Deep Mapping of Small Solar System Bodies with Galactic Cosmic Ray Secondary Particle Showers

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2013 NASA Innovative Advanced Concepts (NIAC) Phase I
Grant number NNX13AQ94G

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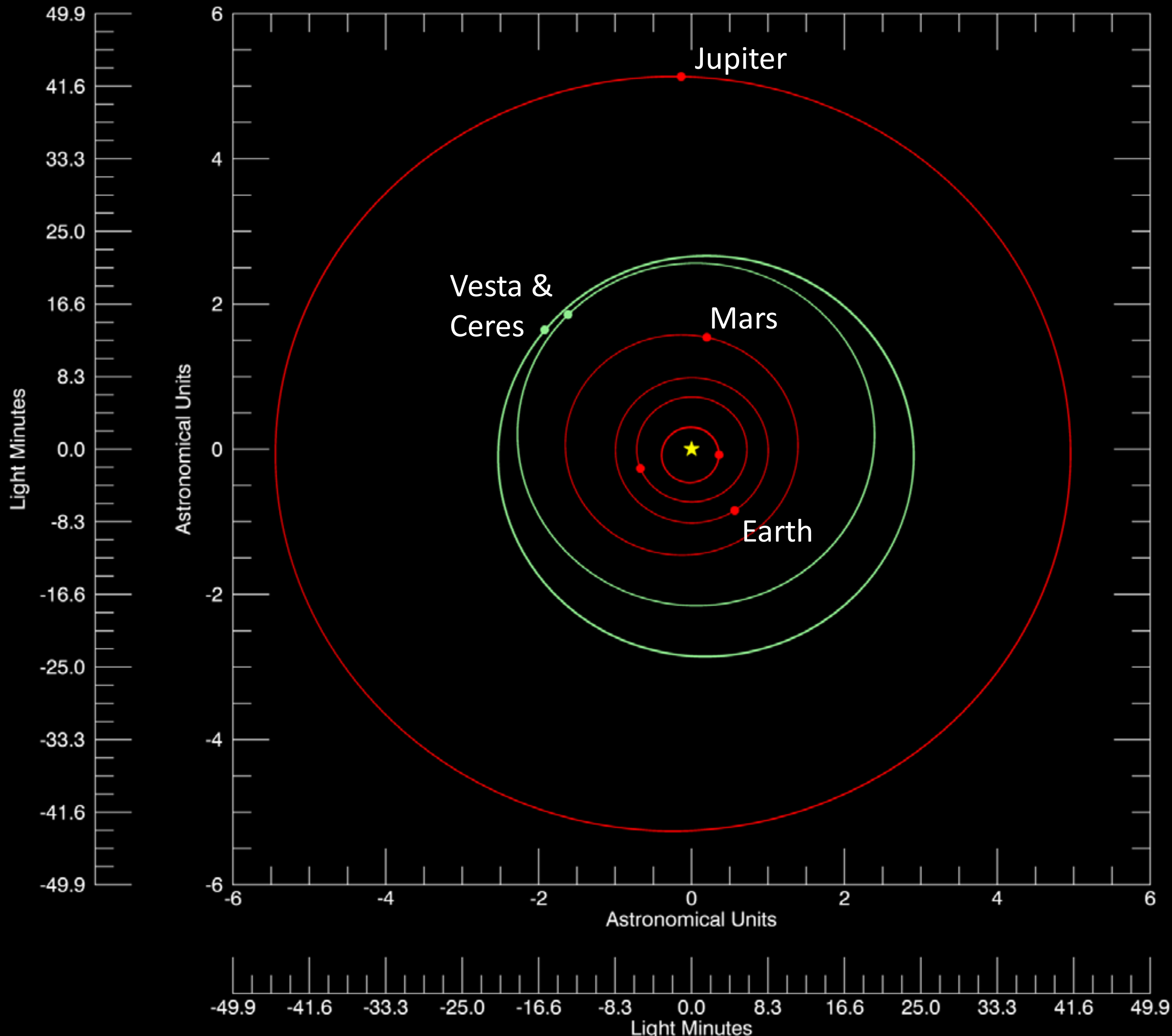
Large

Planets, dwarf planets, large moons and asteroids



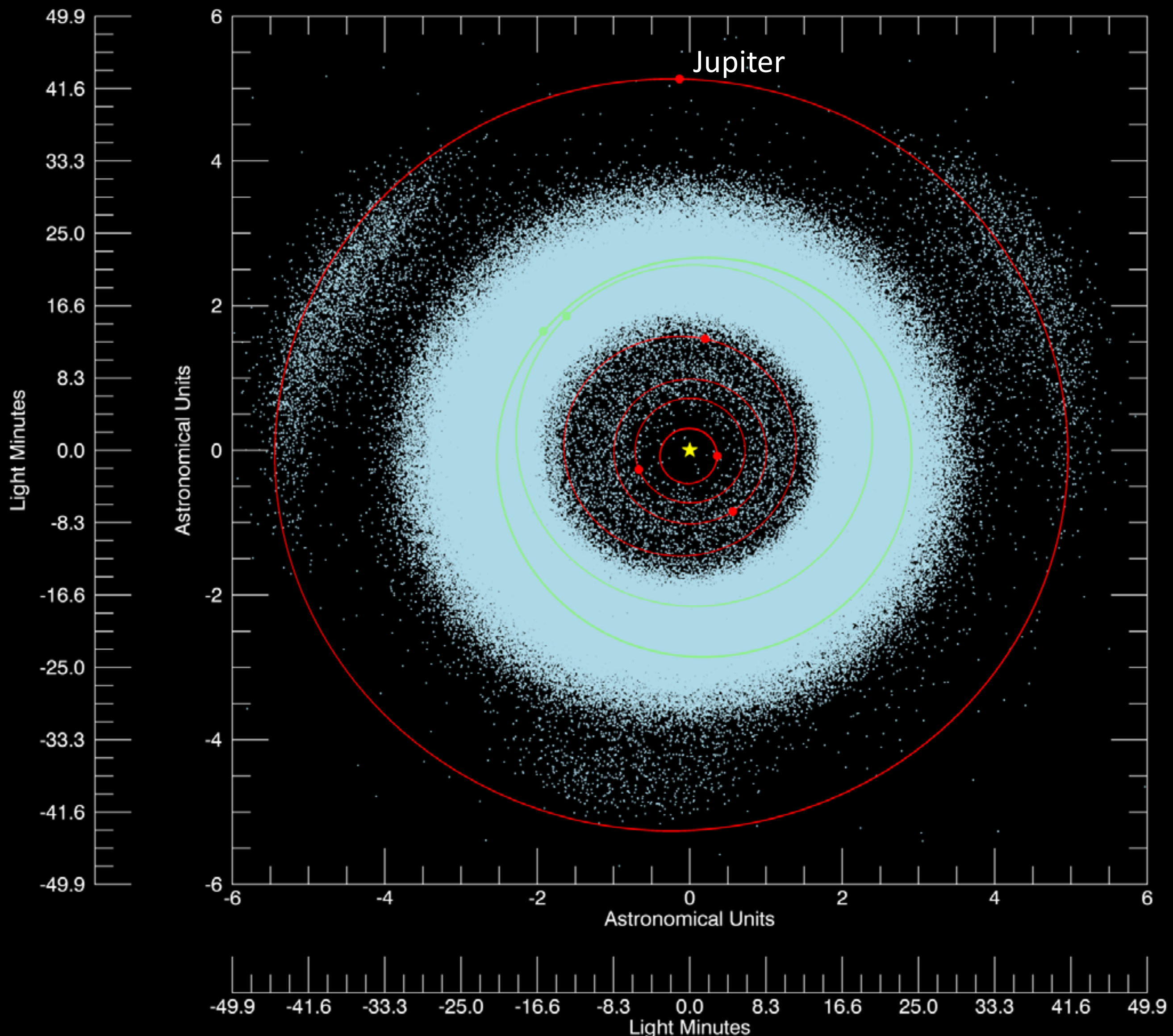

Jupiter by Cassini


Earthrise by Apollo 8


Vesta by Dawn

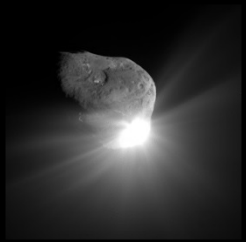
Solar system graphics by T. Prettyman; Images courtesy NASA.

Small



Asteroids, meteoroids, comets, moons of Mars, less than a few 10s of km in scale.

Phobos by Curiosity



Tempel 1 by Deep Impact

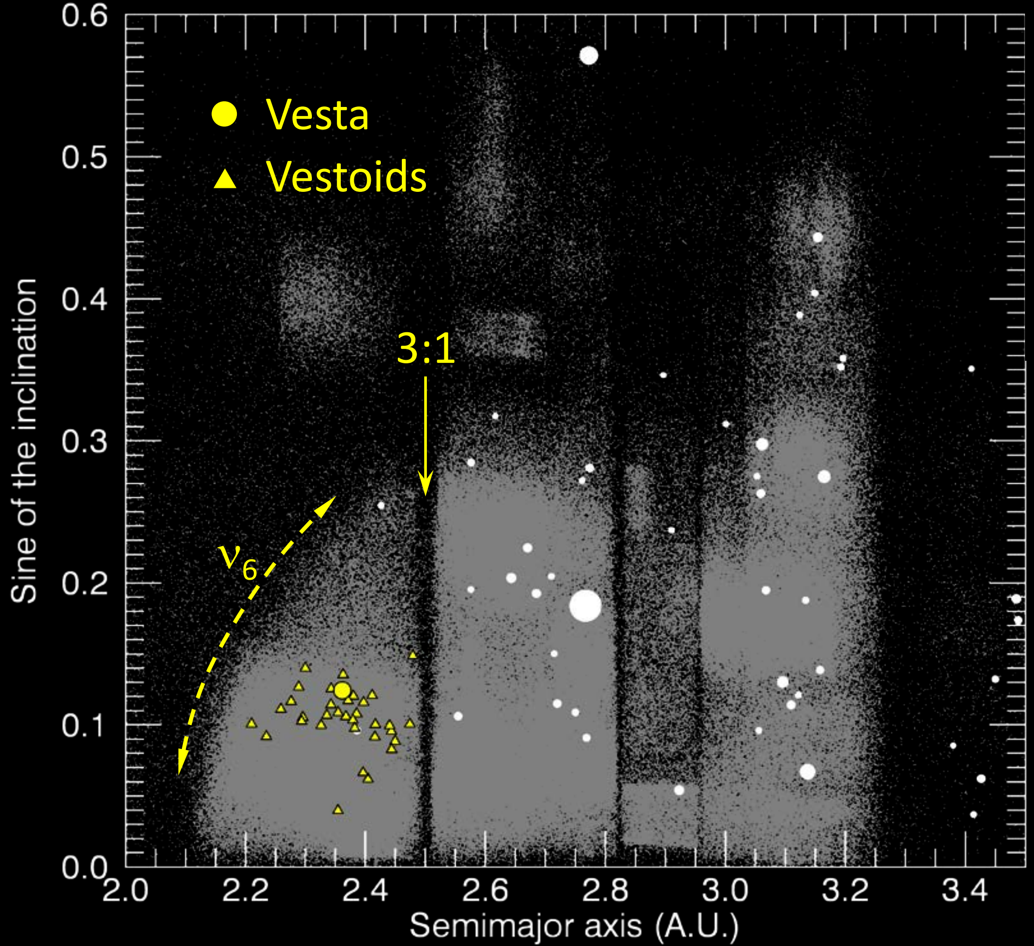
4.5×2.4×1.9 km

5×10^{13} kg

Asteroid Toutatis by Goldstone Radar (Potentially hazardous object)

Solar system graphics by T. Prettyman; Images courtesy NASA.

