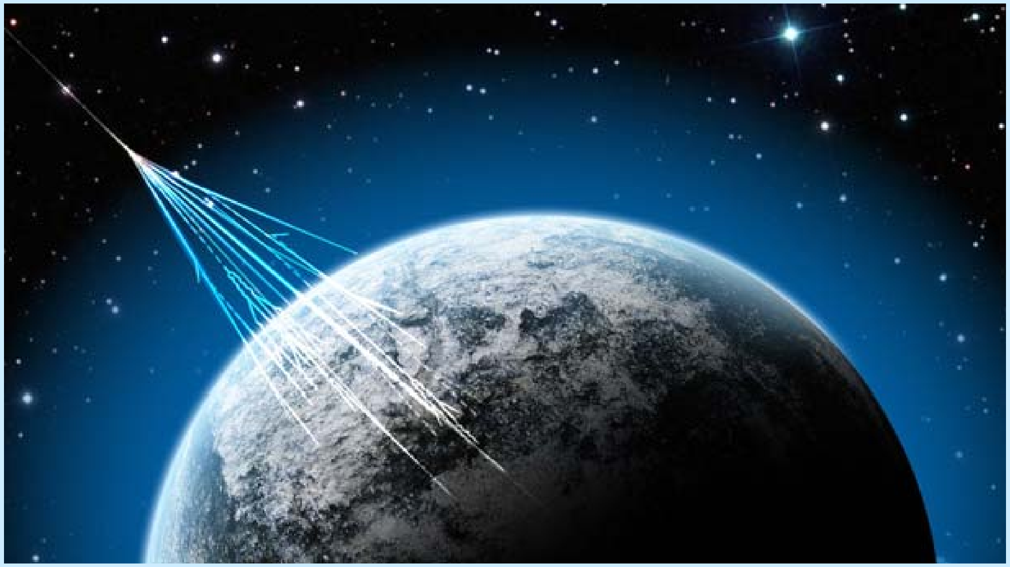
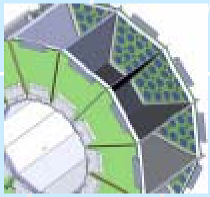
# Geological Exploration and Tomography with Cosmic Ray Muons: A new Application of Particle Physics Technologies



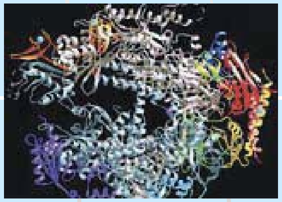
Douglas Bryman
University of British Columbia

# Particle Physics: Benefits to Society



**Medicine**
- Cancer therapy with x-rays, protons, neutrons, heavy ions
- Medical diagnostics e.g. PET

**Accelerators - Sciences**
- Synchrotron radiation facilities
- Biomedicine, drug development
- Protein structure analysis, materials science, archeology,…



**Computing**
- World Wide Web
- GRID computing

**Geophysics – particle / nuclear techniques e.g. NaI(Tl)**

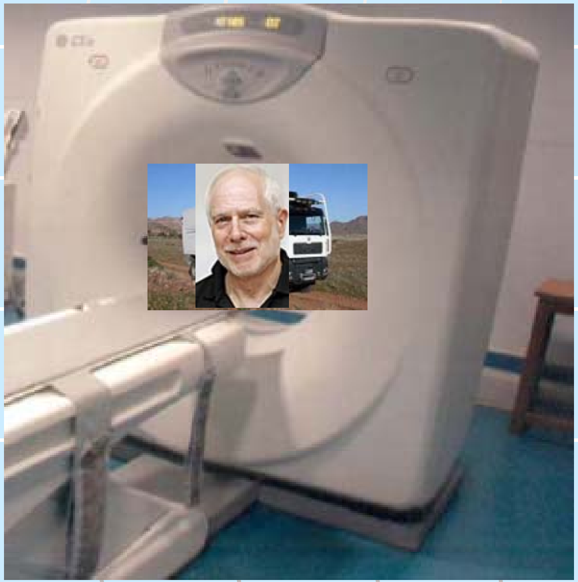
**Security – monitoring nuclear waste, reactors, smuggling…**

**Power transmission with superconducting cables**

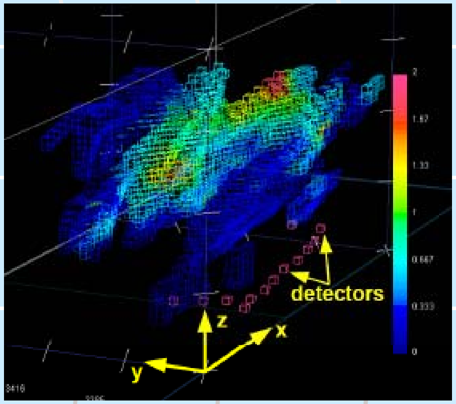
Thanks to Fermilab.

# Muon Tomography:
# "CAT Scans" for the Earth and Large Objects

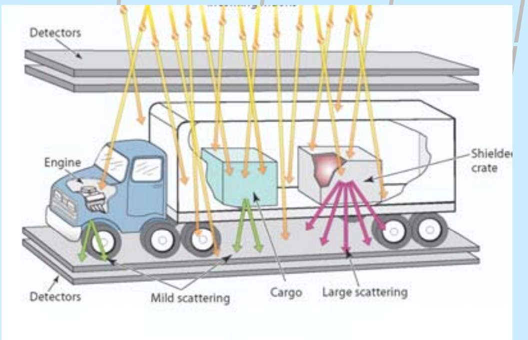
Medical Imaging
CAT Scan



Muon Geotomography

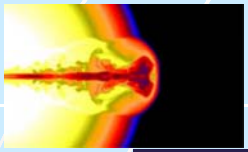



**Muon Tomography for Security Applications**



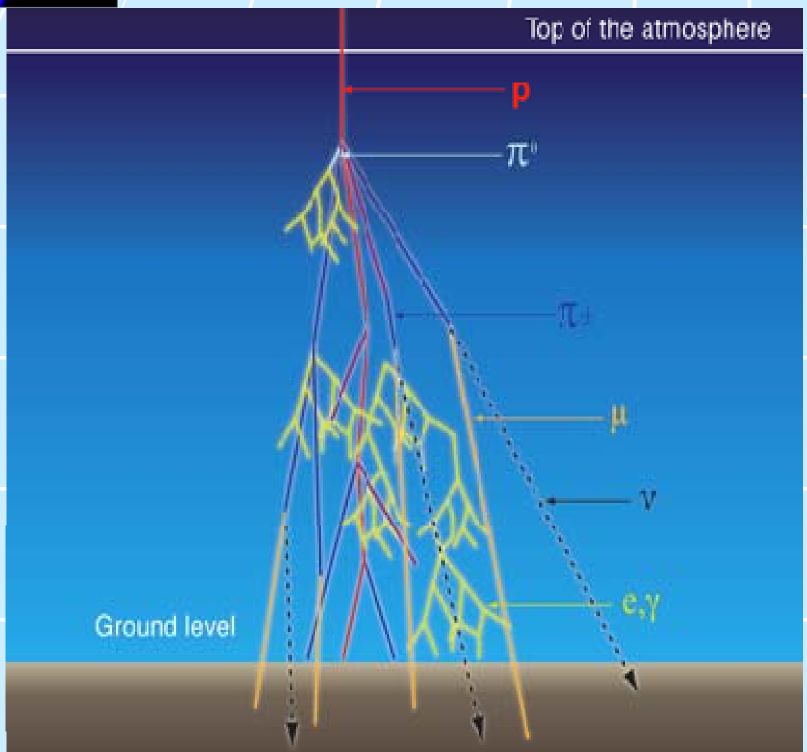
# Cosmic Rays

Star Collapse → gamma ray burst

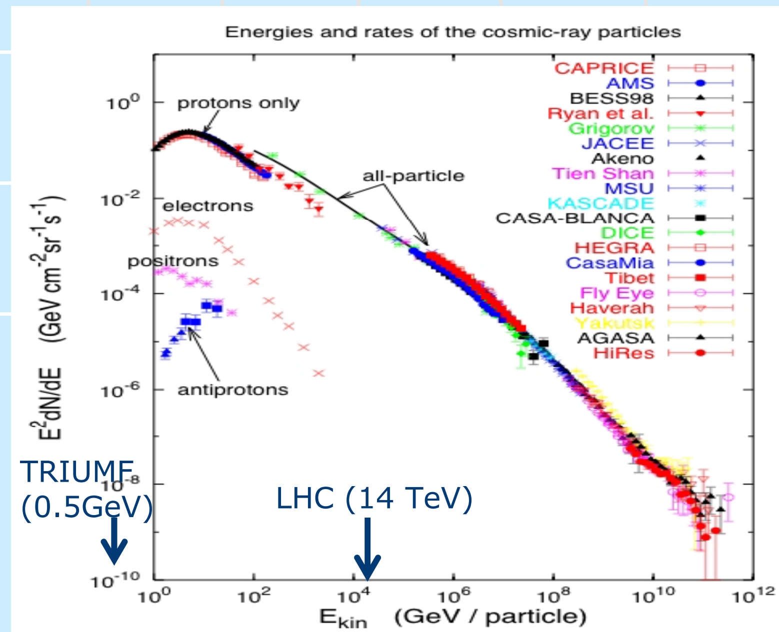


Black Holes

Nature accelerates cosmic rays $10^7 x$ LHC!








Energy (E): Electron Volts (eV)

eV = energy gained by an electron in a potential of 1 Volt

$\text{MeV} = 1{,}000{,}000 \text{ eV} = 10^6 \text{ eV}$

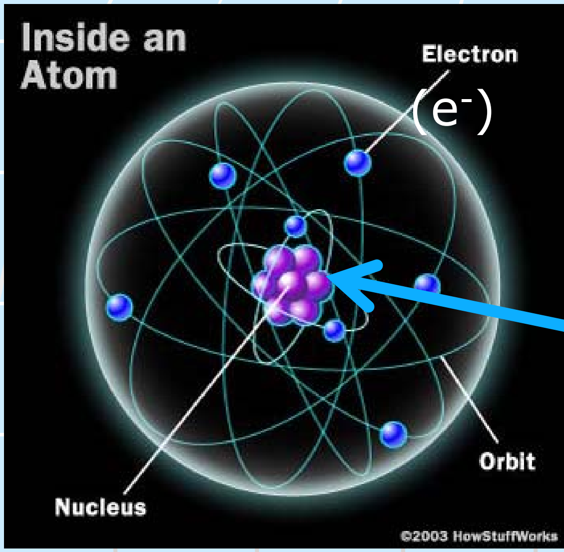
$\text{GeV} = 10^9 \text{ eV}$

$\text{TeV} = 10^{12} \text{ eV}$

T. Gaisser 2005

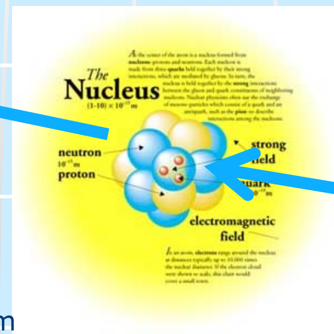
# Muons: “Who ordered that?”

I.I. Rabi
1936



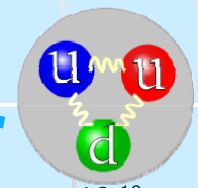

$10^{-10}$ m

Inside the Nucleus:
**Protons (p)**
**and neutrons (n)**




$10^{-15}$ m

Inside the protons
and neutrons: **Quarks**




$<10^{-19}$ m

Proton $(p)$: uud

Neutron $(n)$: udd

Pion$(\pi)$: $u\bar{d}$

**Three Generations:**

Quarks

Leptons

3 “electrons”

