Enabling Port Security using Passive Muon Radiography.

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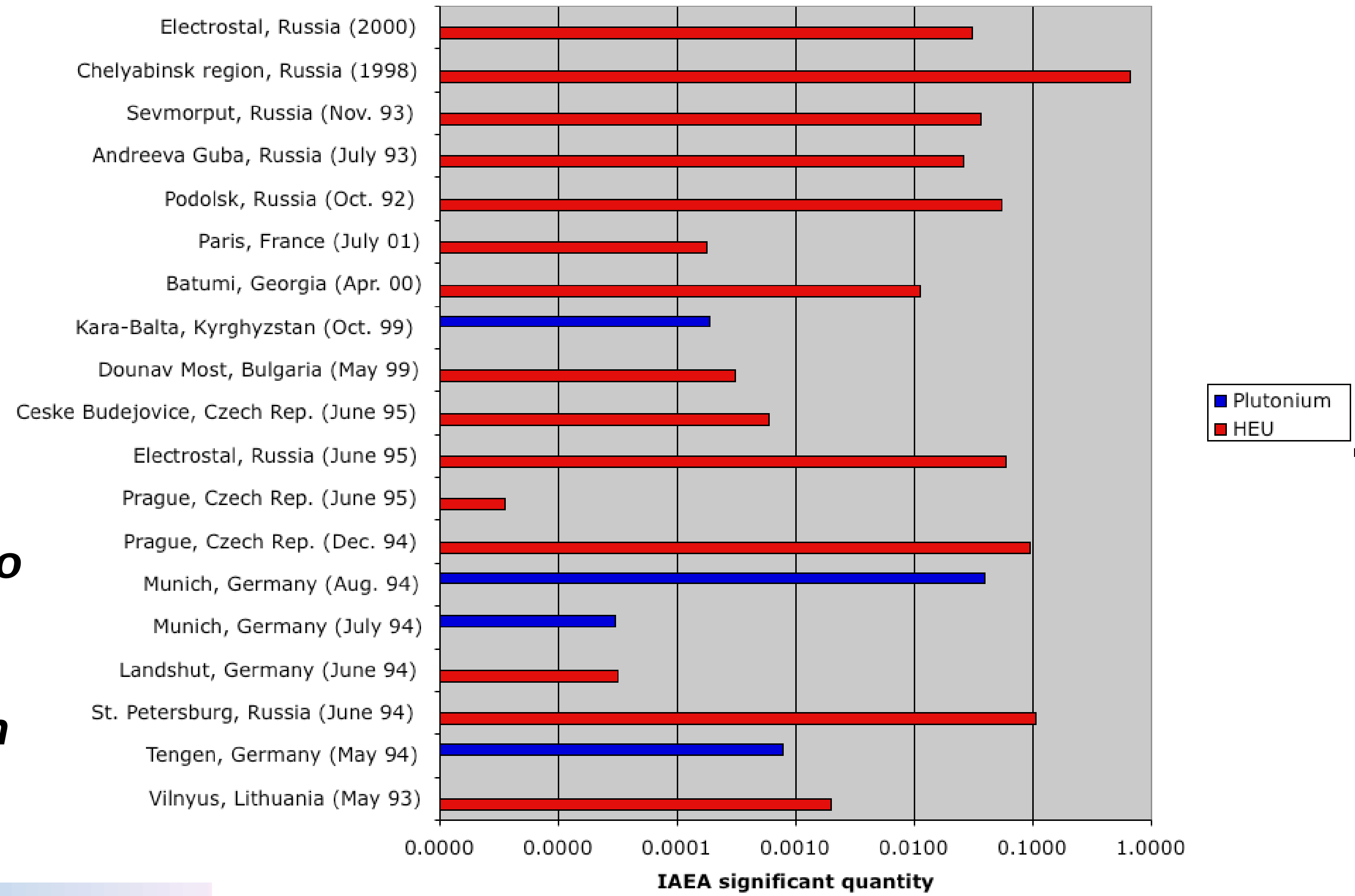
Nuclear smuggling is a clear and present danger

Materials Interceptions

"Law enforcement officials in the US seize only 10 to 40% of the illegal drugs smuggled into the country each year

Russia stops from 2 to 10% of illegally imported goods and illegal immigrants on the border with Kazakhstan"



Los Alamos National Laboratory
October 24, 2002

Stanford Nuclear Smuggling Database:
Dynamics and Trends Over
the Past Decade

Lyudmila Zaitseva

Center for International Security and Cooperation, Stanford University

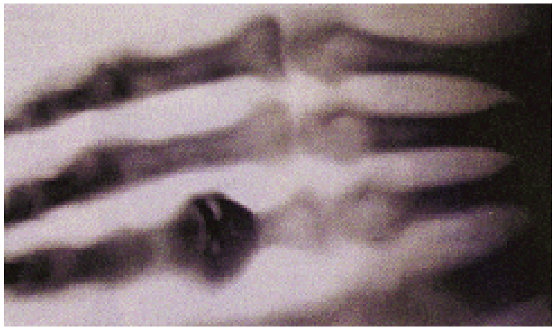
Total = 1.13 IAEA "significant quantities"

(8 kg Pu or 25 kg of U^{235} in HEU)

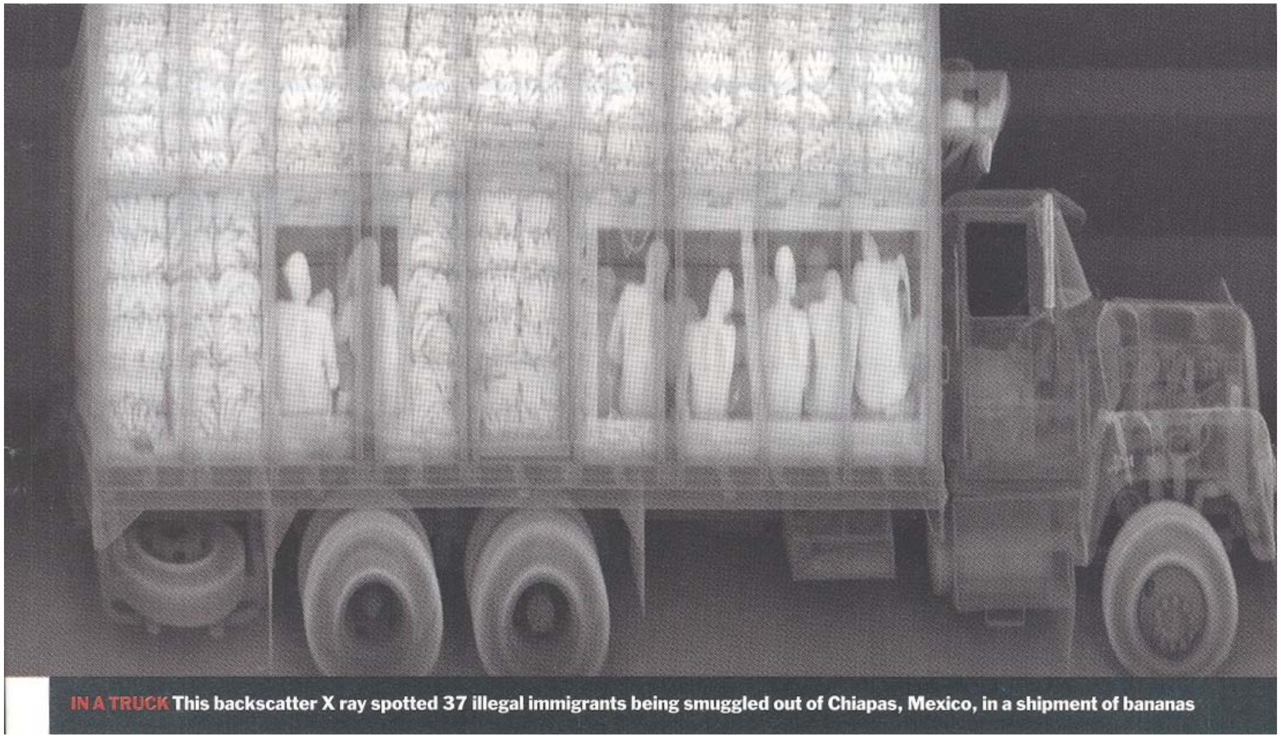
Active radiography is an established inspection technique

To date, radiography has depended on artificial sources of radiation, which bring with them a risk-benefit tradeoff

1895
First x-ray image (Mrs. Roentgen's hand)



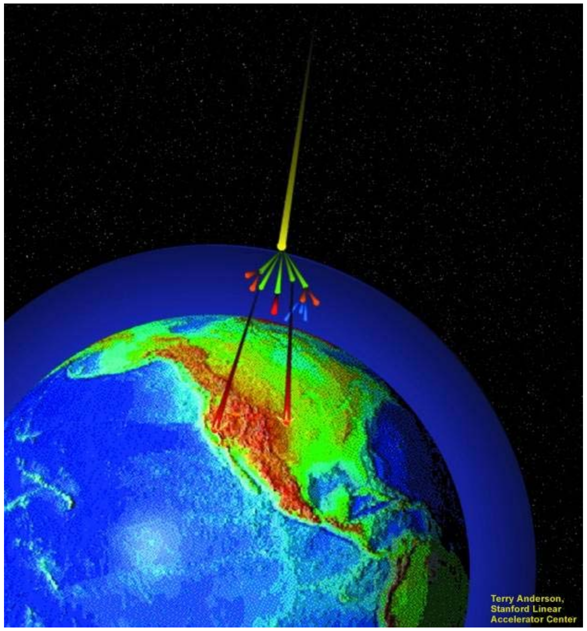
2001
Inspection of truck with American Science and Engineering backscatter x-ray system



Passive Source Radiography: Cosmic Radiation

No artificial radiation means:

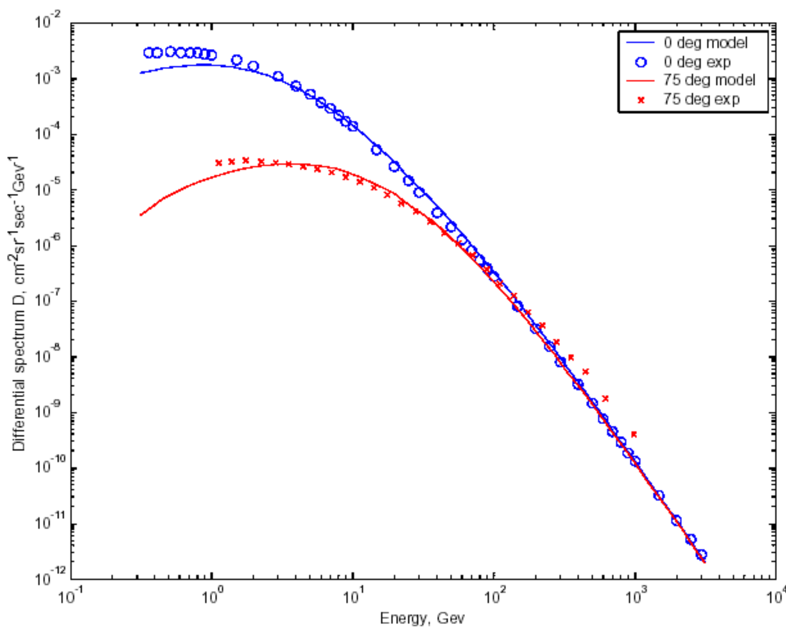
1. Cars and trucks inspection without evacuating the driver
   significant time factor
2. Deployment abroad without local regulatory complications
   Detection at point of origine
3. No radiation signal to set off a salvage trigger
   Minimizes inspection risks.

