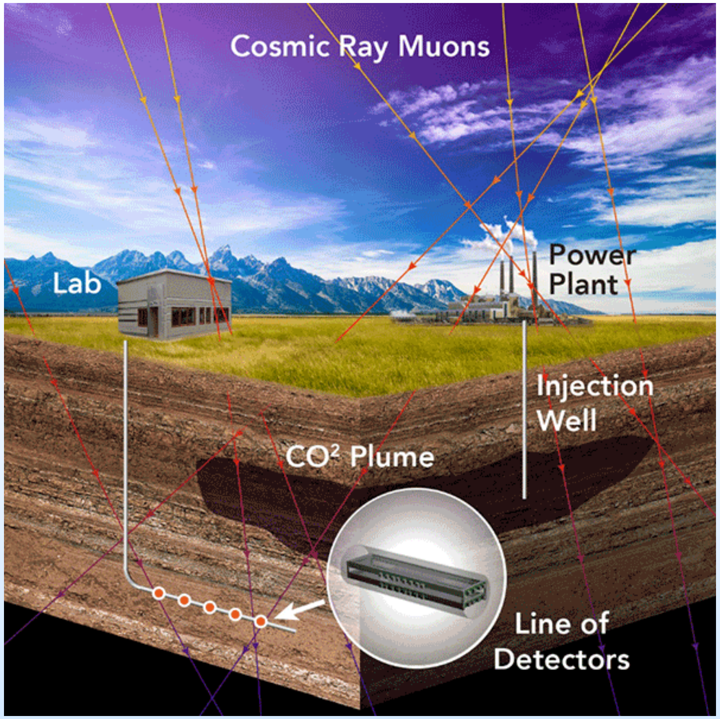
# Borehole Muon Detector for 4D Density Tomography of Subsurface Reservoirs




Project Number 66844


Alain Bonneville

Pacific Northwest National Laboratory



U.S. Department of Energy

National Energy Technology Laboratory

Mastering the Subsurface Through Technology, Innovation and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting

August 16-18, 2016

# Presentation Outline

- Benefit to program and project overview
- Why 4D density tomography?
- Cosmic ray muons
- 1st prototype of Borehole Muon Detector
- Testing in various settings
- Results and comparison with reference instrument
- Joint inversion with seismic data
- Summary and path forward

# Benefit to the Program

The main goals of this project are (i) to develop miniaturized cosmic rays  muon detectors fitting in standard boreholes and (ii) to optimize sensor deployment strategies and geophysical inversion methods.

This will yield to important progress on muon sensor development and allow to obtain high resolution 3D density images of subsurface reservoirs. The monitoring of real time density changes at depth (tracking fluid displacements for example) will be one of the most important benefit.

This project contributes to the Carbon Storage Program's effort of developing and validating technologies to ensure for 99 percent storage permanence.

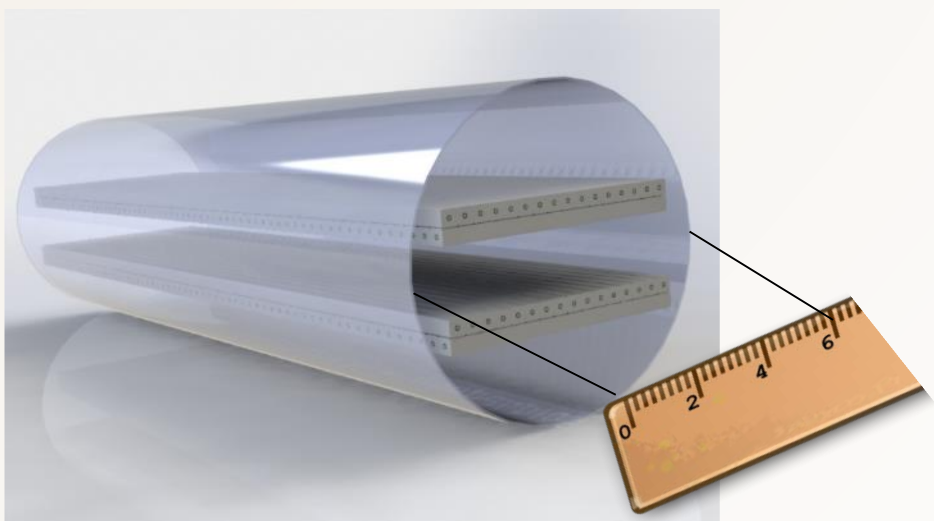
# **Project Overview**: Goals and Objectives

- Develop miniaturized muon tracking detectors capable of fitting in standard boreholes to perform 4D density tomography of geological structures.

- Develop a rapid and efficient inversion method that will take into account not only the different muon paths, but also the data generated by other techniques, such as seismic and gravity.

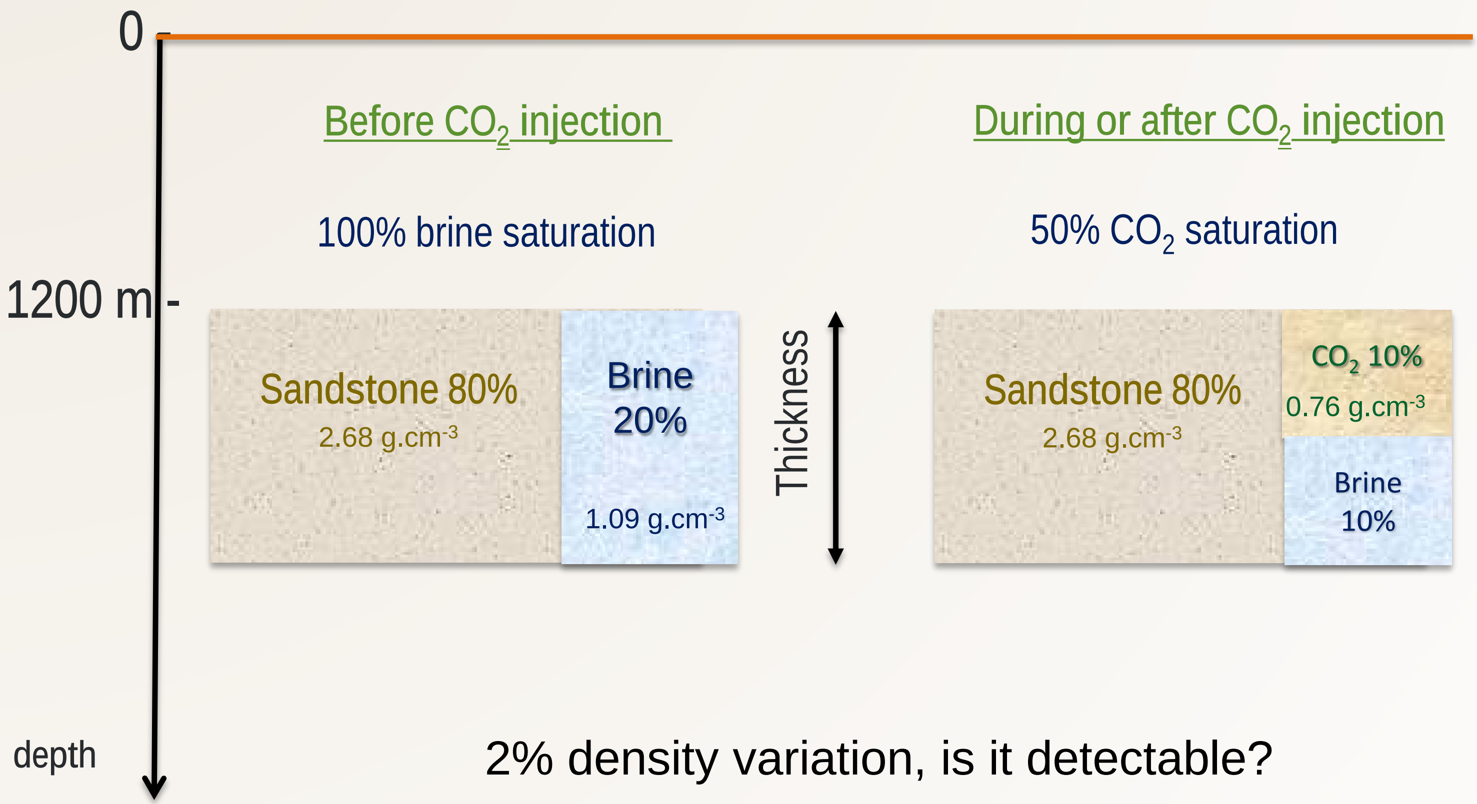
# SubTER Sapling: Borehole Muon Detector for 4D Density Tomography of Subsurface Reservoirs

**PNNL:** Alain Bonneville, Richard Kouzes, Jared Yamaoka
**LANL:** Charlotte Rowe, Elena Guardincerri
**LLNL:** Robert Mellors, George Chapline
**SNL:** Nedra Bonal
**Univ. of Utah:** Azaree Lintereur, Joshua Flygare
**Univ. of Hawaii:** Gary Varner, Isar Mostafanezhad
**Paulsson Inc.:** Bjorn Paulsson



# Why 4D density tomography?

Injection in a sandstone reservoir with 20% porosity




2% density variation, is it detectable?

# How can we measure density variations in the subsurface?

- **Gravity**

Gravity measurements detect changes in the earth's gravitational field caused by variations in the density of subsurface rocks.