**Mass (MeV/c²)**

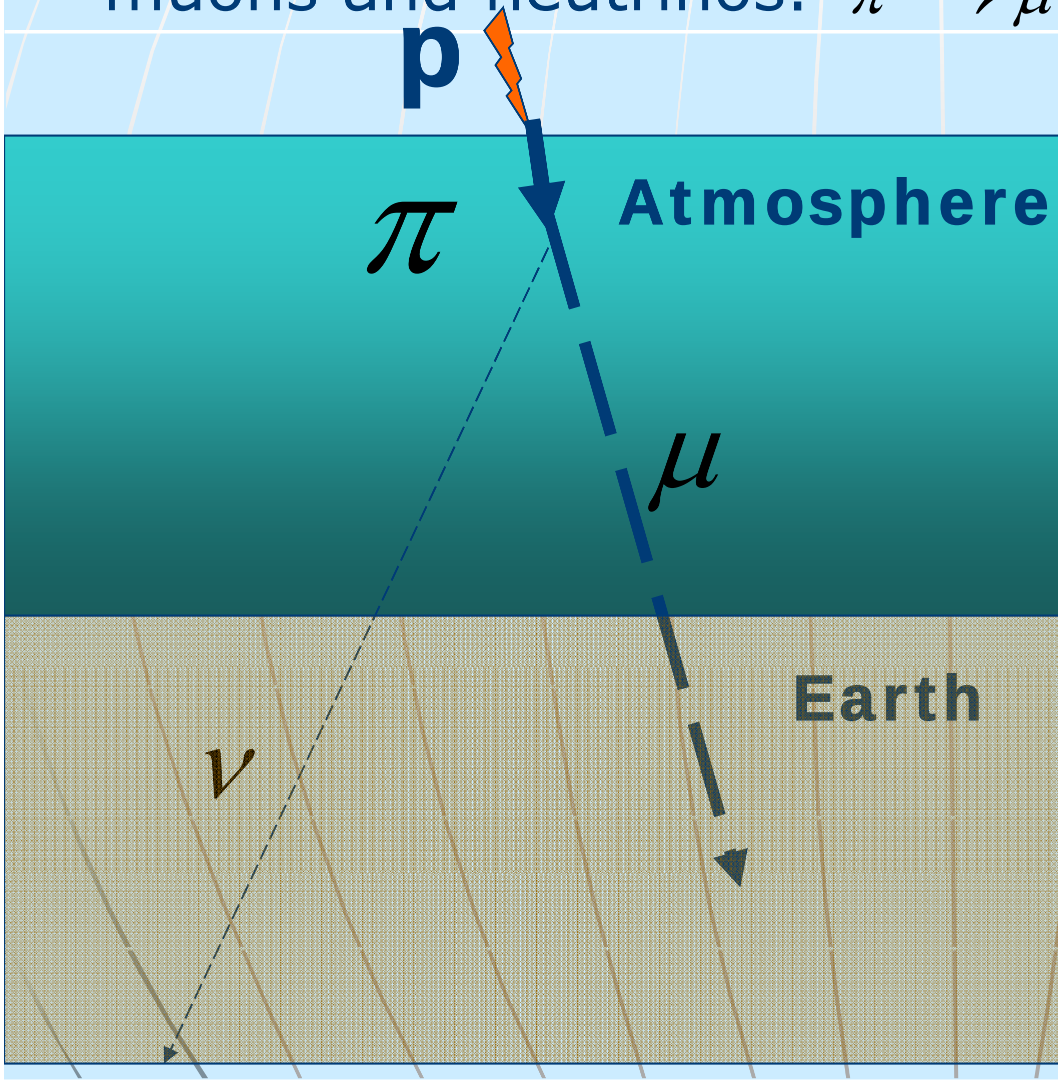
Ordinary
Matter


0.5
106
1777

Charge: +2/3 -1/3 0 -1

# Cosmic Ray Muons

High energy protons impinging on the upper atmosphere produce pions (kaons) which decay to muons and neutrinos. $\pi^+ \to \mu^+ \nu.$




Muons ($\mu$) are "heavy electrons".

Mass: $m_\mu = 105.6\,\mathrm{MeV/c^2}$

$m_e = 0.511\,\mathrm{MeV/c^2}$

$$m_\mu = 207 m_e$$

Muon Decay $\mu^+ \to e^+ \nu_e \nu_\mu$

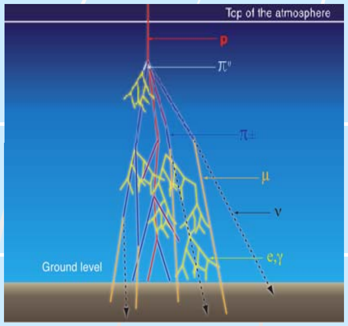
Lifetime $\tau_\mu = 2.2 \mu s$

High energy muons can penetrate the atmosphere and go deep into the earth.

# How do muons survive the trip?

Muon Lifetime: $\tau_\mu = 2.2x10^{-6}s$ ("2.2 micro-seconds")

100 km




Distance = velocity x time

$$< c\tau_\mu = 3x10^8 \frac{m}{s} x2.210^{-6} s = 660m$$

**Einstein's theory of Special Relativity:**

- The speed of light is constant
- Space and time depend on an observer's state of motion

**Consequence: Moving clocks run slow.**

From our point of view, the moving muon lasts much longer than if it were at rest. For the muons we're interested in at 1 TeV the "time dilation" factor is 10,000!

# Cosmic Ray Muons at Sea Level

High energy muon flux : $\sim 1/\mathrm{cm}^2/\mathrm{min}$. $(70/\mathrm{m}^2/\mathrm{s/sr})$

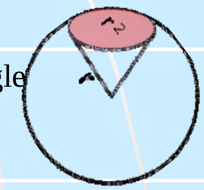
(High Energy $\geq$ 1 GeV)

(Mean Energy = 4 GeV)

$sr$ = Steradian

Unit of solid angle

Sphere=$4\pi$ sr

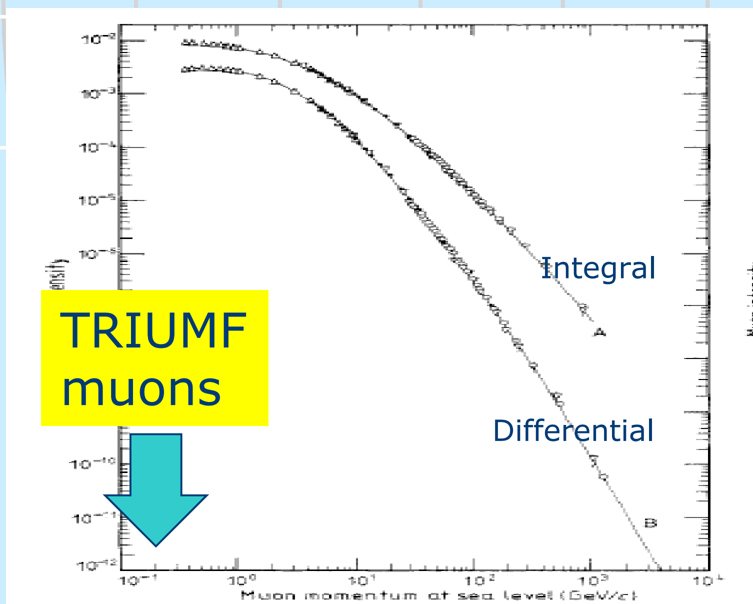


$\{\text{Neutrinos from the sun: } 10^{10}/cm^2/s\}$

Cosmic Ray Muon Intensity vs. Momentum (GeV/c)

*Intensity*

$cm^{-2}s^{-2}sr^{-1}(GeV/c)^{-1}$



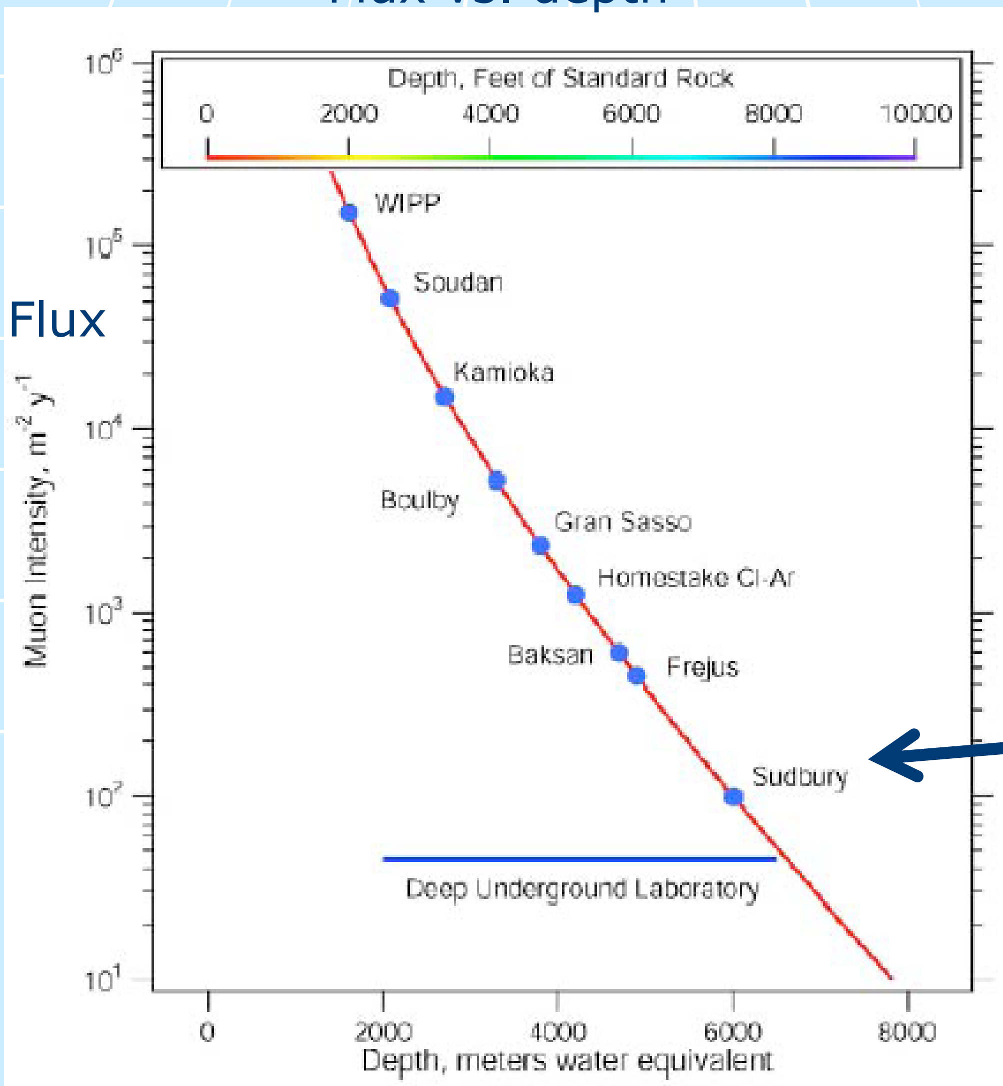

B Rastin J. Phys. G: Nucl. Phys. 10 (1984) 1609–1628.

$P(GeV/c)$

# Underground Physics Labs: Going Deep to Avoid Muons!

Flux vs. depth

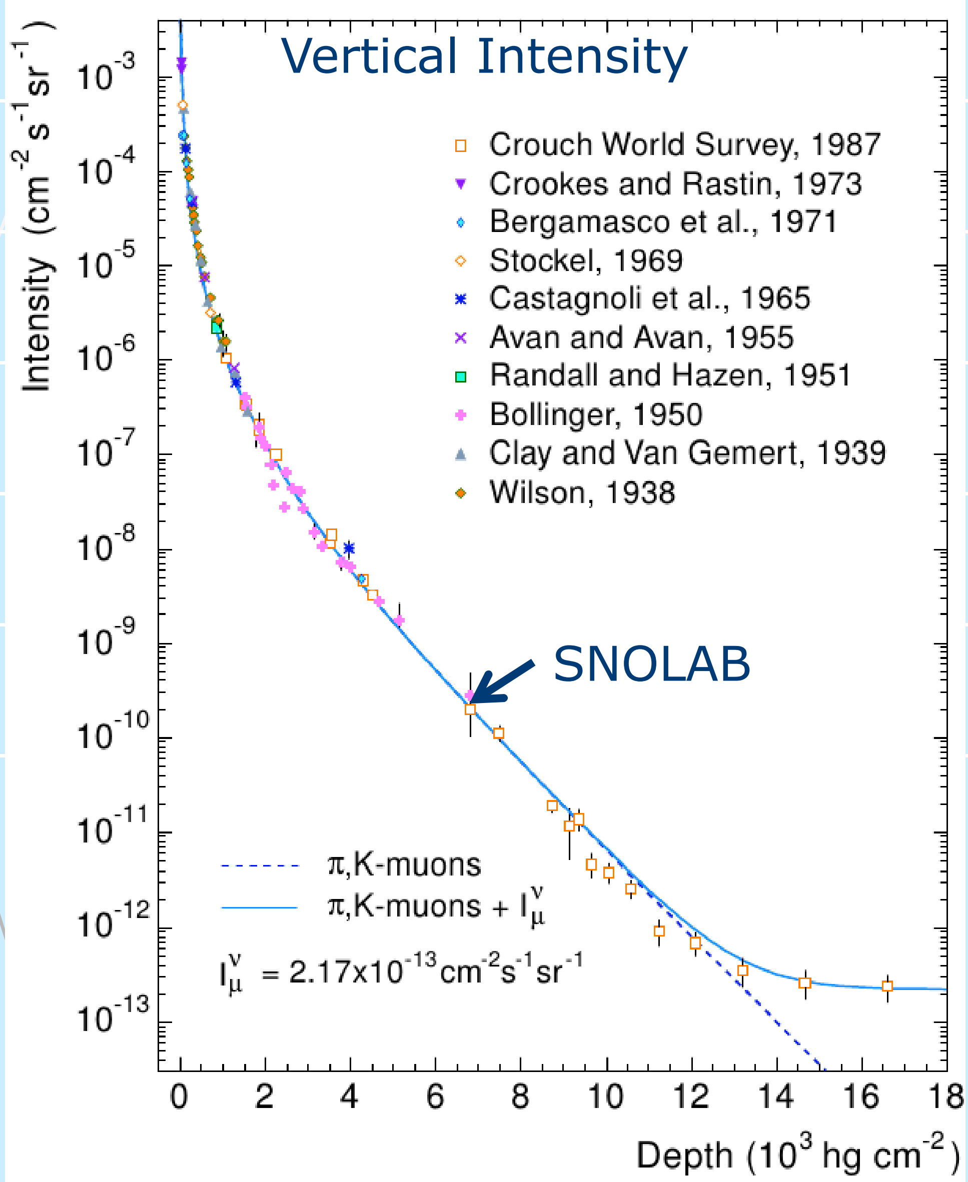
Flux




Sudbury, ON
Canada's
**SNOLAB**
Underground
Research Lab

Depth (Meters Water Equivalent)
(from Hime et al. 2005)