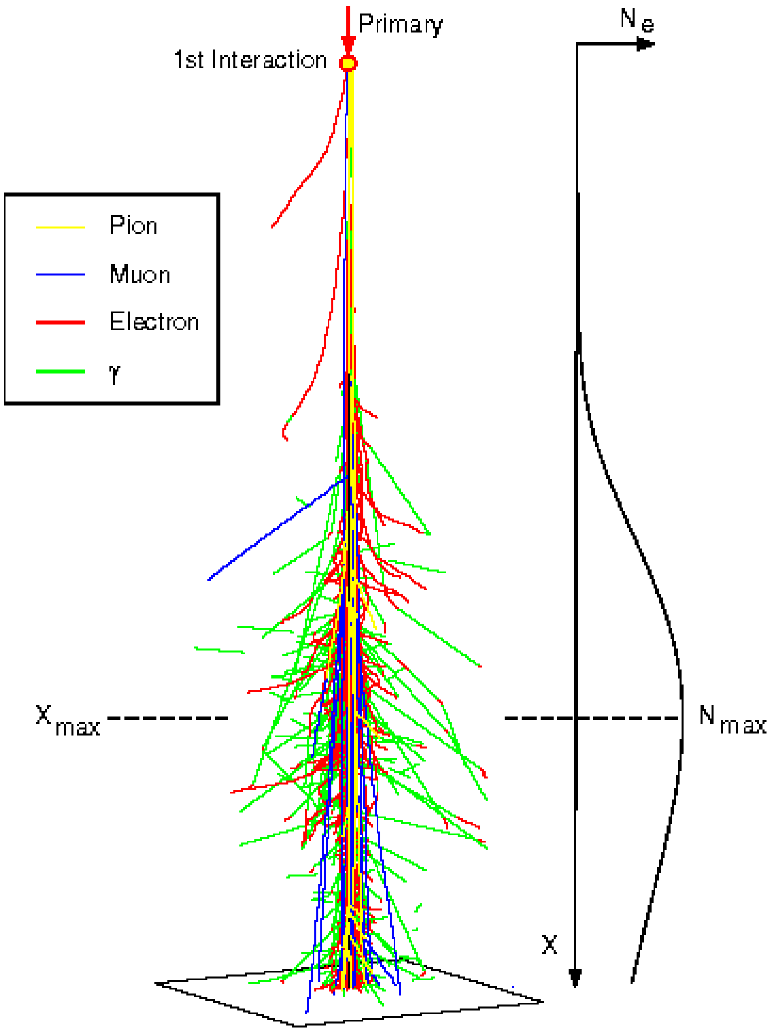


1. Neutrons
2. Neutrinos
3. Electrons
4. Muons
5. Etc.

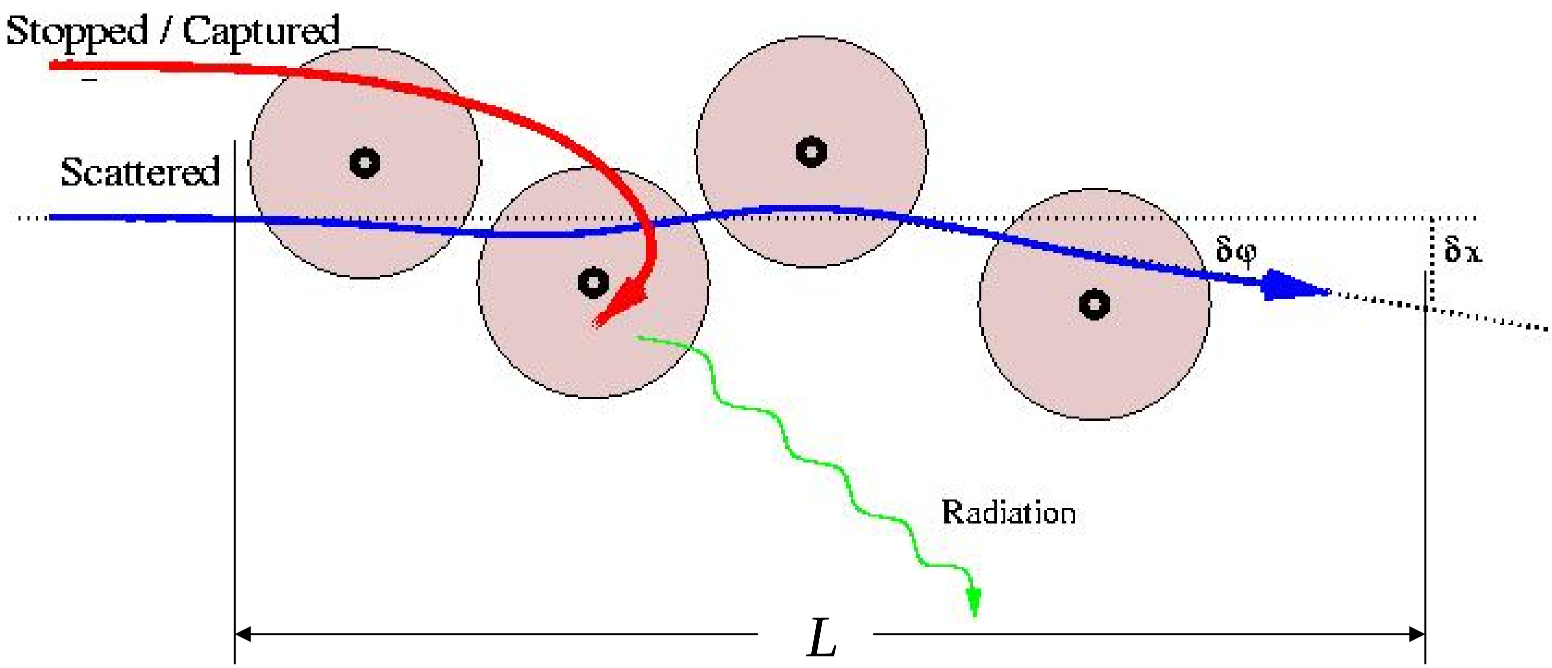
Cosmic-ray muons

- As cosmic rays strike our upper atmosphere, they are broken down into many particle components, dominated by muons.
- Muons have a large penetrating ability, being able to go through tens of meters of rock with low absorption.
- Muons arrive at a rate of 10,000 per square meter per minute (at sea level).





How Muons Interact with Material



Muons are
Charged either
Positive and
negative

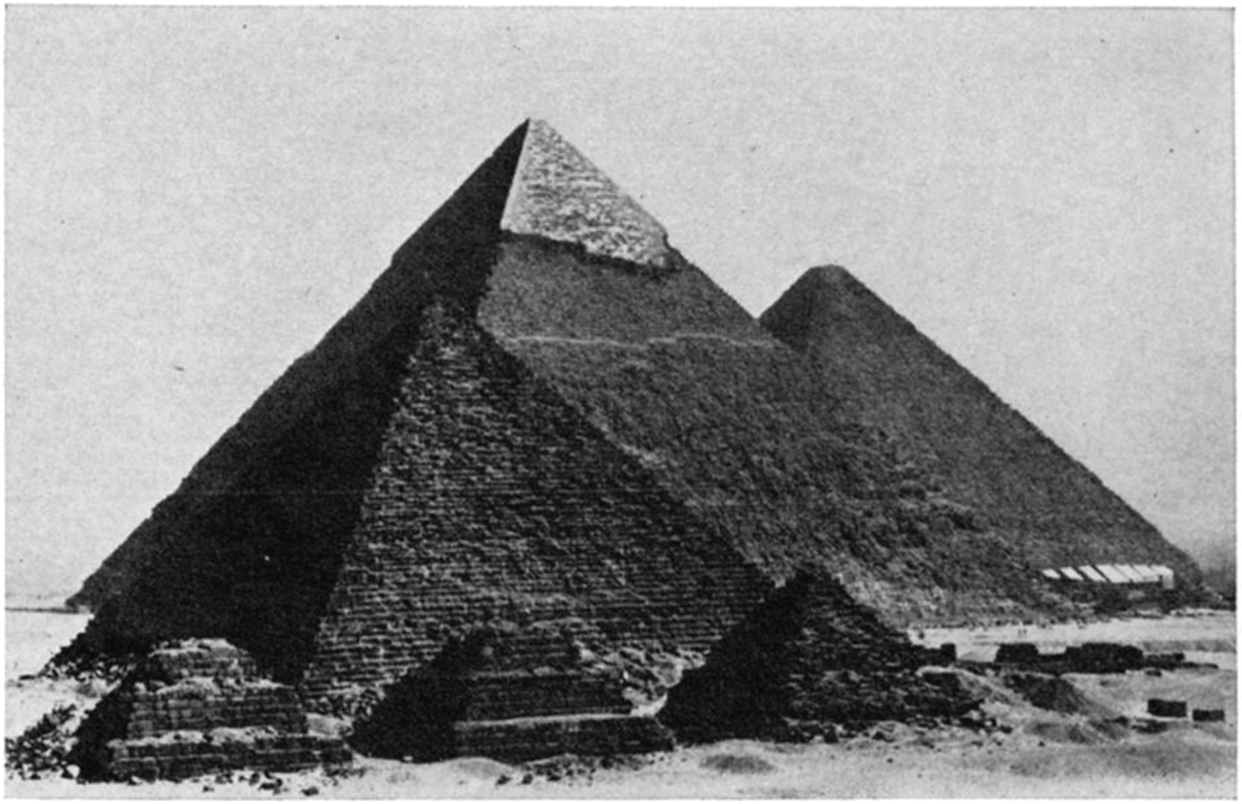
High energy:
Median 3MeV

Two modes of interaction:

Absorption
Coulomb Scattering

History: *absorption* muon radiography

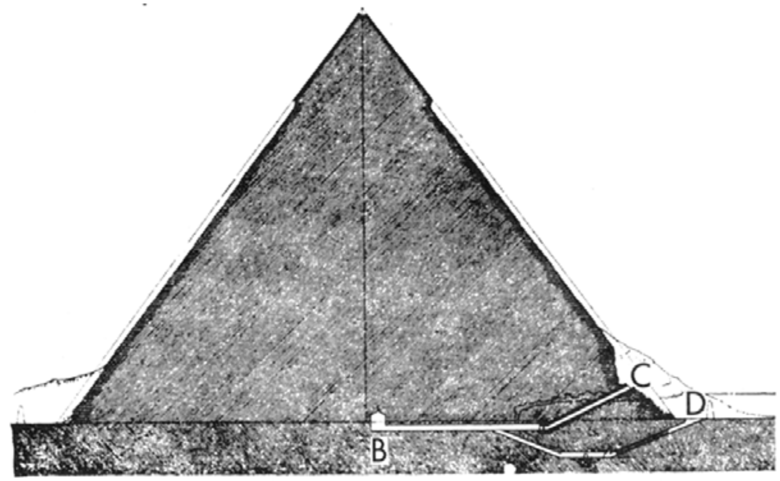
Fig. 1 (top right). The pyramids at Giza. From left to right, the Third Pyramid of Mycerinus, the Second Pyramid of Chephren, the Great Pyramid of Cheops. [© National Geographic Society]



Luis Alvarez, 1950

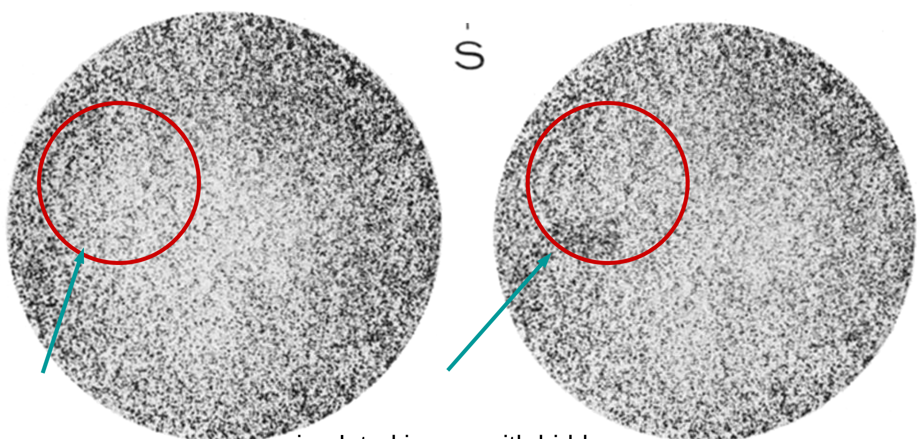
Muon mapping of Chephren’s Pyramid

Science, **167**, p. 832 (1970)
“Search for Hidden Chambers in the Pyramids”
Luis W. Alvarez *et al.*



Alvarez et al. *used only absorption, not scattering*

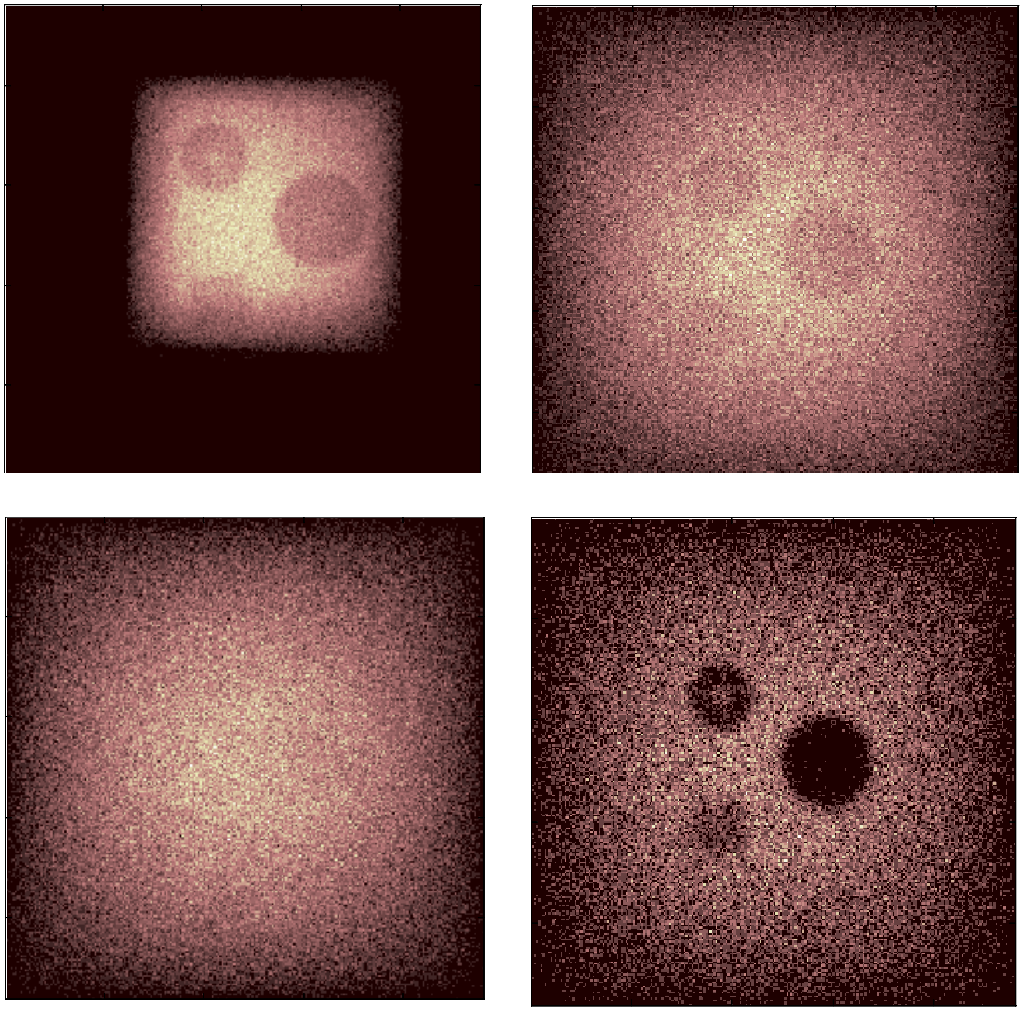
Successful experiment - existence of hidden chamber ruled out



actual image with no hidden chamber

simulated image with hidden chamber like the one in Cheops’ pyramid

Shadowgrams (from scattering)

