Muon vision for planetary geology: A look inside asteroids, comets and surface features

15th Small Bodies Assessment Group

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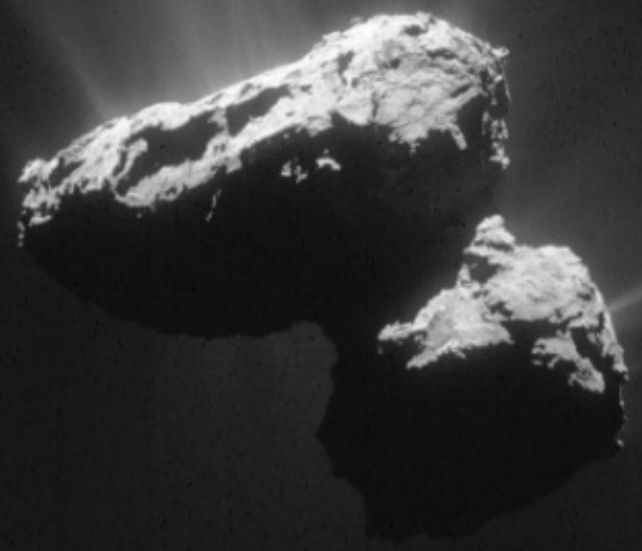
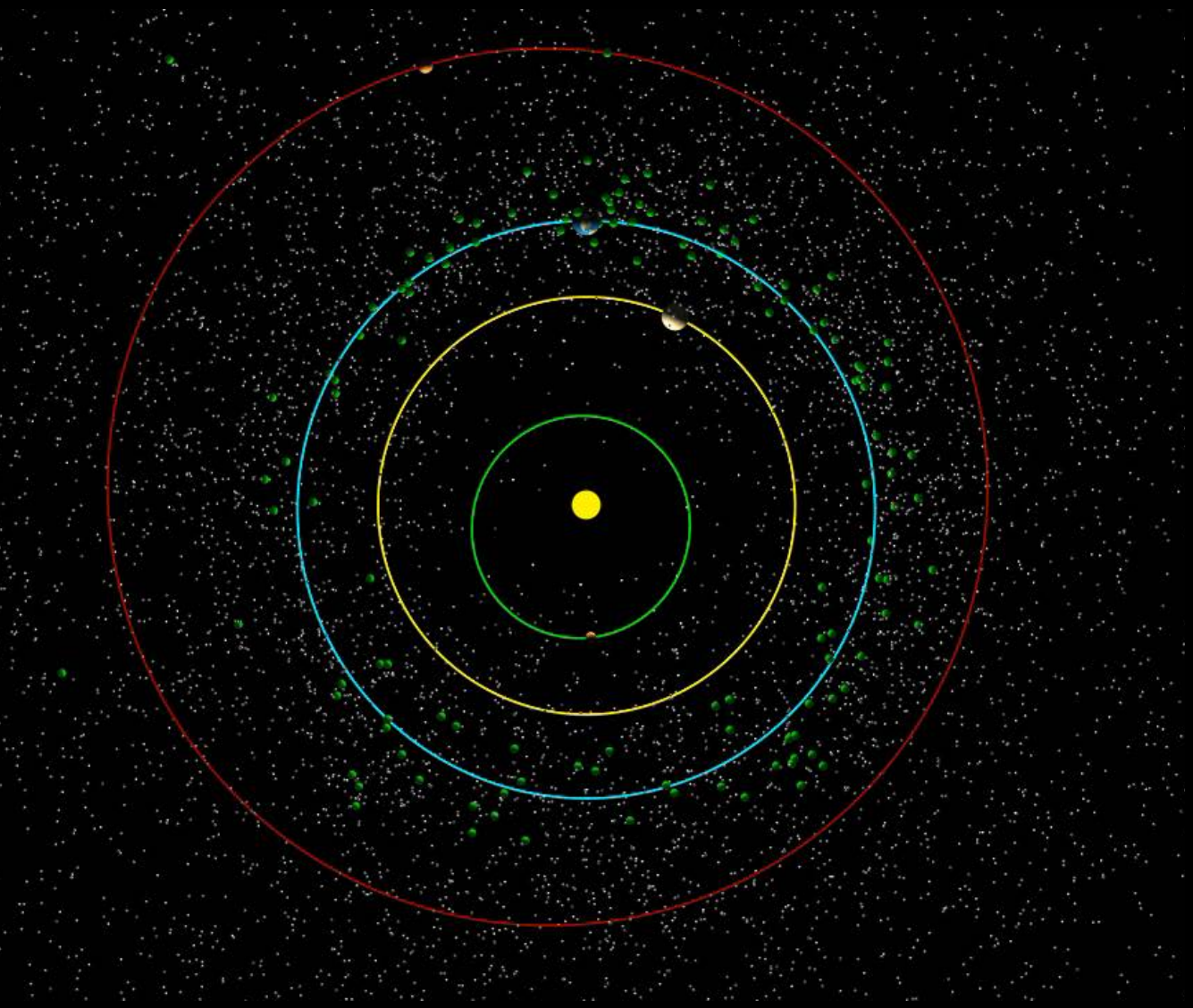


Image credit: ESA/Rosetta

NASA Innovative Advanced Concepts

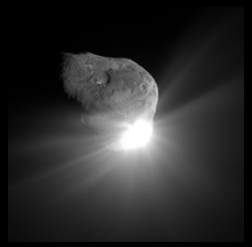
Small Solar System Bodies



Accessible near-Earth asteroids (NHATS) - Image credit: S. Kortenkamp, PSI

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

Phobos by Curiosity



Tempel 1 by Deep Impact

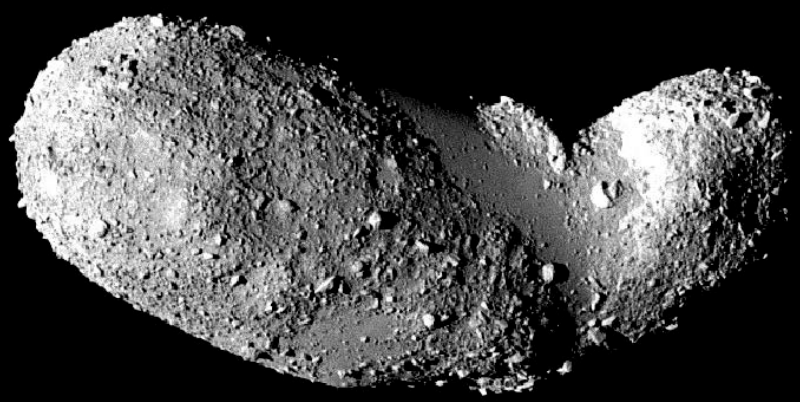
4.5×2.4×1.9 km

5×10^{13} kg

Asteroid Toutatis by Goldstone Radar (Potentially hazardous object)

Note Halloween flyby of "skyscraper-sized" asteroid 2015 TB145.

Interior structure of asteroids and comets?



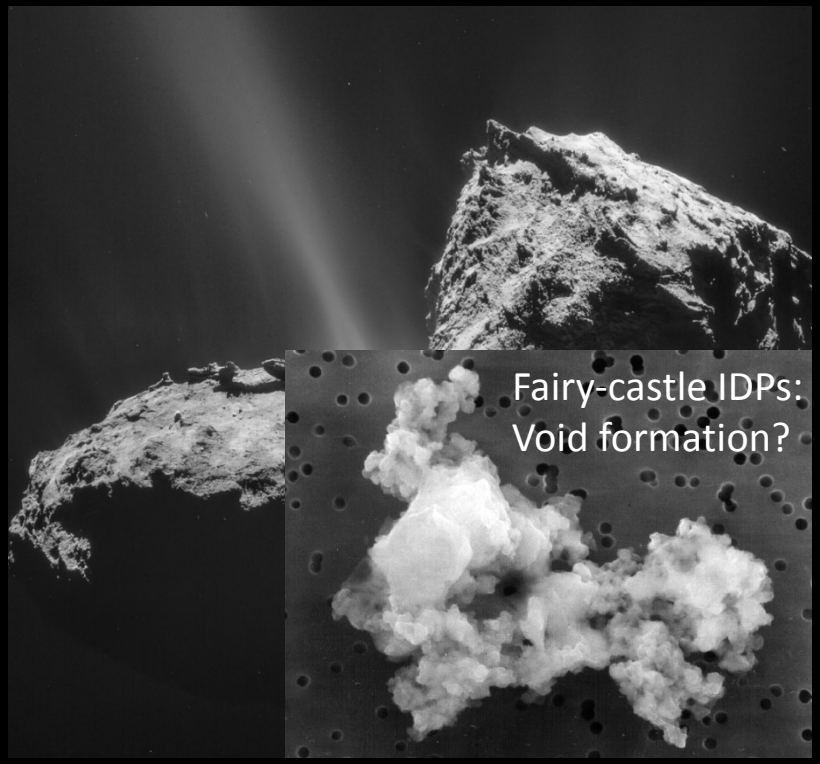
JAXA/Hyabusa/Itokawa

Voids on the order of the size of the constituent fragments comprising the asteroid – possibly larger depending upon the role of friction and van der Waals forces.

Density contrasts: ~3 g/cm^3 (component rock) and 0 g/cm^3 (voids).

Heterogeneous / collisionally - processed.