# CR Muon Intensity Underground




Muon flux is attenuated by passage though the earth :

$70 / m^2 / s / sr$ (surface) $\rightarrow$

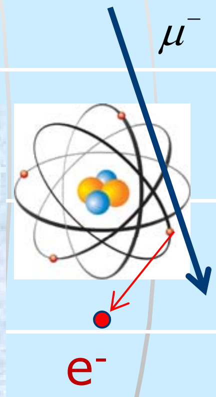
$0.01 / m^2 / s / sr$ (400 m rock)

Muons lose energy in materials principally by ionization:

$$\frac{dE}{dx} \sim 0.6 \text{ GeV/m}$$

in standard rock

$\rho_{rock} \sim 2.7 g / cc$



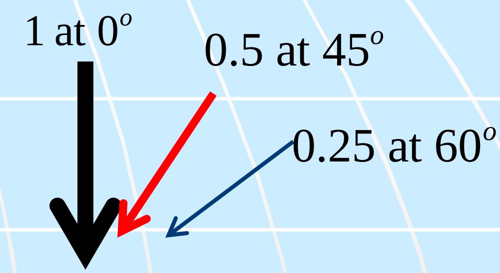



E. V. Bugaev *et al.*,PRD 58 054001 (1998)

# Angular Variation of the Cosmic Ray Spectrum

Angular distribution at ground level

$\sim \cos^2\theta$ for $E_\mu \sim 3GeV$




Intensity vs. Depth Underground

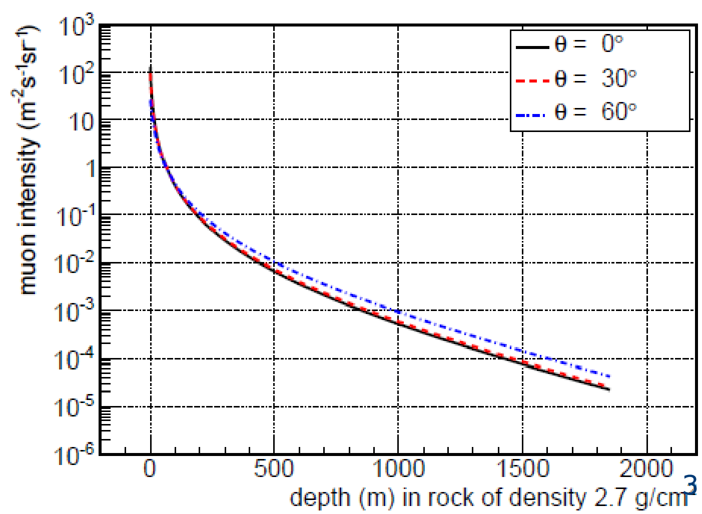



Figure 1: Cosmic ray muon depth-intensity relationship for three zenith angles, derived from Bogdanova et al. (2006).

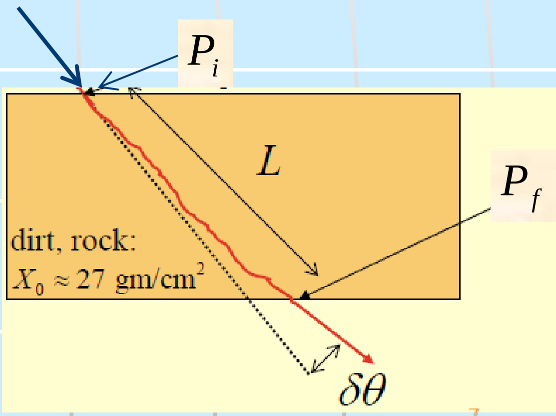
# Muon Scattering

"Multiple Coulomb Scattering"

**High energy muons undergo minimal scattering –**
**travel in ~straight lines**

$$\delta\theta \sim \frac{13.6MeV}{\sqrt{P_i P_f}} \sqrt{\frac{L}{X_0}}$$

$$P_i - P_f = L\frac{dE}{dx}$$




Angular deviation for P> 300 GeV: δθ≤10 mrad;

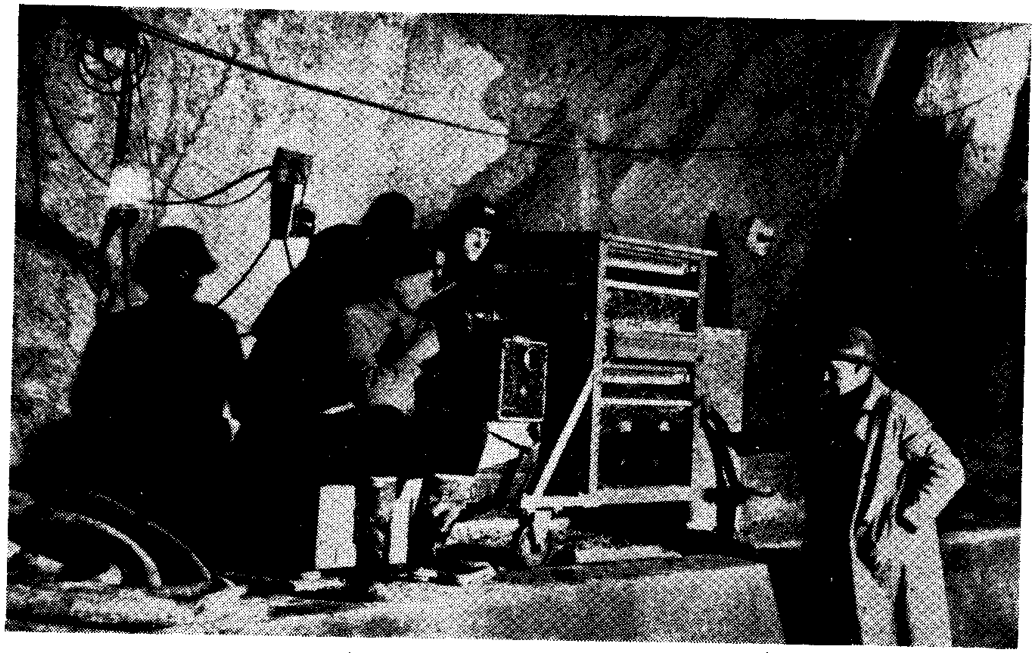
*10 mrad:* ***1 m at 100 m.***

# Cosmic Ray Tomography

Commonwealth Engineer, July 1, 1955



## Cosmic Rays Measure Overburden of Tunnel



● Fig. 1—Geiger counter "telescope" in operation in the Guthega-Munyang tunnel. From left are Dr. George and his assistants, Mr. Lehane and Mr. O'Neill.

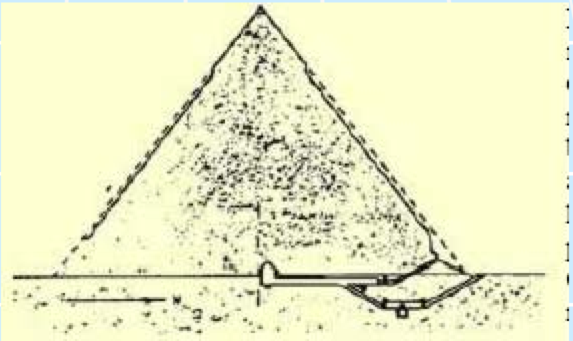
**Geiger counter telescope used for mass determination at Guthega project of Snowy Scheme . . . Equipment described**

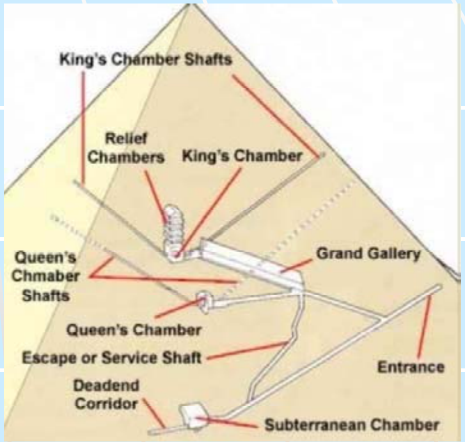
By Dr. E. P. George*
University of Sydney, N.S.W.

**Luis Alvarez**
**1965**

***Cosmic ray muons used to search for chambers at Giza.***

Khufu's Great Pyramid






*L.W. Alvarez et al., Science 167 (1970) 832.*    *Photo Source: www.touregypt.net/featurestories/**secretchambers1**.htm by Alan Winston*

# “Super-K” Muon Tomography

Kamioka Mountain Lab

Google Earth

**100 m contours – constant density**

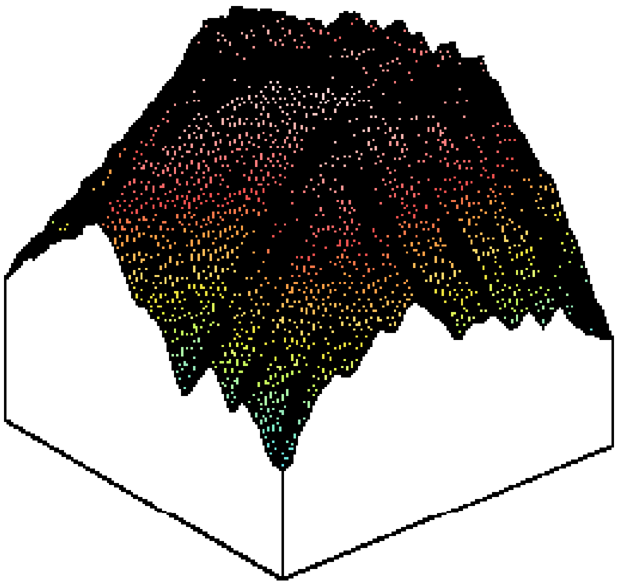


*Fig. 2: Topographic maps of the mountain housing the Super-Kamiokande instrument made with downgoing muon data. The view is towards the East, from 15 degrees elevation.*

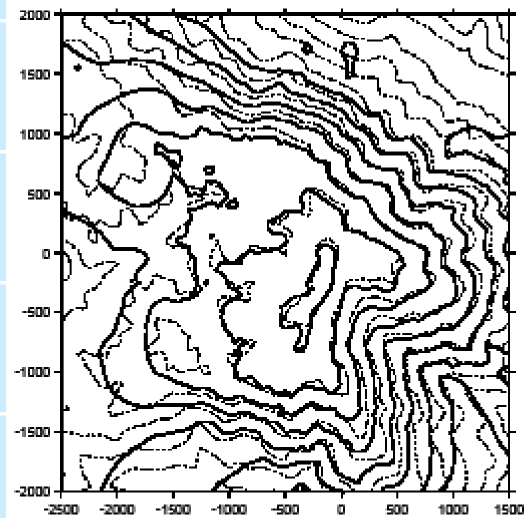



*Fig. 3: Topographic map calculated from the observed muon flux at the Super-Kamiokande detector superposed on the geodetic map (dashed contours). The contours are at 100 m intervals, the scale is in m, and the top is SE.*

Lab Depth ~ 2750 m.w.e.

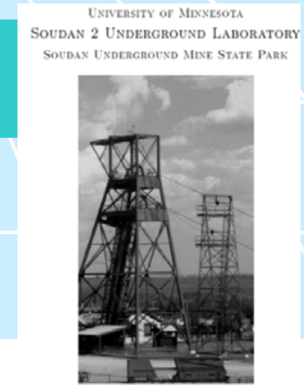
**Kamioka zinc mine (Japan)**

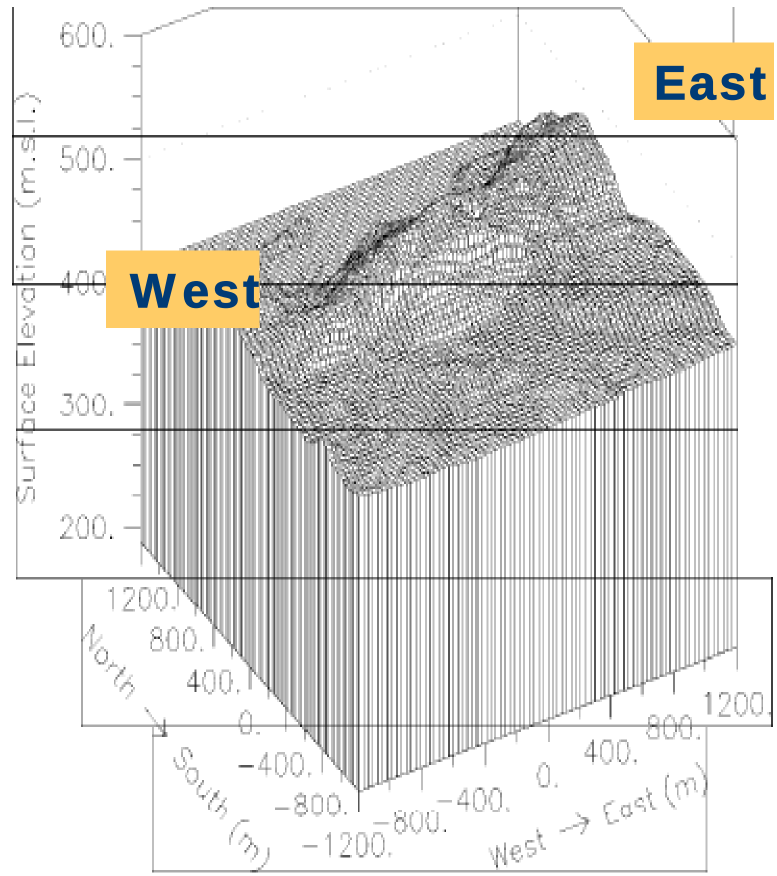
. G. Learned, 25th ICRC, DuJrban So. Africa  (1997).