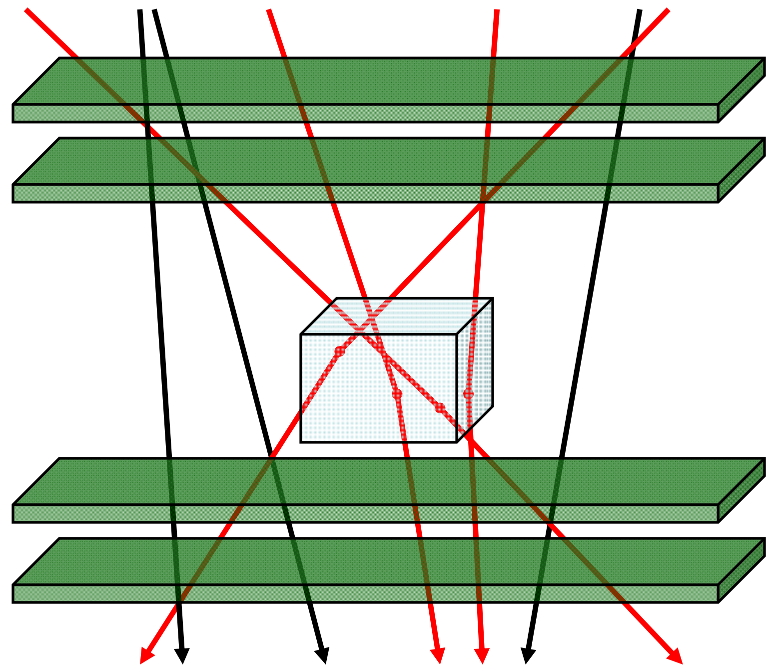


Possible to get shadowgrams from scattering instead of absorption

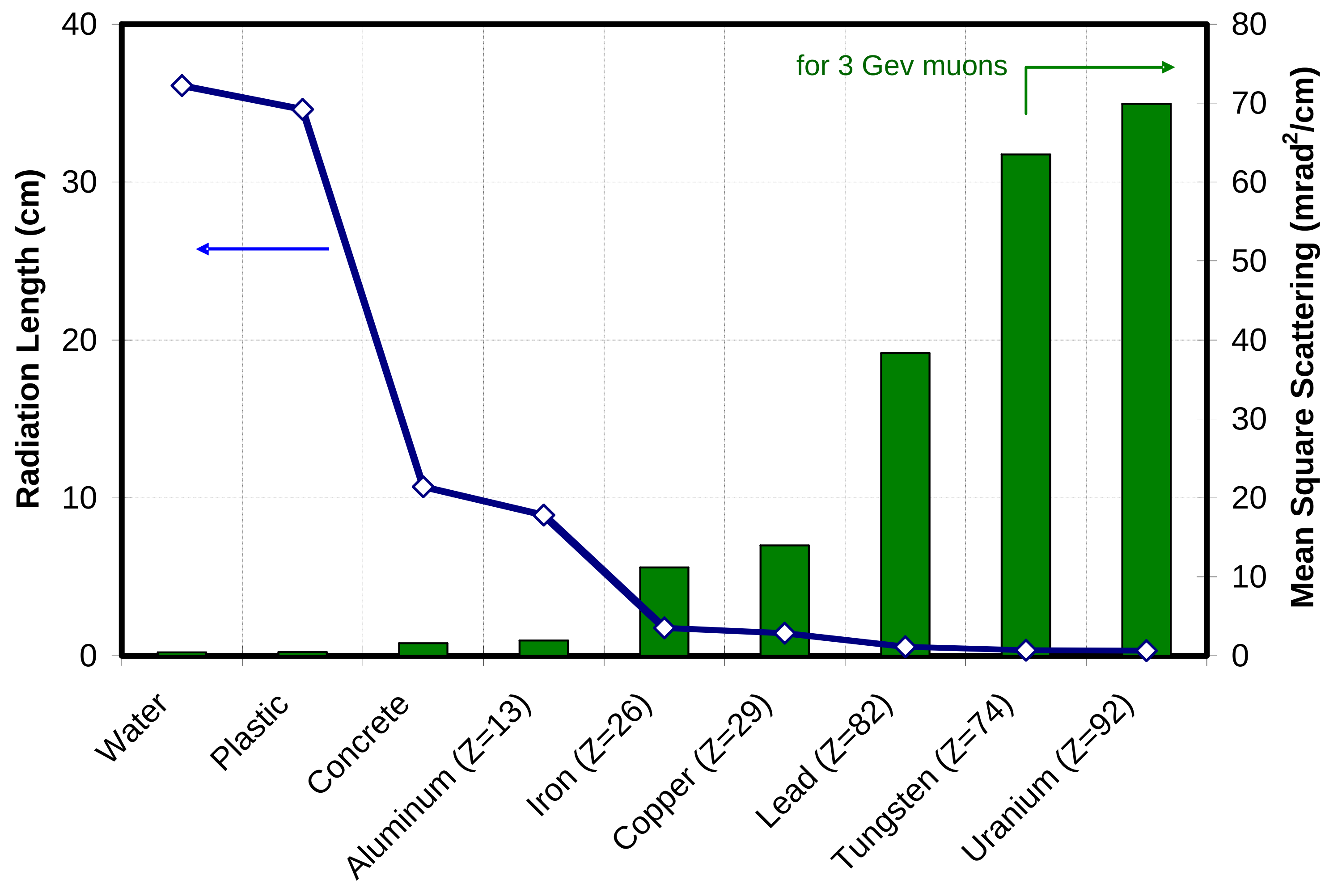
Proton radiography

Basic Concept of Multiple-Scattering Muon Radiography

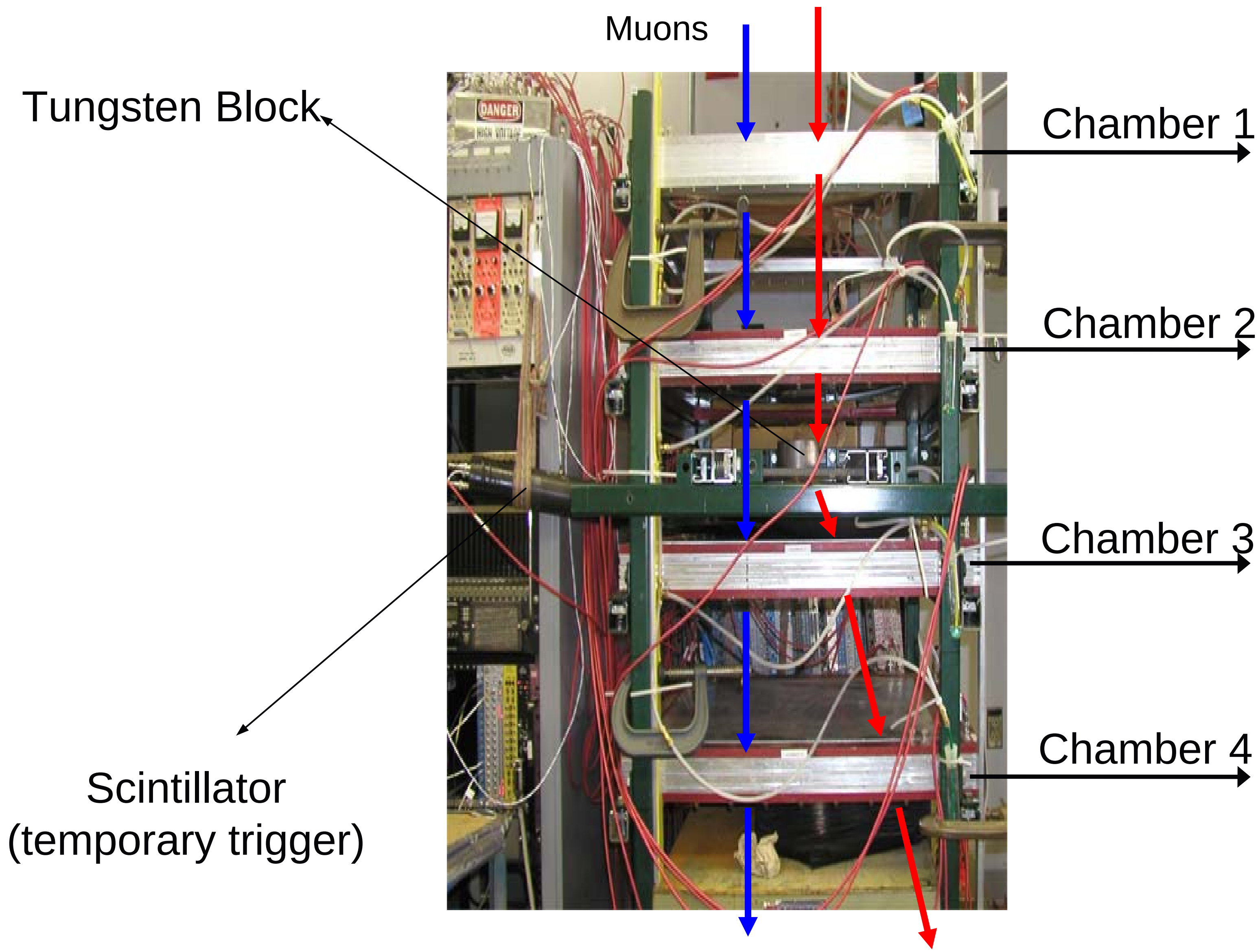
- **Track <u>individual</u> muons (possible due to modest event rate).**
- **Track muons <u>into</u> and <u>out of</u> an object volume.**
- **Determine scattering angle of each muon.**
- **Infer material density within volume from data provided by many muons.**