Delivery mechanism for achondritic (HED) meteotrites



A recent basin-forming impact (~1 Ga) launched many km-sized objects from Vesta, forming the Vesta dynamical family

Chips off these "Vestoids" migrate to nearby resonances (e.g. 3:1) and are deflected into Earth-crossing orbits.

e.g., Binzel and Xu 1993; Vilas et al. 2000; Burbine et al. 2001; Moskovitz et al. 2010

Meteors and Meteorites

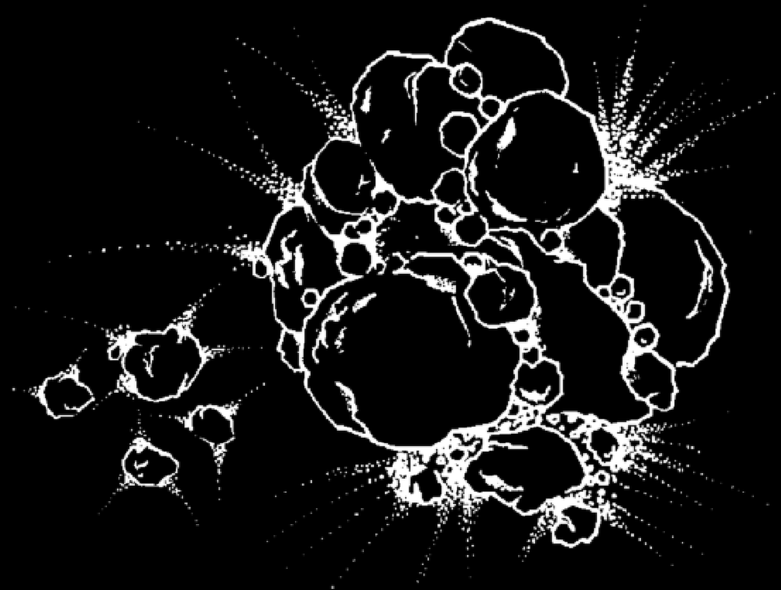
Chelyabinsk ~20 m diameter, 500 kT (low end of Torino Scale)

Beauty is only skin deep

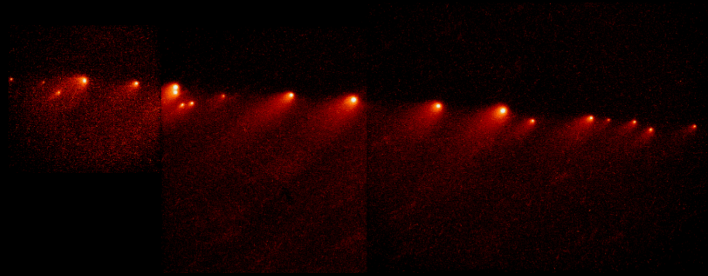
- What if we could peer inside a small asteroid or comet?
- At present, internal structure of small bodies must be inferred from surface morphology and other observations.
  - Methods to directly image the interior of these objects are sought.
- Information on the porosity, density distribution and internal structure of comets and small asteroids would provide powerful constraints on their formation, evolution and impact history.
  - For example, physical processes within cometary nuclei (venting mechanisms & transport of volatiles within their interiors) are poorly understood.
- This information would also be useful in developing planetary defense strategies and for in situ resource utilization (ISRU) (e.g. OH/H_2O, Fe-Ni).

Comets

81P/Wild 2 (NASA/Stardust, 2004)



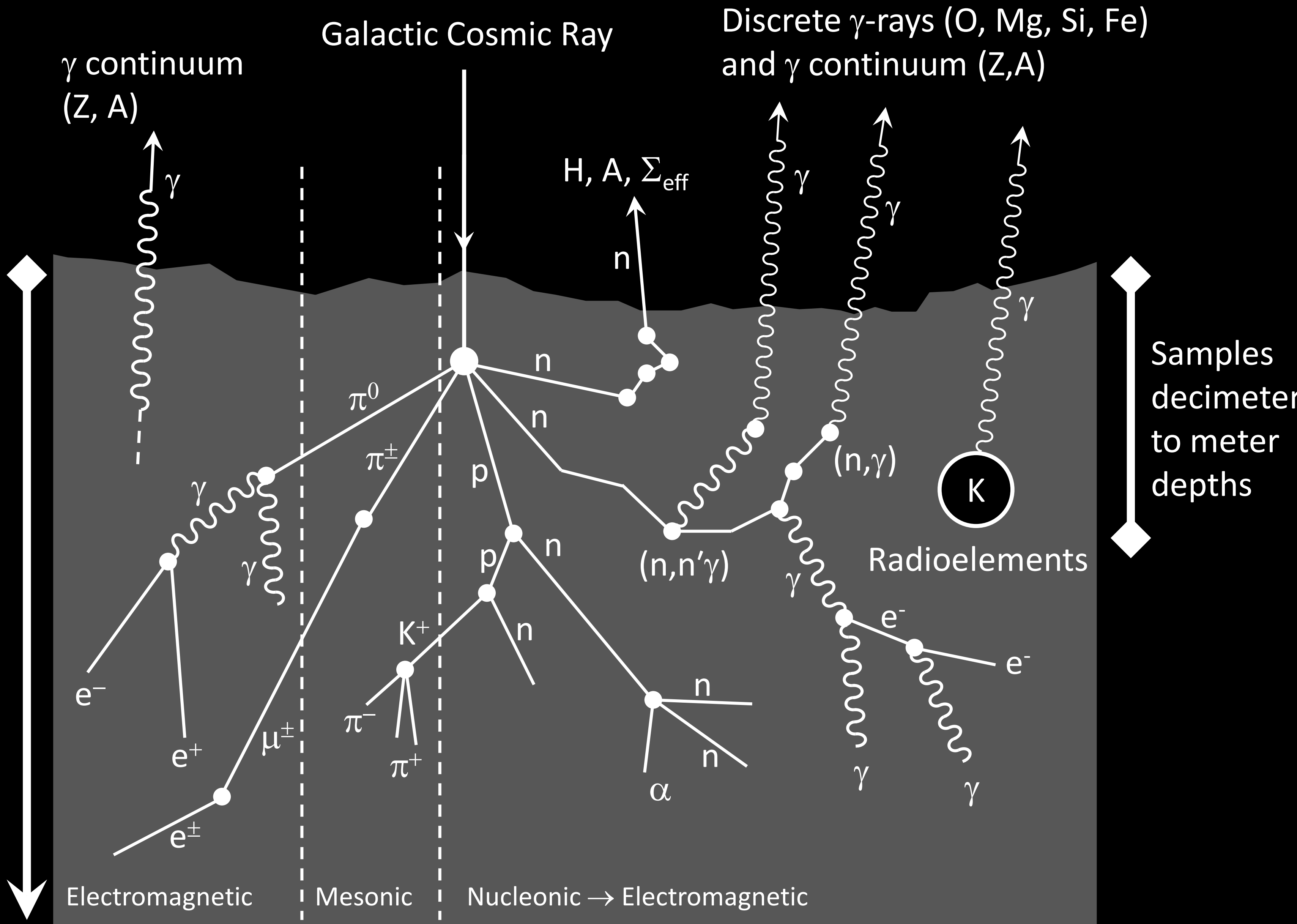
Rubble-pile: One of several hypotheses for the structure of cometary nuclei. Artist's conception from Weissman & Lowry (2008).



Tidal disruption of Shoemaker-Levy 9 (NASA/HST) supports the "rubble pile" hypothesis (Weissman & Lowry, 2008)

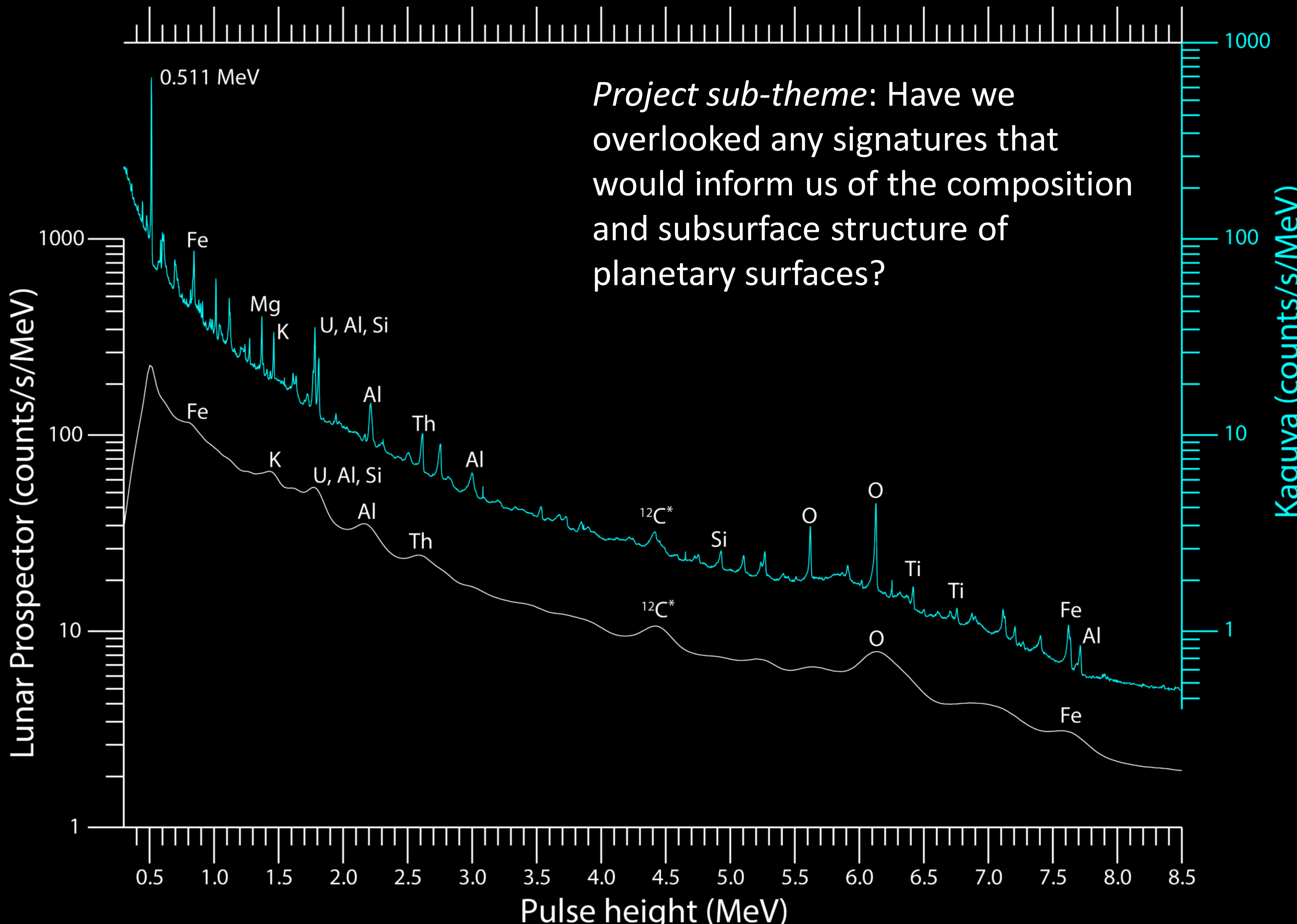
Our Concept

- Planetary surfaces and atmospheres are exposed to a steady rain of high energy particles (baryons), known as Galactic Cosmic Rays (GCRs).
- A shower of secondary particles (hadrons and leptons) is produced when GCRs interact with nuclei near the surface.
- Muons, leptons produced in hadronic showers, can penetrate km-scale structures.
- The interiors of small bodies and surface structures could be mapped with high spatial resolution using a muon telescope (hodoscope) deployed in close proximity (in situ or from orbit).