- **Seismic waves**

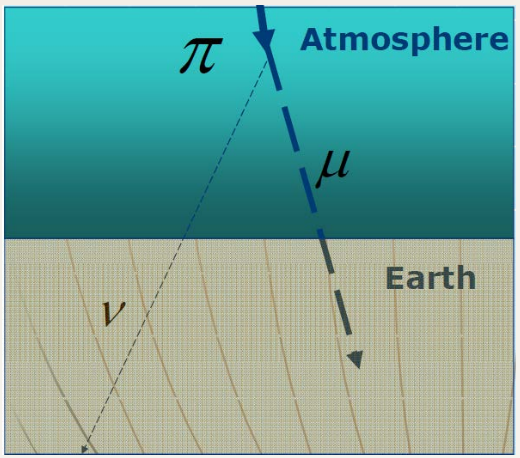
Velocity of seismic waves depend on the elastic properties and density of the geologic units.

- **Muons**

Cosmic rays muons penetrate the Earth and their flux is attenuated as they pass through geologic layers. This attenuation depends on the density of these layers.

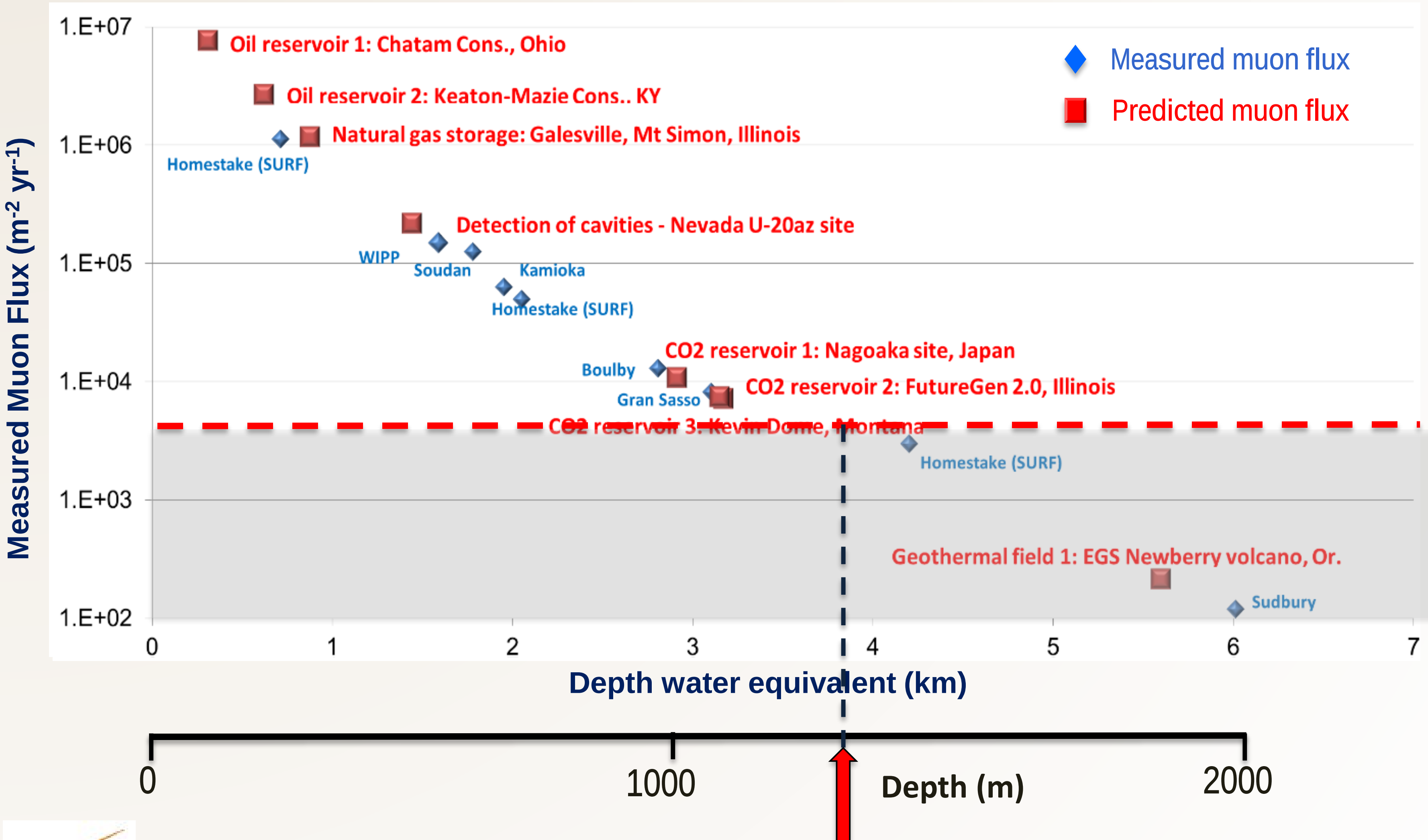
# Cosmic Ray Muons

Rapid decrease of the Muon flux with depth : only 119 muons/$m^2$/yr at 2000 m.




- Discovered in 1936
- Fundamental particles
- Similar to electrons, but much more massive
  - ~207 times an electron mass (105.7 MeV)
- Created when high energy cosmic rays interact with the atmosphere
  - Secondary cosmic rays are produced at approximately 15 km
  - Decay product of pions and kaons
  - Average energy is 6 GeV
- Muons lose about 2 MeV/g/$cm^2$
- Total surface muon flux = 5.26 $10^6$/$m^2$/yr

# Predicted muon flux for various subsurface features

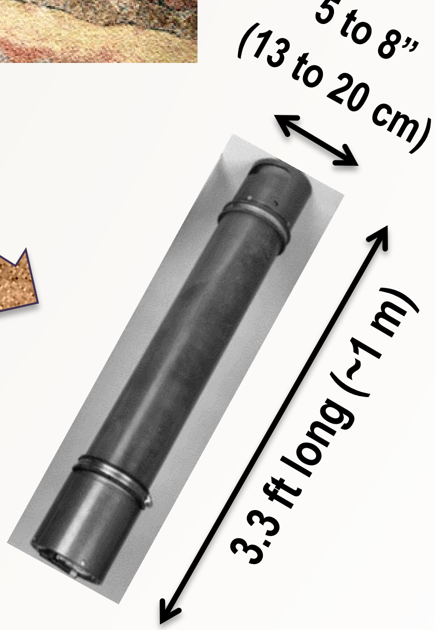



Depth limit ~ 1372 m (4500 ft)

# Detector Design: the challenge

LANL Mini Muon Tracker (MMT)

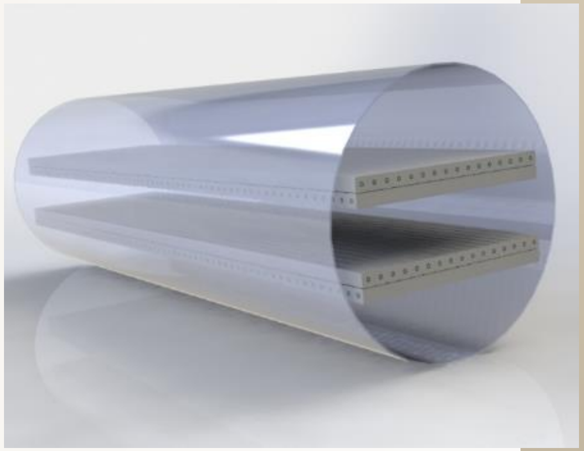
From a rack size detector….



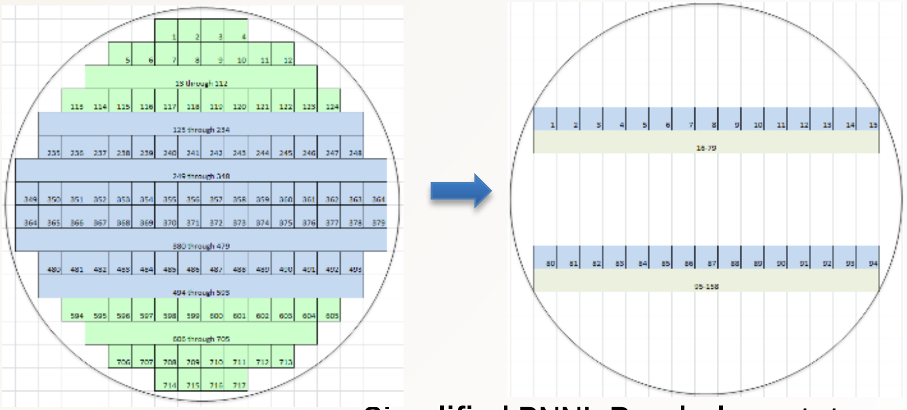

…to a borehole detector.