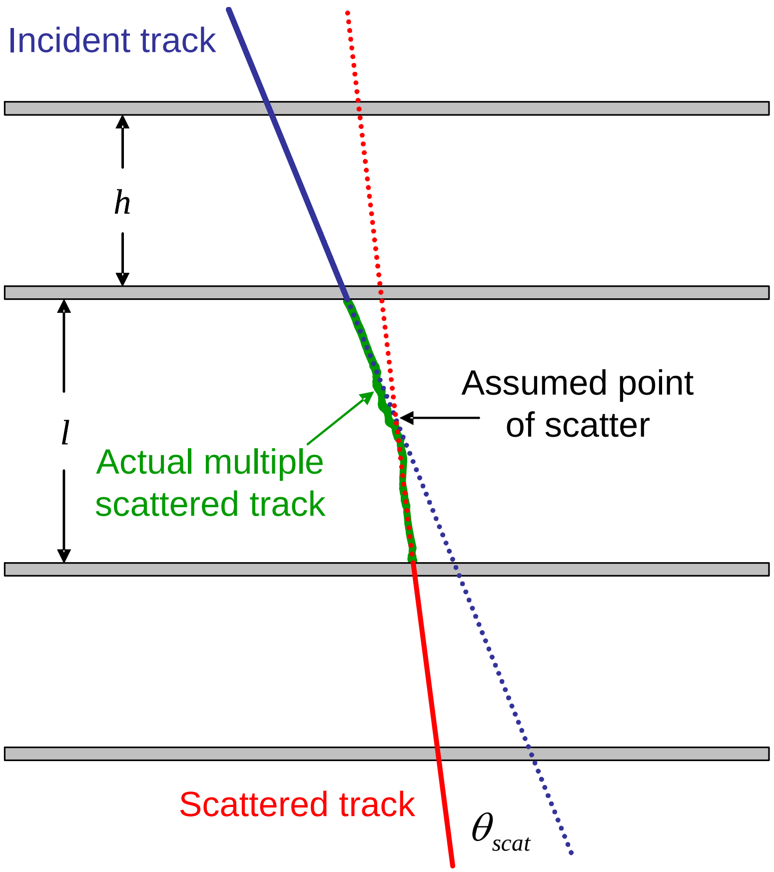
Scattering is Material Dependent



Prototype Los Alamos instrument

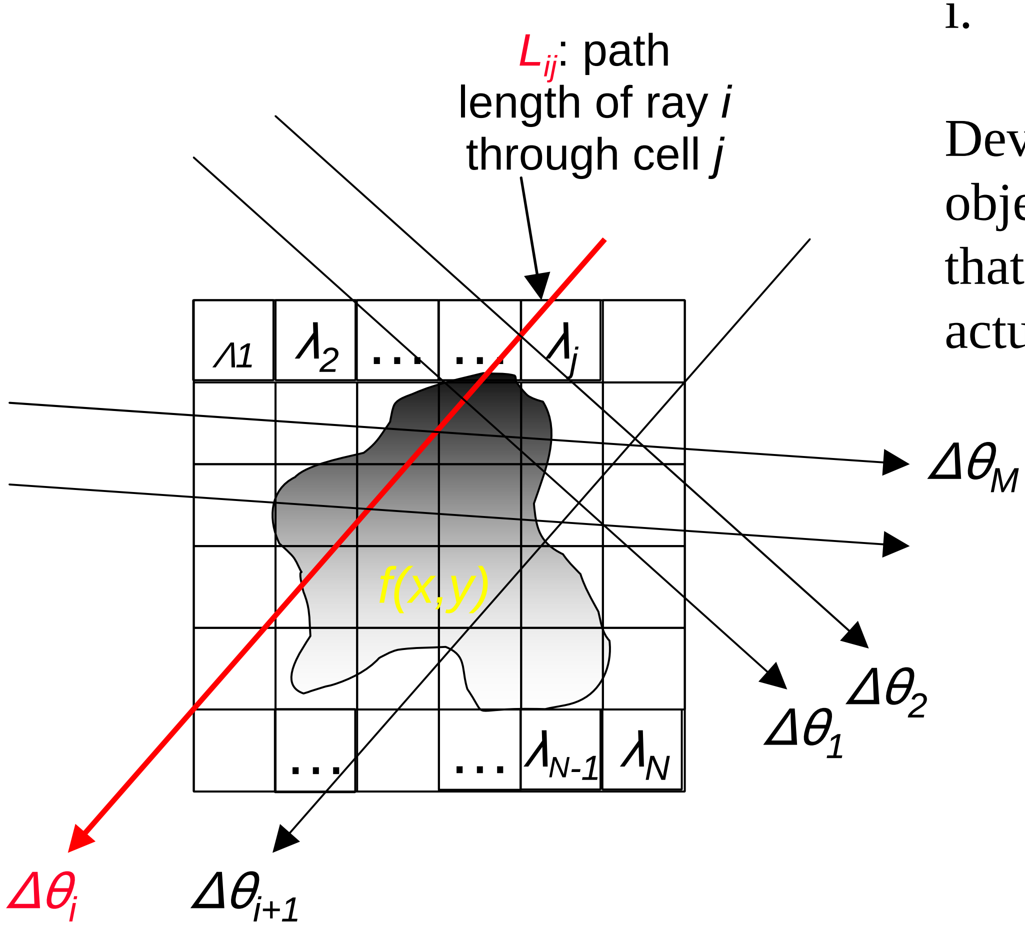


Reconstruction – Localizing Scattering



- Assume multiple scattering occurs at a point
- Find point of closest approach (PoCA) of incident and scattered tracks
- Assign (scattering angle)^2 to voxel containing PoCA
- Since detectors have known position uncertainty, signal may be spread over voxels relative to PoCA uncertainty.
- Simply add localized scattering signals for all rays.

Maximum Likelihood Image Reconstruction



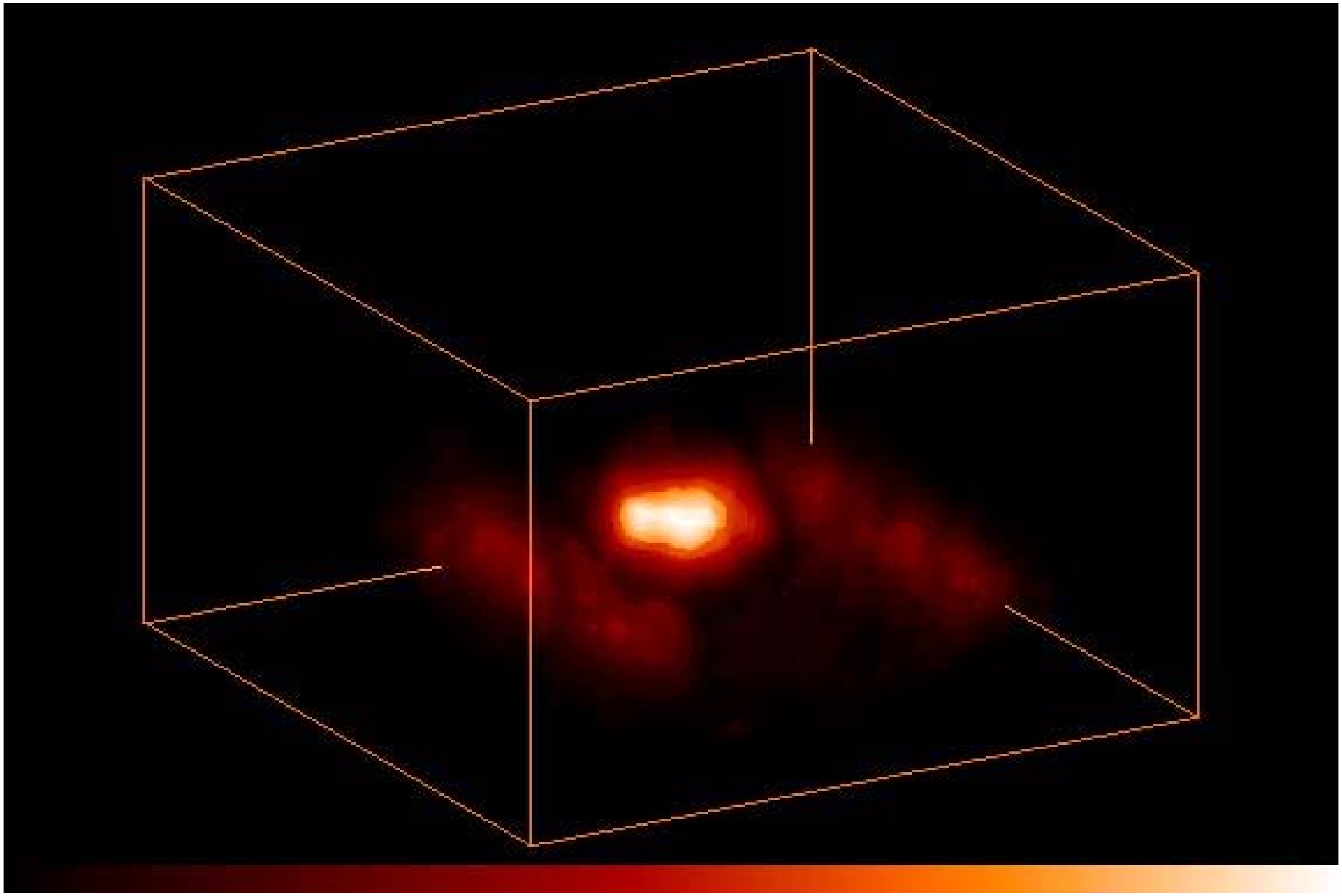
Use single layer probability model to calculate the contribution of voxel j to the observed displacement of ray i.

Develop a model of the unknown object that maximizes the likelihood that we would observe what we actually observed.

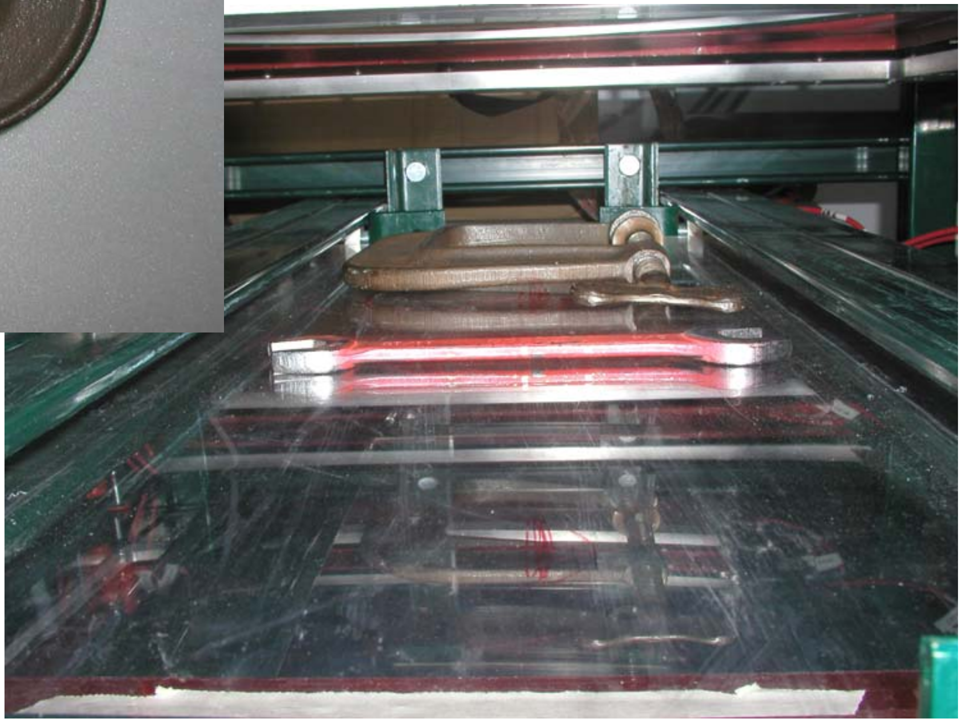
E-M works well:

Can handle large voxalization
Compute as data comes in

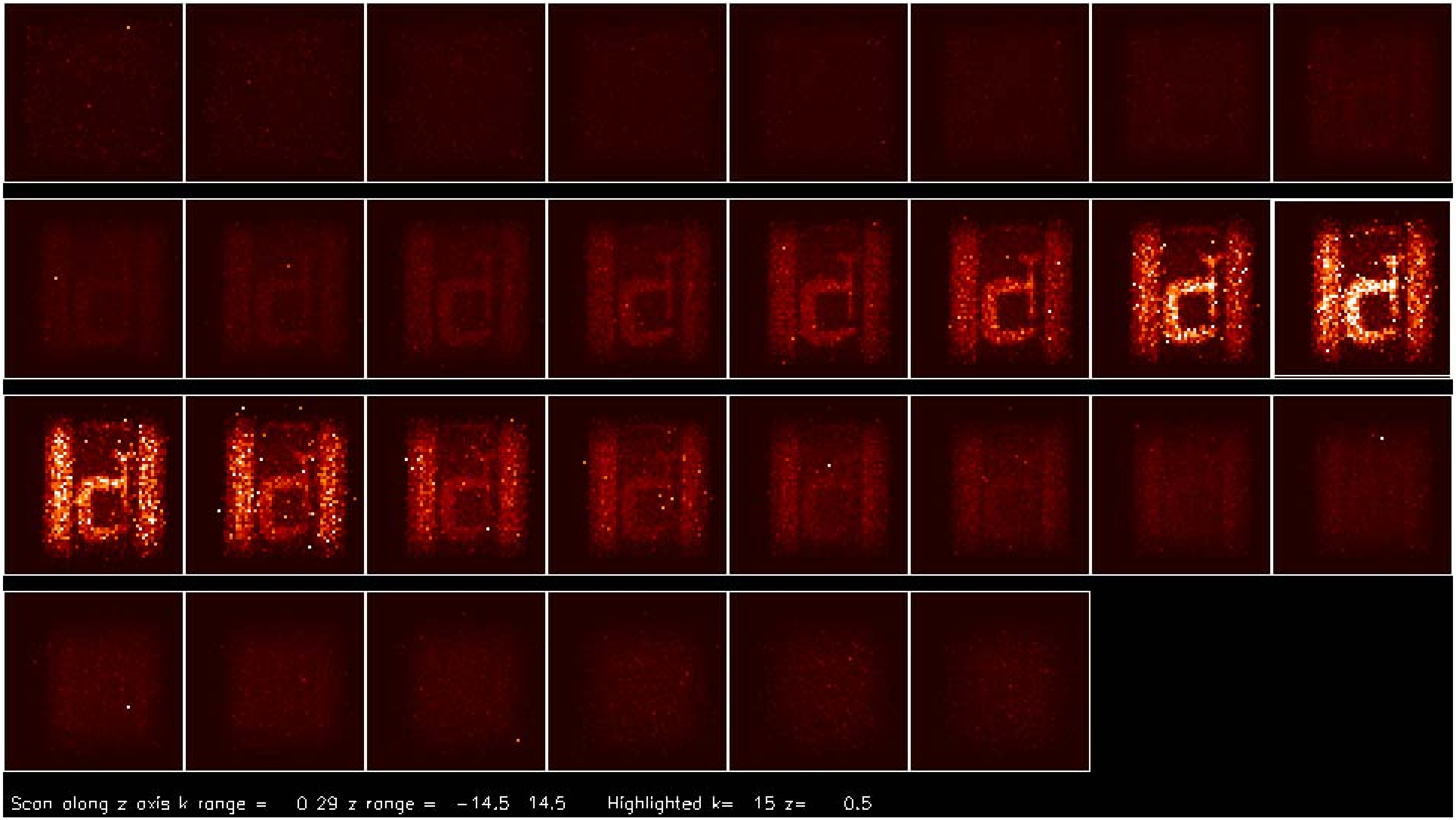
First Muon Radiograph



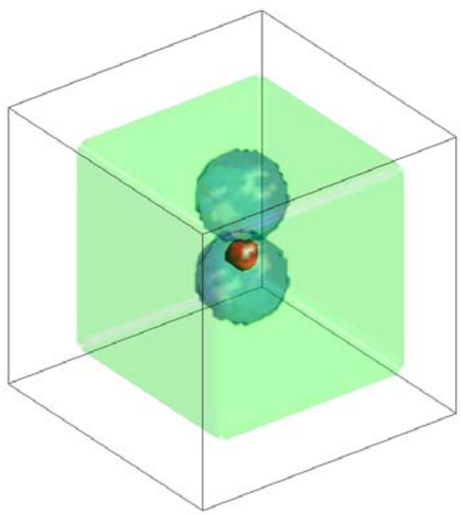
Radiograph of another object



Clamp in z-projections

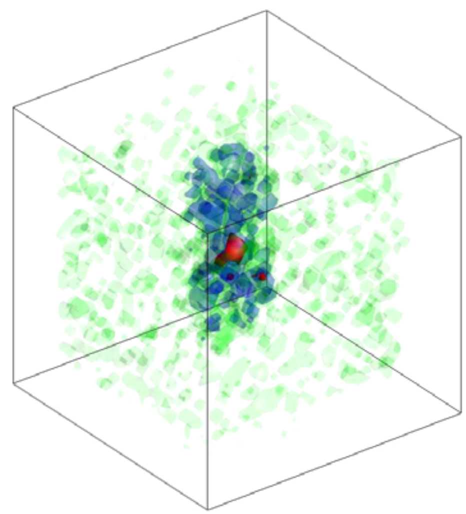


Tomographic Maximum Likelihood Reconstruction (20 x 20 x 20 voxels)



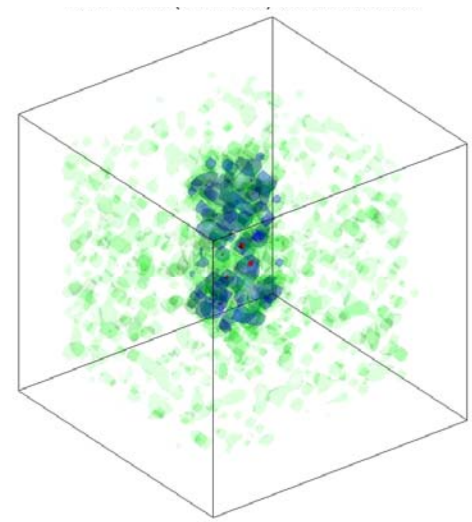
Objects

1x1x1 m3 Fe box (3 mm walls)
Two half density Fe spheres (automobile differentials)



ML reconstruction

1 minute exposure; with U sphere



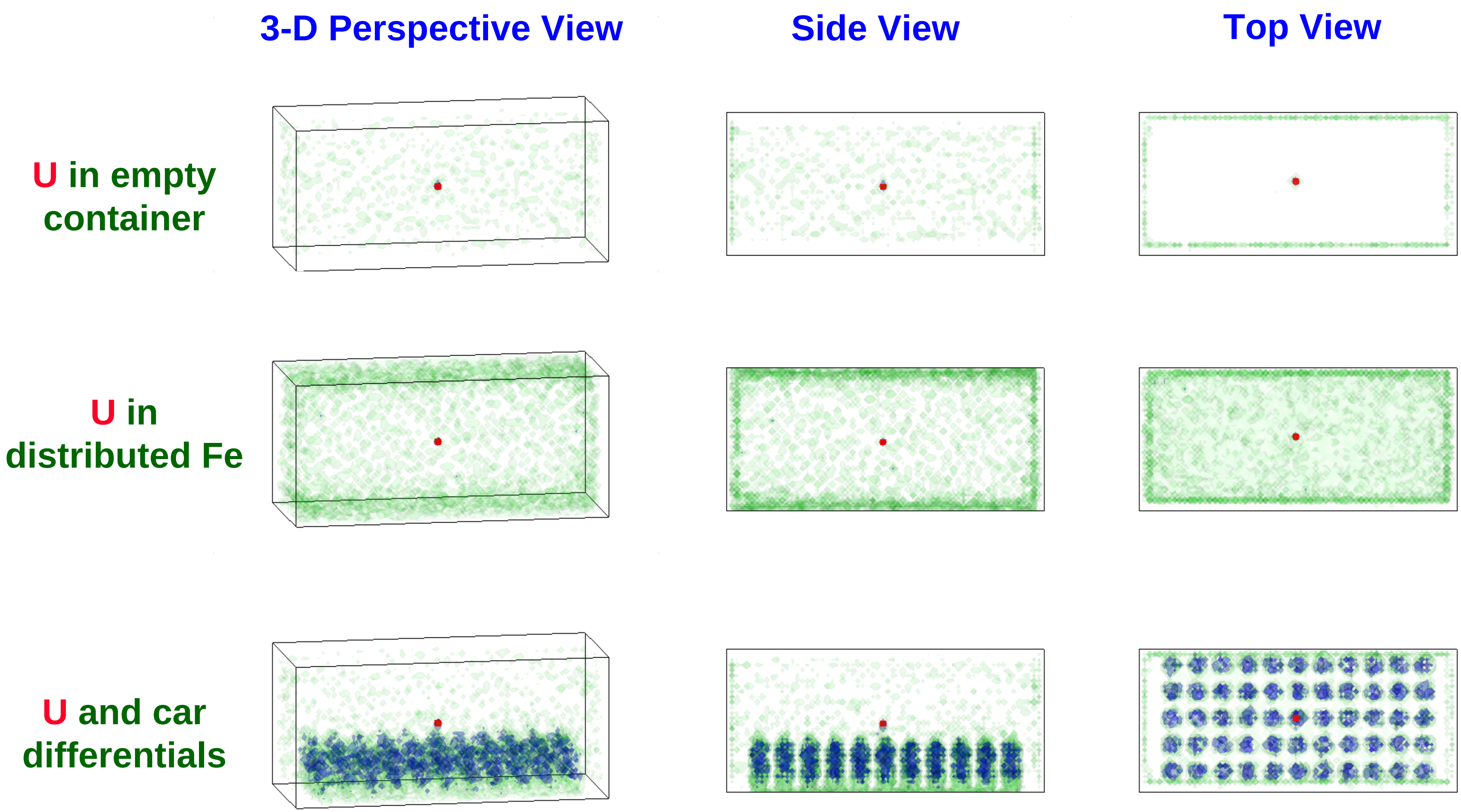
ML reconstruction

1 minute exposure; No U sphere

Shielding of SNM works to our advantage!

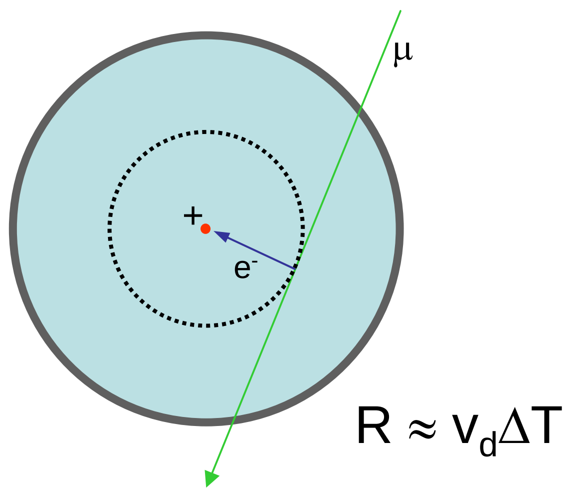
Maximum Likelihood Tomographic Reconstruction

28x28x64 voxelation, 1 minute simulated data

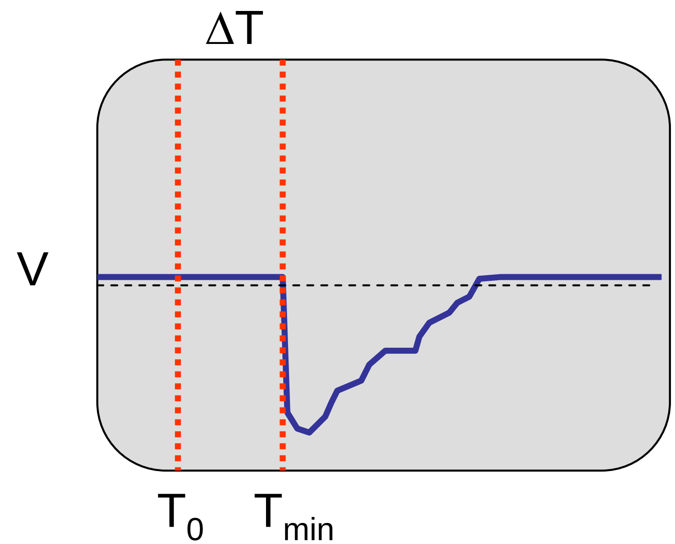


Calculation time: ~2 min on a 3 GHz single-processor Windows PC

Real data from drift tubes.



Cylindrical Drift Tube Geometry

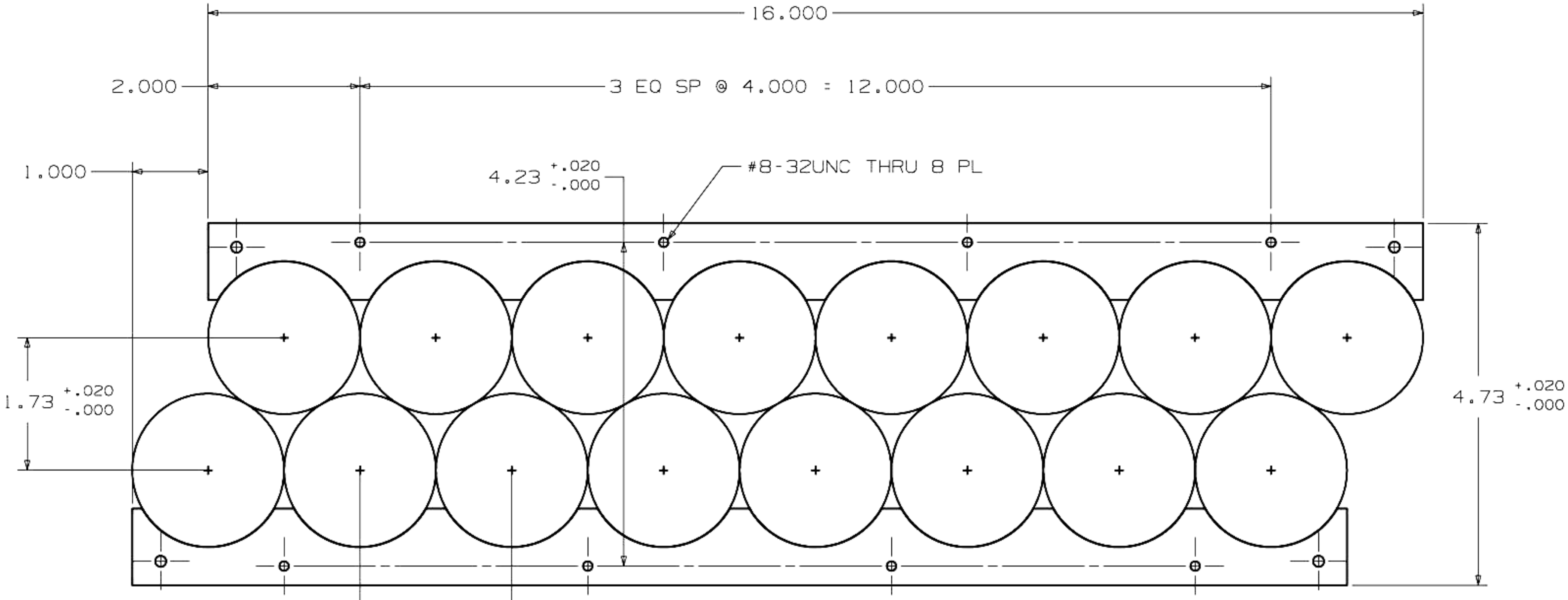


Representative Anode Signal

- High E field at 20 μm wire causes gas avalanche multiplication
- e^- Drift Time ≅ 20 ns/mm × R in gas:
  $0 \leq \Delta T \leq 500$ ns
- Radius of closest approach given by ΔT and saturated drift velocity v_d.
- Spatial resolution goal ≤ 0.4 mm