μ± (muons) can penetrate to km depths

Lunar Gamma Ray Spectra



Project sub-theme: Have we overlooked any signatures that would inform us of the composition and subsurface structure of planetary surfaces?

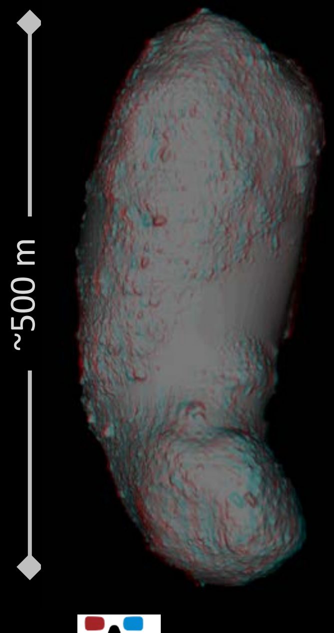
Lunar Prospector data from NASA Planetary Data System; Kaguya data courtesy N. Hasebe, Waseda University, Japan.

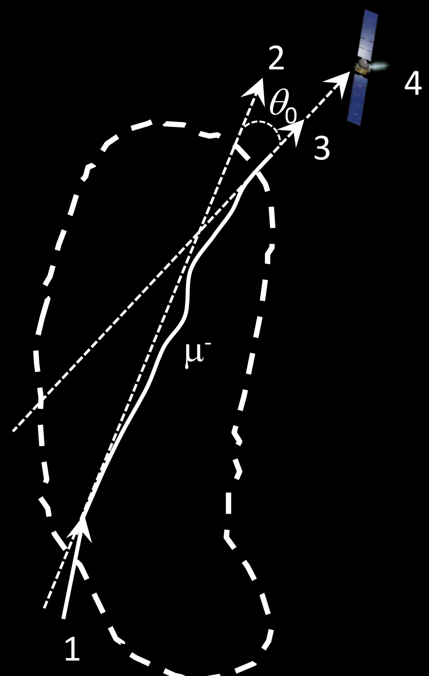
Muon radiography & tomography

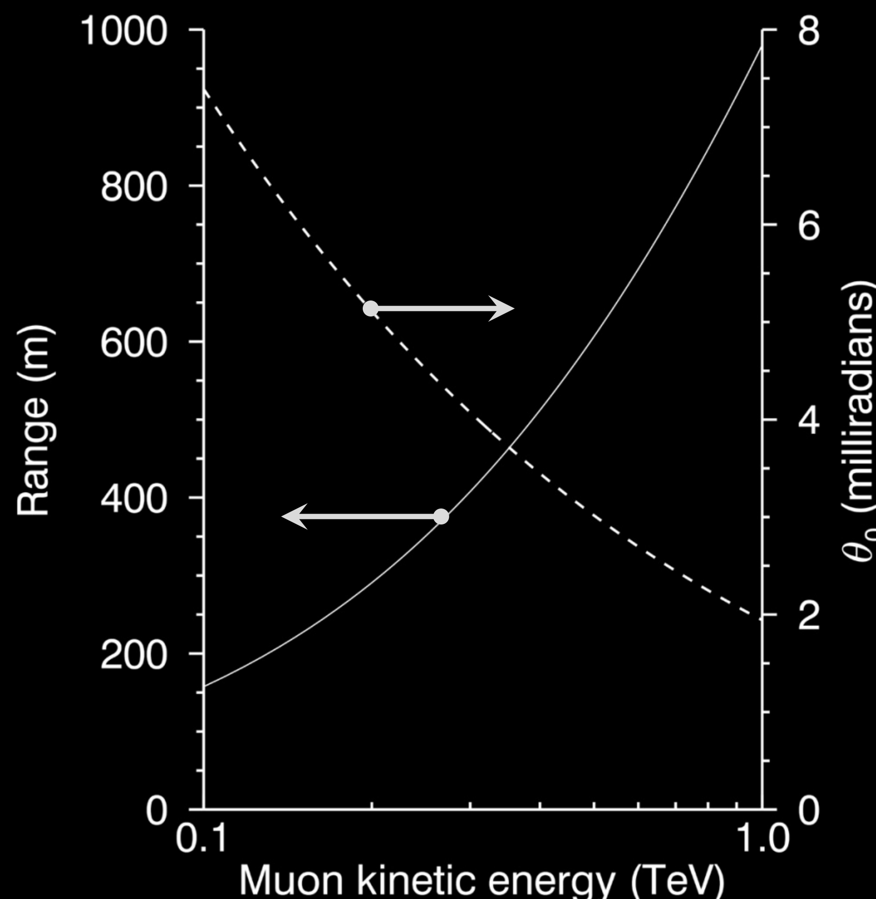
"Muonography"

Muons can penetrate large distances through rock, while undergoing minimal deflection by multiple coulomb scattering.

Asteroid Itokawa
(JAXA/Hyabusa)







1. Galactic cosmic ray primary
2. Initial direction of high-energy muon (μ^-)
3. Exit direction
4. Detection by orbiting particle telescope

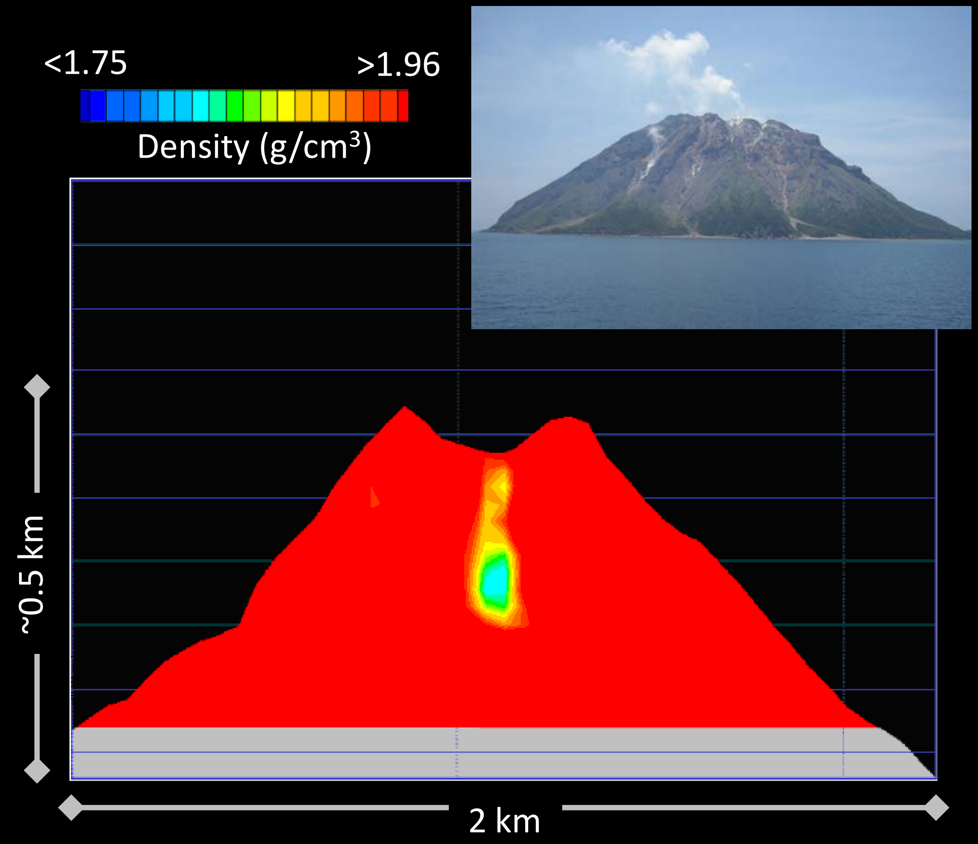
Feasibility?

Muons produced in extended air showers have been used to map the interior of large structures on Earth.

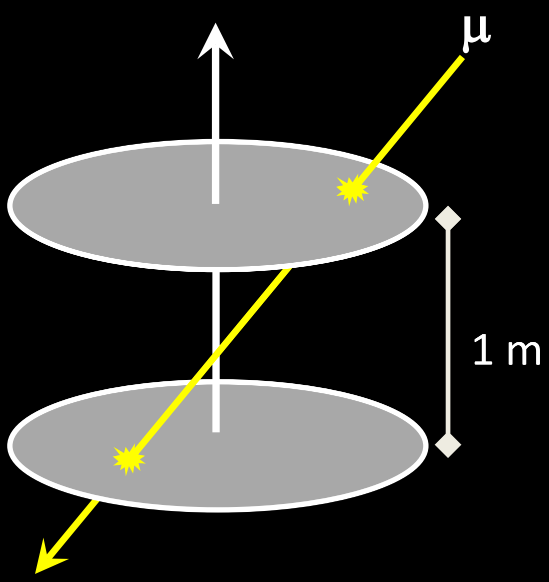
Challenges for space applications:

- Is the production rate of muons in solid surfaces and thin atmospheres sufficient to meet imaging requirements?
- Can muons be separately measured from other particles in the space environment by a telescope that can be deployed on a planetary mission?
- For airless bodies, can interior structures be separated from surface features?