# Detector 1st Design

- Miniaturization of the detector elements and of the electronics.
- Angular resolution is required, in both directions
- Goal: detect 1% change in density per year
- Must fit in a borehole (5-8 in)
- Must survive temperature >45°C and pressure > 10 MPa
- Detector components
  - ✓plastic scintillator rods shielded
    - Easy to make angular measurements
    - Require photomultiplier tube
  - ✓optical fibers (Saint-Gobain BCF-922)
  - ✓PMT or light sensor (like Hamamatsu H8500C 64 pixels)



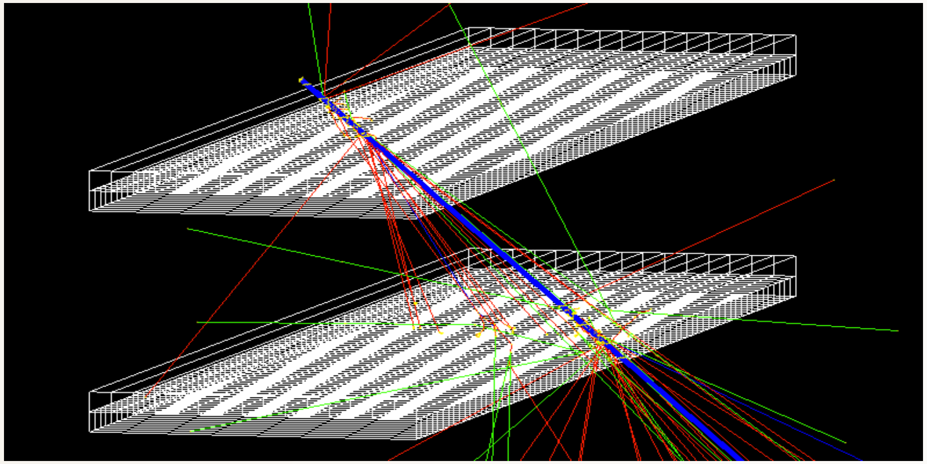
- Multilayer approach
- Starting with preliminary design of 2 layers for proof of concept and model validation

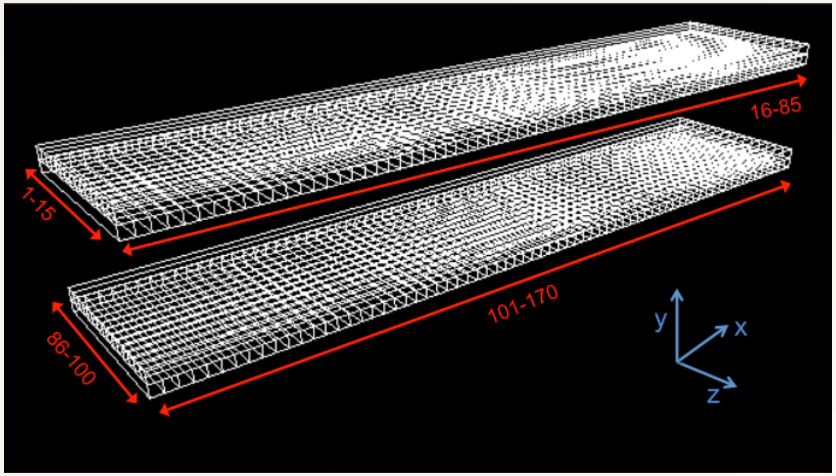


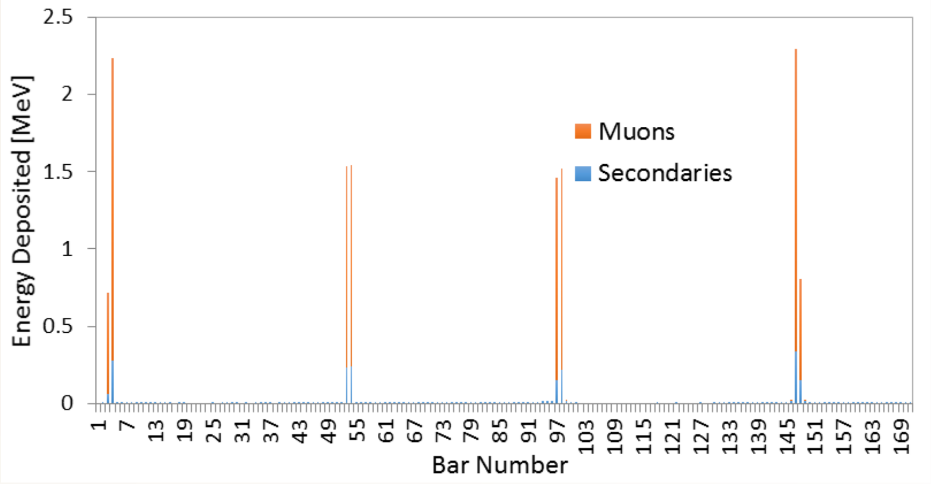
Simplified PNNL Borehole prototype

# Four Layer Simulations

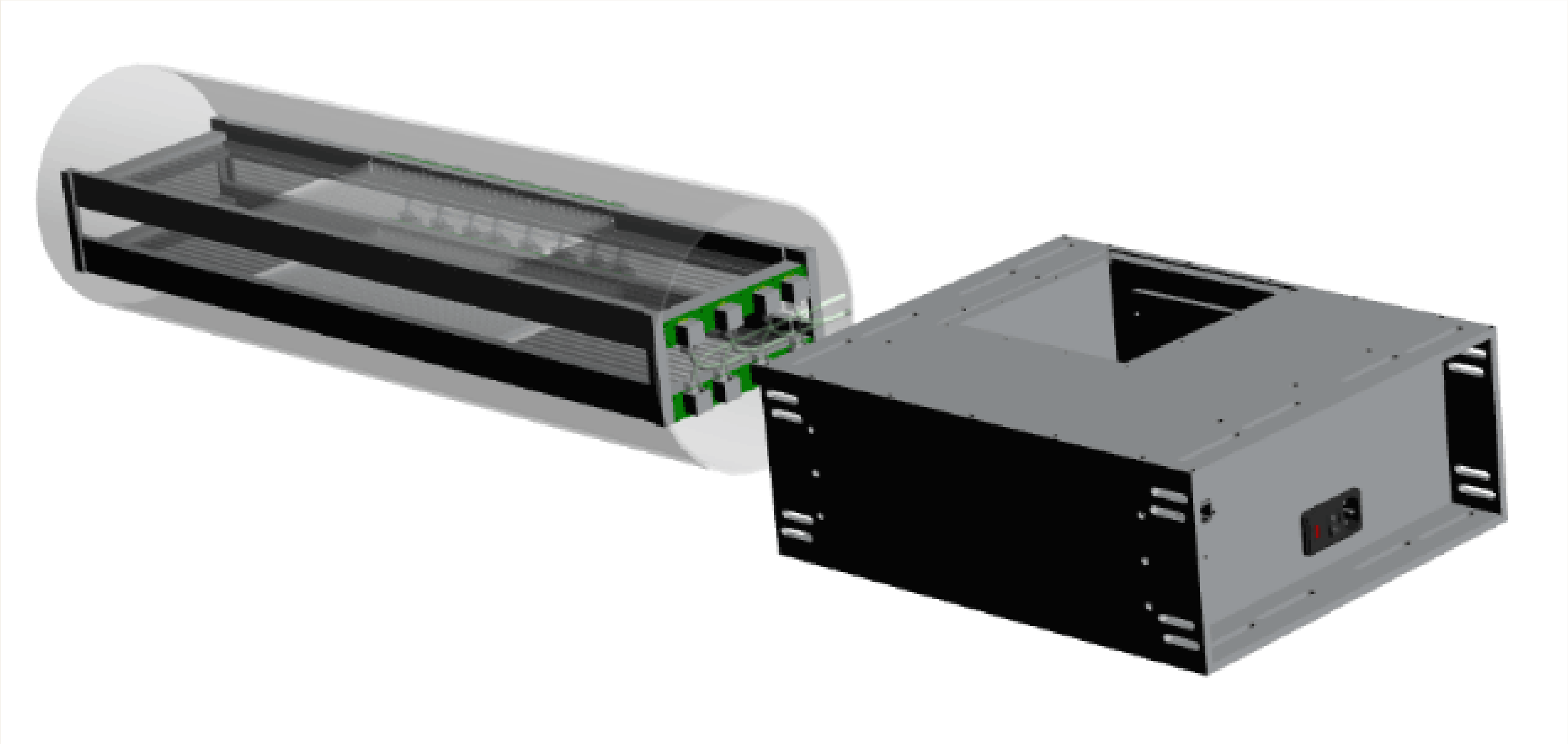
- Prototype model to predict performance capability and explore four-layer effects
- Four layers are required to resolve the incoming muon angle.