ESA/Rosetta/CG-67P

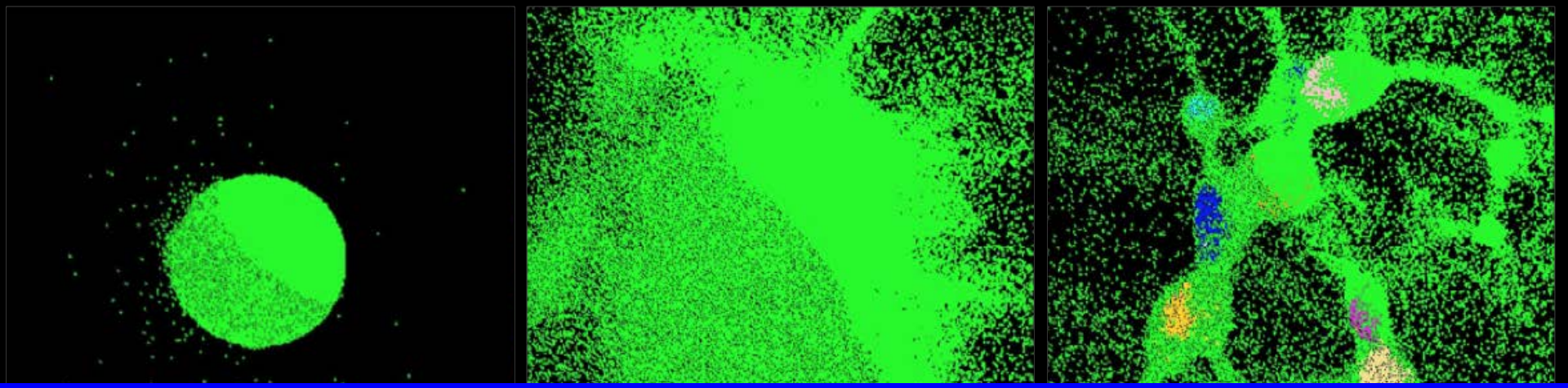


Density discontinuities between compressed and uncompressed comet material, perhaps manifested as sheets of high-density within low-density material.

Density contrast: 0.5 g/cm^3 (uncompressed) and 2 g/cm^3 (compressed).

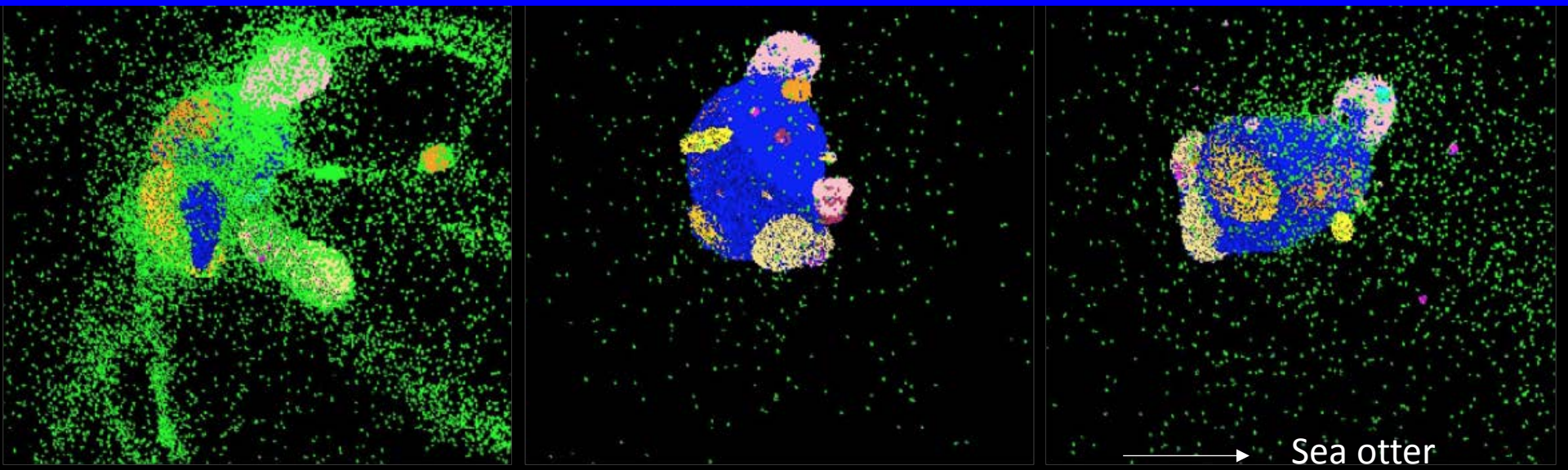
Collisional processing

Michel & Richardson, A&A 554, L1 (2013)



Itokawa as a gravitational aggregate

Brazil nut effect - Are the larger pieces on the outside?



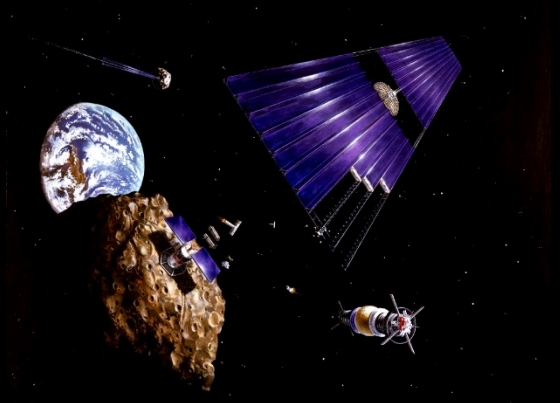
Deep Mapping Significance:

Interior structure, composition & properties

- Density & macroporosity
- Rubble-pile v. homogeneous
- Volatile content
- Strength of materials

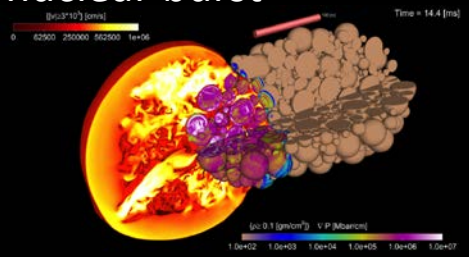
Resources & exploration

Mining, capture, in situ resource utilization (ISRU), radiation environment



Planetary defense

Kinetic impactor vs. nuclear burst



Plesko et al., AstroRecon 2015

Planetary science

Origins and evolution

NASA initiatives

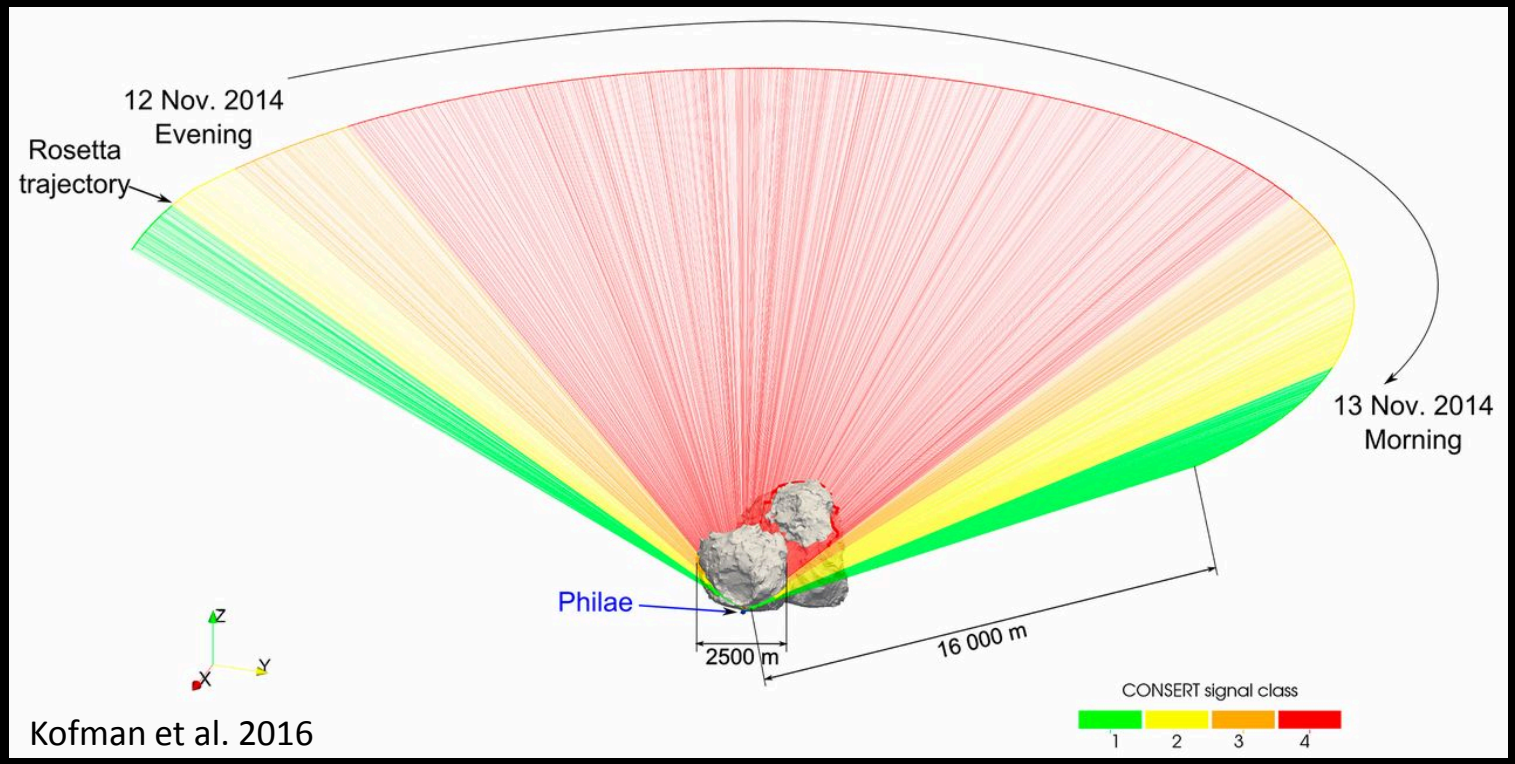
Asteroid Mission Strategic knowledge gaps (SBAG, e.g. Abel & Rivkin, AstroRecon 2015)

Prospective Deep Mapping Methods

Method	Physical Parameter	Object Size/depth	Resolution limit	Issues
Radar	Dielectric constant, conductivity	kilometers	meters	Contrast detection, ambiguous
Gravimetry & Radio Science	Gravity field	Whole-body, regional mass anomaly	?	Model based
Seismic	Seismic velocity, density	kilometers	Thin structures challenging	Contrast detection, ambiguous
Muon imaging	Density (electron)	< 3 km	meters	Long integration times

Some combination of these methods may be required!

Rosetta: Gravimetry and radar



Kofman et al. 2016

- Radar measurements indicate CG-76P is homogeneous on scales of several meters, but cannot not rule out larger blocks (Kofman et al., *Science*, 2016)
  - Constrained volumetric dust/ice ratio (0.4 to 2.6) and porosity of (75 to 85%)
- Gravity measurements confirm high porosity, absence of large voids (Patzold et al., *Nature*, 2016)

Muon fundamentals

Muons are elementary charged particles (leptons), like electrons, but 200× more massive.