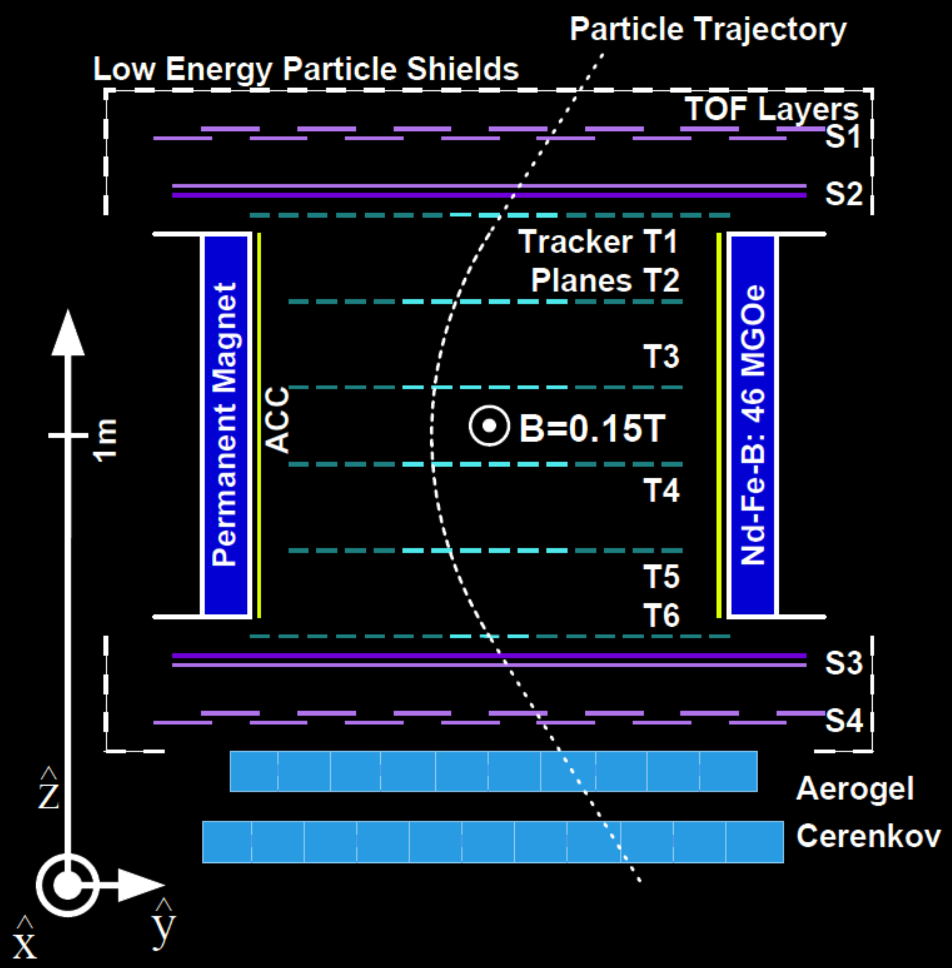
Internal structure of Satsuma-Iojima volcano using a 1 m^2 muon telescope (Tanaka et al., 2010) – "Muonography"



Hodoscope Fundamentals

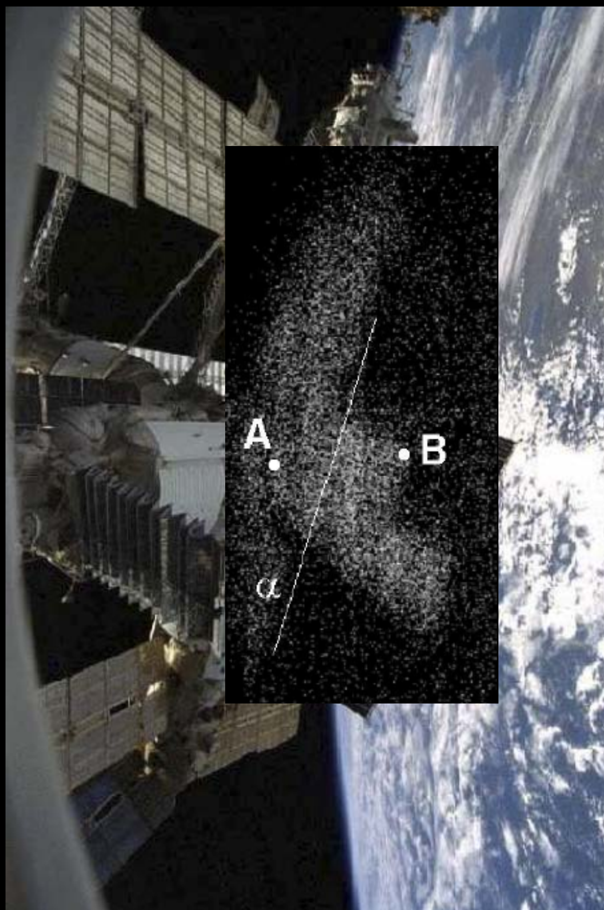


Tanaka et al. (2010) demonstrated a transportable muonography system for geology on Earth.

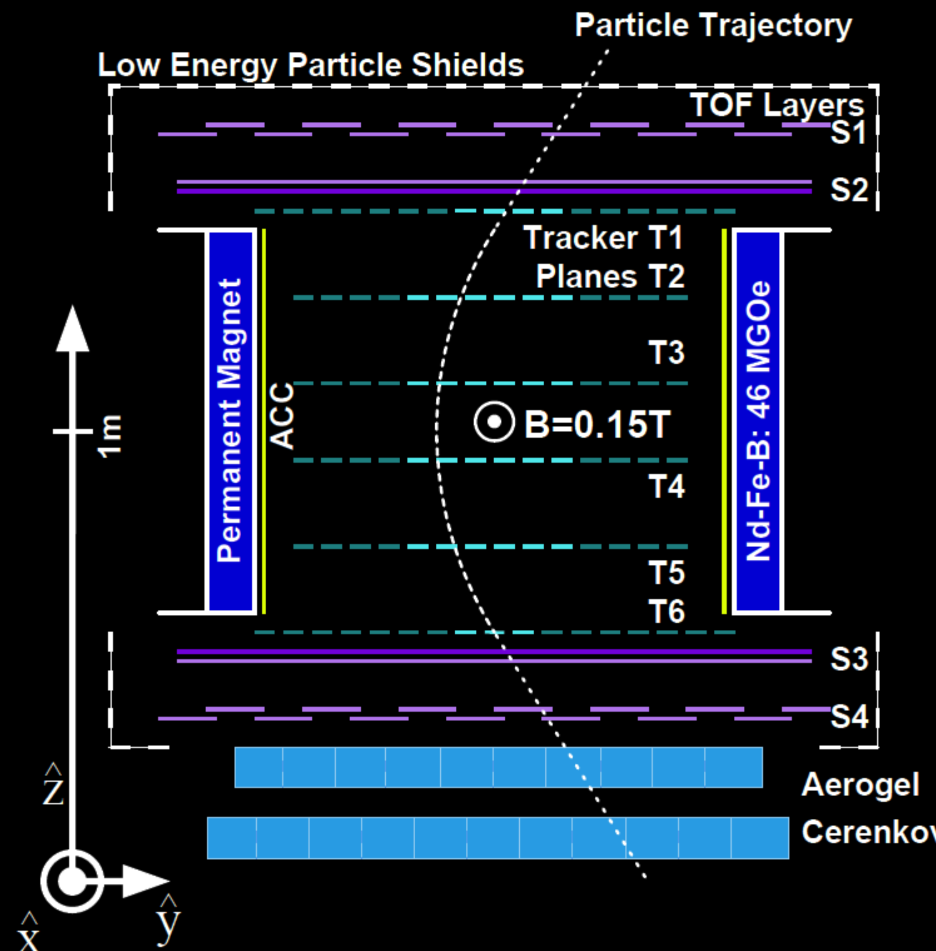


Alpha Magnetic Spectrometer 1
From Aguilar et al. (2008) NIM-B.

AMS-1 Image of MIR



AMS-1 image of the MIR space station using secondary π^- and μ^- emissions

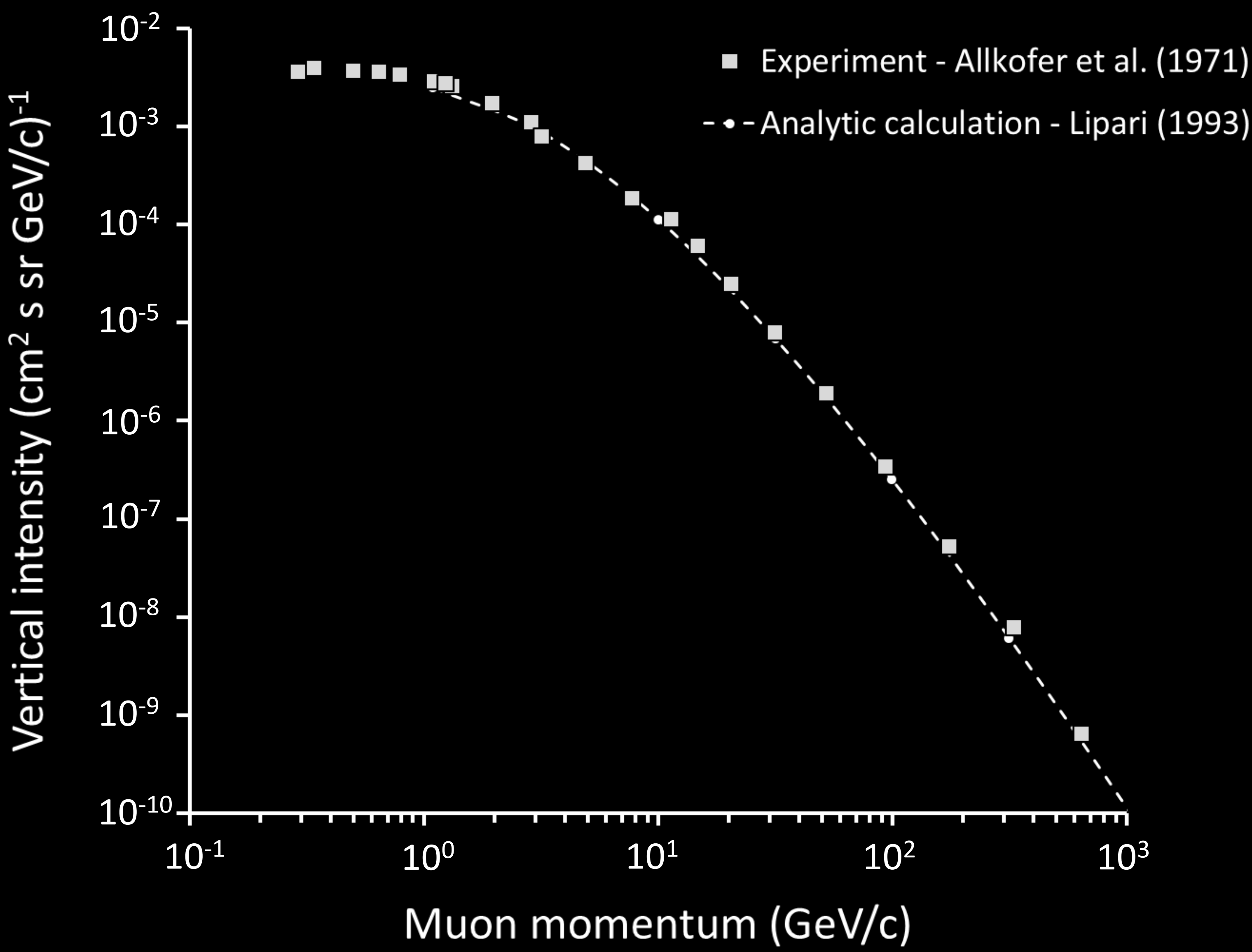


Alpha Magnetic Spectrometer 1
From Aguilar et al. (2008) NIM-B.