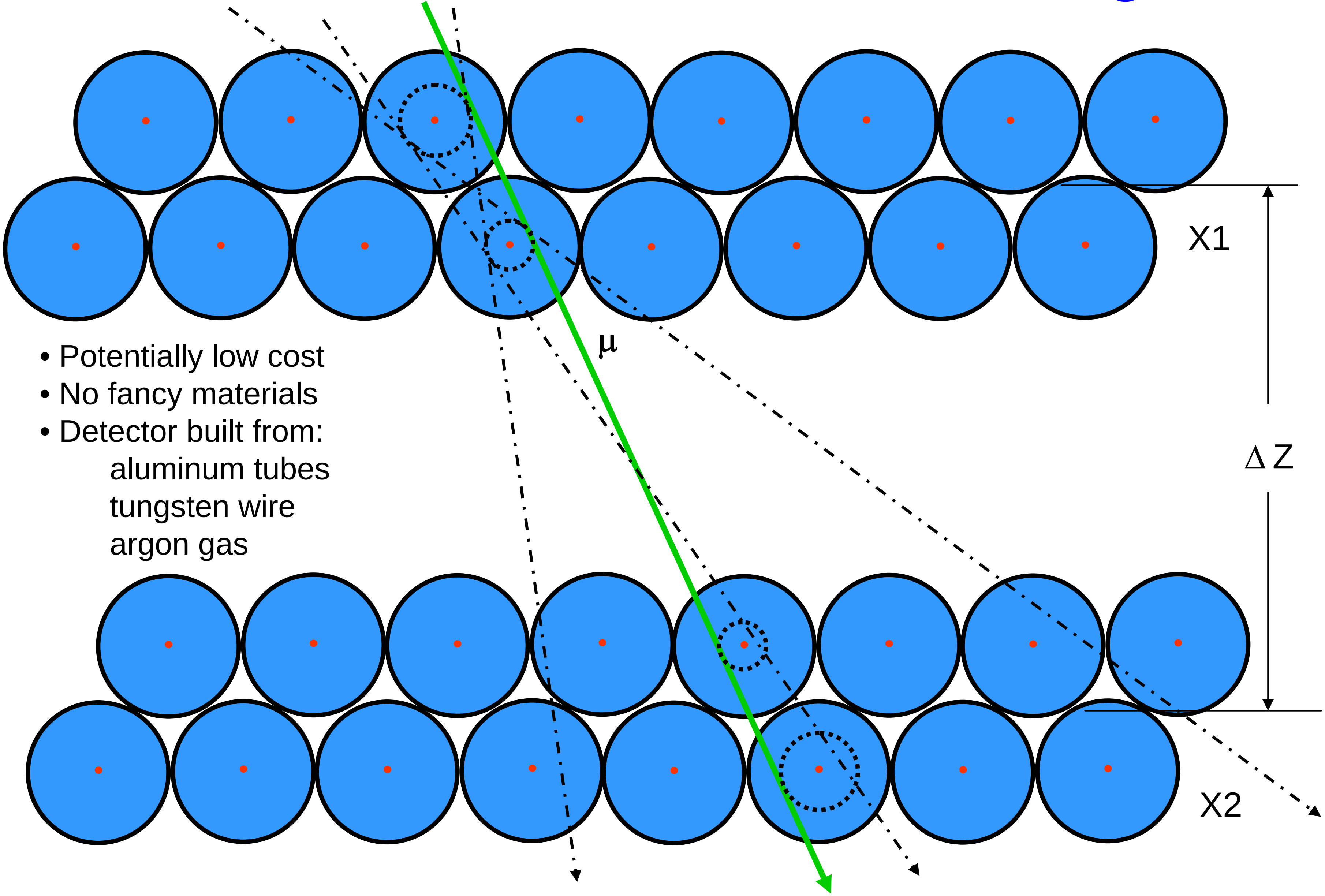
- **Low count rate (~kHz) and multiplicity**
  ⇒ Relatively large cell size allowed:
  D ~ 2 inch
- **Larger cell size ⇒ fewer channels**

Drift Tubes Bonded into Modules



RCS 9/21/04

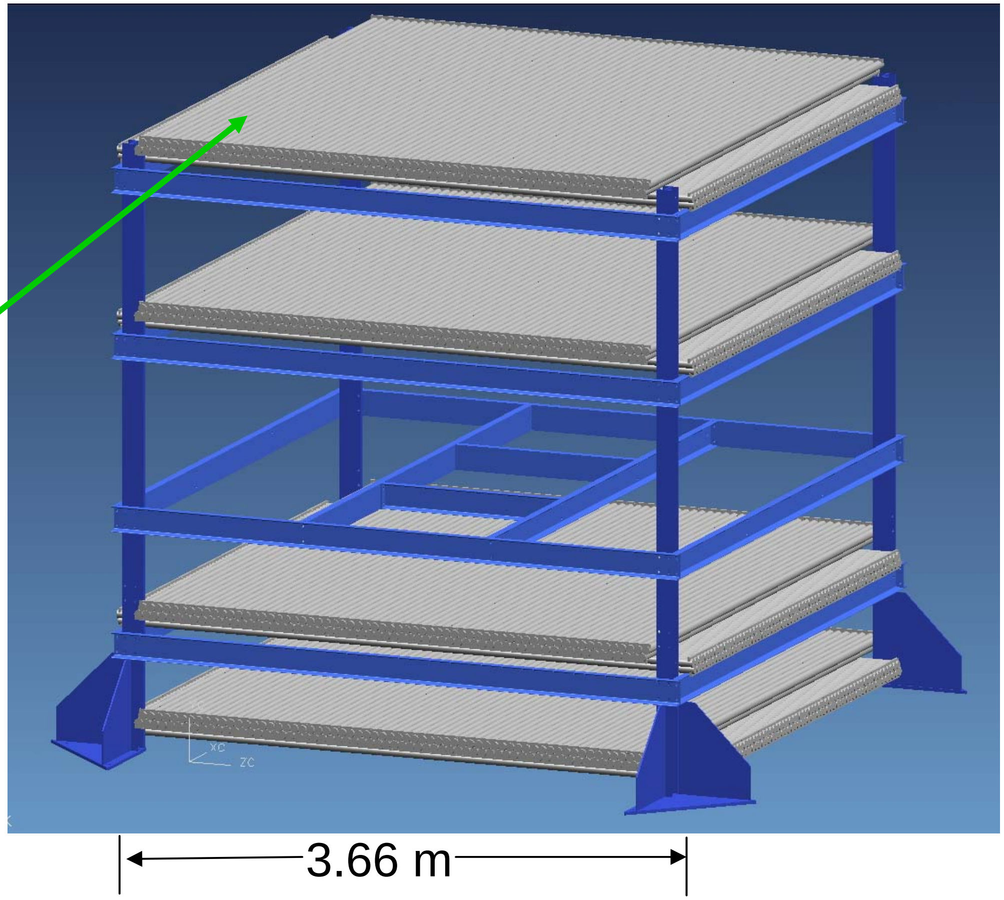
Drift tubes for muon tracking



- Potentially low cost
- No fancy materials
- Detector built from:
  - aluminum tubes
  - tungsten wire
  - argon gas

Modules combined into Muon Tracker

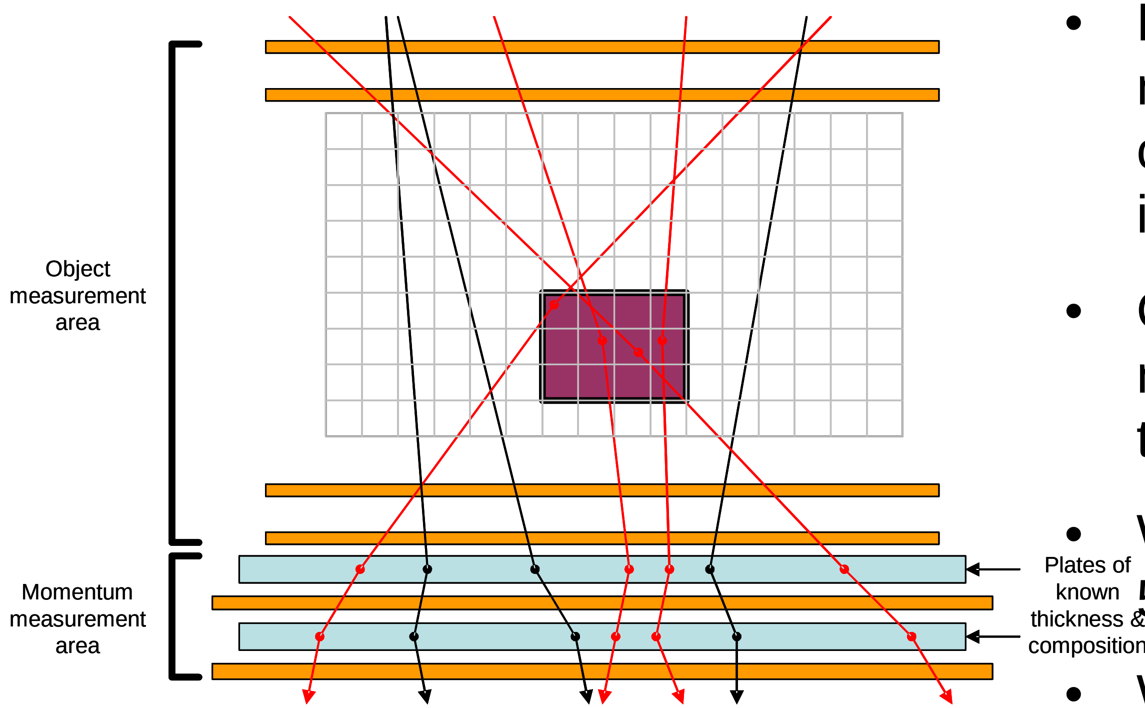
- Drift tube detectors
- 4 x-y planes
- 128 tubes per x or y
  - 1024 channels total
- Reconfigurable



EOY 2004 Goal: 40 modules, 64” x 64” active area with good solid angle

Large Muon Tracker

Momentum Estimation



- Measuring particle momentum increases confidence in material inference.
- One method is to estimate momentum from scattering through known material.
- With 2 plates $\Delta p/p$ is about 50%.
- With N measurements $\Delta p/p$ approaches:

$$\sqrt{\frac{1}{2N}}$$

Bonus Material

Absorbtion

Data: $Z_i = \begin{cases} 1 & Absorbed \\ 0 & Not \end{cases}$

Stoppage $S = \int_{\gamma} \rho(\gamma(s))ds$

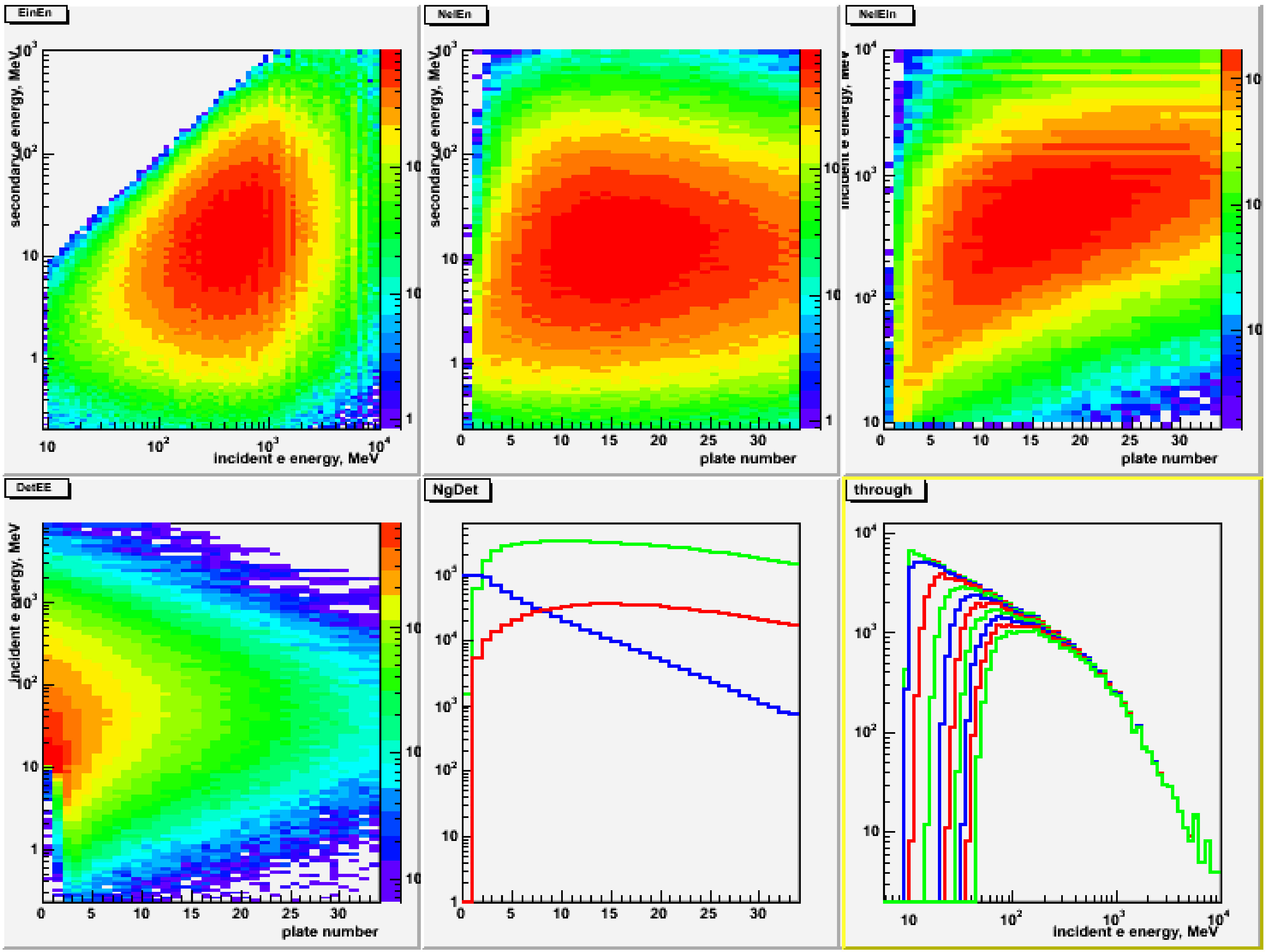
Model $P[Z=1 \mid S=s, E=e] = G(s-e)$

Problem:
Different physics for stoppage
Than scattering. Can
We really combine data?