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

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

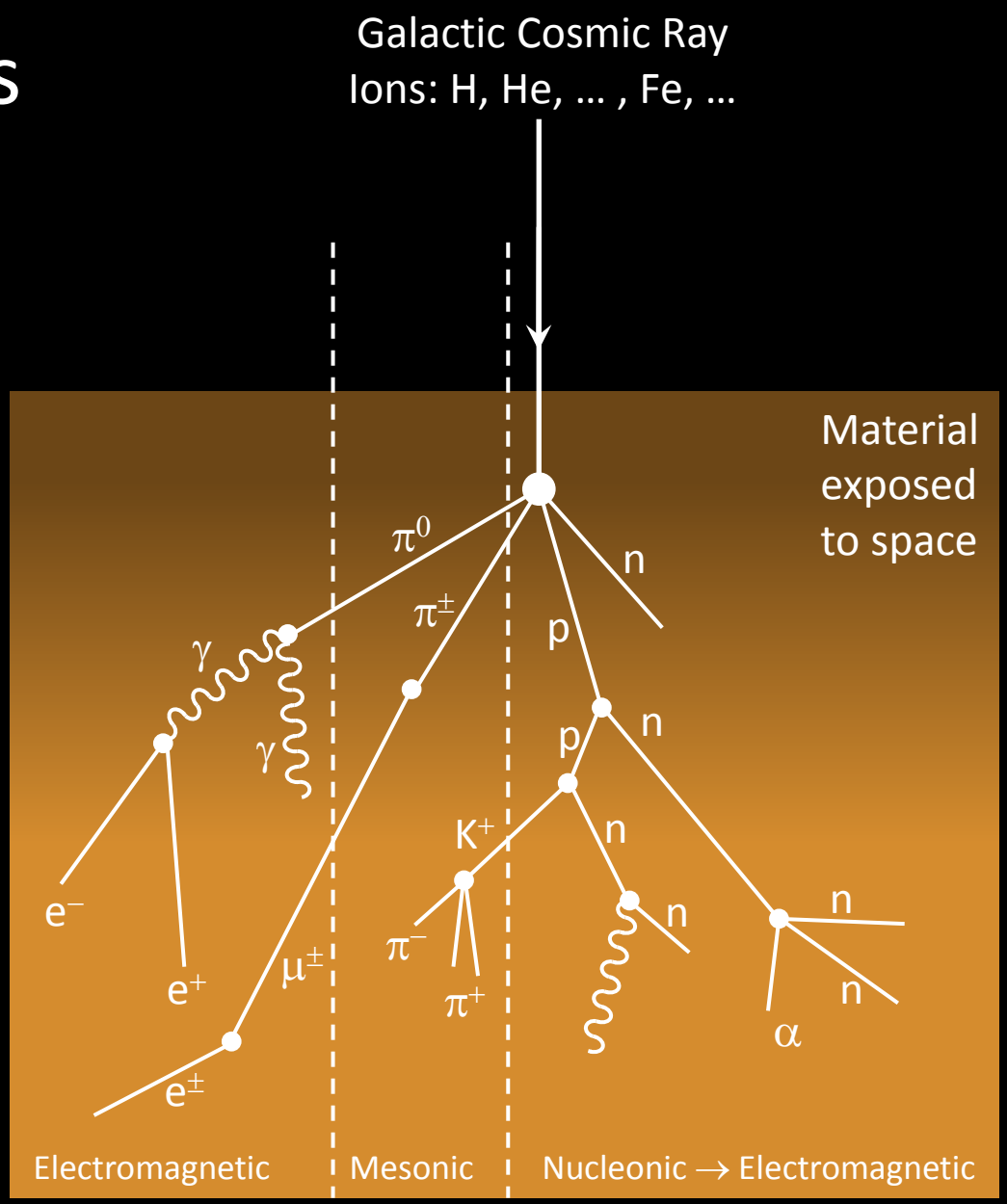
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

Muons subsequently decay, e.g.

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

Muons undergo weak interactions:

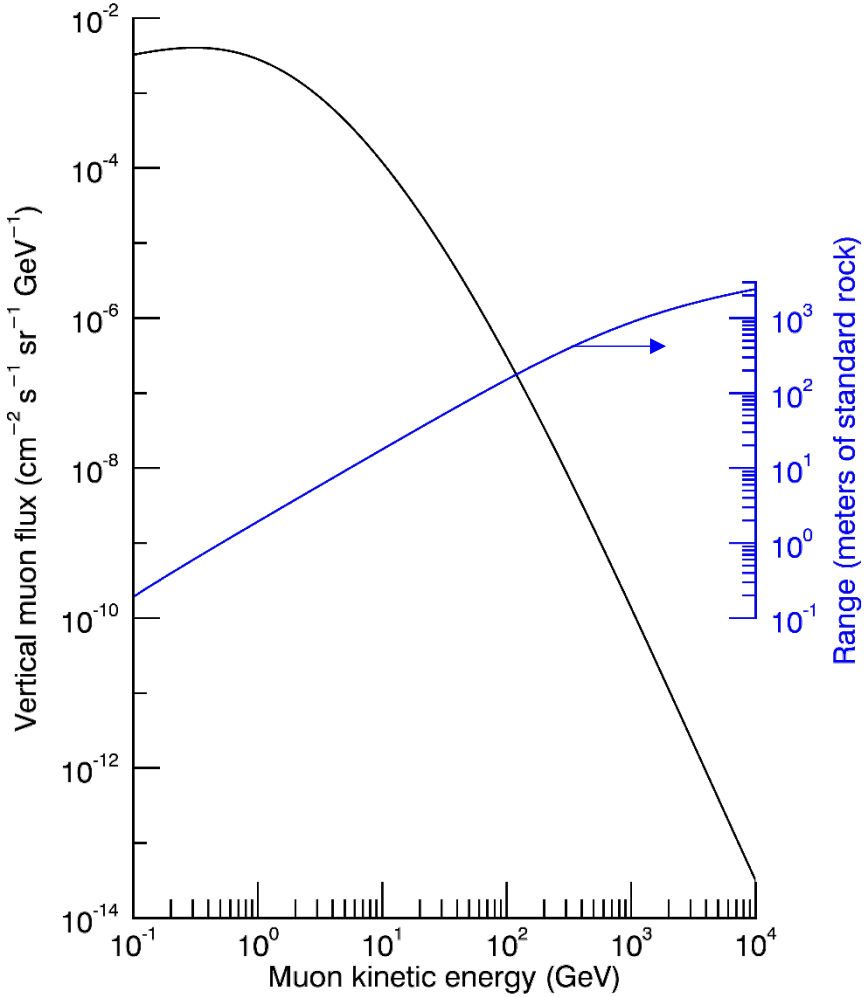
- Energy loss by ionization, radiative & nuclear processes
- Destruction is dominated by decay (2.2 μs mean lifetime)
- *High-energy muons can penetrate kilometers of rock*



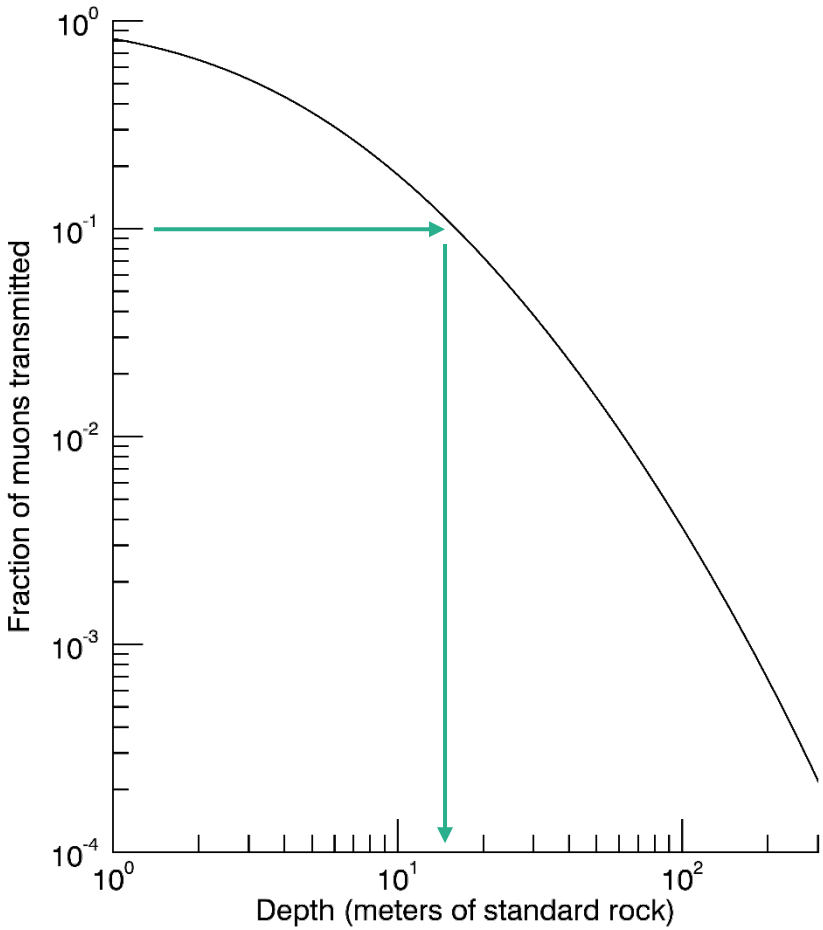
Muon range and transmission

(total muon flux as a gage of thickness)

Spectrum of muons at Earth's surface



How many muons arrive at depth?