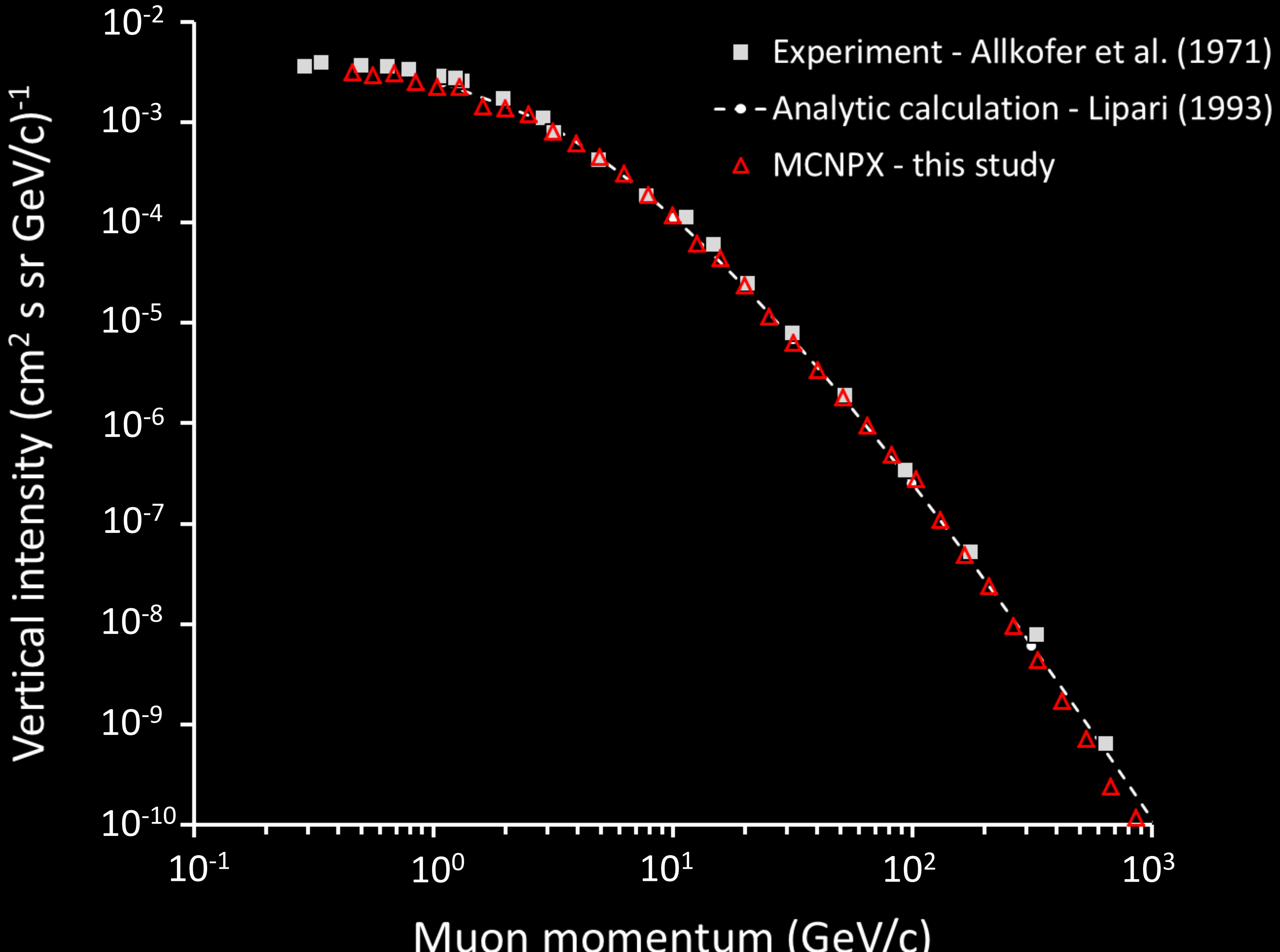
Technical Approach

- Use high energy physics codes (e.g. FLUKA & MCNPX), analytical models and scaling relationships to estimate the production rate of secondary particles, such as muons, in regolith materials.
  - ➢ Validate the codes against experimental data for extended air showers.
- Investigate concepts for space-based muon hodoscopes.
- Simulate muon radiographic imaging and tomography of small airless bodies.

Muon flux at sea level



Muon flux at sea level



Muon production in Earth's Atmosphere

Atmospheric muons are produced primarily by the decay of pions and kaons, e.g.

$$K^+ \rightarrow \mu^+ + \nu_\mu$$

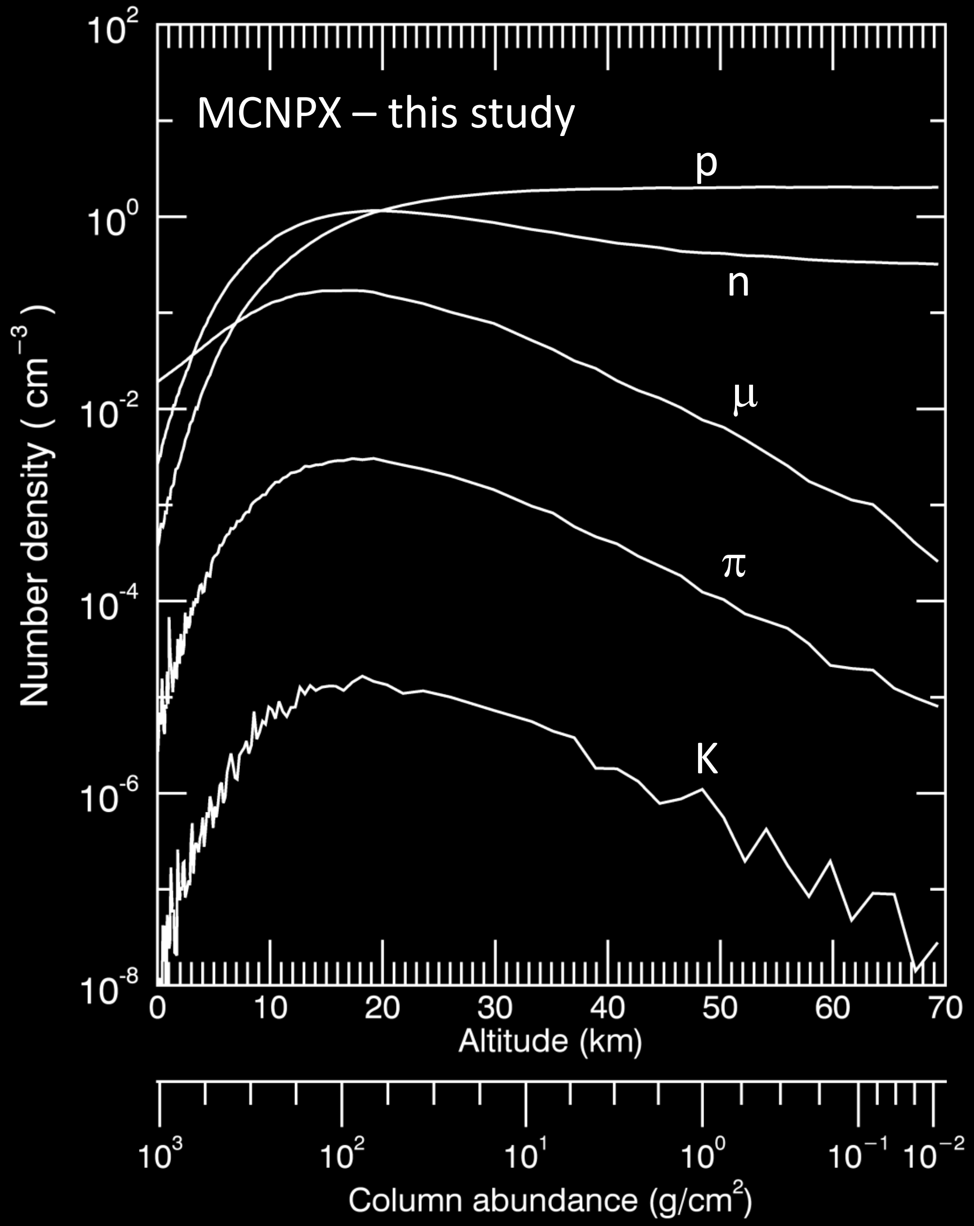
$$\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$$

Muons subsequently decay, e.g.

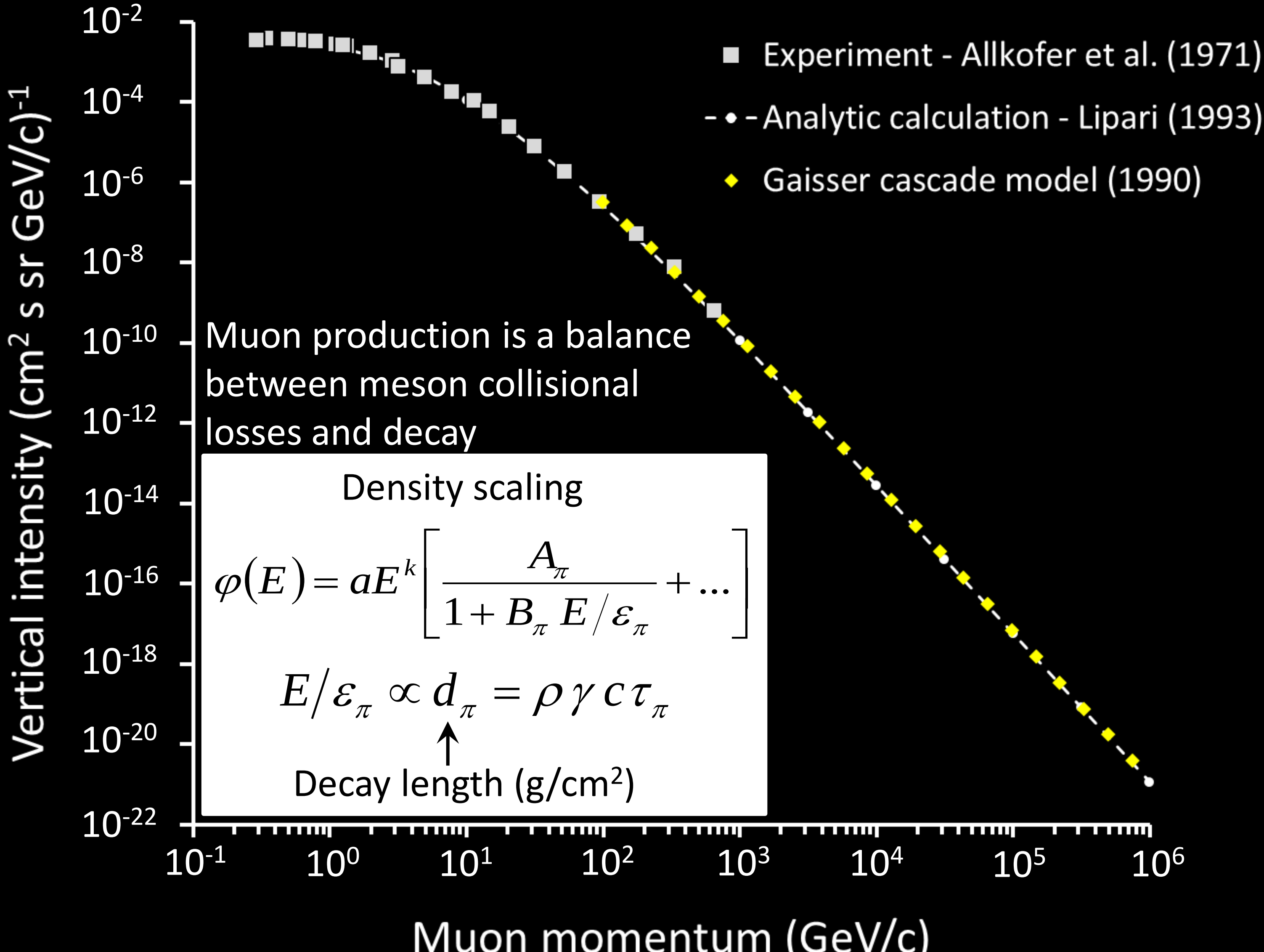
$$\mu^- \rightarrow e^- + \overline{\nu}_e$$