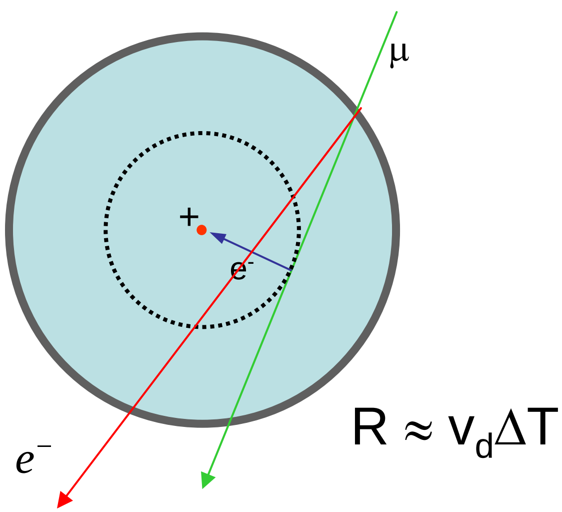
Are planning experiments to estimate H

$$P[Z=1 \mid S=s] = \int G(s-e)F(de) = H(s)$$

Nice little inverse problem


EinEn
secondary e energy, MeV
incident e energy, MeV
NeIEn
secondary e energy, MeV
plate number
NeIEin
incident e energy, MeV
plate number
DetEE
incident e energy, MeV
plate number
NgDet
plate number
through
incident e energy, MeV

Secondary particle polution



Knock off electrons and Bremsstrallung confuses the drift tubes (~5%)

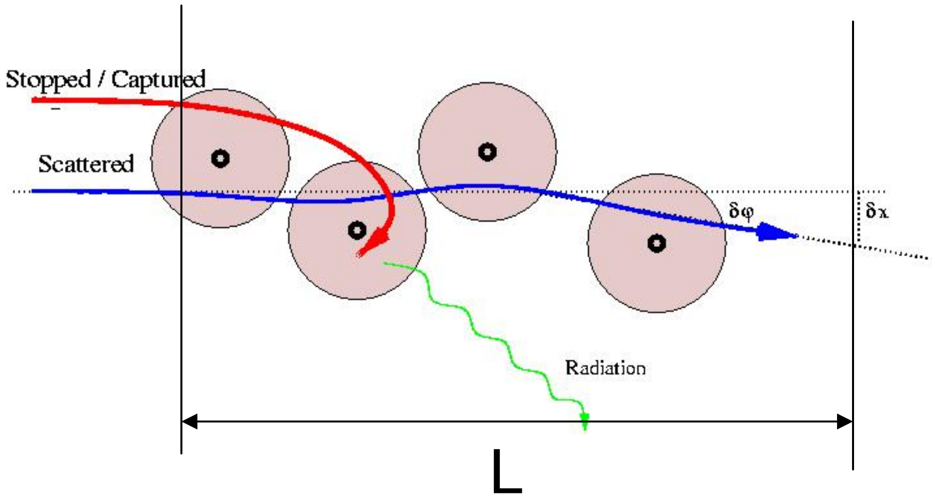
Physics for electron-matter interaction different from muon-matter interaction.

Drift tubes detected charged particles, not type.

Sources of electron:

1. Knock-off (delta-rays)
2. Bremstrallung
3. In-flight decay

Modeling Muon Scattering



Data from scattered muons:

Change in position Δx
Change in angle $\Delta\theta$

Inverse problem with the signal in the variance

$$E[\Delta\theta] = E[\Delta x] = 0$$

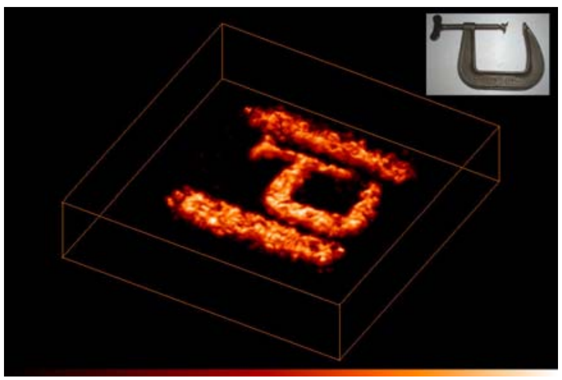
$$Var[\Delta\theta] \propto \frac{1}{p^2} \frac{L}{L_{rad}}$$

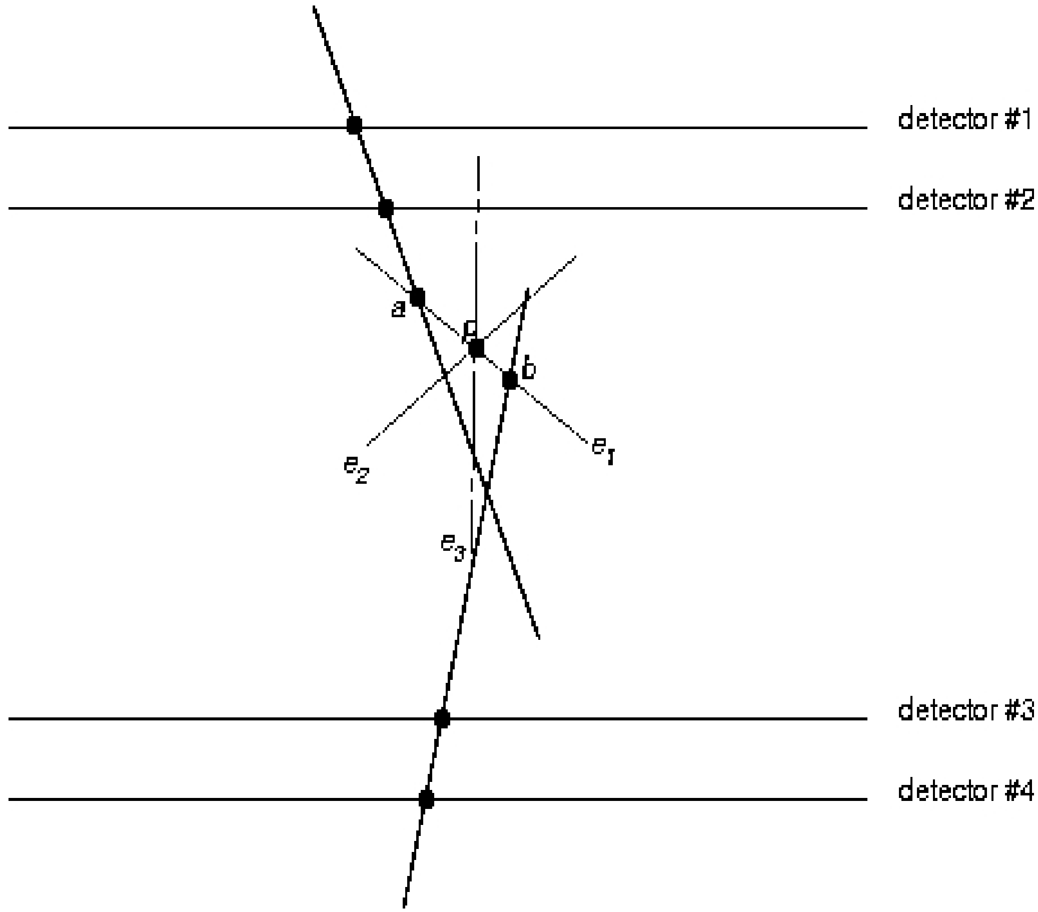
Material specific parameter λ

Momentum (unknown)

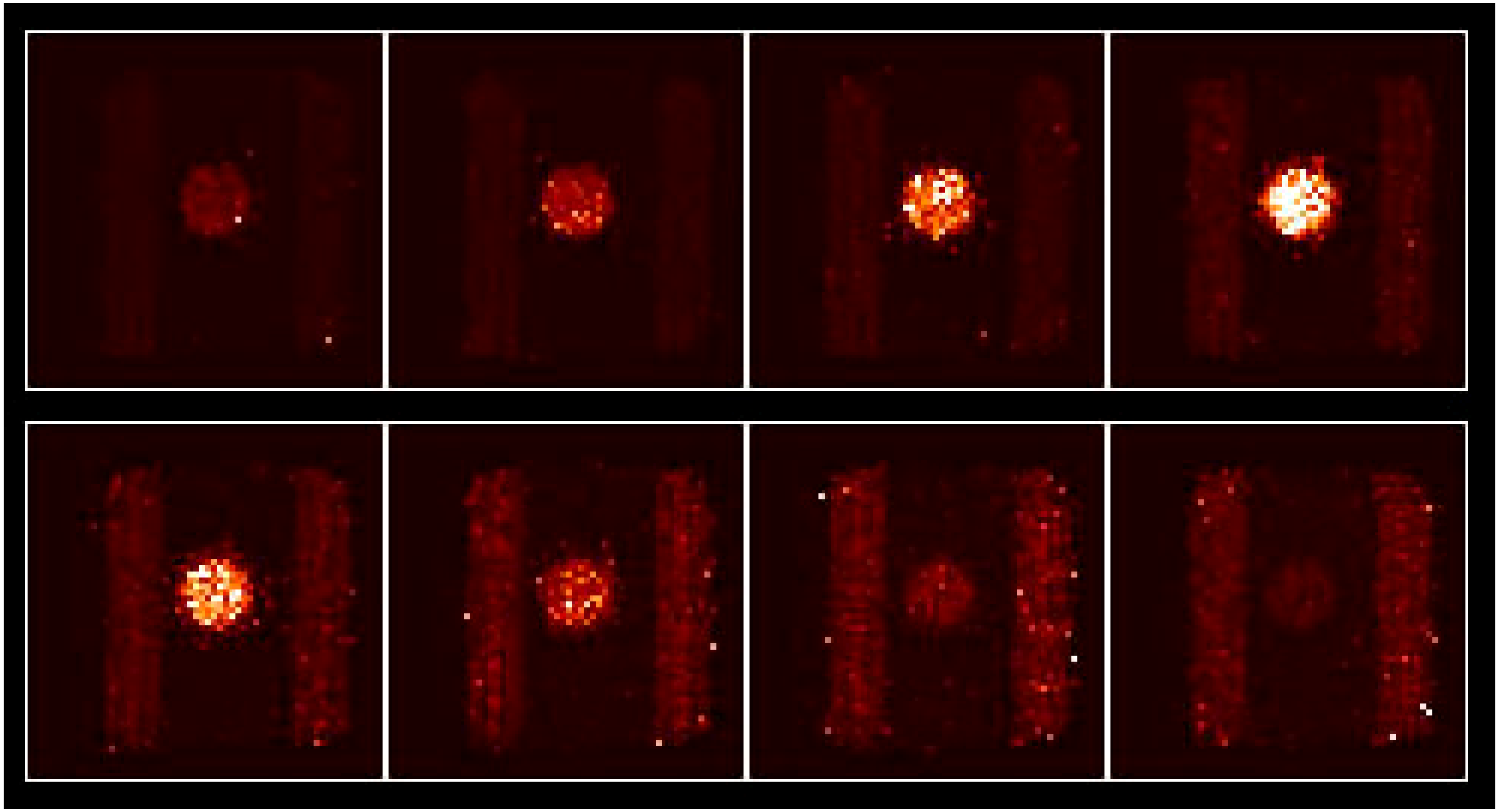
Point of Closest Approach (PoCA)
Original Approach (2003)

Assumes that the scattering took place at the point where the incoming and outgoing paths come closest