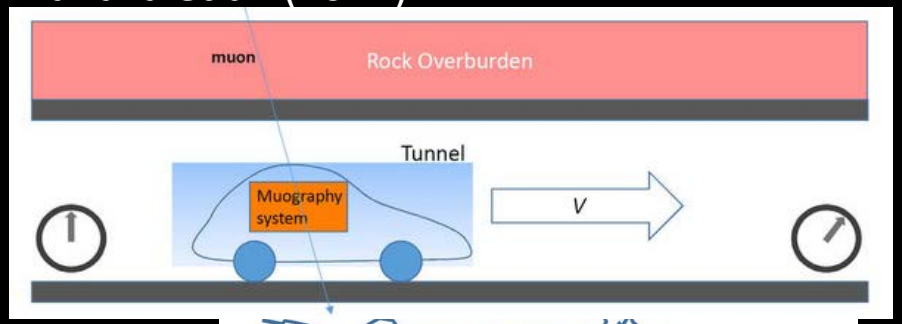


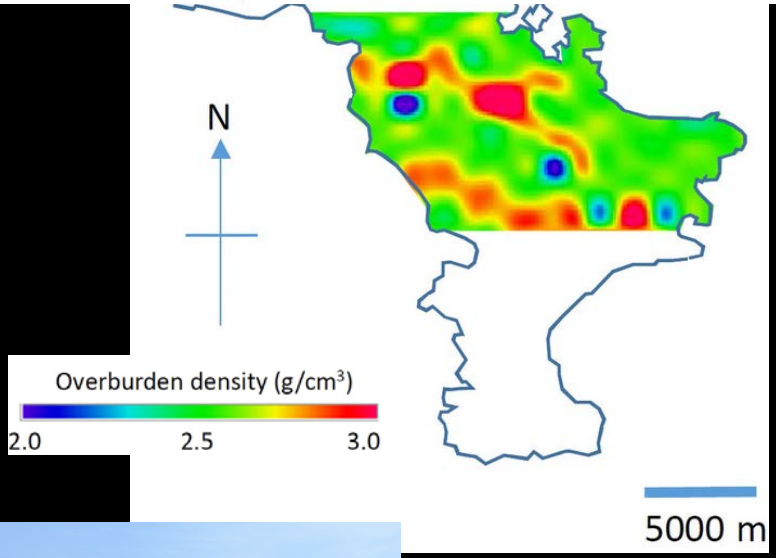
Standard rock: ρ = 2.65 g/cm^3

Muon imaging

- Application of muons to radiography and tomography
- About 10,000 muons per square meter at Earth's surface
  - A uniform source for radiography
  - Atmospheric muons are ***far*** more penetrating than any other particle used for radiography
- Atmospheric muons used to measure tunnel overburden in the 1950's for civil engineering and *today* for geology!
- The first reported radiographs were by Alvarez et al. (1970) of the Pyramid of Chepren (Khafre)
- Muons are used today to study damaged Fukushima-Daiichi reactor cores, homeland security, architecture, civil engineering, and geophysics.

Tanaka et al. (2014)





MusikAnimal/CC-by-sa

Alvarez et al. (1970)*

DigitalGlobe/CC-by-sa

Imaging Rx cores: LANL

*Compared images measured with a hodoscope to simulated images with "hidden" chamber.

Muon imaging in geophysics

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

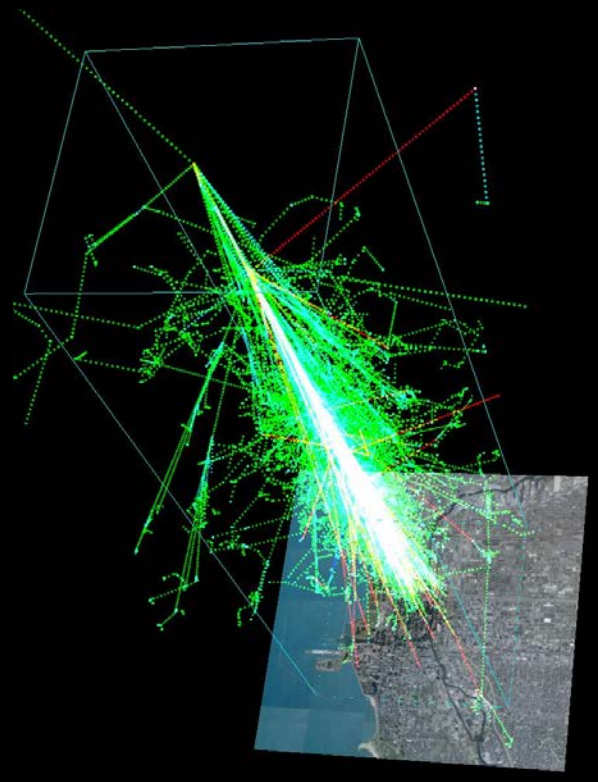
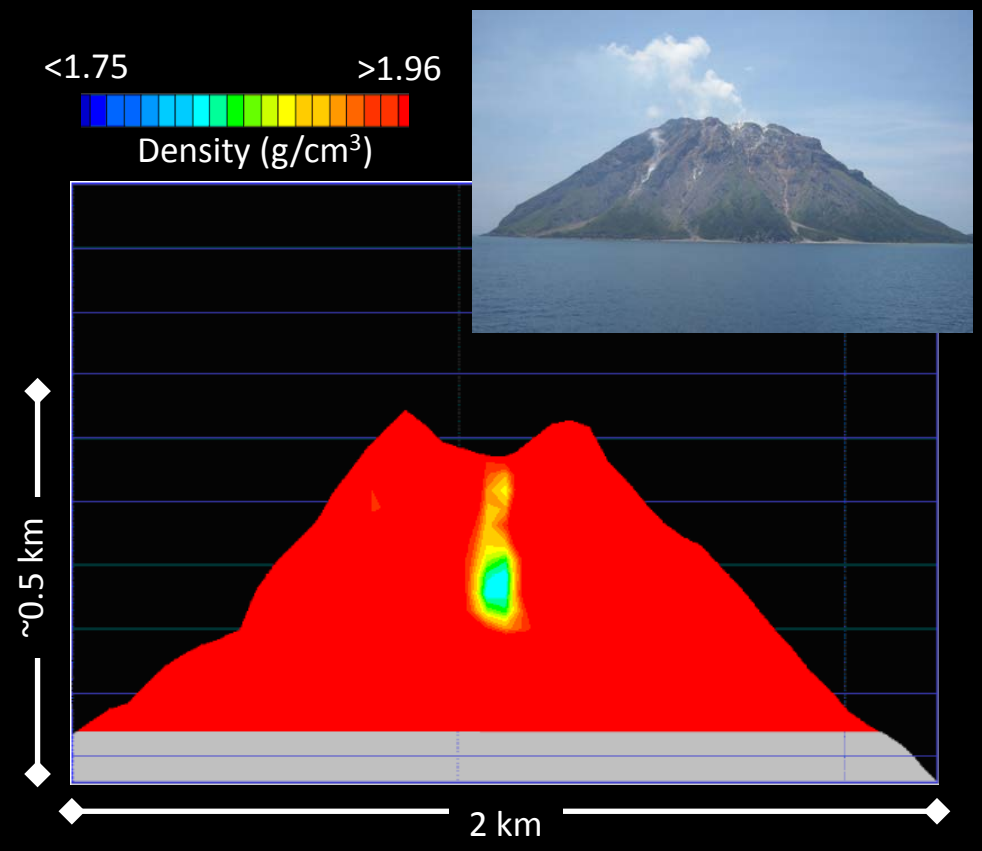
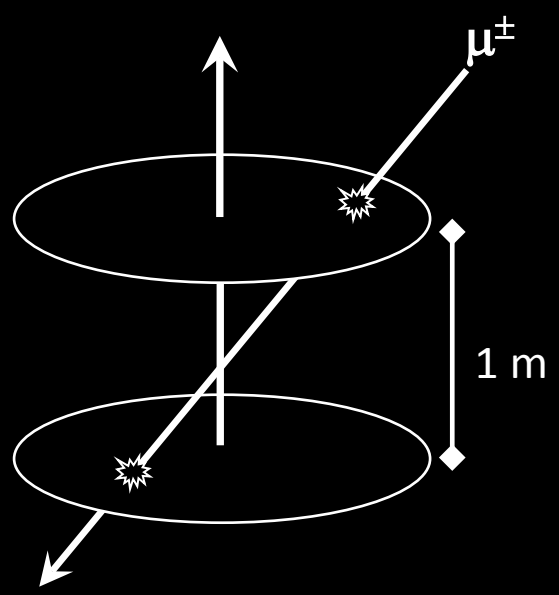


Image by University of Chicago & Kavli Institute for Cosmological Physics & the Pierre Auger Observatory (CC-BY-2.5)

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



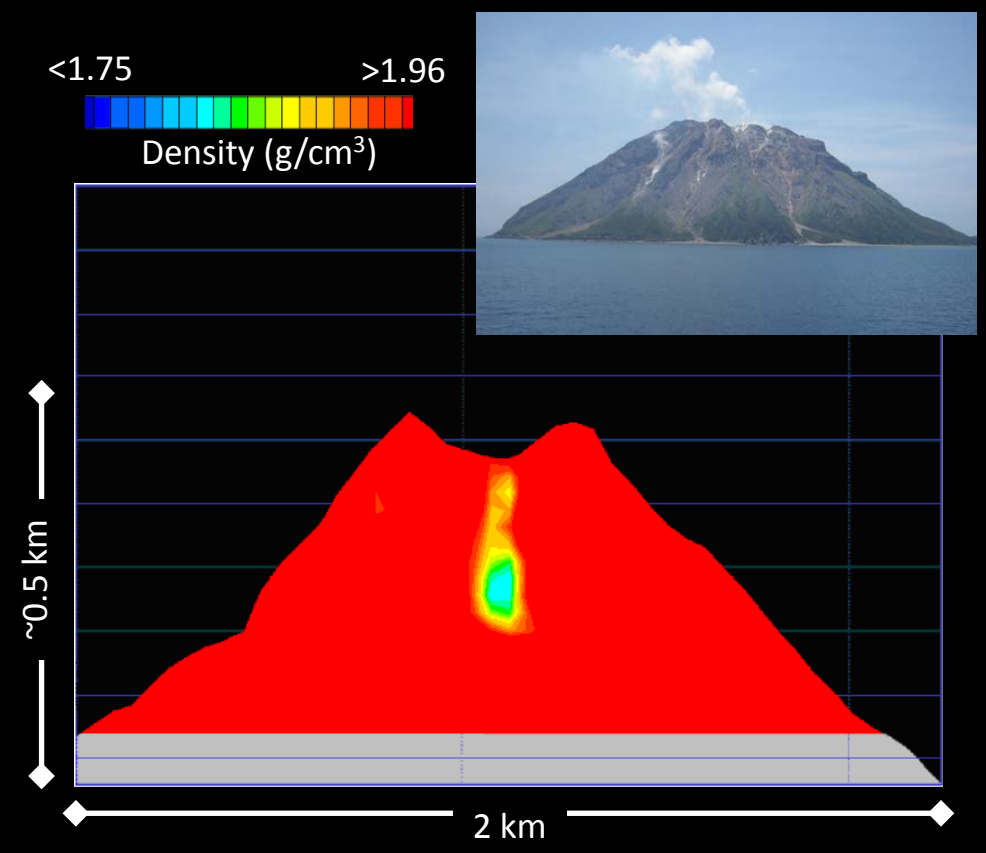
Muon imaging in geophysics



Hodoscope: Tracking planes determine particle trajectory.

hodos + scopos = path + observer

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



Application to asteroids?