Prompt muons are also made by short-lived, charmed hadrons: $D^\pm, D^0, \overline{D}^0, \Lambda_c^+$

Particle	Decay length cτ (cm)
$\mu^\pm$	6.6×10^4
$\pi^\pm$	780
$K^\pm$	371
$D^\pm$	0.028



Muon flux at sea level



Muon production is a balance between meson collisional losses and decay

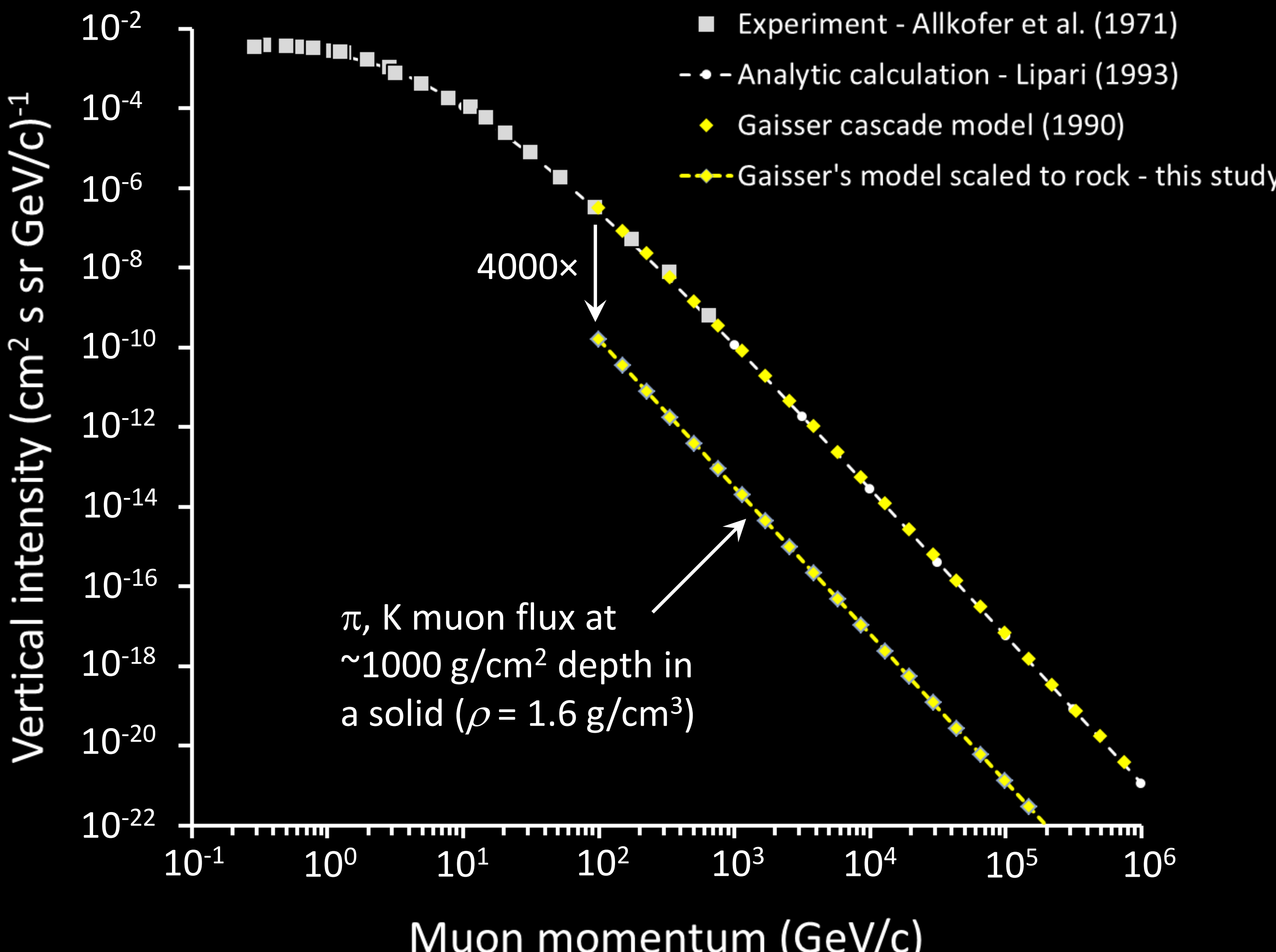
Density scaling

$$\varphi(E) = aE^k\left[\frac{A_\pi}{1+B_\pi E/\varepsilon_\pi} + \ldots\right]$$

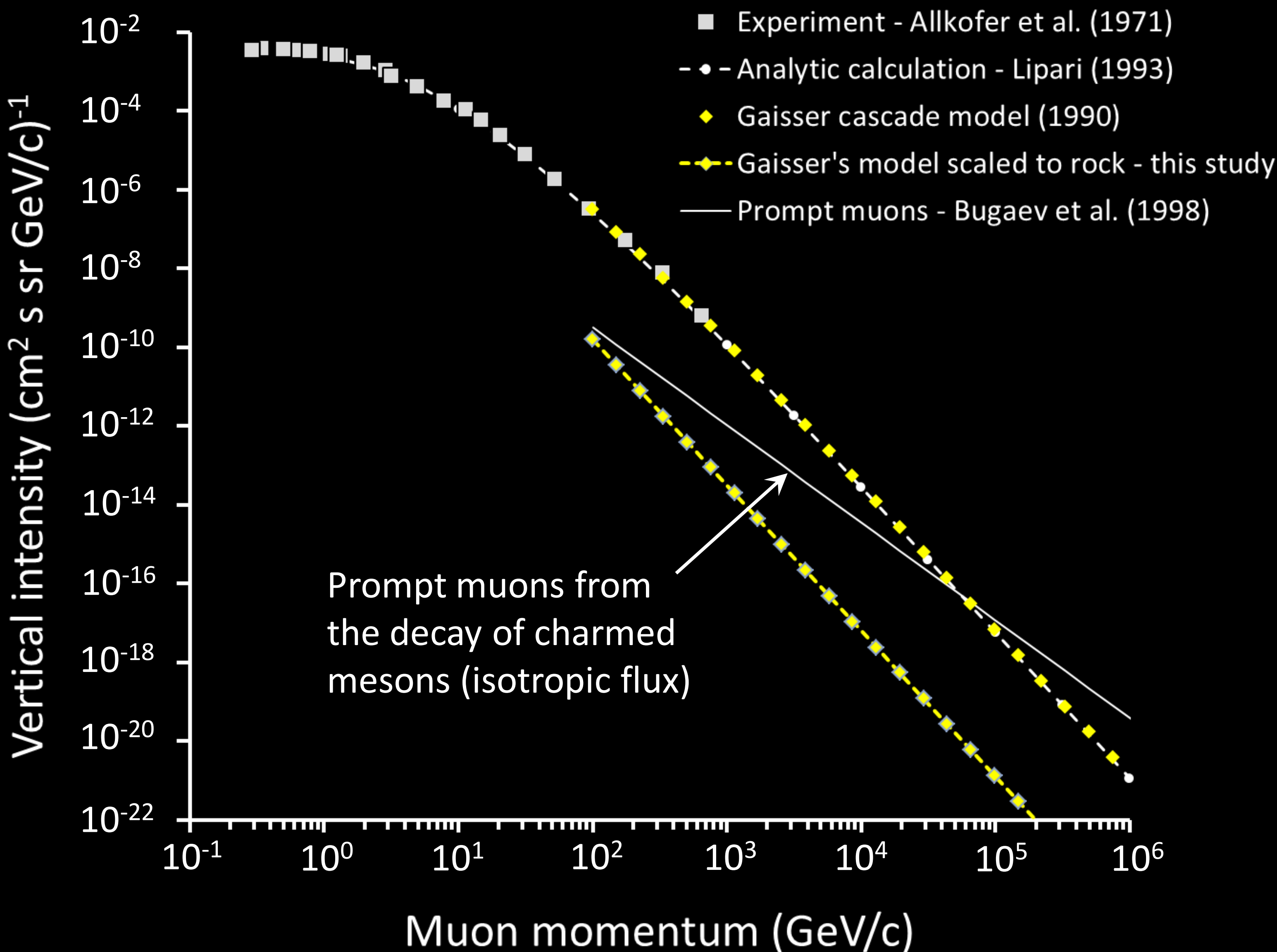
$$E/\varepsilon_\pi \propto d_\pi = \rho\,\gamma\,c\,\tau_\pi$$

Decay length (g/cm²)