Slices through reconstructed volume



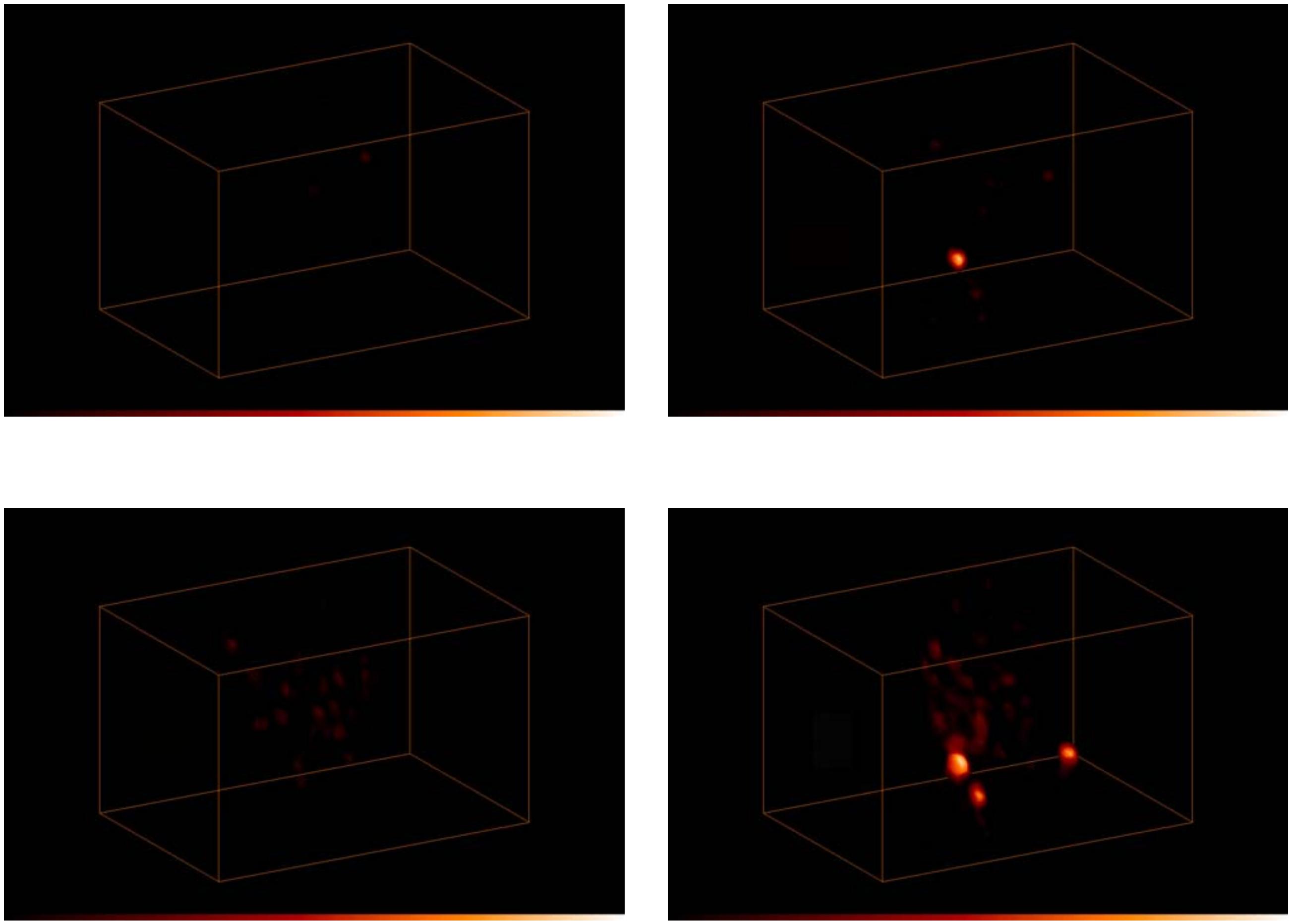
Ray-crossing algorithm cuts clutter

No contraband

3 uranium blocks
(20 kg each)

30
second
exposure

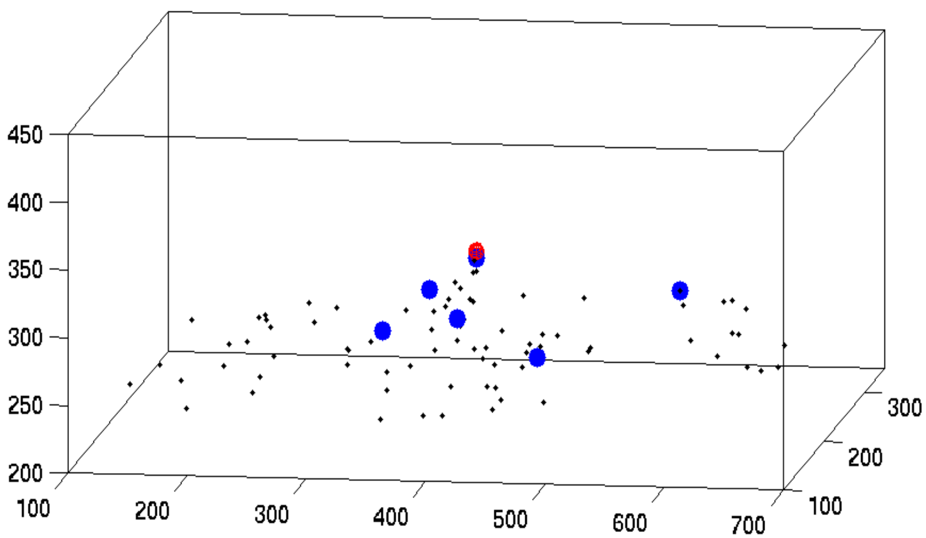
120
second
exposure



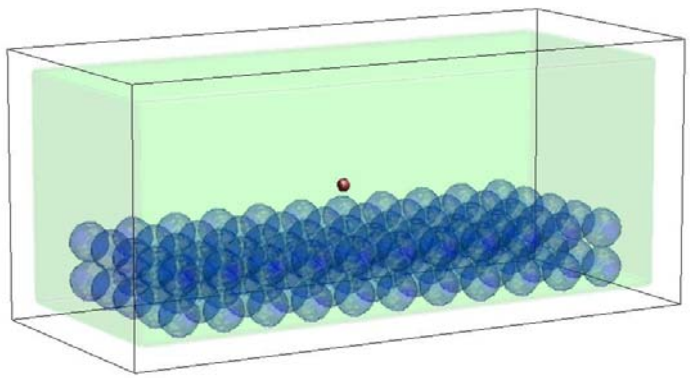
10 tons of distributed iron filling the container

Clustering algorithms to automatically search for dense objects

- Look at significantly scattered muons
- If high-Z object present, inferred locations of scattering will "cluster"
- Cluster centroids are considered the candidate locations for a threat object, and passed to a classifier

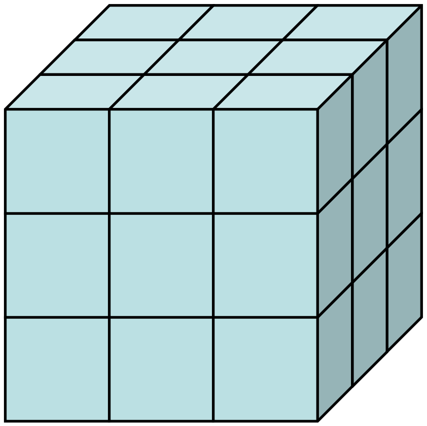


Identified clusters, including the real one



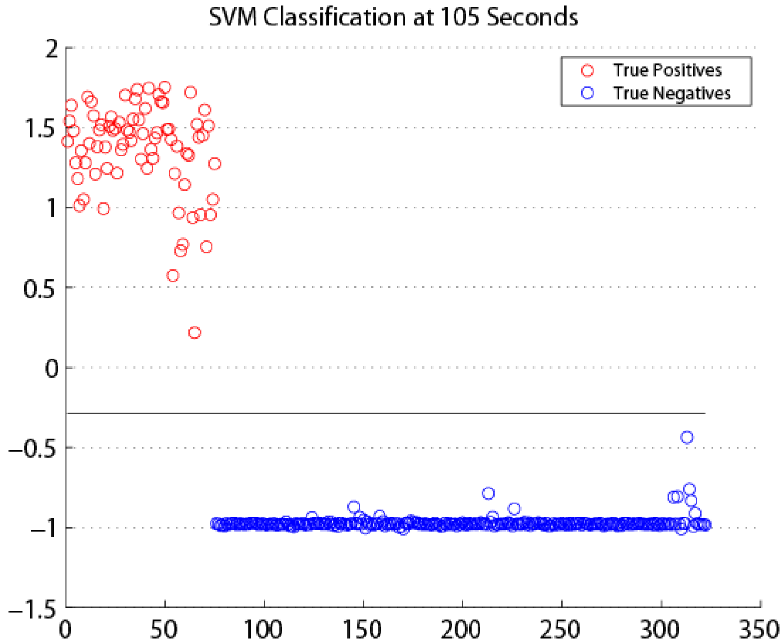
Input to simulation:
Shipping container full of automobile differentials & one uranium sphere

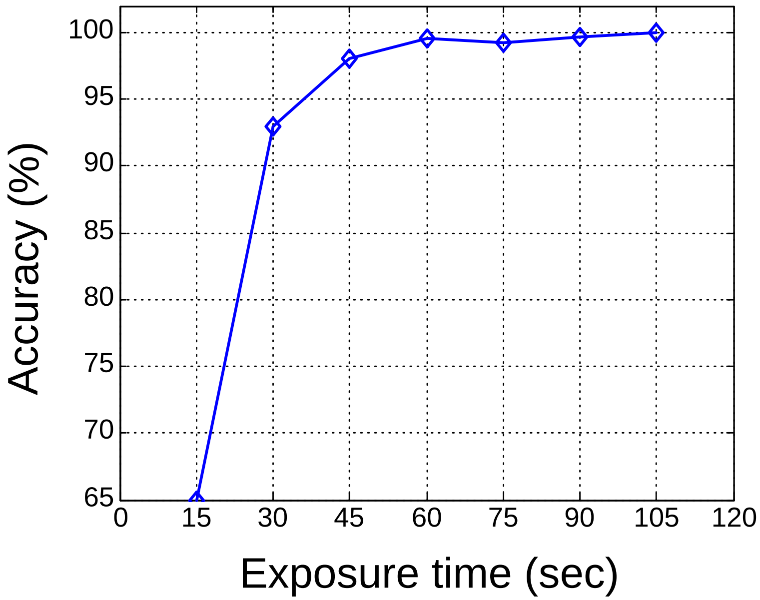
Candidate clusters can be tested with a “machine-learned” algorithm



Breakthrough: Algorithm has found a good set of features based on statistics of a local, 27-voxel cube

Result: Low error rates for two-minute exposures





Single layer model

Observations: $(\theta_i, \Delta\theta_i, \Delta x_i)$. Conditionally on $\theta_i = 0$,

$$D_i = \begin{pmatrix} \Delta\theta_i \\ \Delta x_i \end{pmatrix} \sim \mathcal{N}\left(0, \frac{\lambda}{p^2}\begin{pmatrix} L & \frac{L^2}{2} \\ \frac{L^2}{2} & \frac{L^3}{3} \end{pmatrix}\right).$$

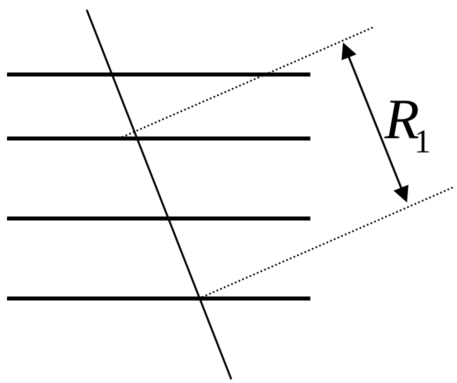
If $\theta_i \neq 0$, distribution of $D_i|\theta_i$ is approximatively mean zero Gaussian with variance-covariance

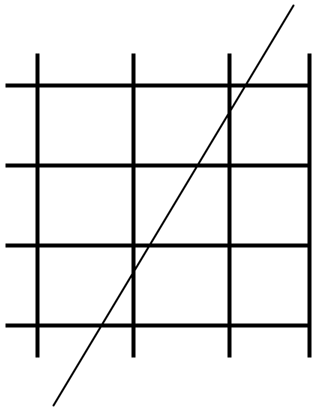
$$\frac{\lambda}{p^2}\begin{pmatrix} L\tan\theta_i & \frac{(L\tan\theta_i)^2}{2} \\ \frac{(L\tan\theta_i)^2}{2} & \frac{(L\tan\theta_i)^3}{3} \end{pmatrix} = \frac{\lambda}{p^2}\Sigma_{\theta_i}$$

- Parameter λ specific of material.
- Site specific distribution of momentum p known.

Model path as an integrated Brownian motion

An Identifiability Surprise





$$\Delta\theta = \sum_j \Delta\theta_j \qquad \Delta x = \sum_j \Delta x_j + R_j \Delta\theta_j$$

$$E[\Delta\theta_j] = E[\Delta x_j] = 0$$

Function of the path length in each layer

Lemma 1: Parameter identifiable if three of less homogeneous layers.

Lemma 2: In voxelized volume, parameters are identifiable.