Steps for 3D filtered backprojection

Acquisition of hodoscope data

↓

Ray-sorting/binning → projection geometry

↓

Conversion of counts to density integrals

↓

Tomographic reconstruction

Ideal projection data for a small asteroid with a dense inclusion

Animation progression:
Asteroid exterior → Projected density → Filtered projection

Application to asteroids?

Steps for 3D filtered backprojection

Acquisition of hodoscope data

↓

Ray-sorting/binning → projection geometry

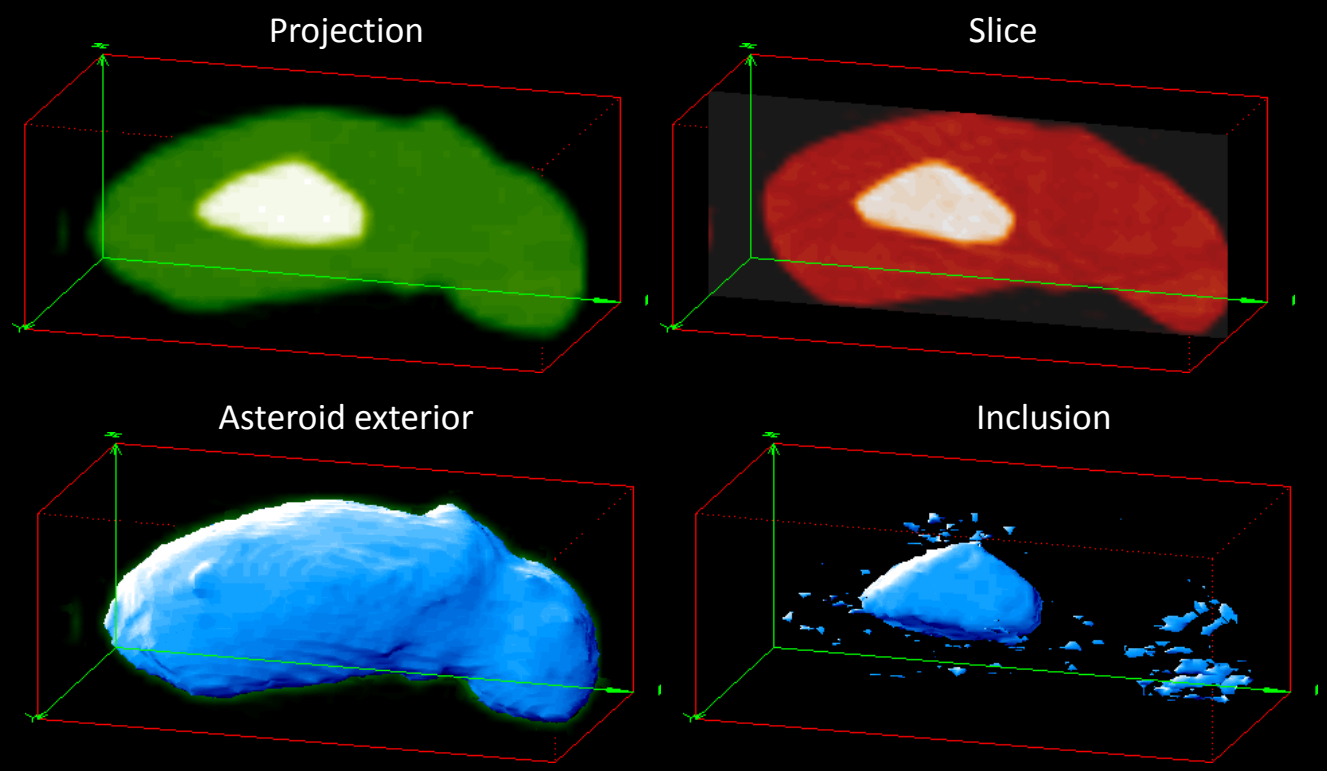
↓

Conversion of counts to density integrals

↓

Tomographic reconstruction

Reconstructed interior density structure



- In practice, months in close proximity could be required to acquire data for 3D interior mapping
- Integration time depends on inclusion scale and contrast, hodoscope design, and concept of operations

Challenges for asteroids & comets:

Are there enough muons?

- Yes – Integration times "typical" for mapping missions with 1 m^2 hodoscope

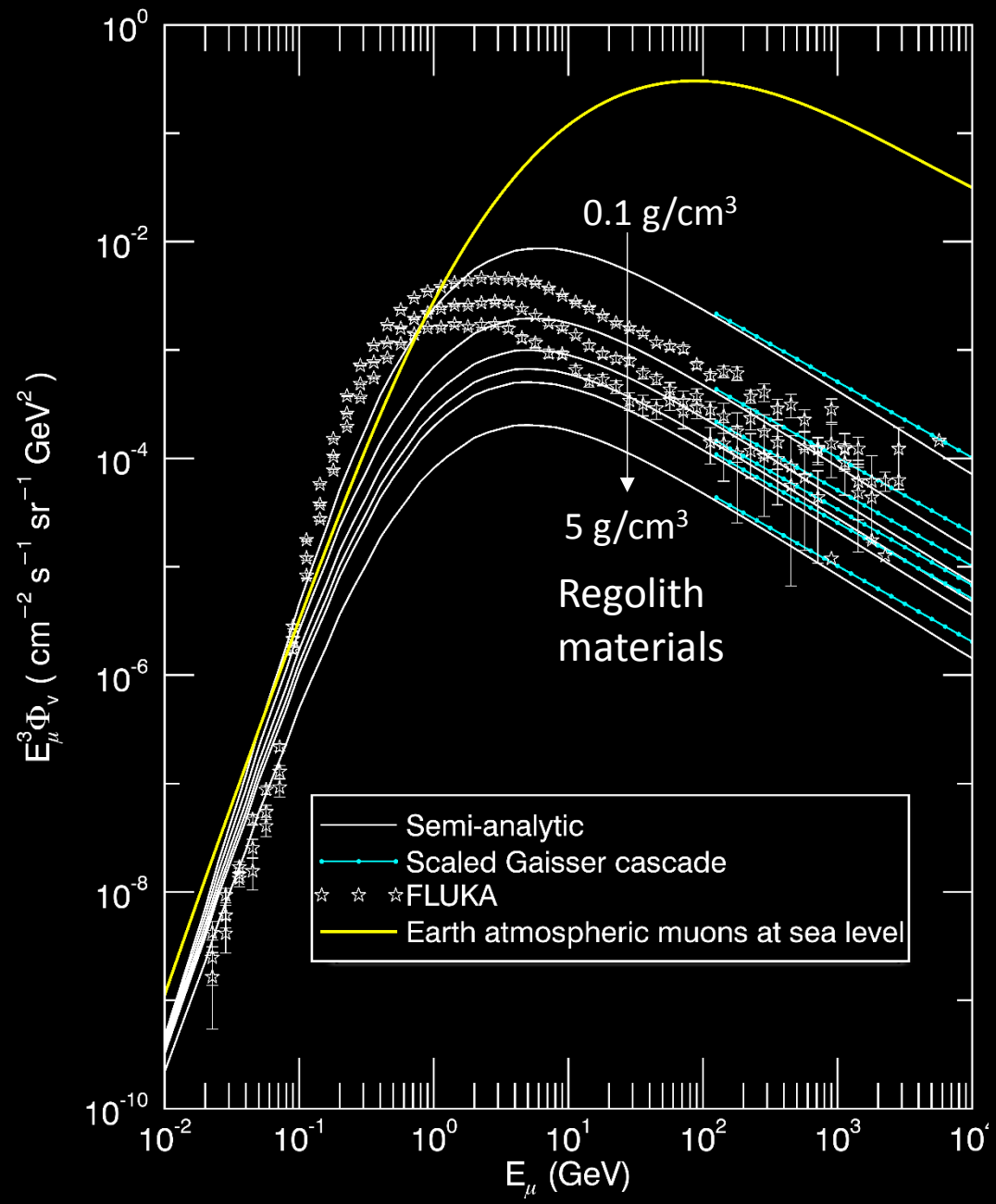
Can interior structures be separated from surface features?

- Yes – Radar measurements of surface density constrain muon production

Can muons be separately measured from other particles by a *practical* imaging system?