# Soudan2 Muon Tomography

S. Kasahara, University of Minnesota Ph.D thesis (1997).

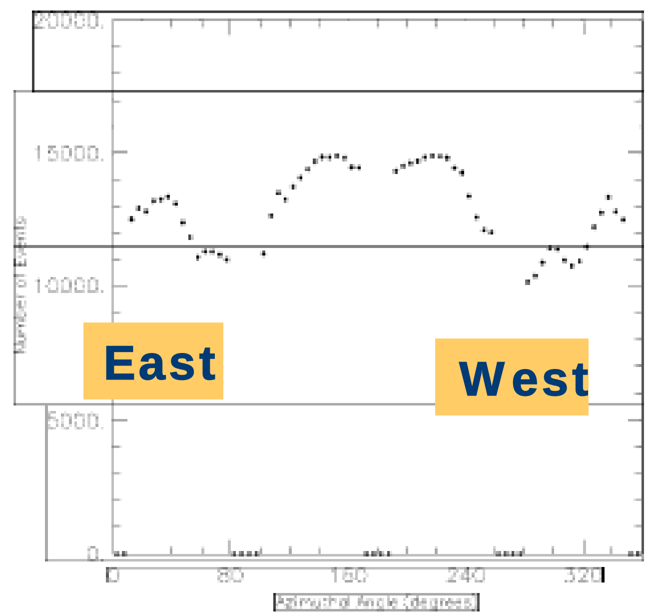
**Soudan, Minn. Iron mine.**
**Depth: 2000 m.w.e (700 m rock)**




Average rock density

$< \rho > \sim 2.8\ \mathrm{g/cm}^3$




igure 4.17: Azimuthal angle distribution of single muon events.

***Uniform density; a good approximation.***

# Practical Applications of Muon Geotomography

**"CT Scanning of the Earth and more"**

- **Studying volcanoes**
- **Exploring for Underground Minerals**

**High density ores like zinc, nickel, copper, U…)**

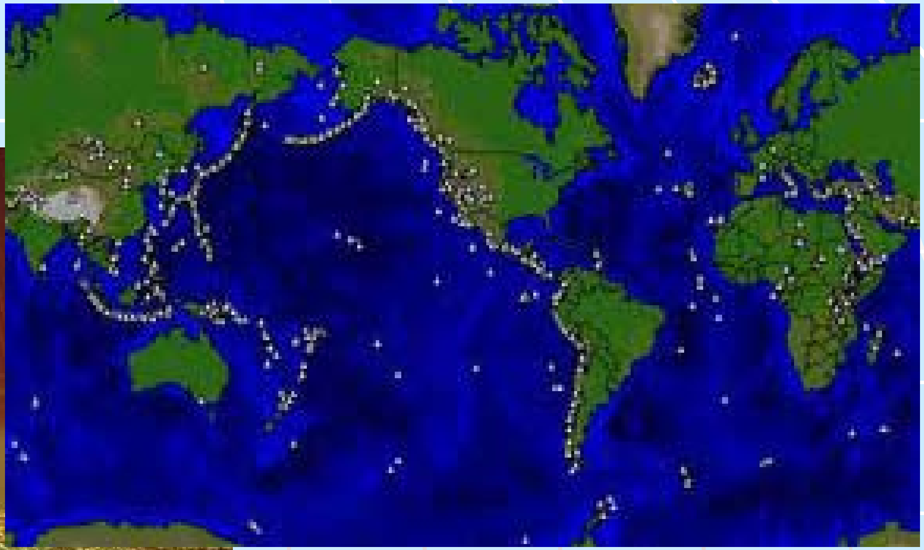
- Ore delineation
- Reserves assessment/appraisal
- Mine development
- Developed mine (brown field) applications
- Green field – bore hole application

Eruption of Mt. Vesuvius in AD 79

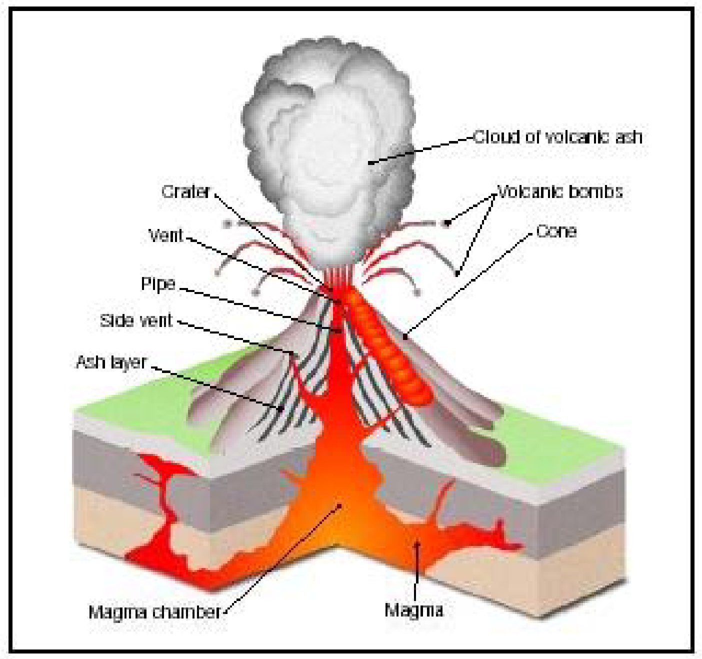

**Pompeii**

**Karl Brullov - The Last Day of Pompeii**

# Active Volcanoes



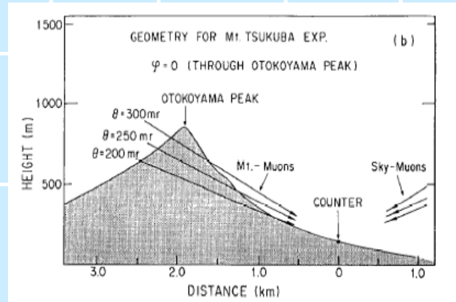
Mt. Etna – near Catania, Sicily

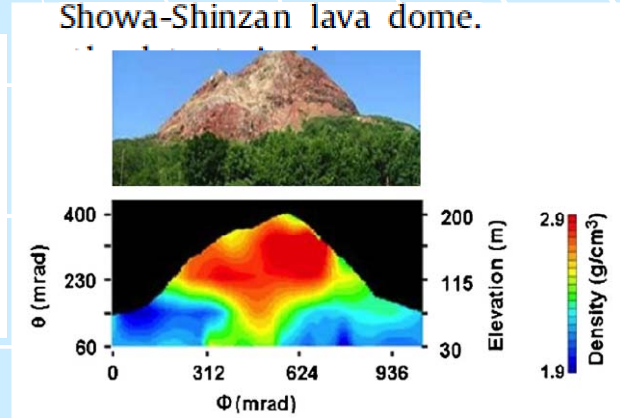


# Muon Tomography at an Active Volcano

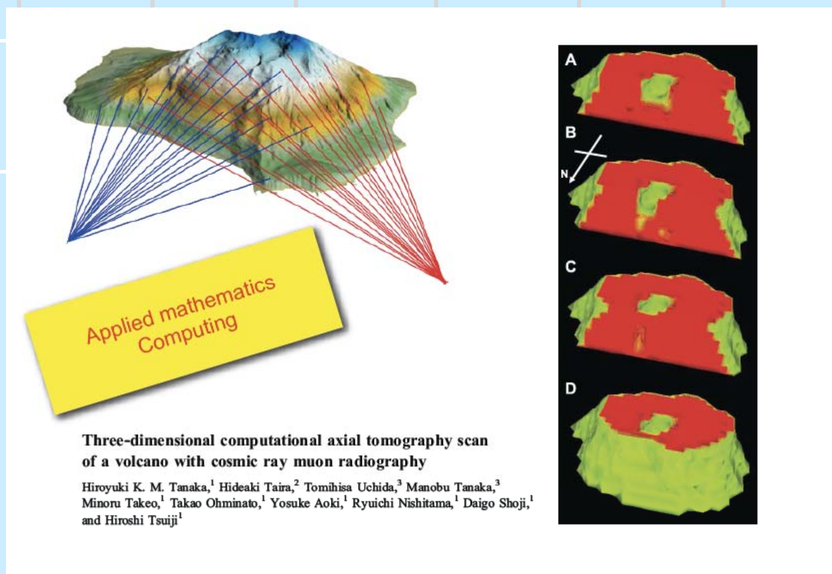
**Nagamine *et al.* (1995, 2003)**

***Used horizontal cosmic ray muons to look for magma chambers at the top of Tskuba volcano.***



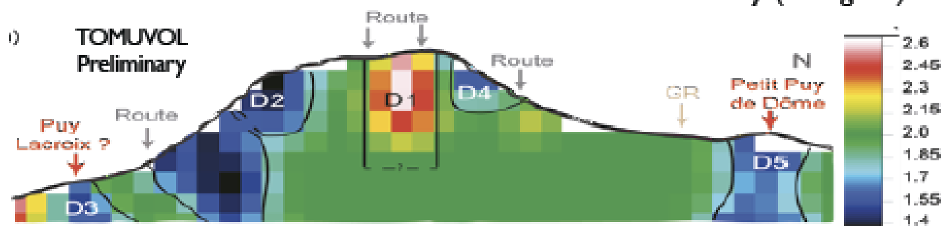

Marteau et al. 2012

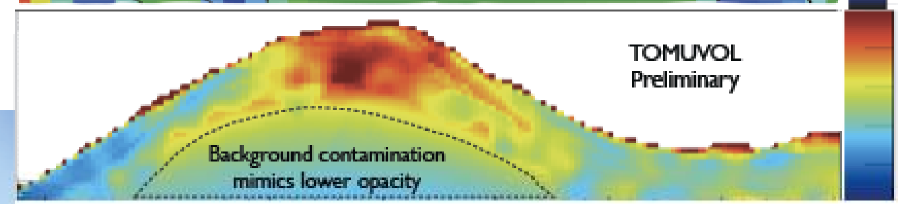


# Monitoring, Studying Volcanoes


Puy de Dôme Inner Structure, imaged through gravimetric tomography (top right) and with atmospheric muons (bottom right)