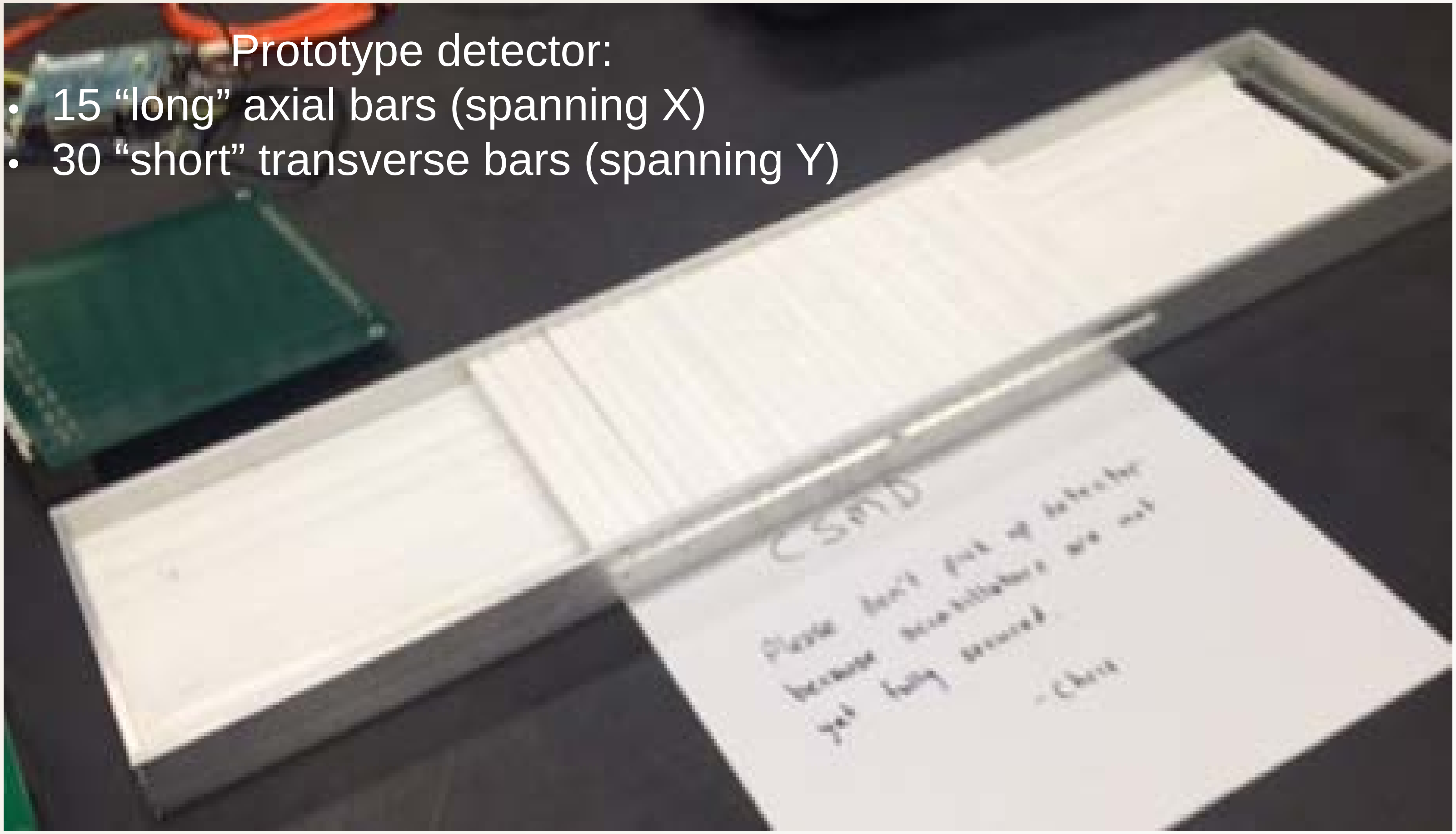



# Building the first prototype



Prototype detector:

- 15 “long” axial bars (spanning X)
- 30 “short” transverse bars (spanning Y)



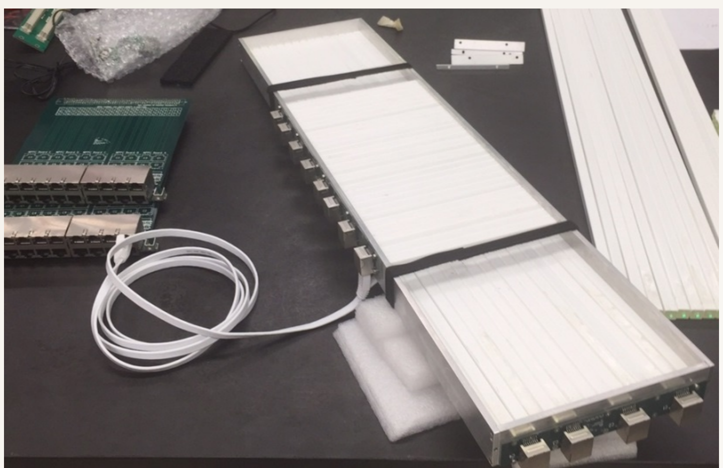
The initial scintillator-rod fit into a frame, prior to finalizing the frame mechanics.

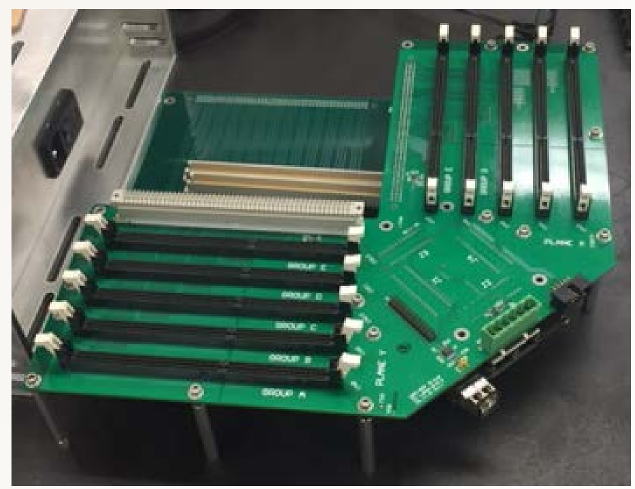
# Prototype electronics

## Signal flow for the prototype detector readout

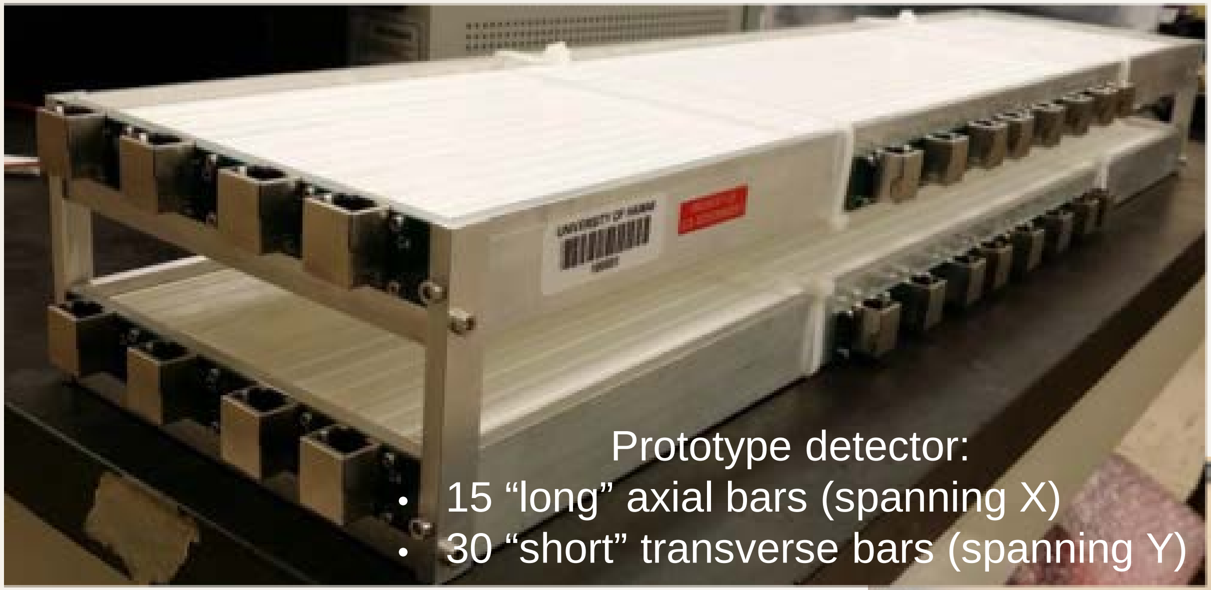
MPPC → BMD Fan-In → Mother Board → Target X → SCROD FPGA → Media Convertor → Laptop

MPPC Photosensors

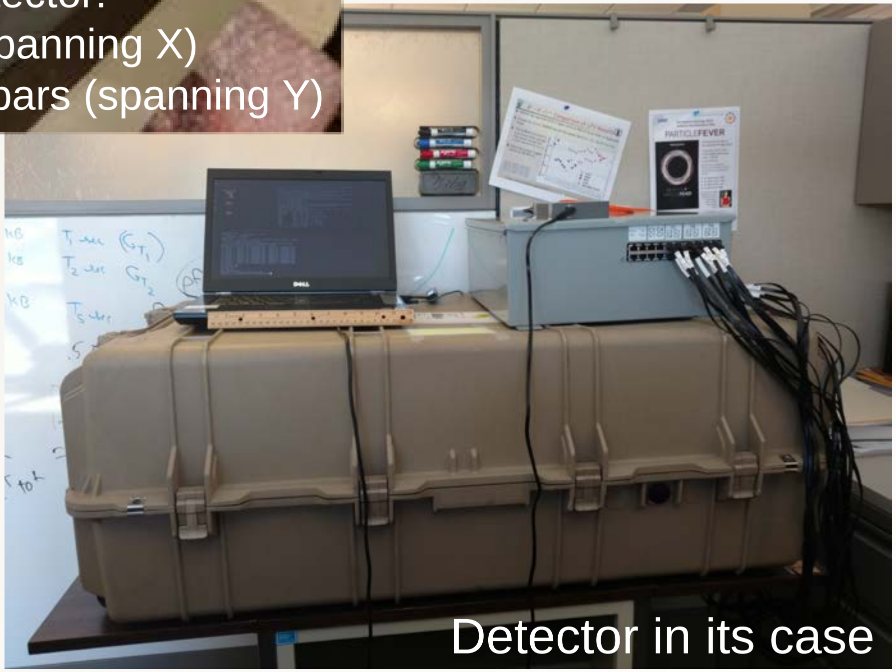




# Detector Prototype




Active area ~15x30 cm



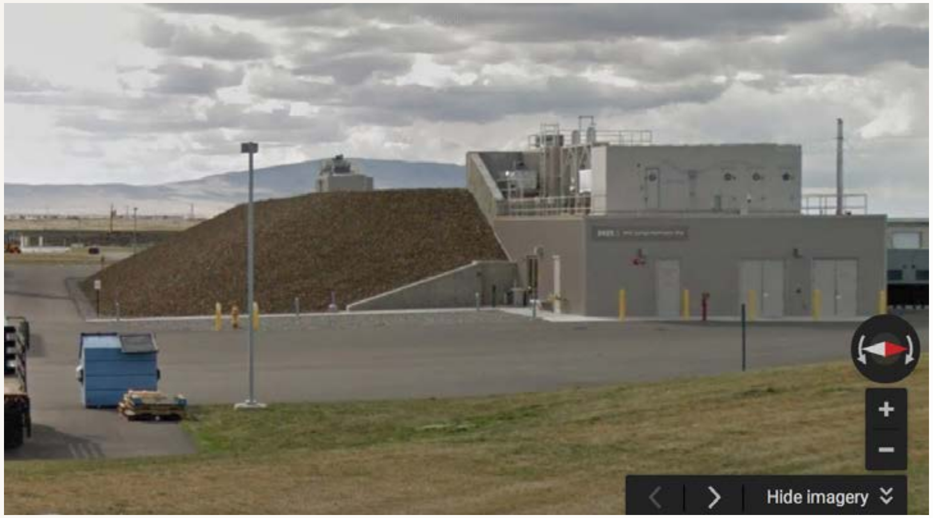
# Simulation of Underground Muon Flux at various sites

To develop analysis methods, estimate required exposure times, and to eventually compare to real data, simulations have been created for several use cases:

- Shallow Underground Lab at Pacific Northwest National Lab
  - The first underground test of the borehole prototype took place in May 2016 at the underground lab at PNNL.
  - The simulations are compared to measurements of the total muon flux at depth.
- TA-41 Vault at Los Alamos National Lab
  - A deeper test of the borehole detector has been taking place at LANL during June and July 2016.
  - The first collected data are compared to simulations and data collected by the LANL MMT detector.