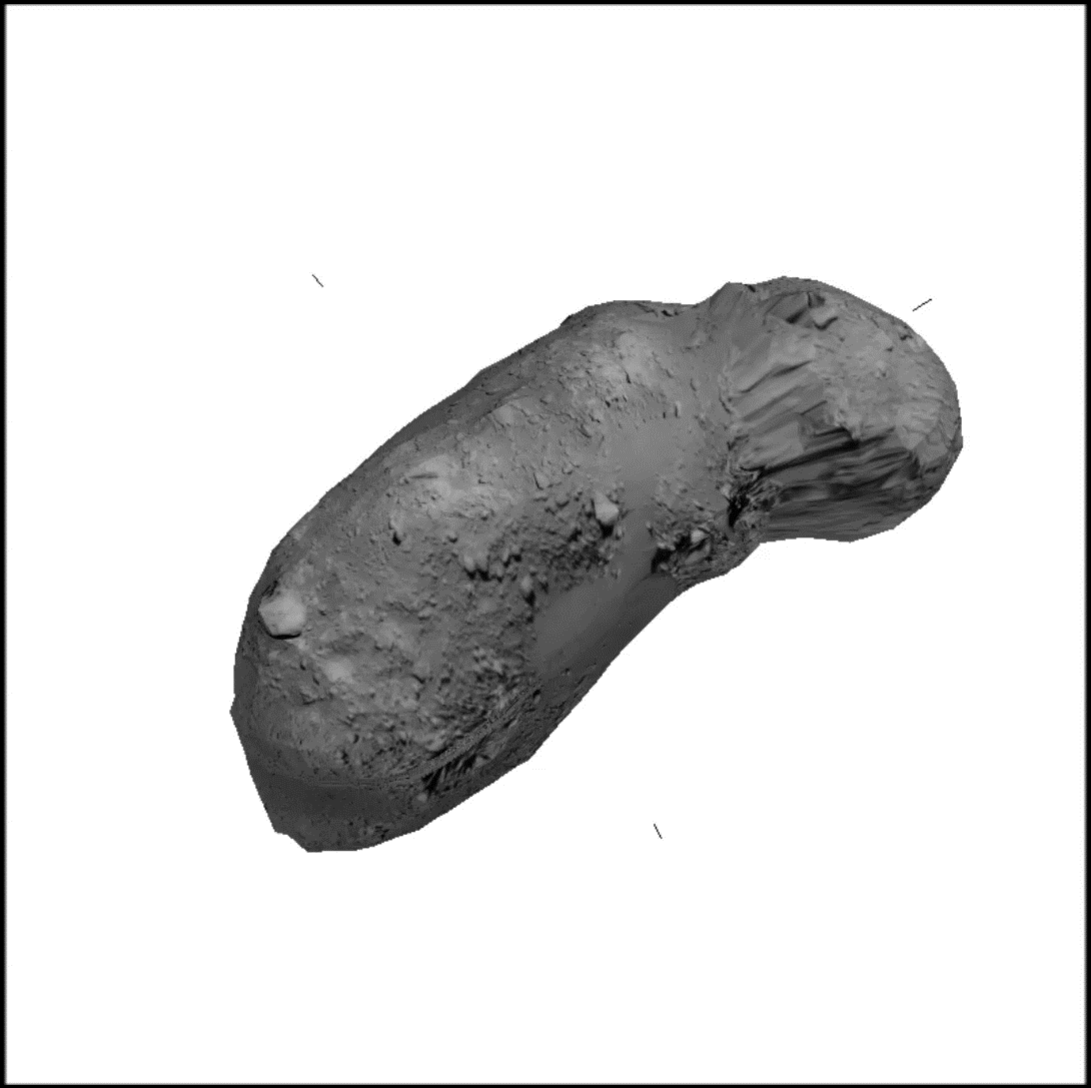
- Probably – however, electrons may pose a challenge

Muon production in solid surfaces and Earth's atmosphere



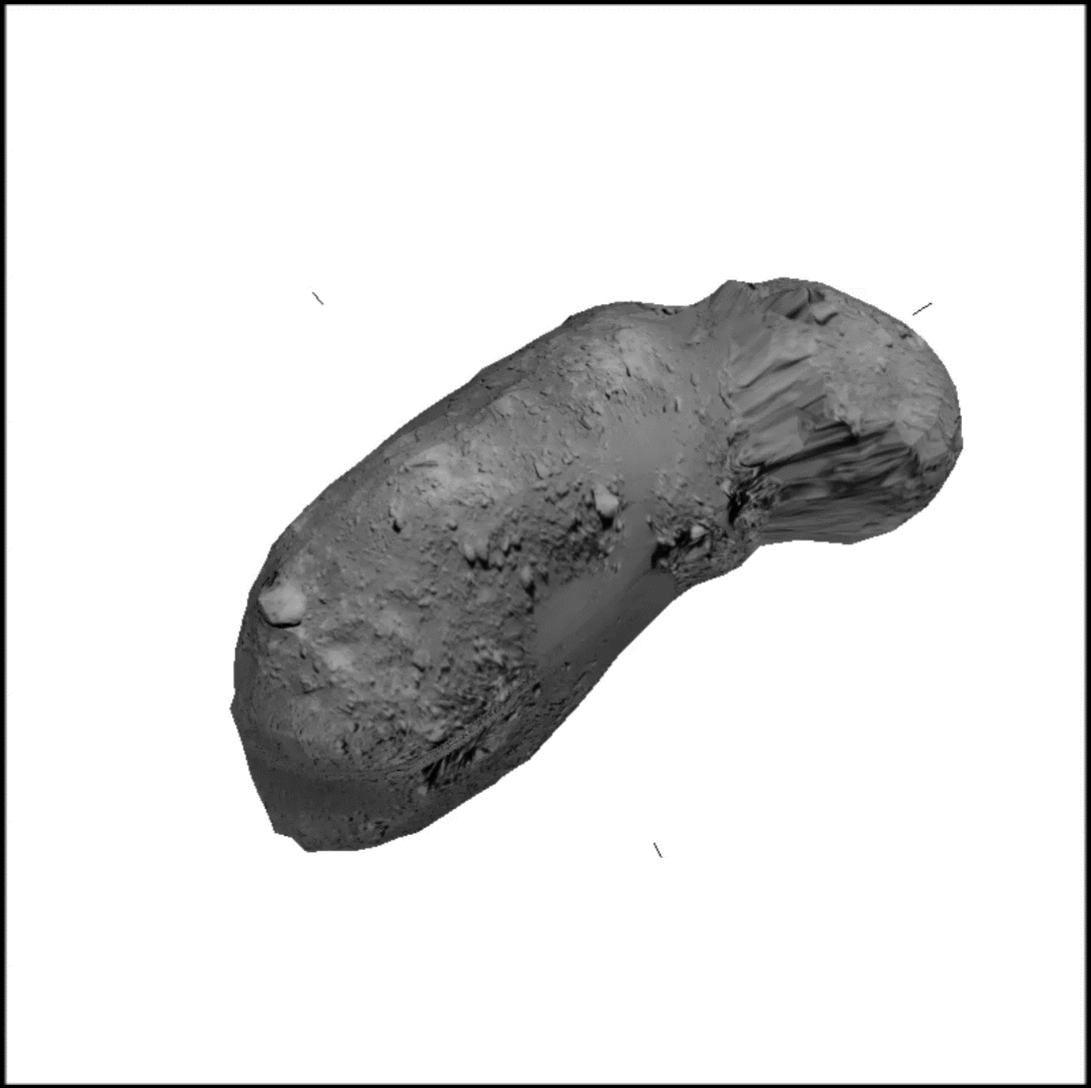
Regolith shower: Signal

- Target:
  - Itokawa shape (500 m length)
  - Low density (0.5 g/cm^3)
- Projectile
  - 10 TeV proton
- Secondaries
  - High-energy muon penetrates interior
  - Co-linear with source
- Details:
  - Logarithmic time steps
  - Event generator: MCNPX
  - All particles sans electrons
  - 1 GeV cutoff



Regolith shower: Spatter

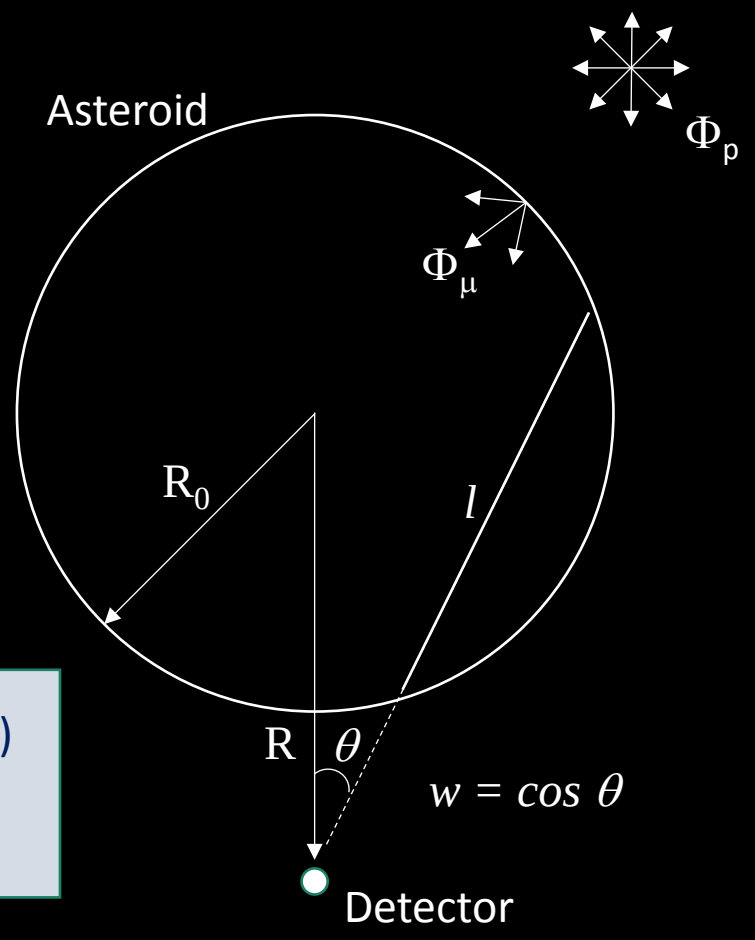
- Target:
  - Itokawa shape (500 m length)
  - Low density (0.5 g/cm^3)
- Projectile:
  - 6 TeV proton
- Secondaries:
  - Low-energy muons emitted on the same side as the projectile
- Details:
  - Logarithmic time steps
  - Event generator: MCNPX
  - All particles sans electrons
  - 1 GeV cutoff



Can we separate transmitted muons from the spatter?