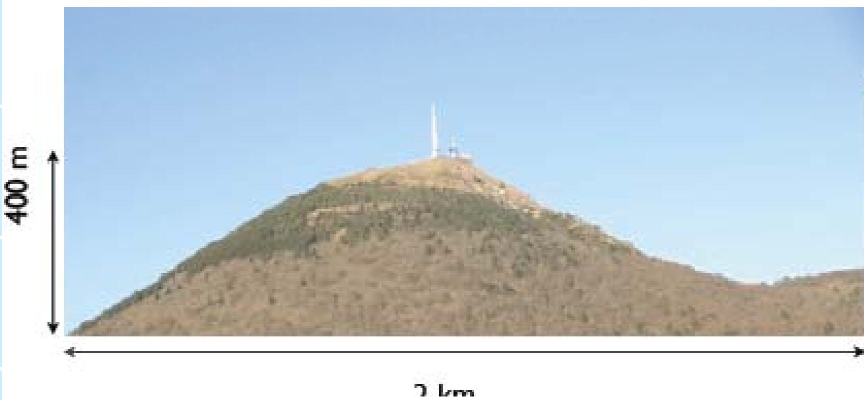
Gravity

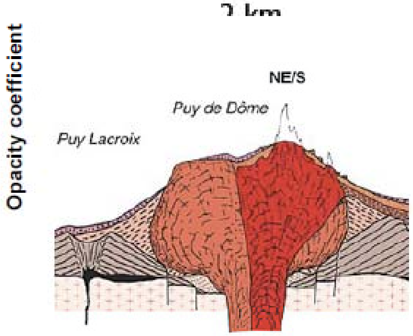



Linear opacity to atmospheric muons

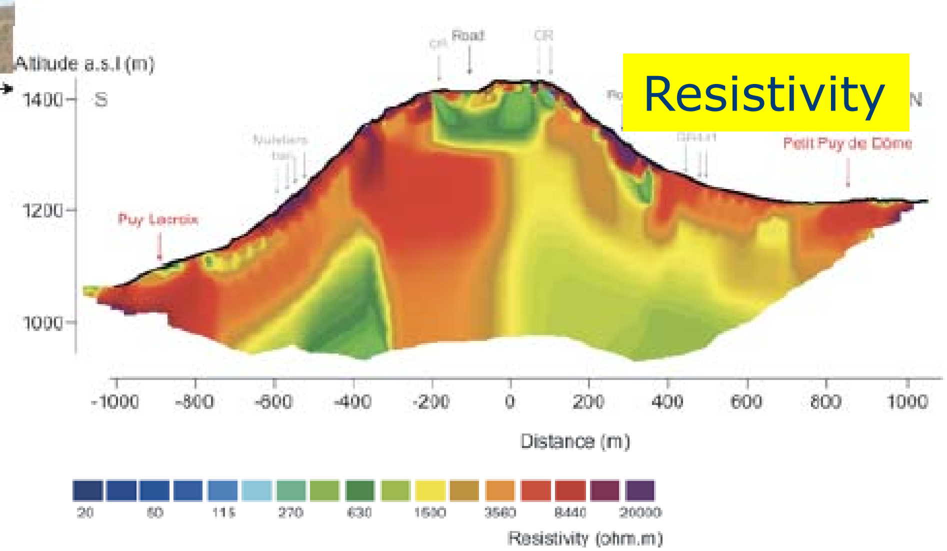
Muon Tomography




*Artiste view `Volcanologie de la chaine des Puys`, EAVUC*

Resistivity




C. Cargolanu LPC Clermont-Ferrand

# Exploration Geophysics Imaging Techniques

## Airborne Electromagnetic Induction Studies

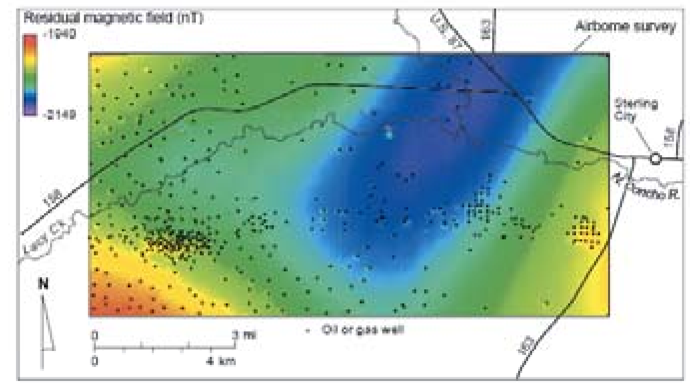



**Figure 4:** Residual magnetic field intensity measured during the Sterling airborne survey. Also shown are oil- and gas-well locations and pipeline locations from the RRC.

Groundwater salinization and resource study in oil well and gas pipeline area

## Arctic E-M Induction Studies

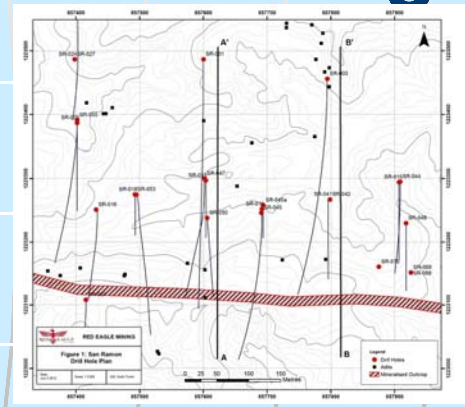
Jamin Cristall – Geophysicist Cameco (UBC Physics/Engineering Graduate 2002)

# Exploration Geophysics Imaging Techniques

- Seismology
- Gravity
- Magnetic methods
- Electric methods
  Resistivity, IP, potentials, radar

  ...

**Hit-or-miss Core Drilling**

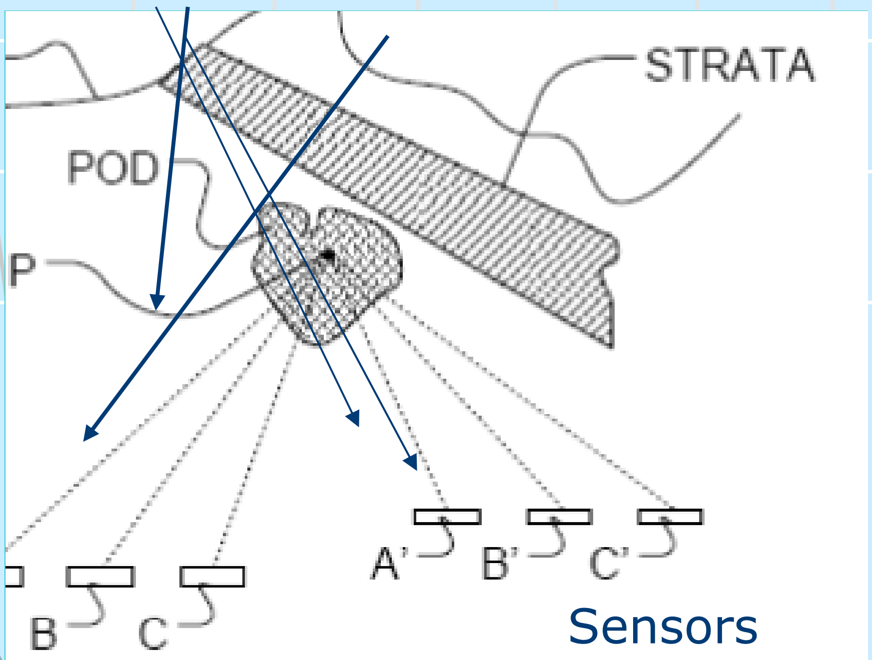


Muon Geotomography?

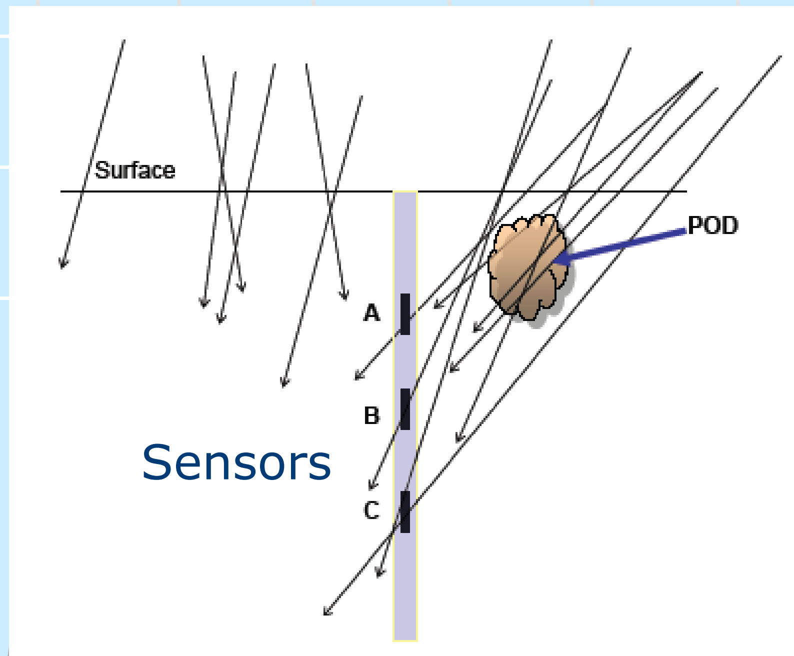
# Geological Tomography and Exploration with Cosmic Rays

Attenuation of Cosmic Rays: Due to an additional high density object there is a deficit of cosmic ray muons in certain directions.

Brownfield Configuration

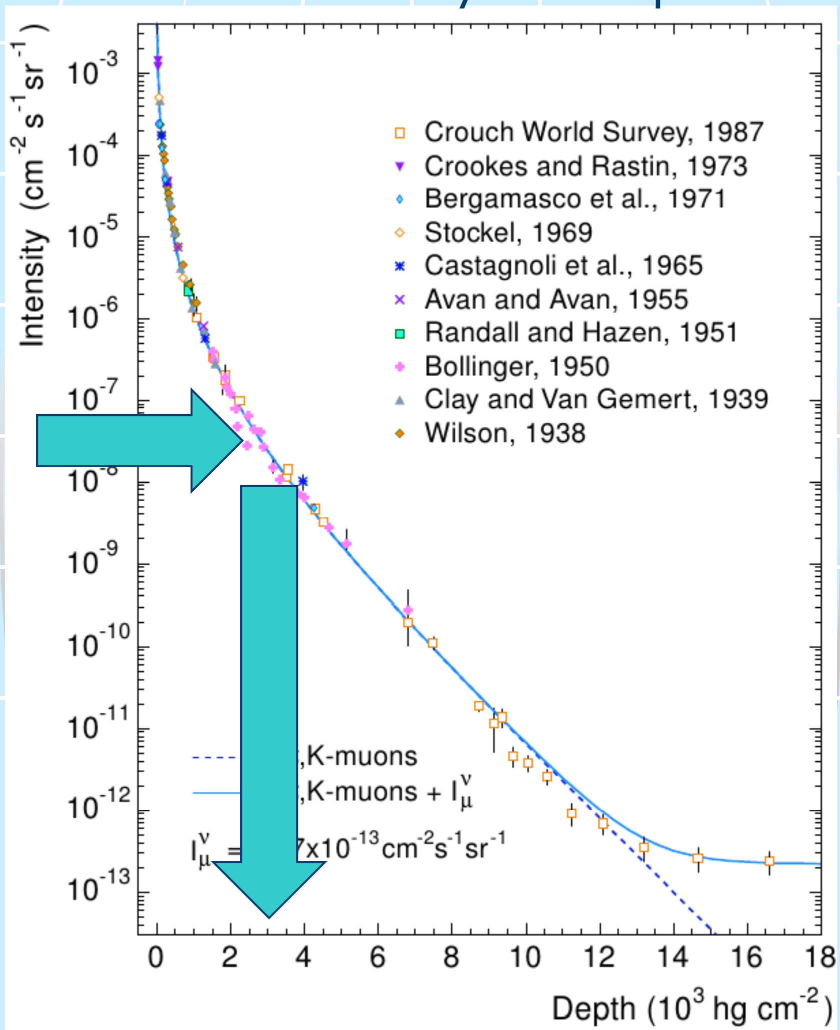



Greenfield configuration



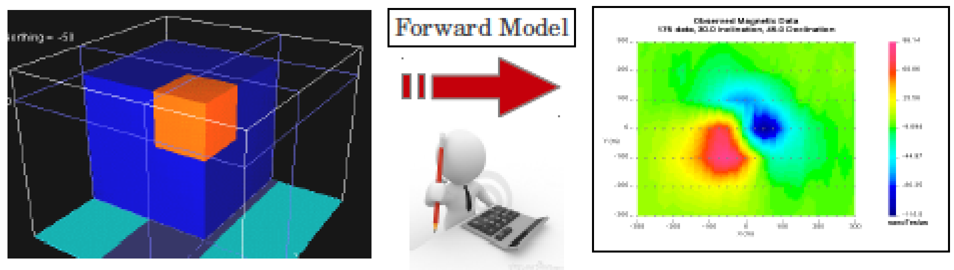
Measure muon intensity → total "depth"

## Muon Intensity vs. Depth




$$\text{Measure } N_\mu(z_i,\theta,\varphi) \rightarrow \text{ mass}_{\text{to surface}}(z_i,\theta,\varphi)$$

# Simulations and Analysis

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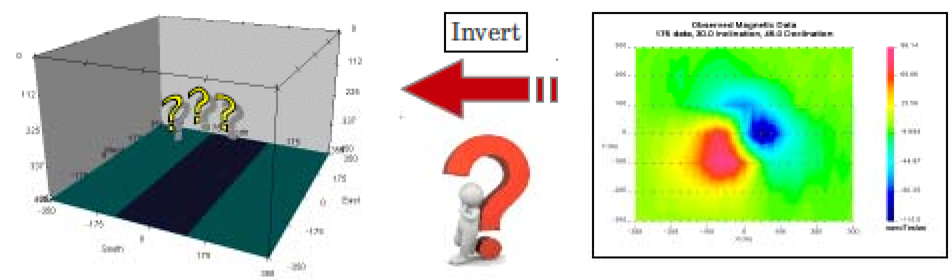
Forward model: predict observed data set given a model of rock density

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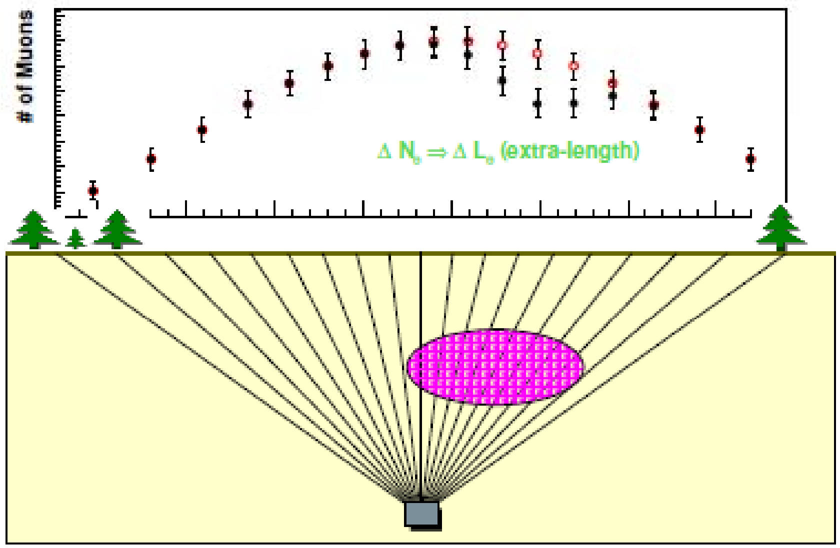
Inversion: solve 3D rock density distribution given observed data