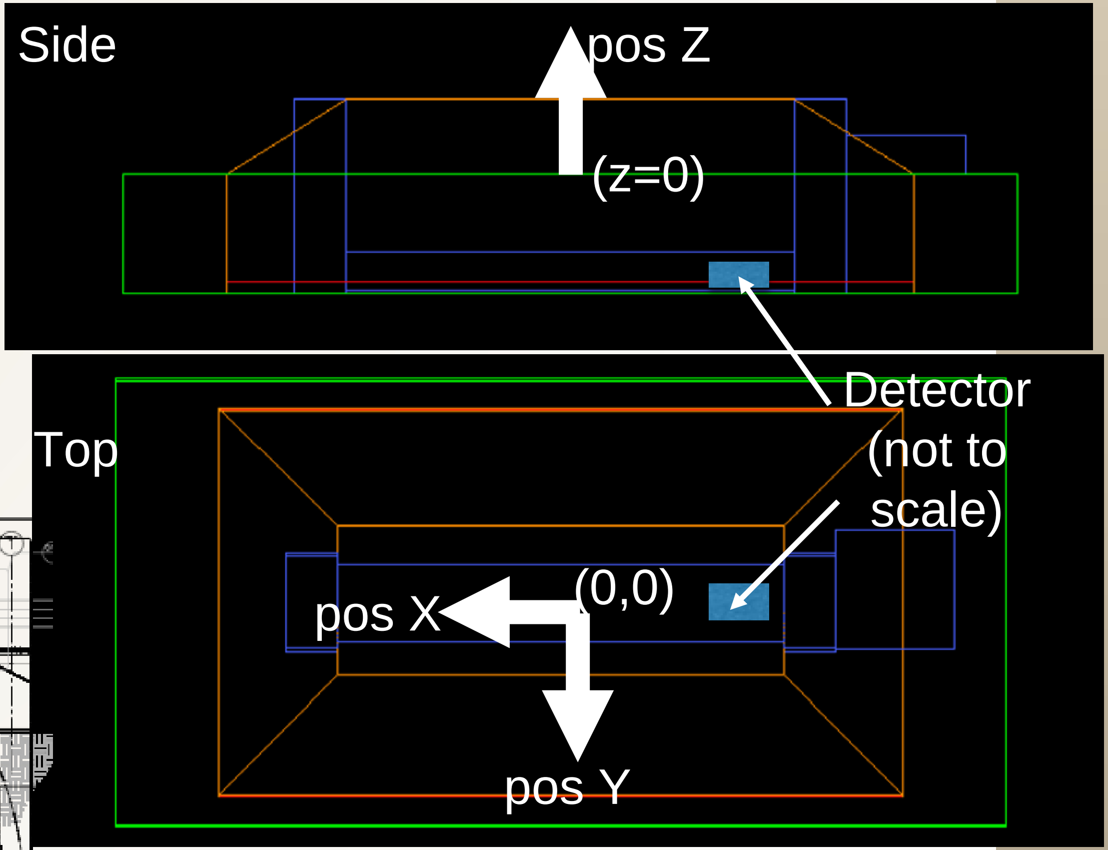
# PNNL Shallow Underground Lab

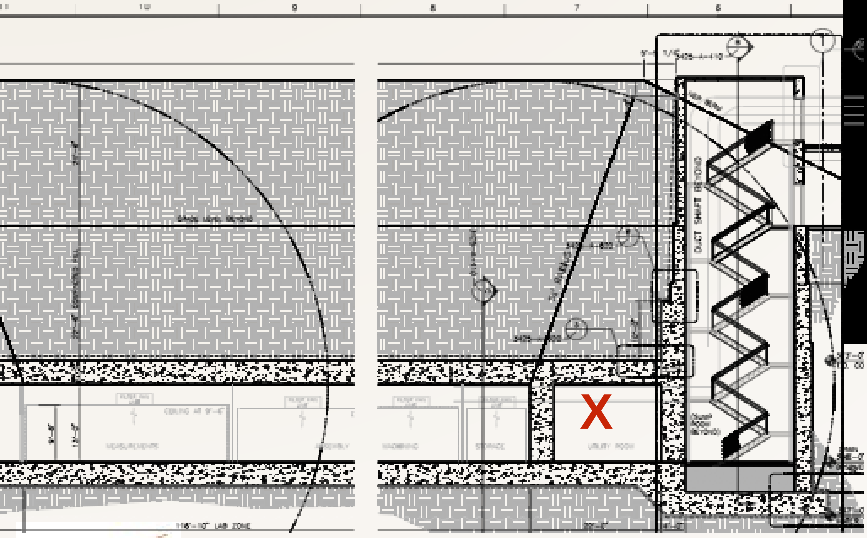
- PNNL Shallow Underground Laboratory: Clean room environment for production of ultra-low-background detectors and ultra-sensitive measurements
- Site of 9 day test run of the BMD detector
- Prior to our test run, generated simulations to estimate sensitivity and optimize analysis

# Simulation and BMD Data Collection

Detector location for simulation and collection (-20,-2,-11) meters

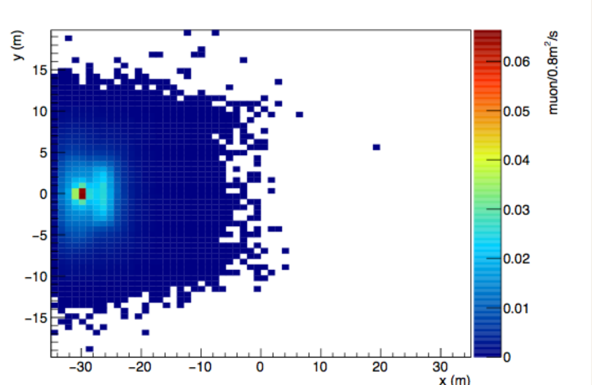


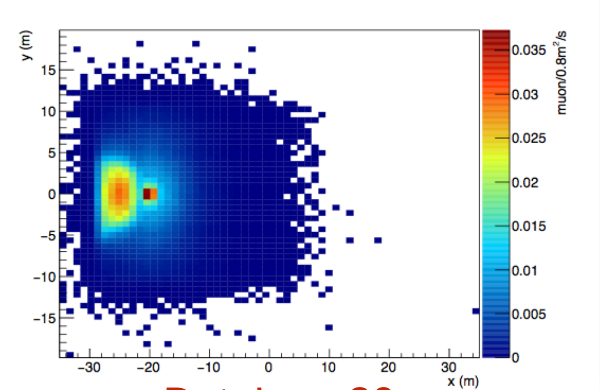
# Varying Detector Location

Projection of detected muons to the surface (z=0) for different detector locations

