*
- **Location:** ~50 km south of Oslo, Norway.
- SINTEF-owned

Deployable Monitoring Methods

Seismic	ERT	Muography
Cross-well, VSP & surface P- & S-wave; DAS receivers; hydrophones	4D electrical resistivity tomography for fluid migration tracking	Borehole muon detectors (plastic scintillator, 60 mm Ø) 13 units per borehole

Well Configuration



Injection well
☐ 65m

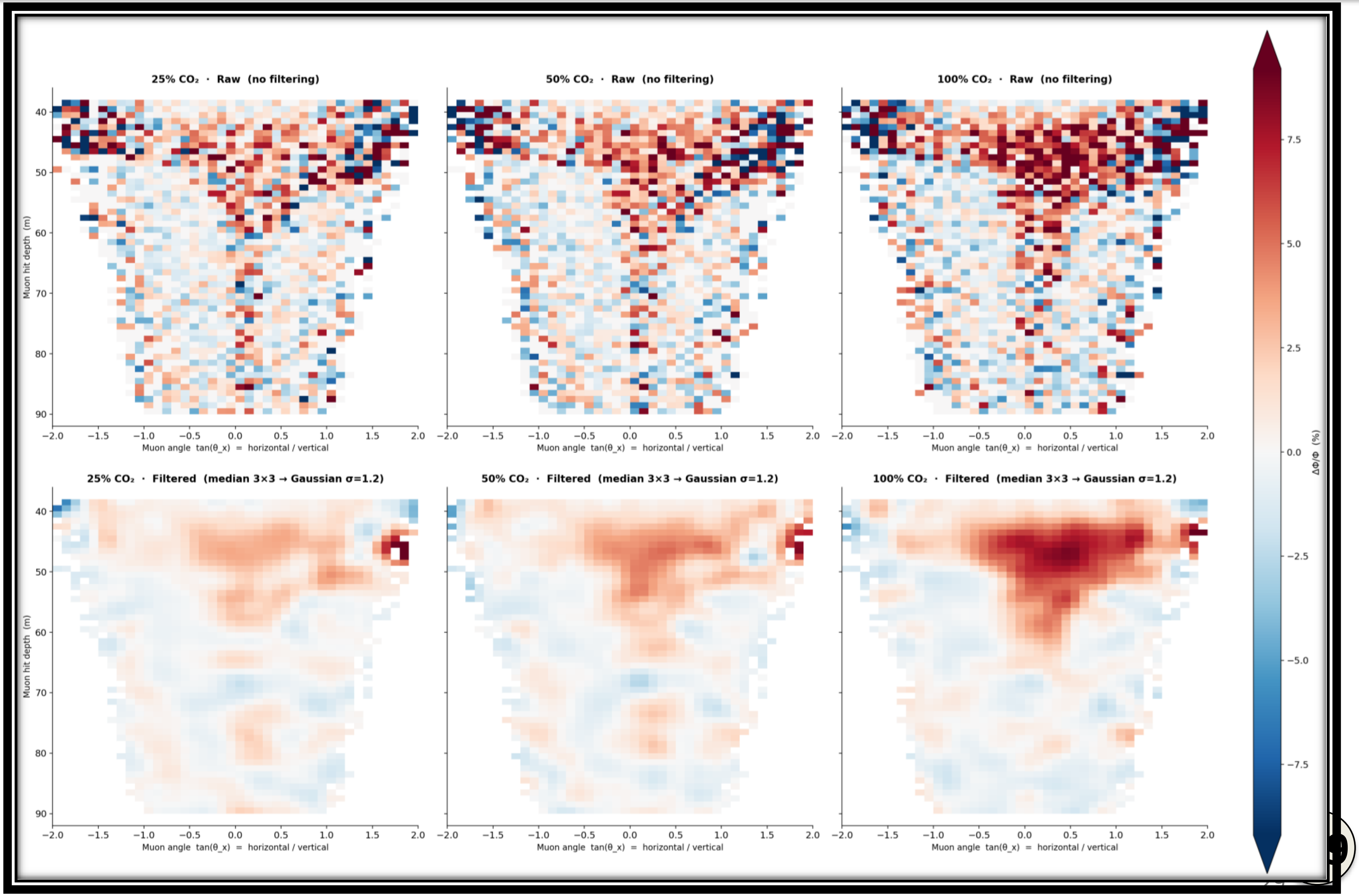
https://www.sintef.no/

- *M1, M2, M3, M4 are observation wells 100m*

Oct–Nov 2023 campaign: 3,687.7 kg CO_2 injected over 30 days· Muon imaging detected ~5% flux increase in plume zone ·

Injection rate is about 8 kg/hour (around 200 kg/day).

# Signal density maps · raw vs filtered · 25 / 50 / 100% CO_2 saturation · Detector M3
Colour = ΔΦ/Φ (%) · shared range ±9.2% · red = less dense (CO_2) · blue = denser



Solution 2 Geometric and energy threshold filtering

Source Biasing (Applied before any particle transport)

1. Select a min energy threshold based on the overburden thickness and sample the sample the surface-level cosmic-ray muon flux.
2. For each muon, trace its trajectory geometrically. If its straight-line path does not intersect the detector acceptance cone, discard it immediately.
3. Pass only the surviving (selected) muons to the transport code (e.g., PHITS, Geant4, Geant4, MUSIC).

↓

✓ We save enormous computational time by never transporting muons that have zero chance of reaching the detector.