# Forward Model



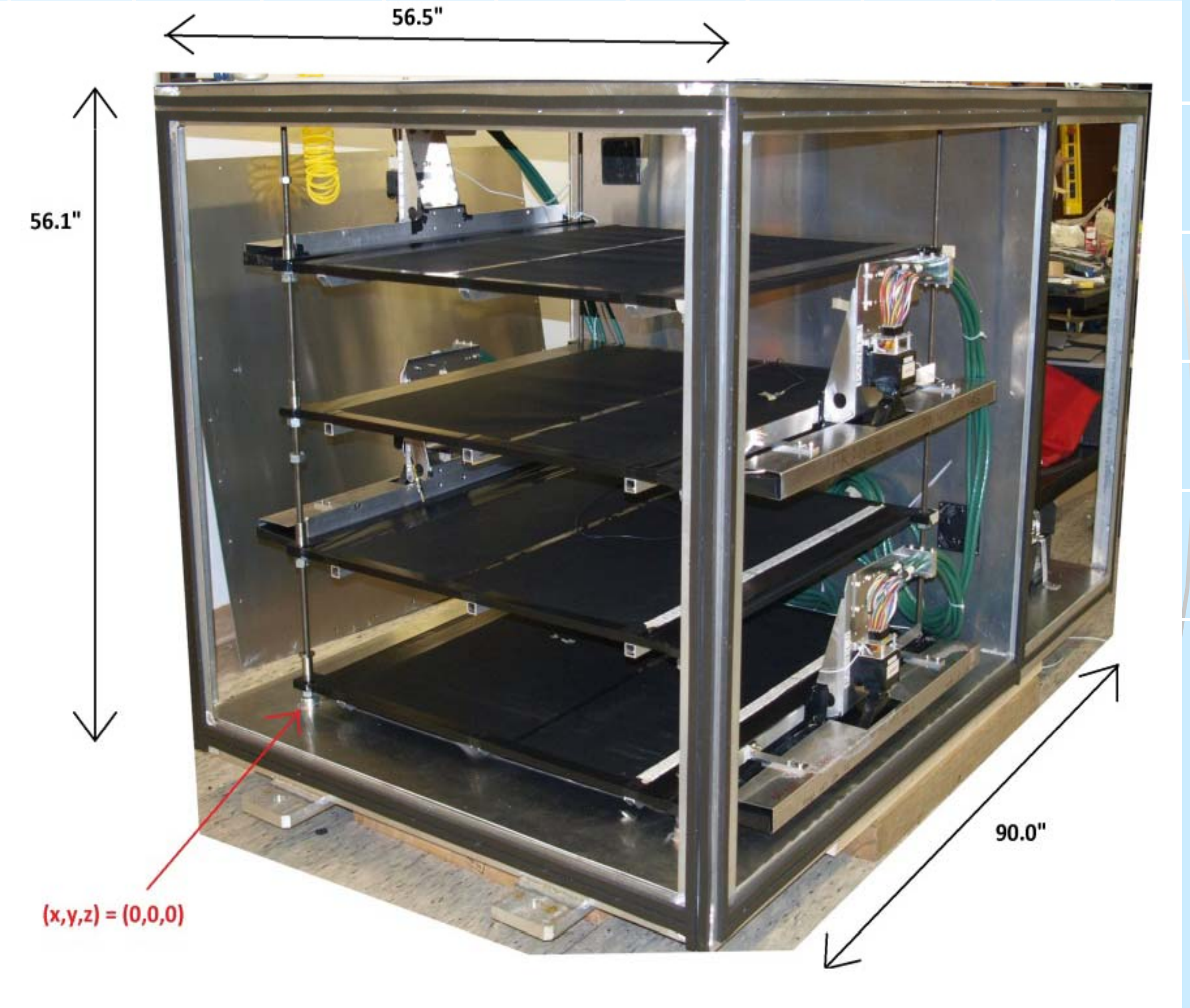

**Forward model**

- Given topological data and target ore body
- Calculate mass length $\int \rho dL$ (or anomalous mass length $\int \Delta\rho dL$)
- Calculate muon flux at detector level
- Estimate muon counts (used for uncertainty estimate)

**Simulation samples**

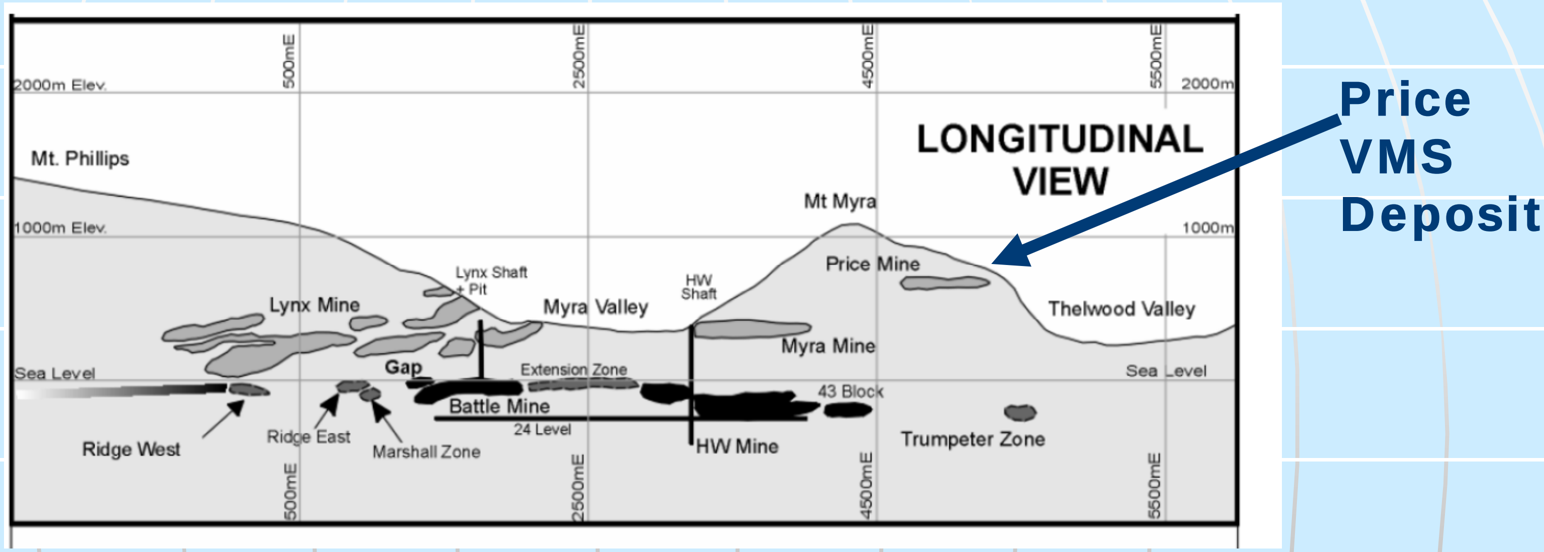
- Based on forward model, generate noise data
- Used to design survey and perform NULL hypotheses tests

# Muon Tracking Detectors



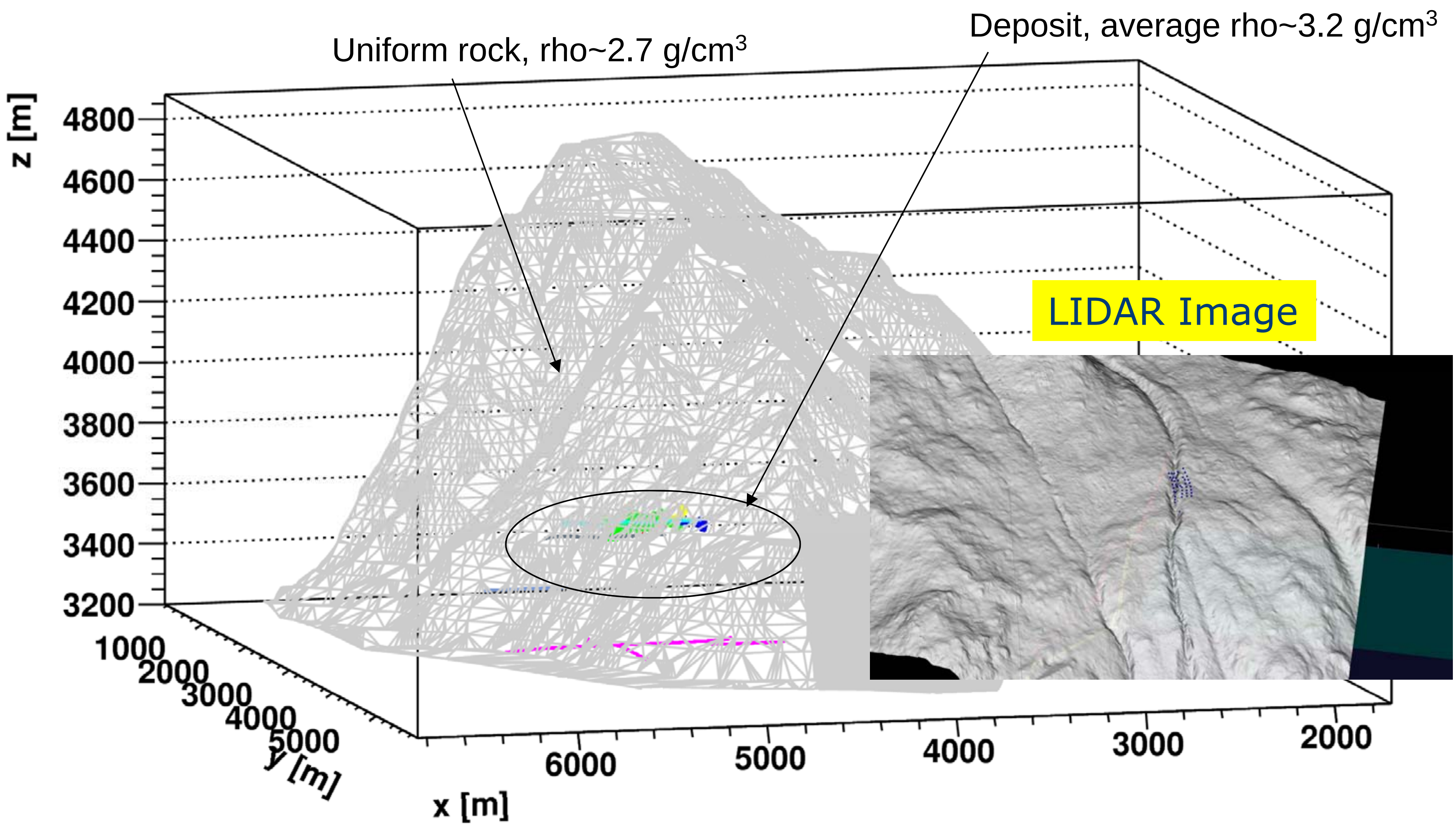
# Proof-of-principle test at the Price Mine