Detailed simulations of particle production and transport were carried out for a spherical asteroid:

- Isotropic GCR protons
- 50 m radius asteroid;
- Uniform, 0.5 g/cm^3 standard rock
- Monte Carlo (*FLUKA*) simulations highlighted
- *We are exploring the sensitivity of results to model assumptions*

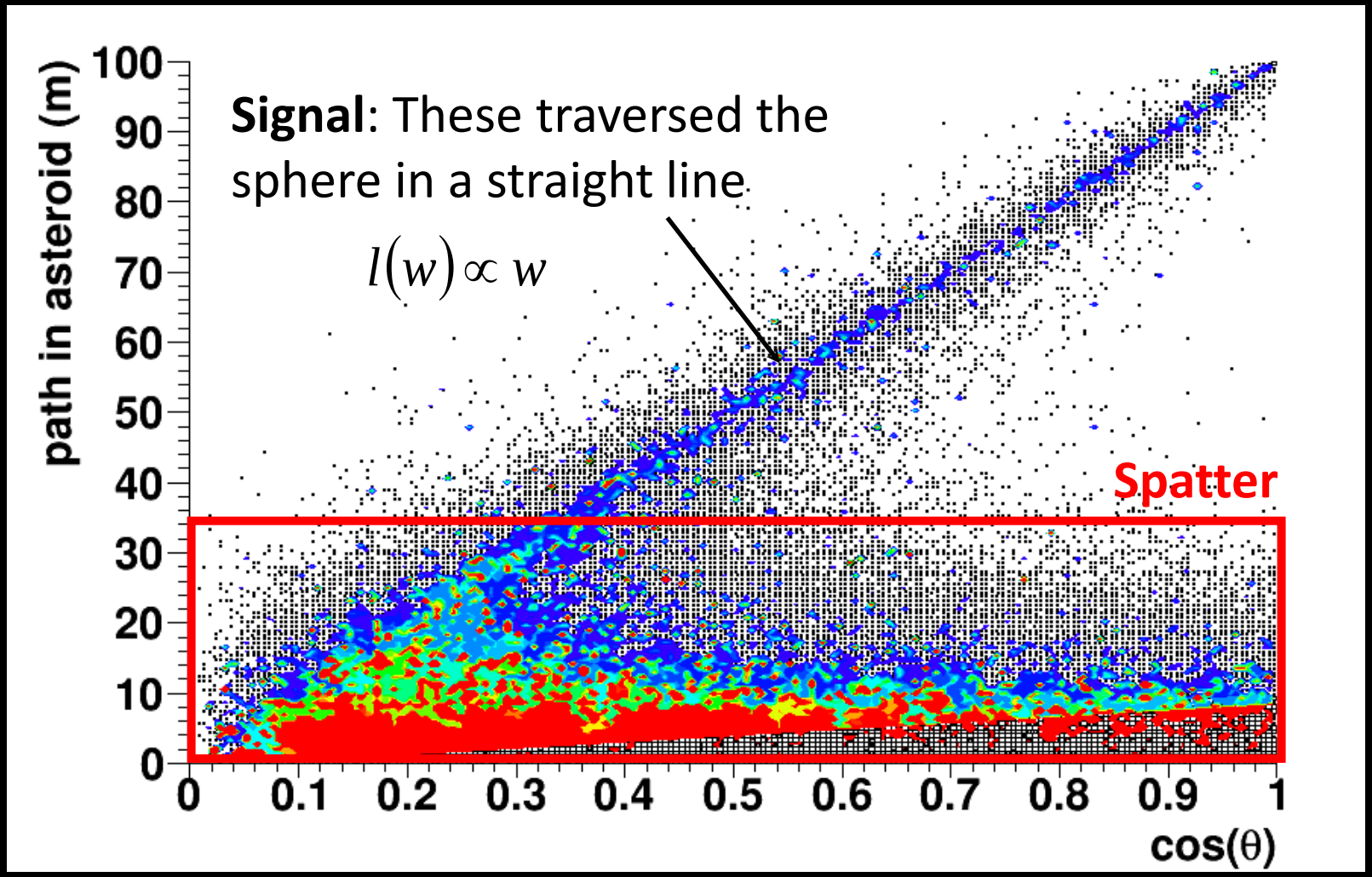


Special case: $R_0 = R$ (on the surface)

$$l(w) = 2R_0 w$$

Muon chord lengths (FLUKA)

All muons, detector on the surface

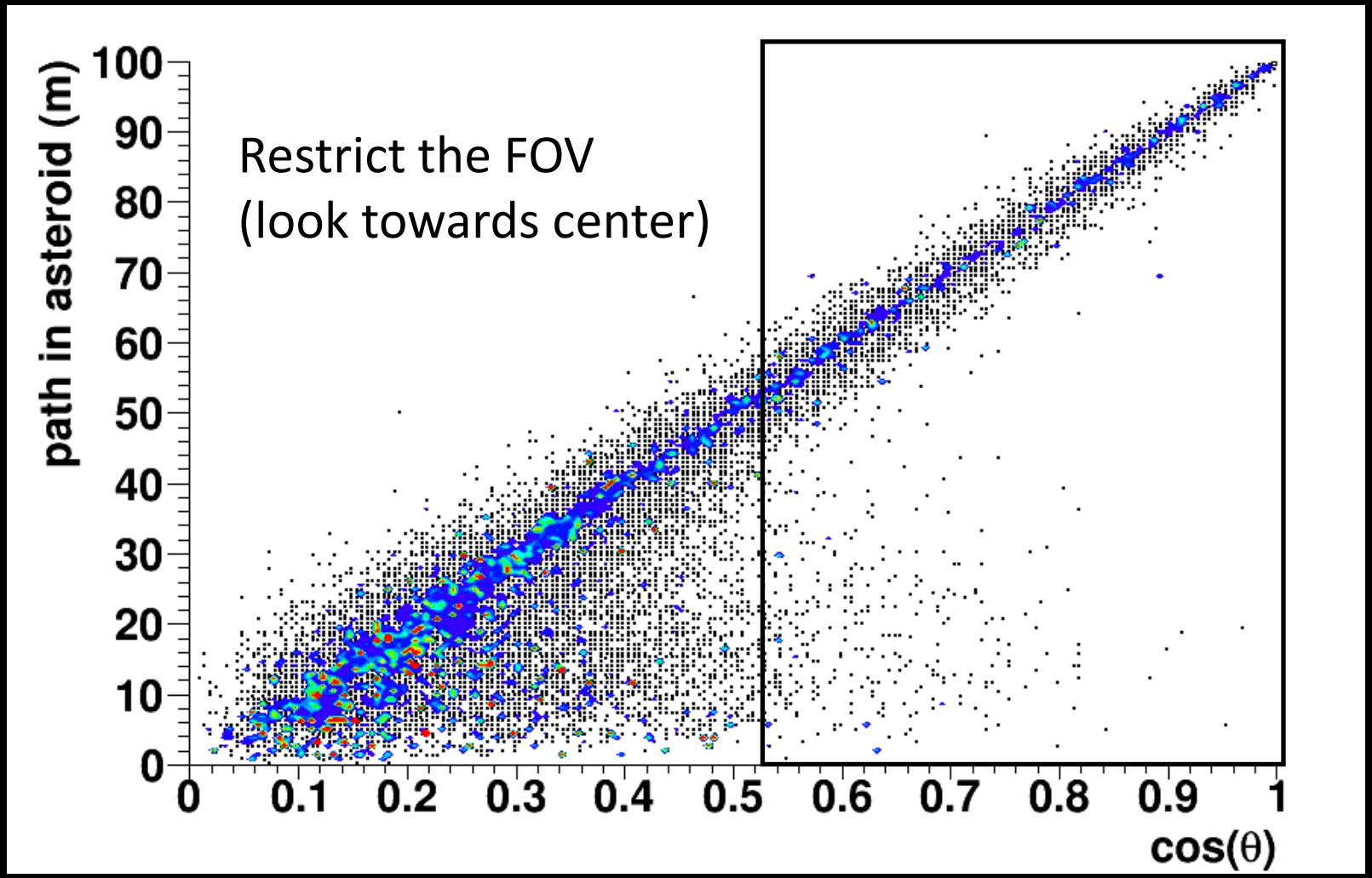


← Towards limb

Towards center →

Muon chord lengths (FLUKA)