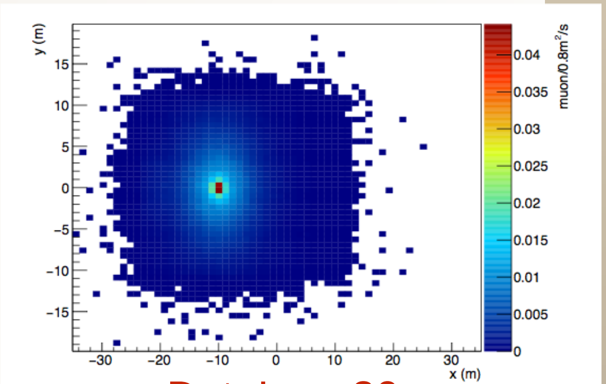
Det. Loc. -30m



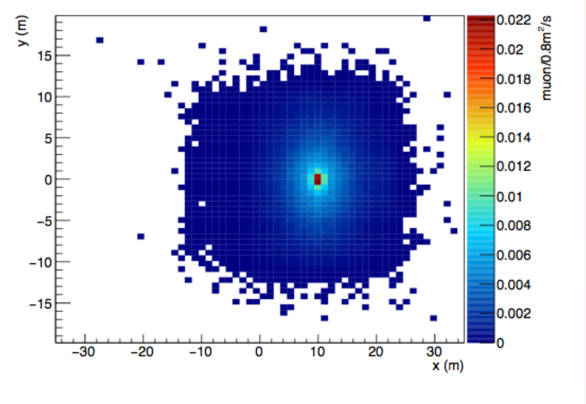

Det. Loc. -20m



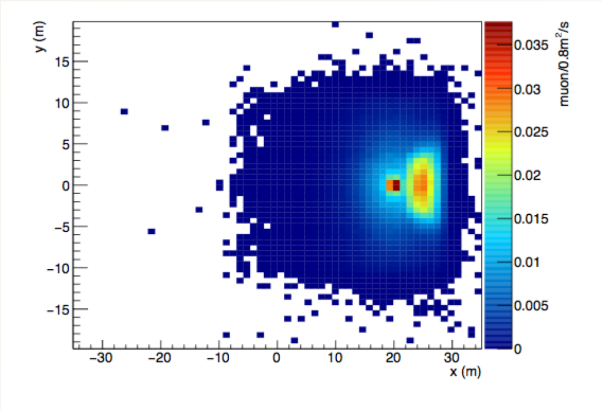

Det. Loc. -10m



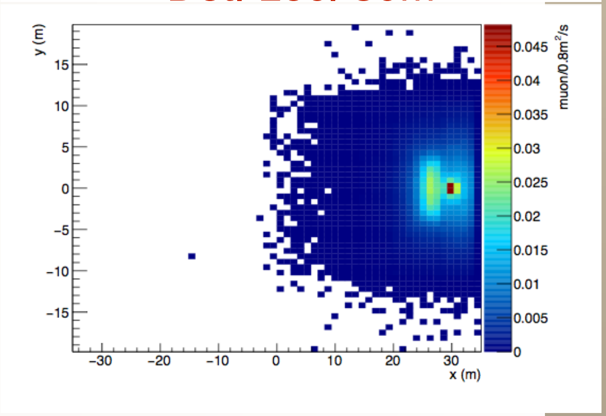

Det. Loc. 10m




Det. Loc. 20m



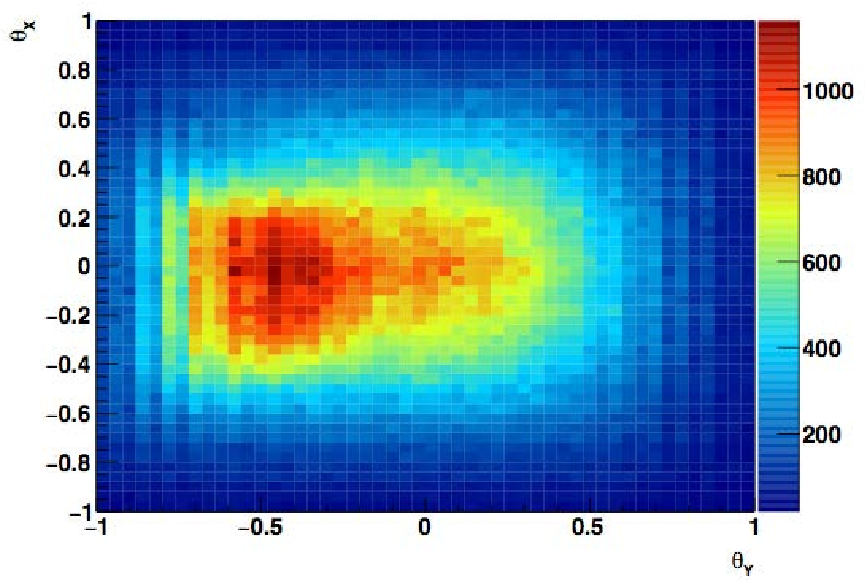

Det. Loc. 30m



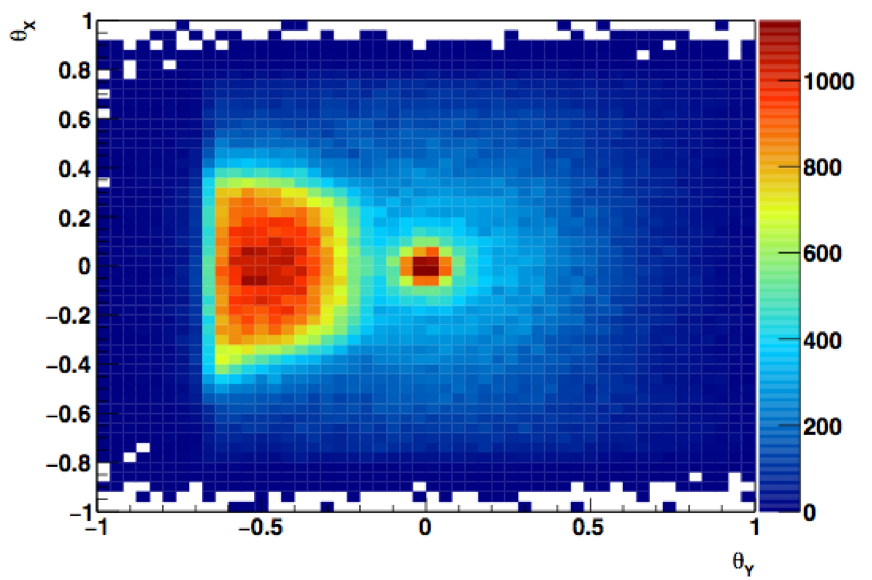
# Compare Data vs Simulation

$\theta_x$-$\theta_y$ plots:  Simulation has much better definition which should be expected.  There are more “vertical” muons in the simulation due to the input spectrum.

Data (9 days)

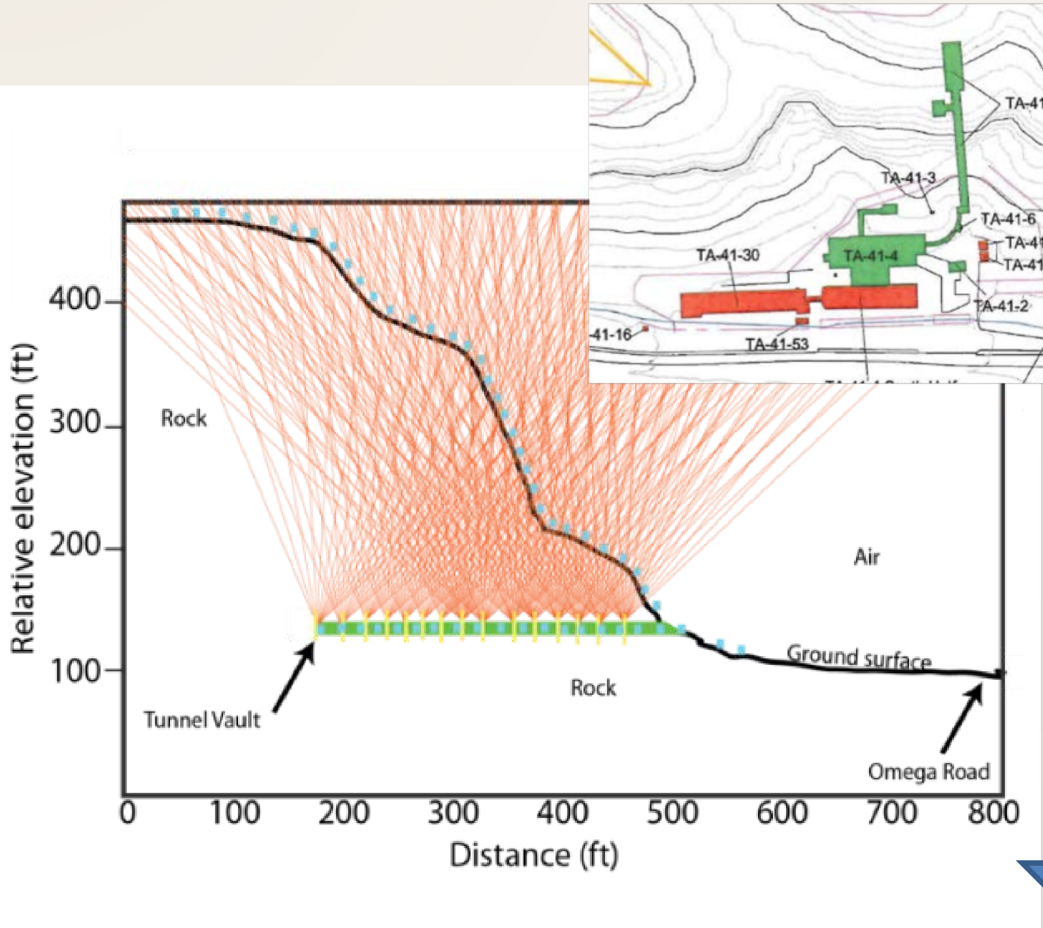


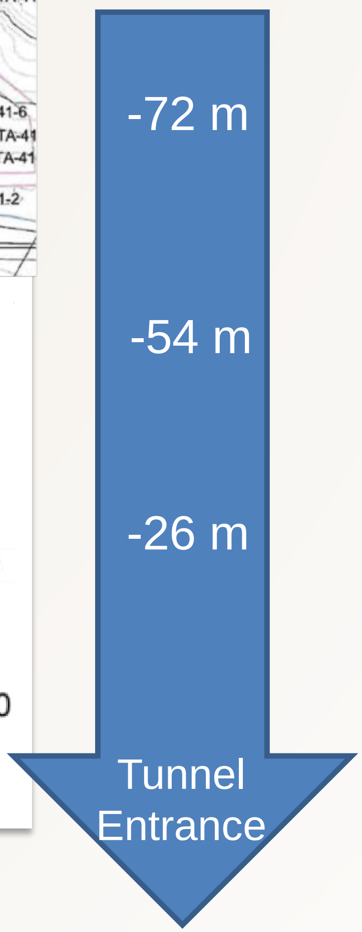

MC (4.1 days)