## (Strathcona Park) Vancouver Island, British Columbia

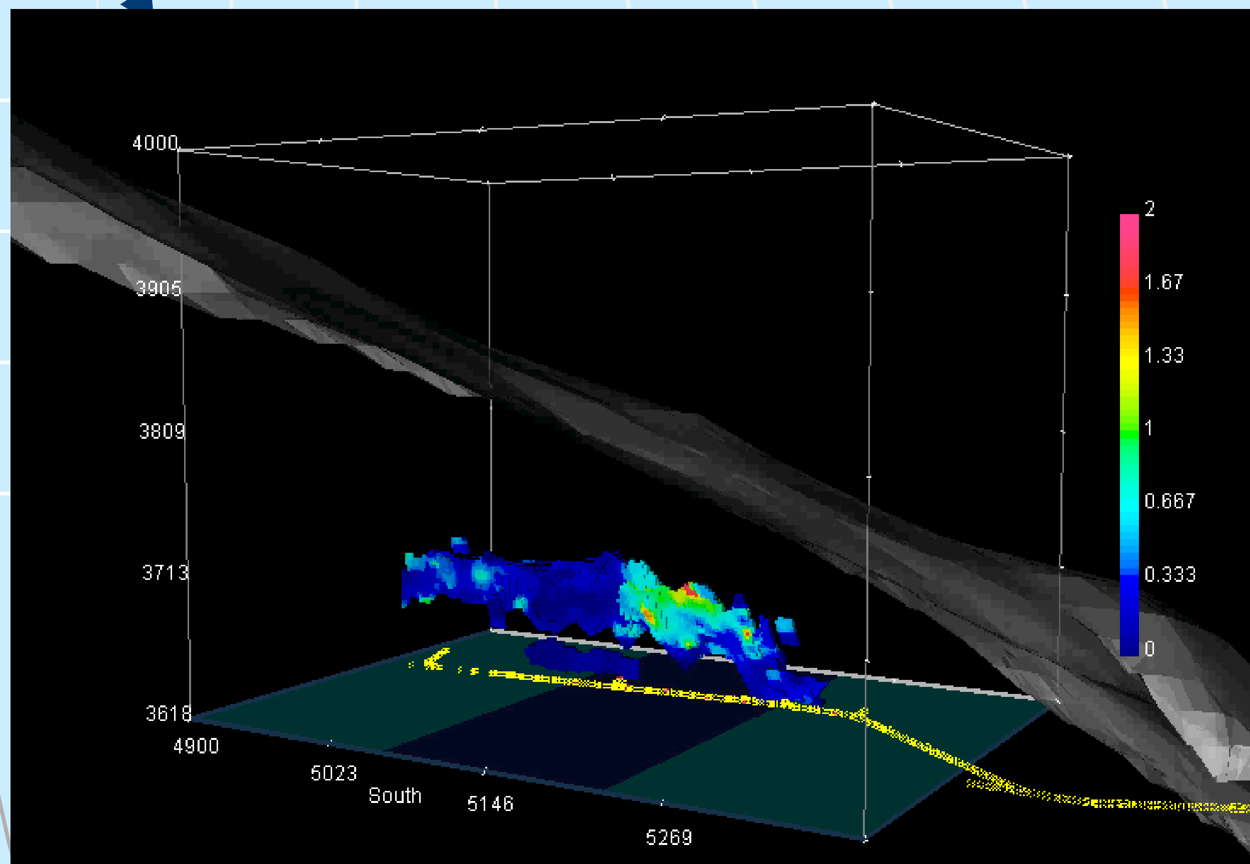



- **Readily accessible site not currently active for mining**
- **Shallow, horizontal access below deposit**
- **Rail and power lines throughout tunnel**
- **Highly cooperative and enthusiastic industry partner**

# Price Mine Deposit

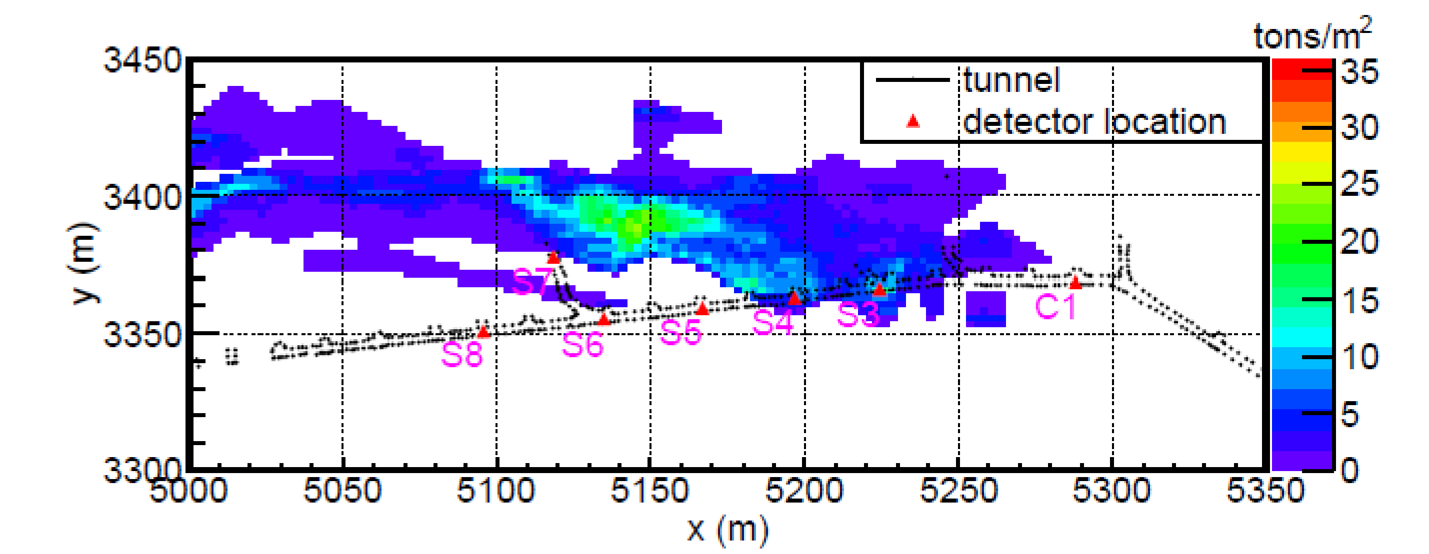


# Field Test of Muon Geotomography




Underground Mineral Deposit-- as determined from drill data model.

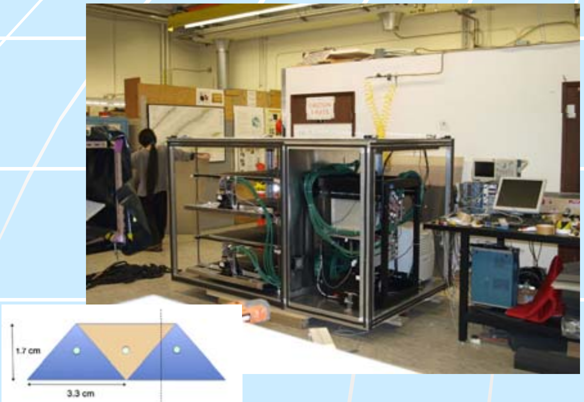
# Top View of Deposit Extra Depth



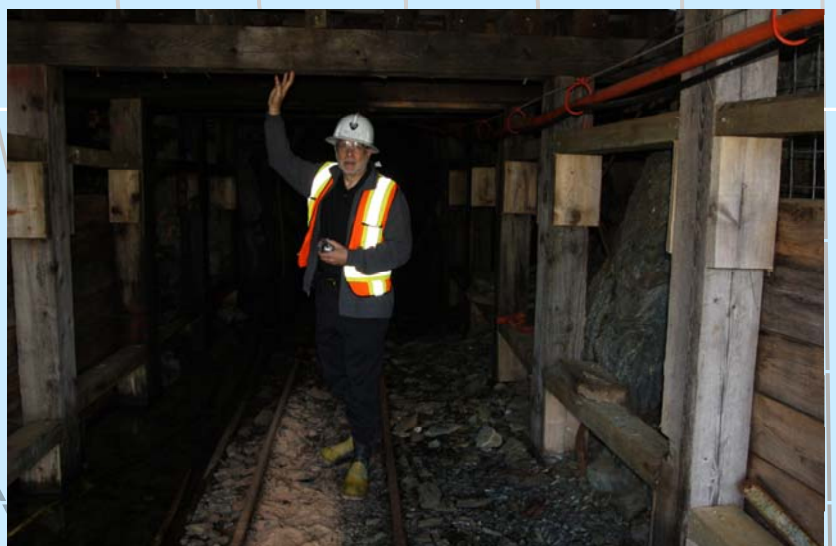

7 scintillator locations
10 emulsion locations

Massive sulfide ore body- average ore body density: 3.2 g/cm$^3$; host rock density: 2.7 g/cm$^3$