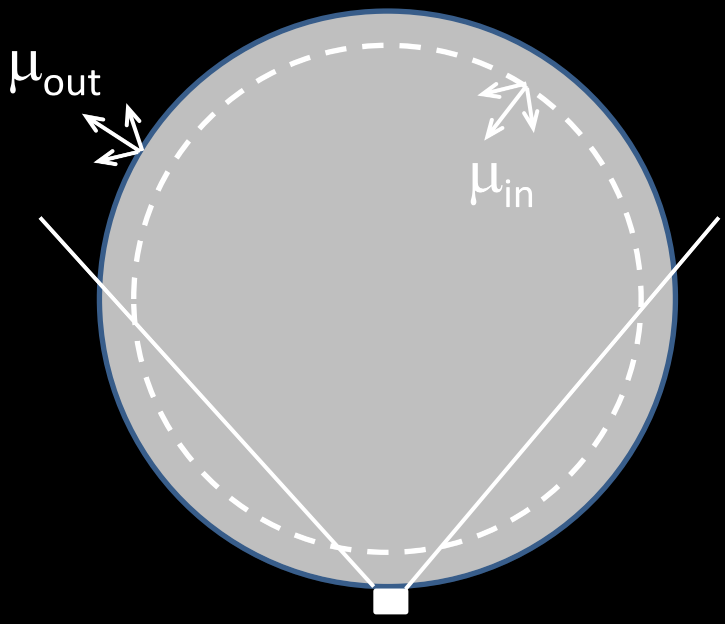
Muon flux at sea level and in rock



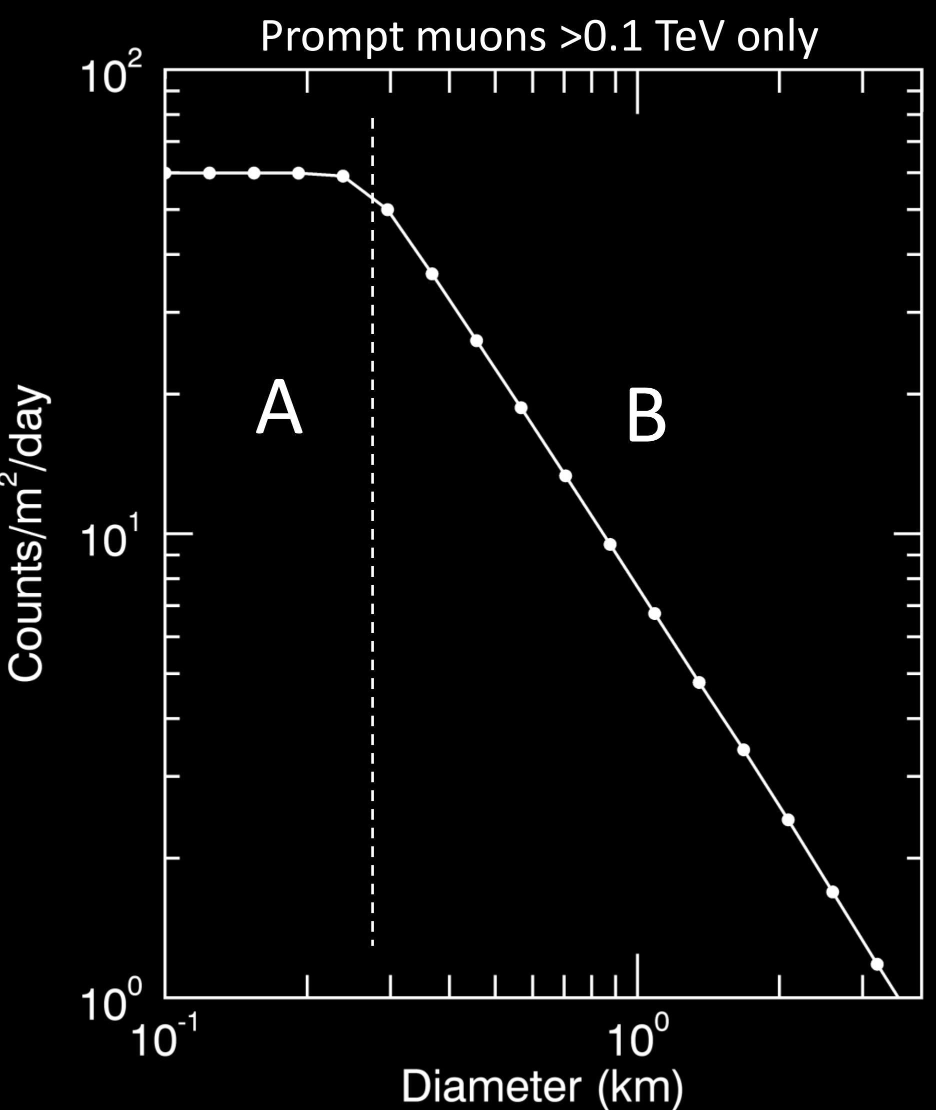
Muon flux at sea level and in rock



Muon Leakage Current

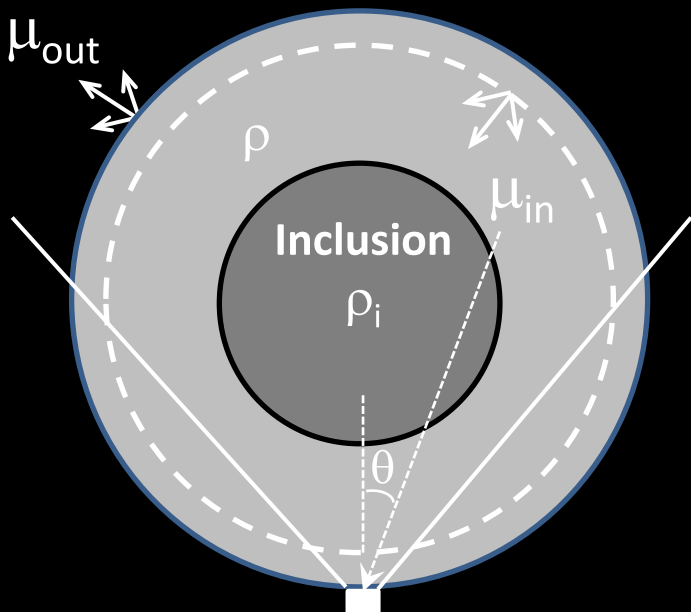


1 m^2 hodoscope (1.8 sr)

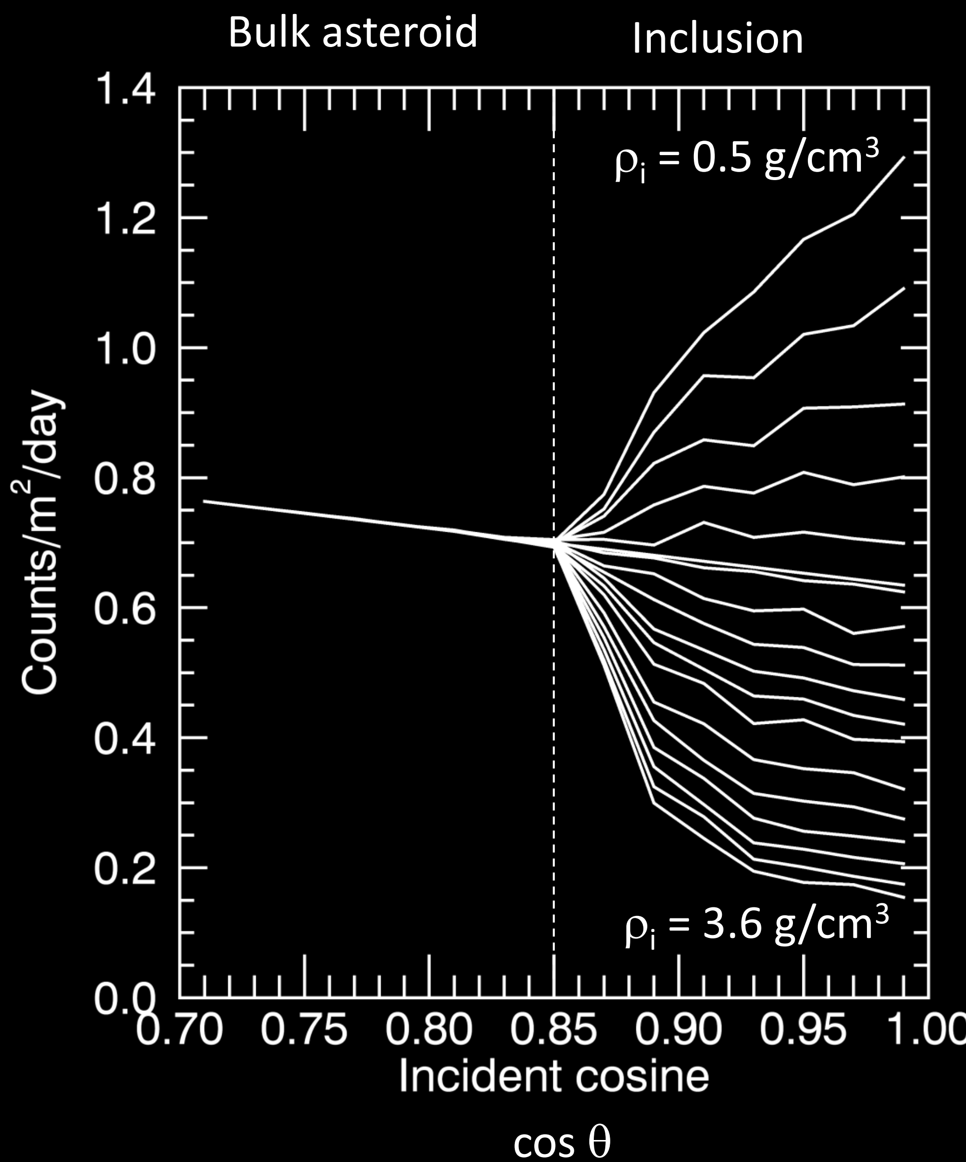


A. Muons > 0.1 TeV punch through (muons in this range are insensitive to density variations; other particles are "filtered out")
B. The muon leakage current is sensitive to intervening materials

Contrast Sensitivity



1 m² hodoscope (1.8 sr)



800 m diameter asteroid
with a 400 m diameter inclusion

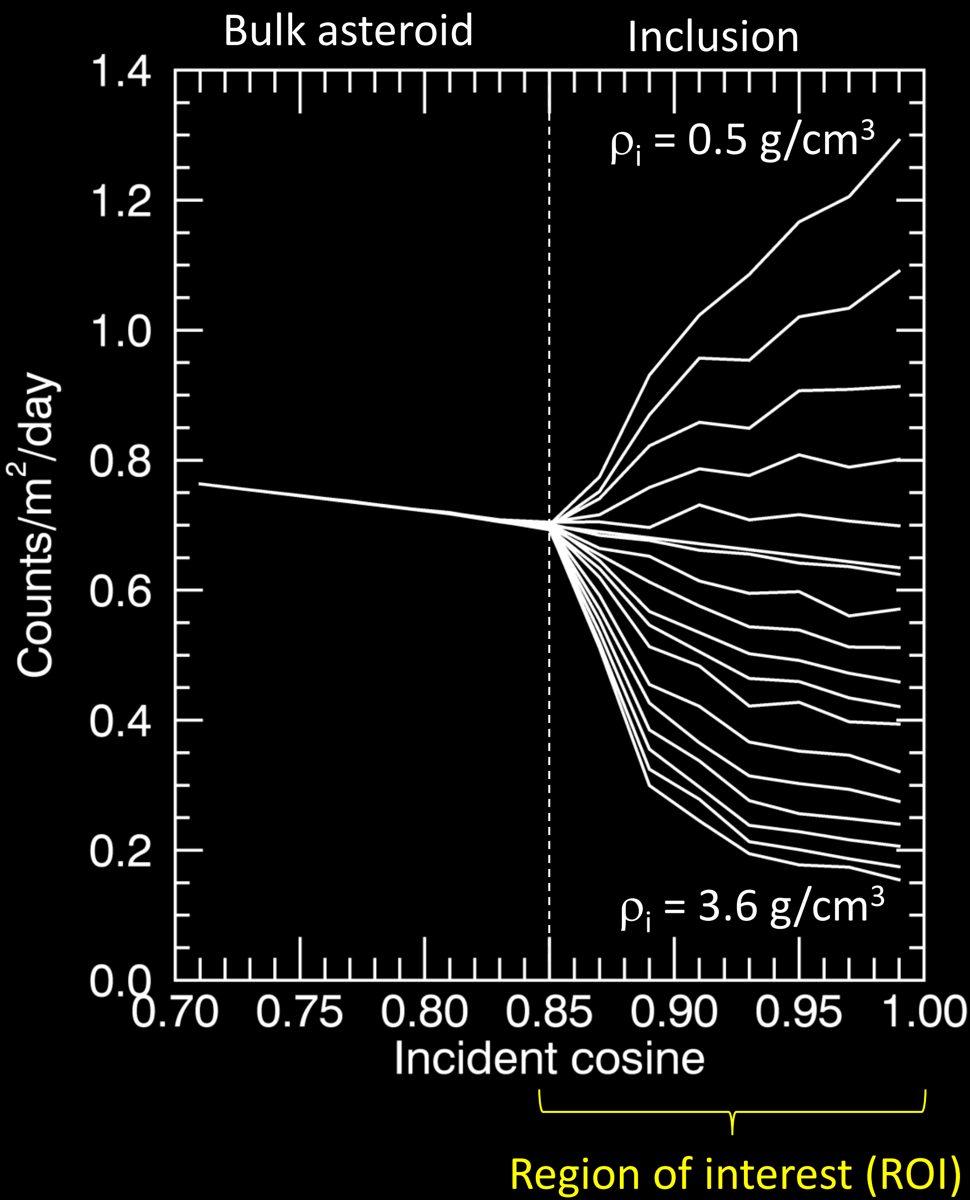
Detection Limit

The signal is the change in counts in the ROI relative to that expected for a homogeneous asteroid:

$$Signal = \frac{Counts_{ROI} - Counts_{Ref}}{Counts_{Ref}}$$

The 3σ Poisson detection limit can be expressed in terms of mean counting rates:

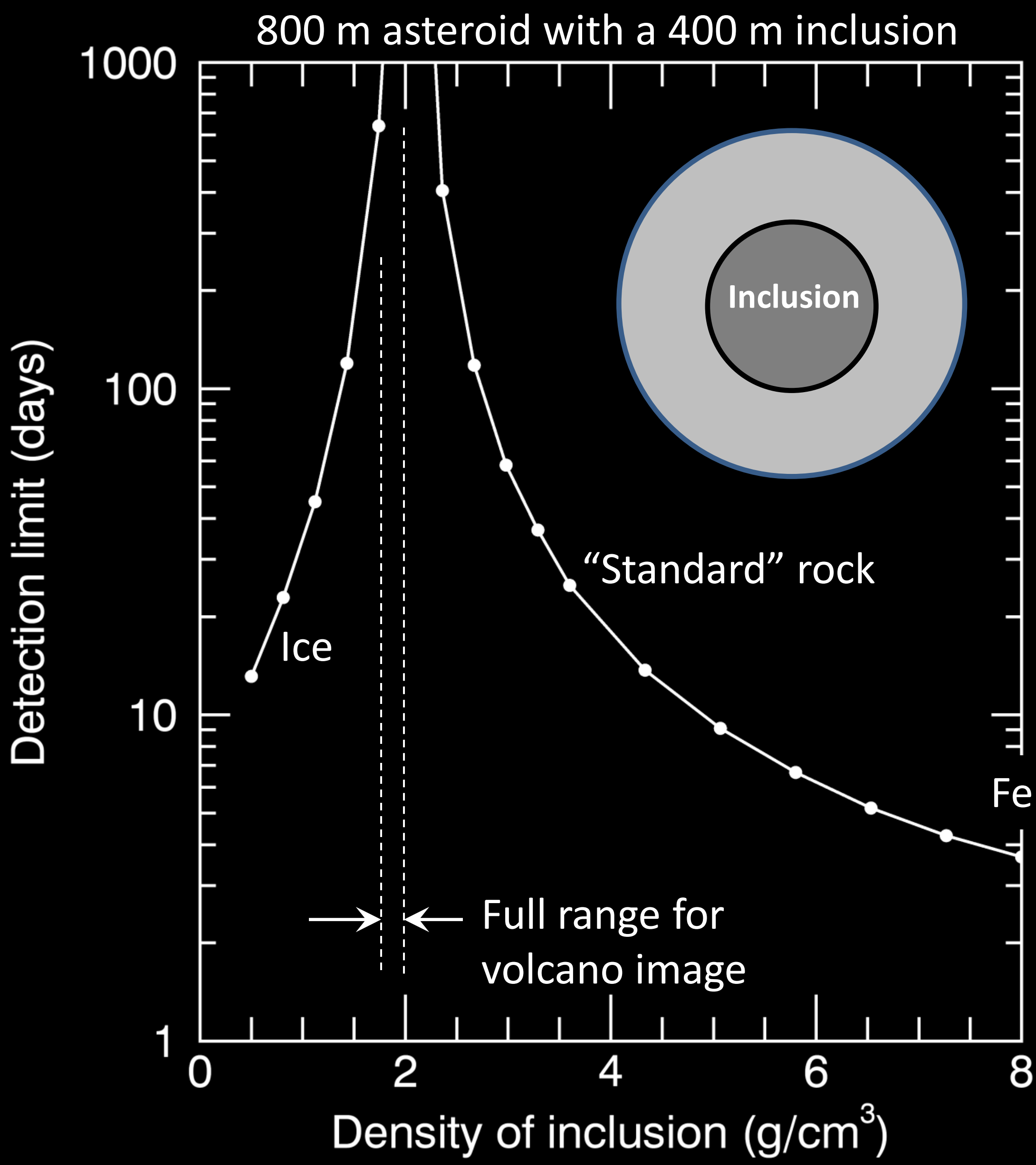
$$Time > \frac{9 \times Rate_{ROI}}{(Rate_{ROI} - Rate_{Ref})^2}$$



Detection Limit

An comet or asteroid may have high density contrast:

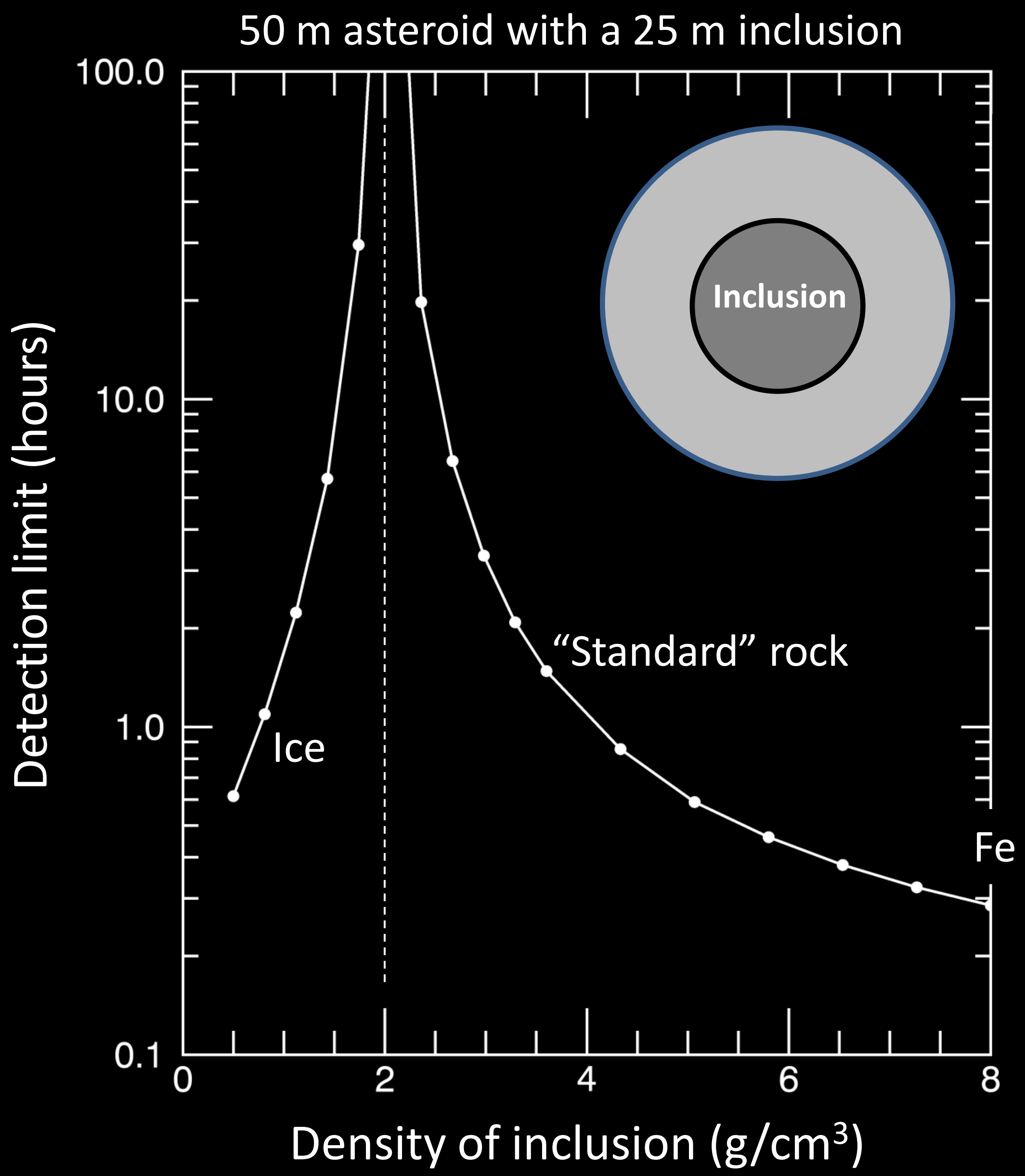
- Silicate regolith surrounding a icy interior (comet)
- Fe-rich region within in a rubble-pile asteroid



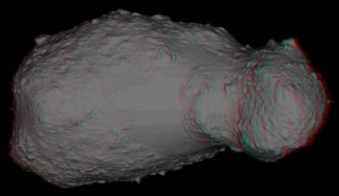
Detection Limit

How about a very small body?

- 50 m diameter
- π, K muons greater than 10 GeV are comparatively abundant and can penetrate the asteroid
- Detection limit decreases



Conclusions



- **Estimates of muon production in solids indicate long integration times for muonography of asteroids and comets; *however*,**
  - A search for *high contrast* interior regions might be feasible for objects with 100 m to 1 km diameters using muons produced by charmed mesons (>100 GeV)
  - Very small bodies (10- to 100-m) or surface features would likely be accessible by K,π muons, which are more abundant at low energies (10- to 100-GeV)
  - An assessment of muon production as a function of regolith density and composition is in progress
- **The complexity of the hodoscope would depend on deployment**
  - A magnetic spectrometer with active shielding is probably needed for measurements in space
  - A sub-surface spectrometer might be similar to those used on Earth
- **Prospective applications are numerous, but include determining the macroporosity of small asteroids for planetary defense and searching for hydrous inclusions in asteroids for ISRU**
- **Prompt production by charmed mesons may dominate the high-energy muon flux in solid surfaces**
  - The absence of π,K muons on asteroids may enable the detection of this so far elusive, charmed component
  - A cosmic ray observatory on a small asteroid could provide additional data needed to advance our knowledge of cosmic rays and fundamental nuclear physics