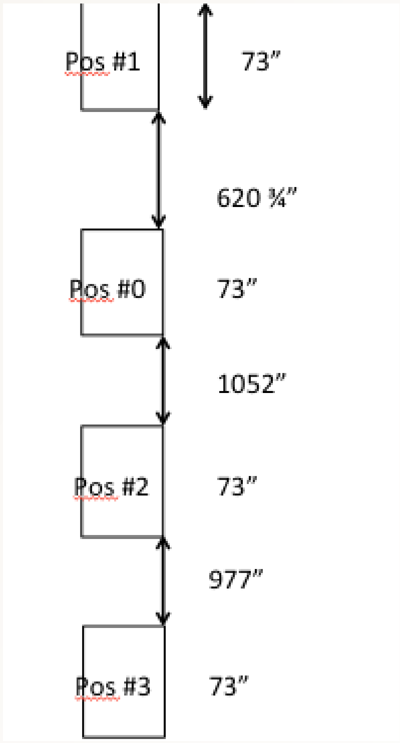


# Tests of Muon detectors in the LANL Tunnel facility


# LANL Tunnel Vault Experiment



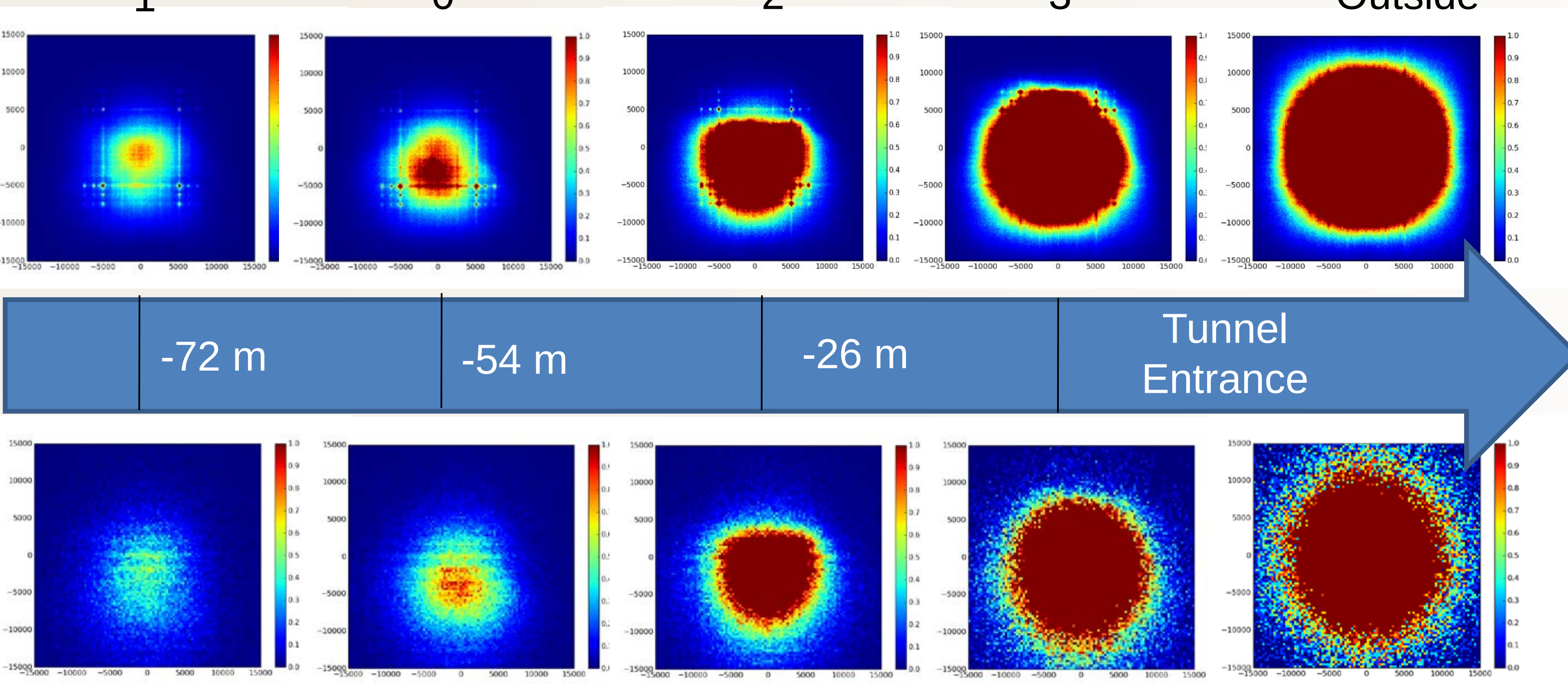



# Comparison between MMT and BMD data (I)

MMT

1 0 2 3 Outside




BMD

Projection at 100m height, axes are in cm, and colored flux values are in muons/m$^2$/hr

Pacific Northwest NATIONAL LABORATORY

# Comparison between MMT and BMD data (II)

| MMT | | | | |
|---|---|---|---|---|
| Position | Counts | Time (hrs) | Rate (hZ) | Norm Rate |
| 1 | 4926229 | 674 | 2.03 | 0.018 |
| 0 | 4668054 | 413 | 3.14 | 0.028 |
| 2 | 13837974 | 333 | 11.54 | 0.104 |
| 3 | 56029748 | 349 | 44.60 | 0.402 |
| outside | 104339250 | 261 | 111.05 | 1.000 |
| | | | | |
| BMD | | | | |
| Position | Counts | Time (hrs) | Rate (hZ) | Norm Rate |
| 1 | 77000 | 110.8 | 0.19 | 0.020 |
| 0 | 172000 | 161.3 | 0.30 | 0.031 |
| 2 | 290000 | 91.8 | 0.88 | 0.091 |
| 3 | 147000 | 12.7 | 3.21 | 0.331 |
| outside | 128000 | 3.7 | 9.68 | 1.000 |

*Detector area ratio MMT/BMD = 32.5*

Rate ratio MMT/BMD =

| | |
|---|---|
| 1 | 10.52 |
| 0 | 10.60 |
| 2 | 13.16 |
| 3 | 13.90 |
| outside | 11.47 |

# Combining muons and seismic data

Seismic data (velocity)

$$Vp,\ Vs = \sqrt{\frac{\lambda+2\mu}{\rho}},\ \sqrt{\frac{\mu}{\rho}}$$

Time-lapse seismic variations
Low spatial resolution

Check consistency with empirical relationships between density and velocity

**Constrain model**

Muon data (density)

$$\rho(x, y, z)$$

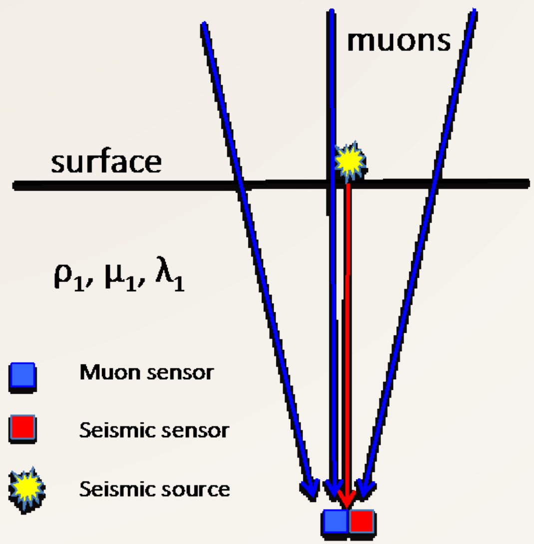
Time-lapse density variations
Low temporal resolution
Good spatial (near borehole or tunnel)

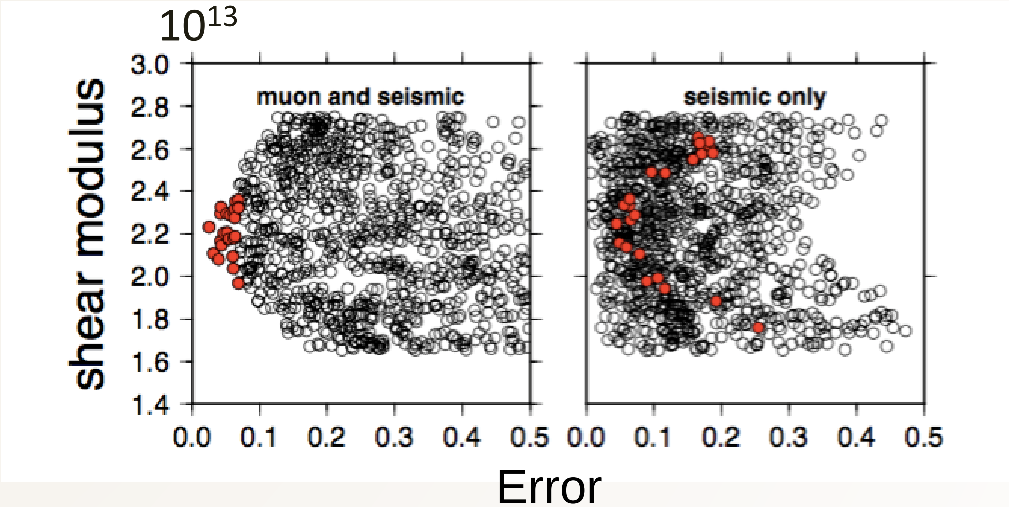
**Questions:**

- What is the value of the combined data?
- What are possible approaches?

# Traveltime example

- Estimate values of shear modulus.
- Measure P and S arrival times and density from muons




- Dots indicate 1000 test realizations (vary three values: density, and both elastic moduli)
- Red dots indicate top 5% based on fit to data. (real answer is shear modulus = 2.2 $10^{13}$)
- Seismic data (Ts, Tp) only cannot resolve all three unknowns
- Seismic data (Ts, Tp) and muons data (density) can resolve all three unknowns.

# Accomplishments to Date

- Strong collaborative team built with clear roles and responsibilities for each member
- Simulations of detector response at different sites completed
- Detector tested in underground test sites and results successfully compared with simulations and LANL instrument
- First attempt of a joint inversion of seismic and muons data completed
- Design of the 2nd prototype completed.