# Tracker: “Minerva” Scintillators



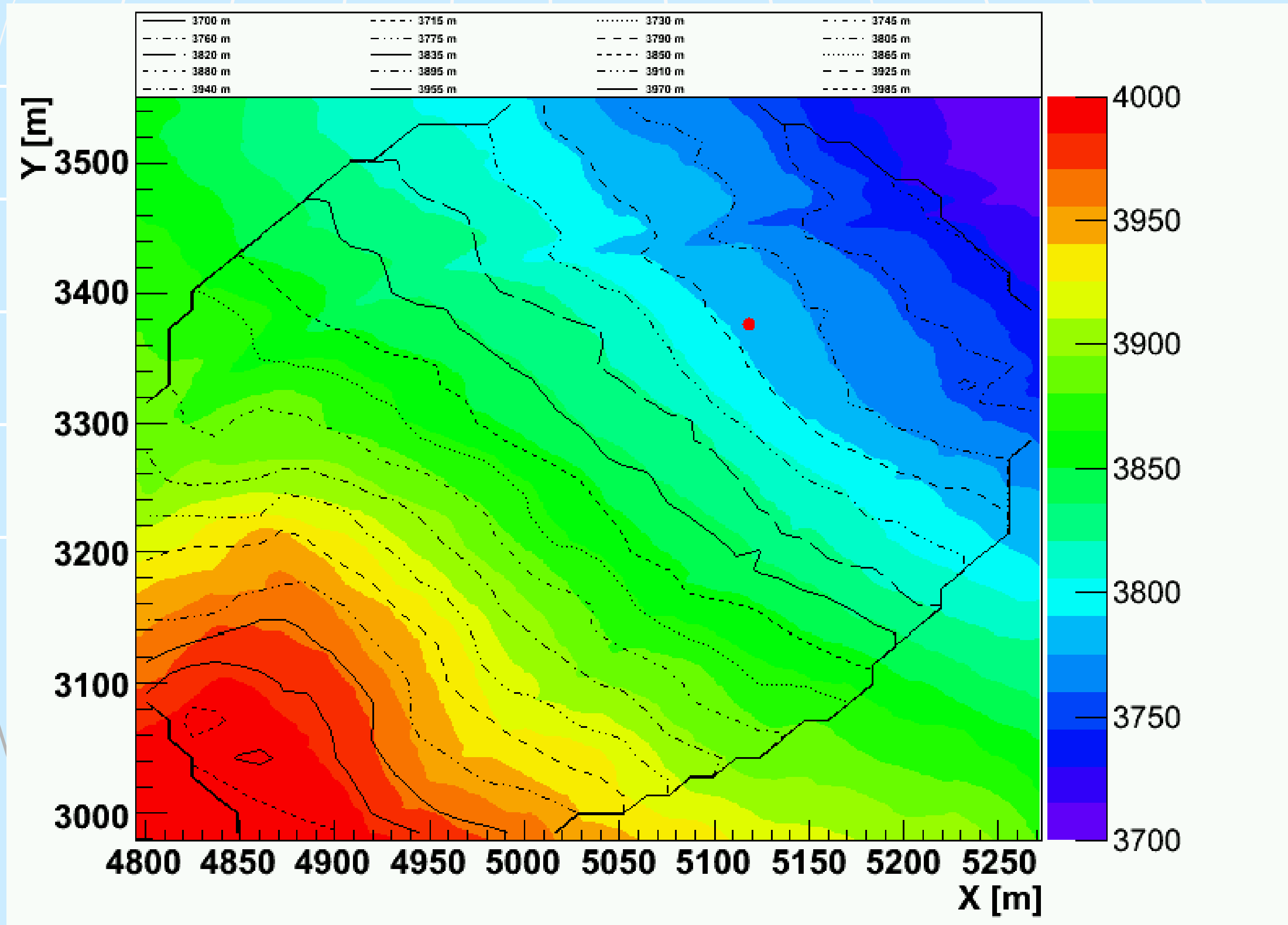

1 m$^2$ Active Area



# Topography (LiDAR)- Muon Data Comparison

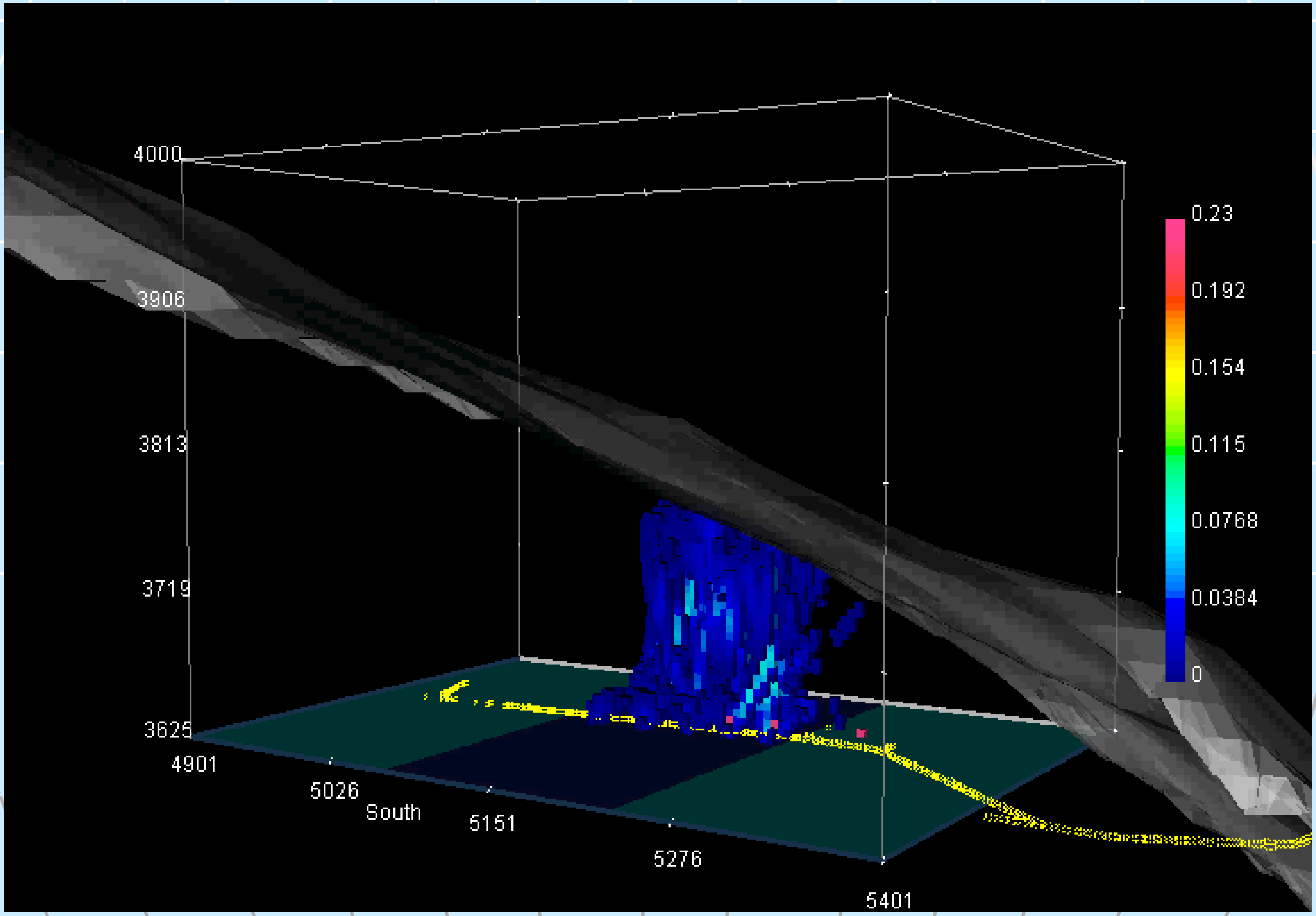
Colors:
LIDAR

Lines:
Muon data



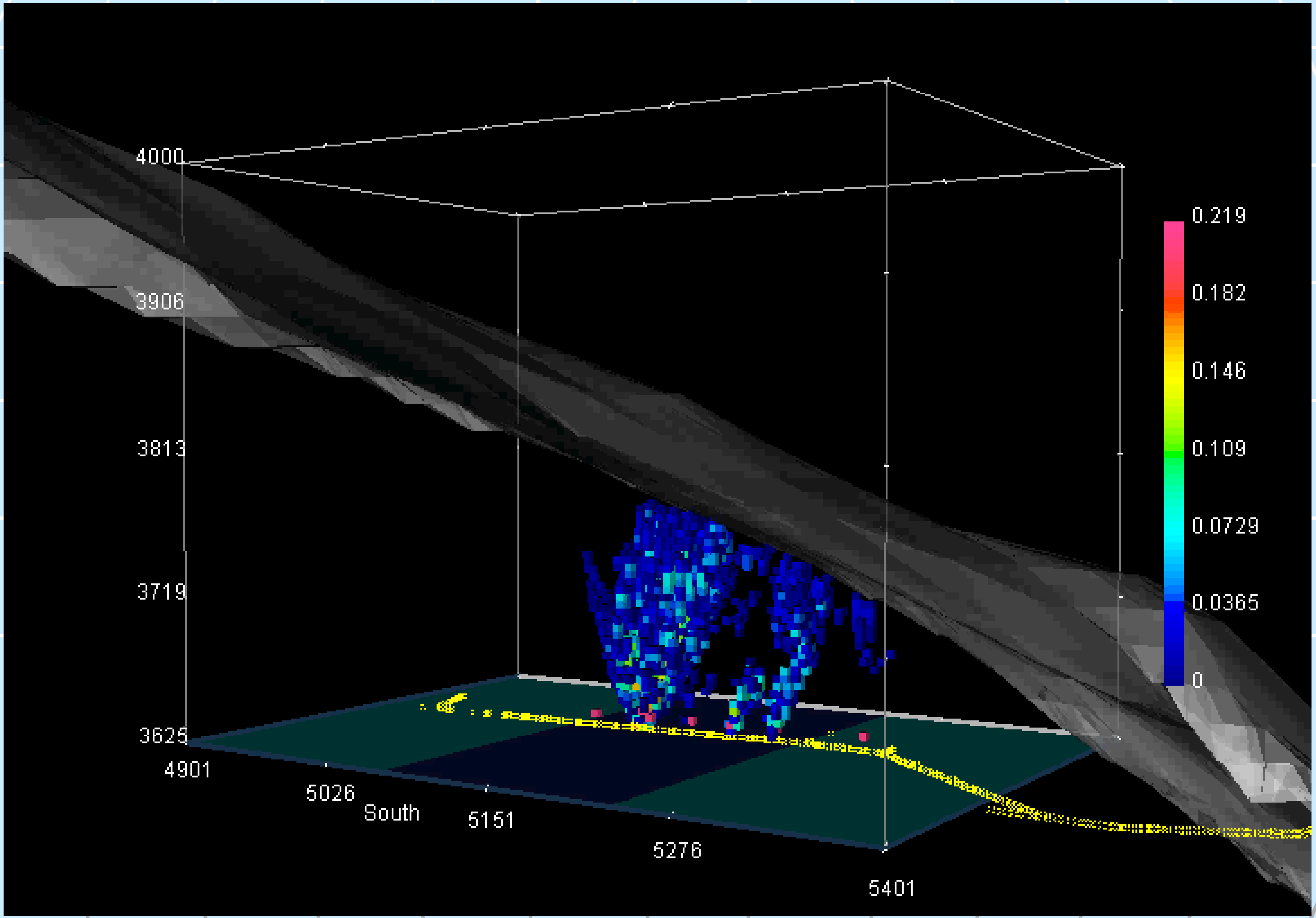
# Simulation: Data in 3D from Inversion

Inversion of Simulated data



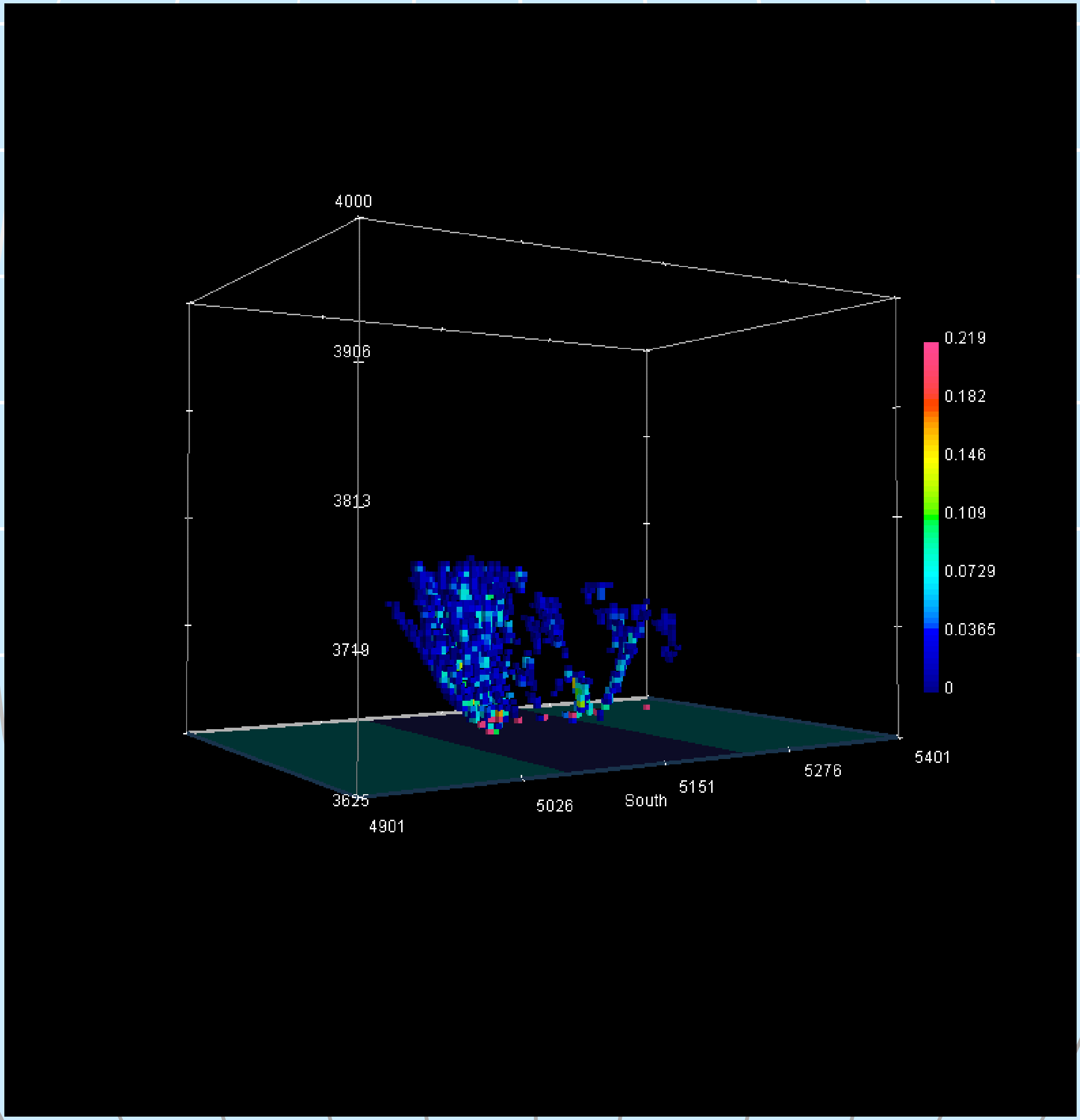
# Experiment: Data in 3D from Inversion

Inversion of Experimental data




Background densities (2.7 g/cc) + 0.15 g/cc subtracted to reduce noise

# Density Distribution within Ore Body

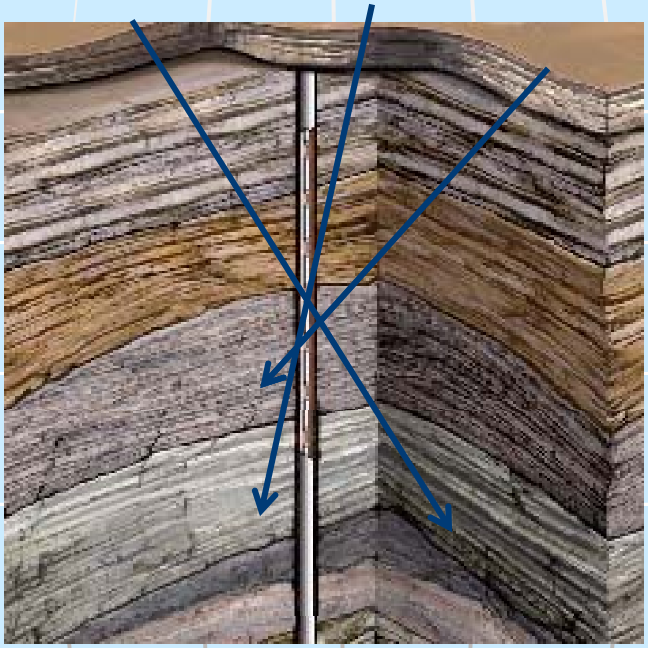


# Comparison of Drill Data, Simulations and Experimental Data

**Simulation** **Experiment**

| | Drill data model | Inversion of drill data | Inversion of experimental data | Difference between inversions |
|---|---|---|---|---|
| Excess-mass over 2.7g/cm$^3$ | 28.9K tons | 14.5K tons | 12.3K tons | 2.2K tons |
| $x_{\mathrm{CM}}$ | 5150.0 m | 5158.7 m | 5123.1 m | 35.6 m |
| $y_{\mathrm{CM}}$ | 3388.0 m | 3384.9 m | 3409.3 m | -24.4 m |
| $z_{\mathrm{CM}}$ | 630.3 m | 637.9 m | 657.3 m | -19.4 m |

# Future Development: Borehole Instruments



# Muon Geotomography: Summary and Conclusions

- **Muon tomography is a spinoff from Particle Physics**

  ***Studying the magma chambers of active volcanoes.***

  ***A new tool for geophysical Mineral Exploration***

  ***Other possible applications:***

  - Monitoring carbon sequestration
  - Monitoring water seepage
  - Identifying voids
  - Archeology
  - Monitoring Nuclear waste and reactors
  - Scanning for contraband nuclear materials

- **A successful field trial has been performed.**

  *Muon geotomography imaged a known massive sulfide deposit in a complex geological environment.* Inverted 3D density images of the deposit are similar to a model derived from drill data.

  *Limitations arise from inversion ambiguities, access locations, and statistics.*

- **Borehole detectors are being developed**

# Project Collaborators

| | |
|---|---|
| UBC/AAPS | Doug Bryman(UBC), Zhiyi Liu, James Bueno, Richard Hydomako |
| Bern High Energy Physics Group | Antonio Erditato, Akitaka Ariga, Ciro Pistillo, Francesca Giacoppo, Igor Kreslo, Jiro Kawada |
| UBC-GIF | Doug Oldenberg, Vlad Kaminski, Kris Davis |
| Geological Survey of Canada | Mark Pilkington |
| NVI/Breakwater/ Nyrstar | Rick Sawyer |

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