# Synergy Opportunities

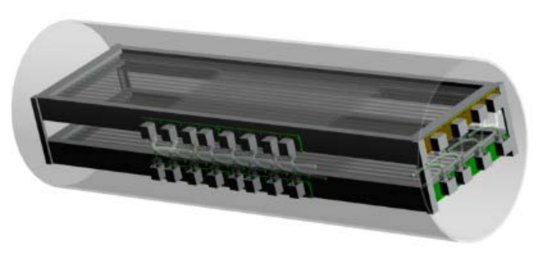
1) 
- **Hydraulic Fracture and Stimulation in a Deep Mine Investigation** – Lawrence Berkeley National Laboratory – Curtis Oldenburg/Patrick Dobson
- **Development of microBayesloc Location Method** - Lawrence Livermore National Laboratory - Steve Myer

2) 
- **Evaluating the State of Stress Beyond the Borehole** - Los Alamos National Laboratory - Andrew Delorey
- **Ultrasonic Phased Arrays and Interactive Reflectivity Tomography** - Oak Ridge National Laboratory – Hector Santos-Villalobos

3) 
- **Novel 3D Acoustic Borehole Integrity Monitoring** - LANL - Cristian Pantea
- **Imaging Fracture Networks using Joint Seismic and Electrical Change Detection** - Sandia National Laboratory Hunter Knox

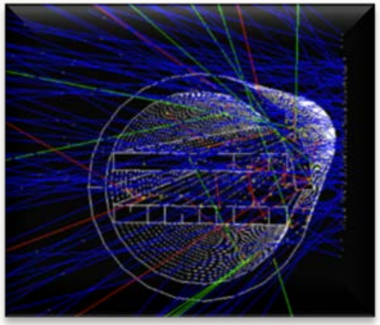
# Summary

- Detection of density anomalies in the subsurface using borehole detectors theoretically possible;
- First prototype built and working well;
- Detector tested in underground test sites and results successfully compared with reference instrument;
- First attempt of a joint inversion of seismic and muons data completed showing the contribution of muon to improve the solution. More to come with addition of gravity data
- Design of the 2nd prototype completed.



## Next Steps

- realization of the 2nd prototype and integration in high pressure casing
- borehole test
- engage with industry (sensors production and deployment)

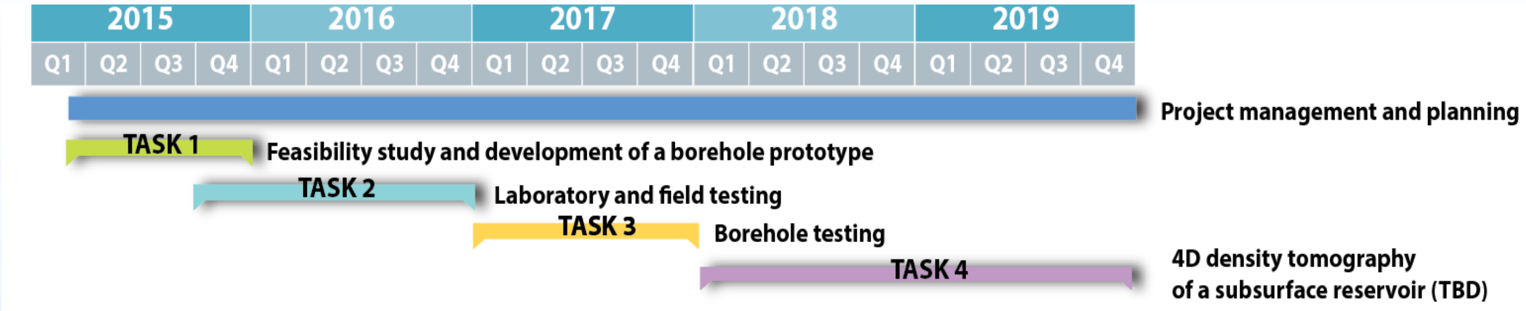


# Organization Chart

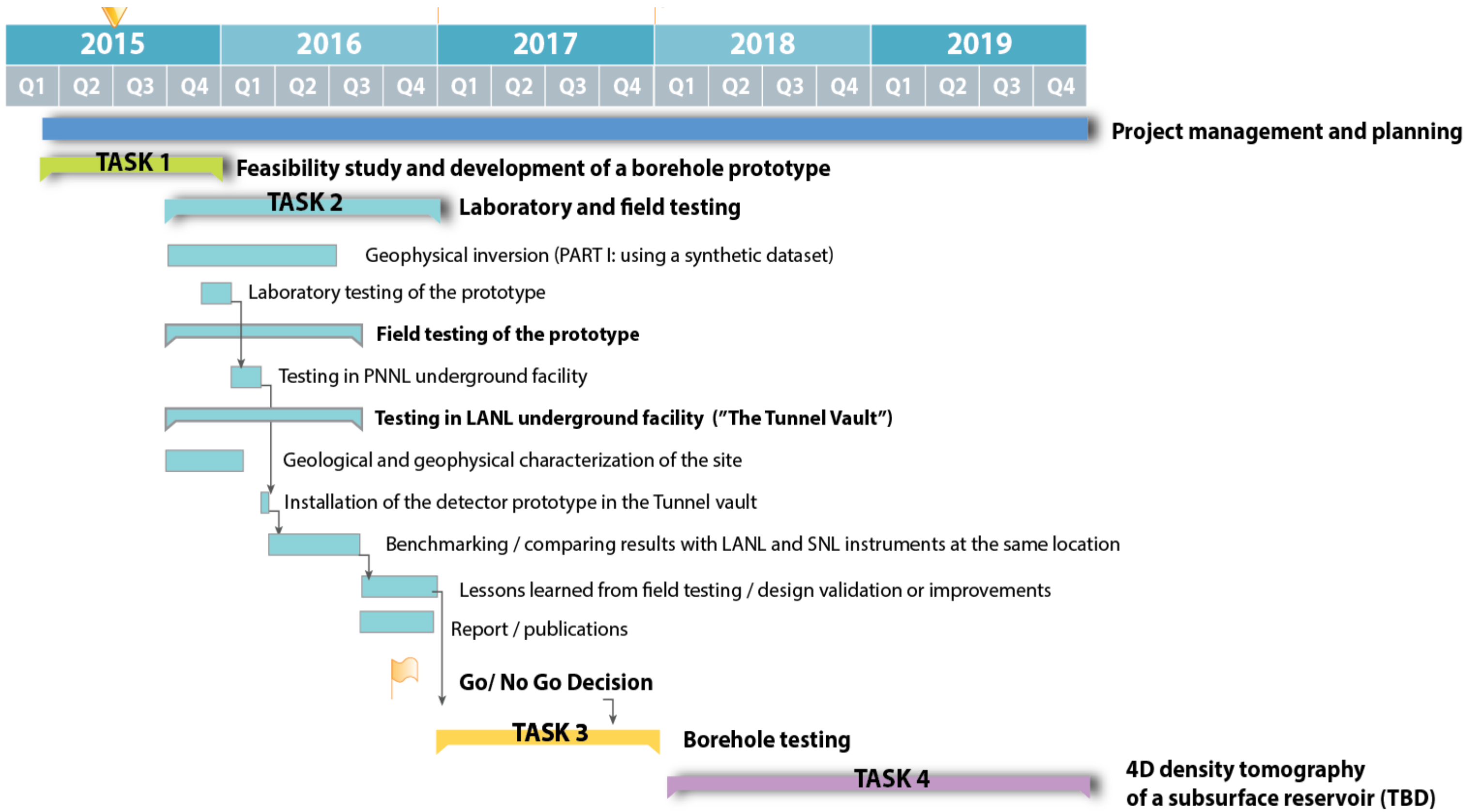
| Team participant | Role |
|---|---|
| ▪ Pacific Northwest National Laboratory (PNNL) | ▪ Project management , instrument design, muons simulation of subsurface conditions, applications. |
| ▪ University of Hawaii (UH) | ▪ Customized electronics |
| ▪ University of Utah (UoU) | ▪ Simulation for various designs |
| ▪ Los Alamos National Laboratory (LANL) | ▪ Comparison (benchmark) with LANL large detector, and joint inversion of muon and gravity data |
| ▪ Sandia National Laboratory (SNL) | ▪ Comparison with SNL large detector |
| ▪ Lawrence Livermore National Laboratory (LLNL) | ▪ Joint inversion of muon and seismic data |
| ▪ Paulsson, Inc. | ▪ Instrument packaging for downhole use |

**PNNL:** Alain Bonneville; Richard Kouzes; Jared Yamaoka
**LANL:** Charlotte Rowe ; Elena Guardincerri
**LLNL:** Robert Mellors; George Chapline
**SNL:** Nedra Bonal; Leiph Preston
**UH:** Gary Varner; Isar Mostafanezhad
**UofU:** Azaree Lintereur; Joshua Flygare
**Paulsson Inc.:** Bjorn Paulsson

# Gantt Chart



2015
2016
2017
2018
2019
Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4
Project management and planning
TASK 1
Feasibility study and development of a borehole prototype
TASK 2
Laboratory and field testing
TASK 3
Borehole testing
TASK 4
4D density tomography
of a subsurface reservoir (TBD)

2015
2016
2017
2018
2019
Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4
Project management and planning
TASK 1
Feasibility study and development of a borehole prototype
TASK 2
Laboratory and field testing
Geophysical inversion (PART I: using a synthetic dataset)
Laboratory testing of the prototype
Field testing of the prototype
Testing in PNNL underground facility
Testing in LANL underground facility ("The Tunnel Vault")
Geological and geophysical characterization of the site
Installation of the detector prototype in the Tunnel vault
Benchmarking / comparing results with LANL and SNL instruments at the same location
Lessons learned from field testing / design validation or improvements
Report / publications
Go/ No Go Decision
TASK 3
Borehole testing
TASK 4
4D density tomography
of a subsurface reservoir (TBD)

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