Muons escaping with kinetic energy > 600 MeV

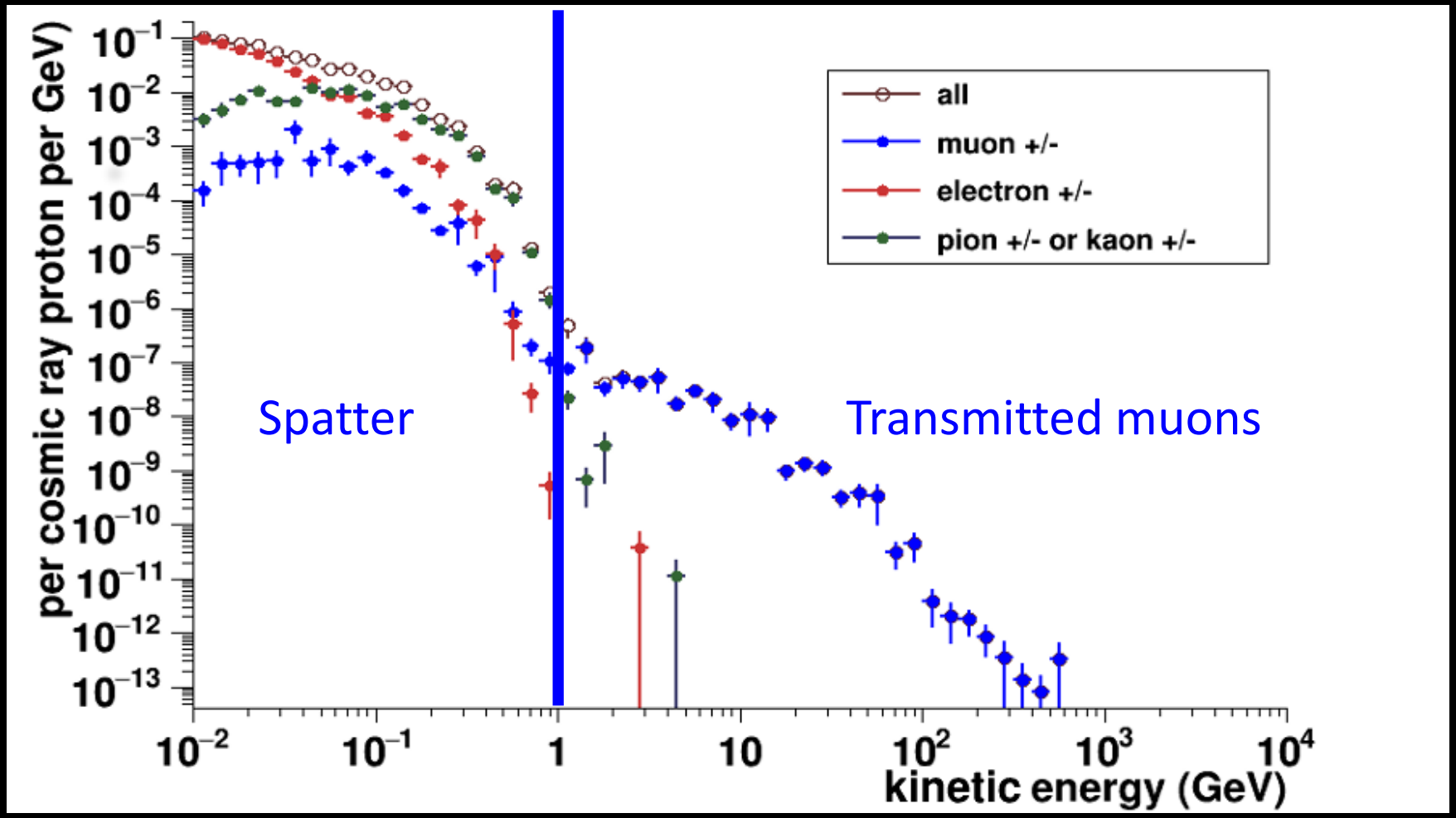


← Towards limb

Towards center →

Particle energy distributions

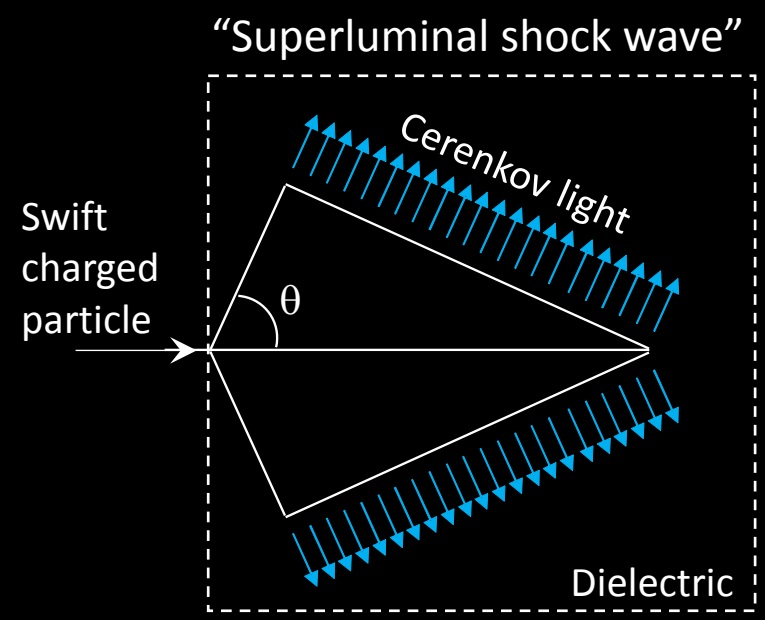
Emission angles less than 30°, detector on the surface



Cerenkov Radiation – Velocity Filter

- Passage of a swift charged particle through a dielectric medium produces EM radiation
  - Radiation emitted when $v/c = \beta > 1/n$
  - Conical wave front, $\cos\theta = 1/n\beta$
  - Threshold kinetic energy:

$$E/m_0 > \left(\frac{1}{\sqrt{1-1/n^2}} - 1\right)$$



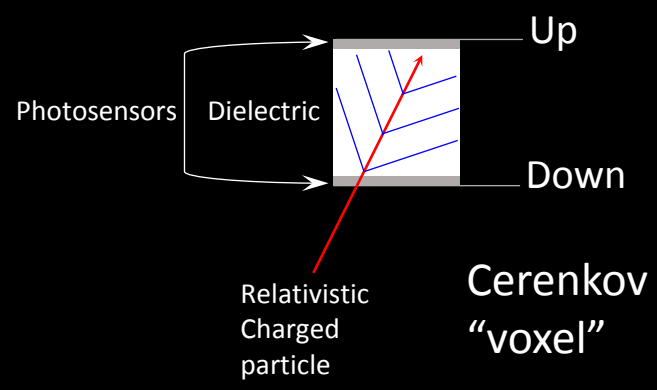
- Amount of EM radiation emitted at a given wavelength range is given by the Frank-Tamm formula:

$$N = 2\pi\alpha Z^2 L \sin^2\theta \times \left(\frac{1}{\lambda_{min}} - \frac{1}{\lambda_{max}}\right)$$

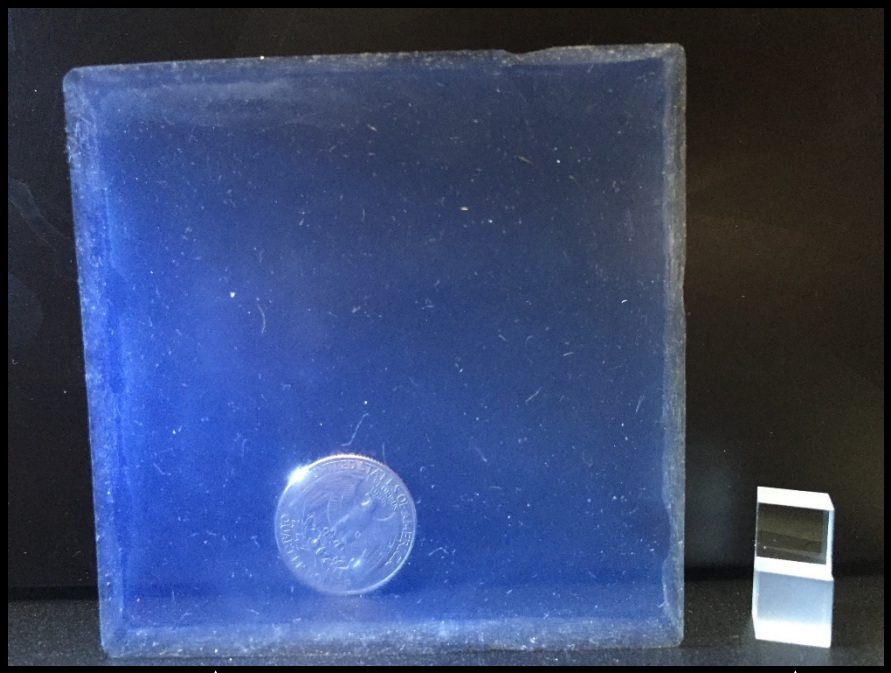
	Quartz	Water	Aerogel
n	1.46	1.33	1.01
E/m_0 thresh.	0.37	0.52	6.1
$\theta^\dagger$	47°	41°	8.1°
$\sin^2\theta^\dagger$	0.53	0.43	0.02
N/L (cm^{-1})‡	320	260	12

†β=1 ‡300-500 nm for β=1

Candidate materials



- Gas or aerogel provide required threshold β
  - Could be incorporated into tracking planes
  - Up-down discrimination may be limited by Rayleigh scattering
- Fused silica (quartz)
  - Easy to work with
  - Good candidate for tracking planes
  - Up-down discrimination
  - Rejects low velocity particles

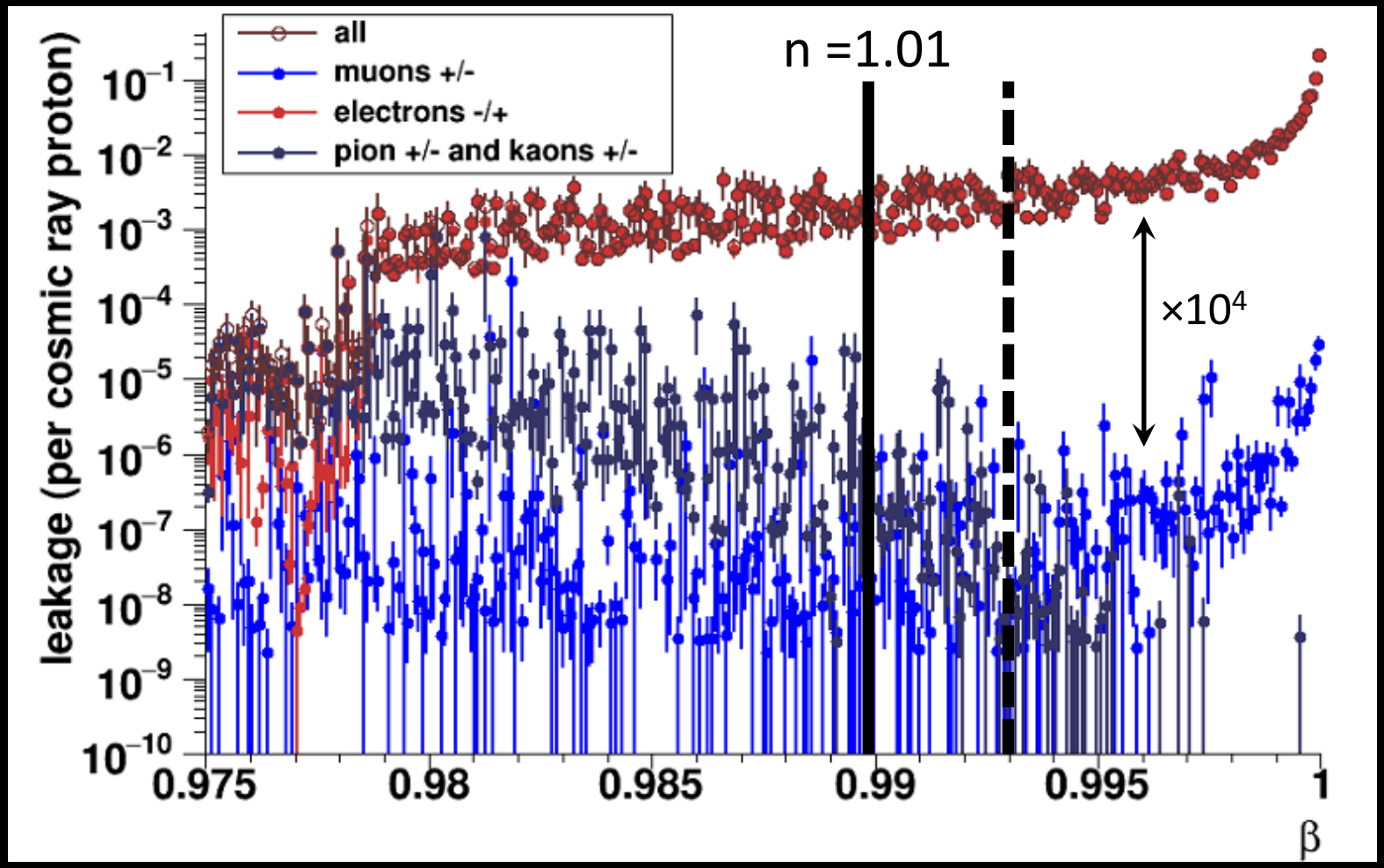


Aerogel tile
1.010 < n < 1.012
Aspen Aerogels

Quartz
n = 1.46

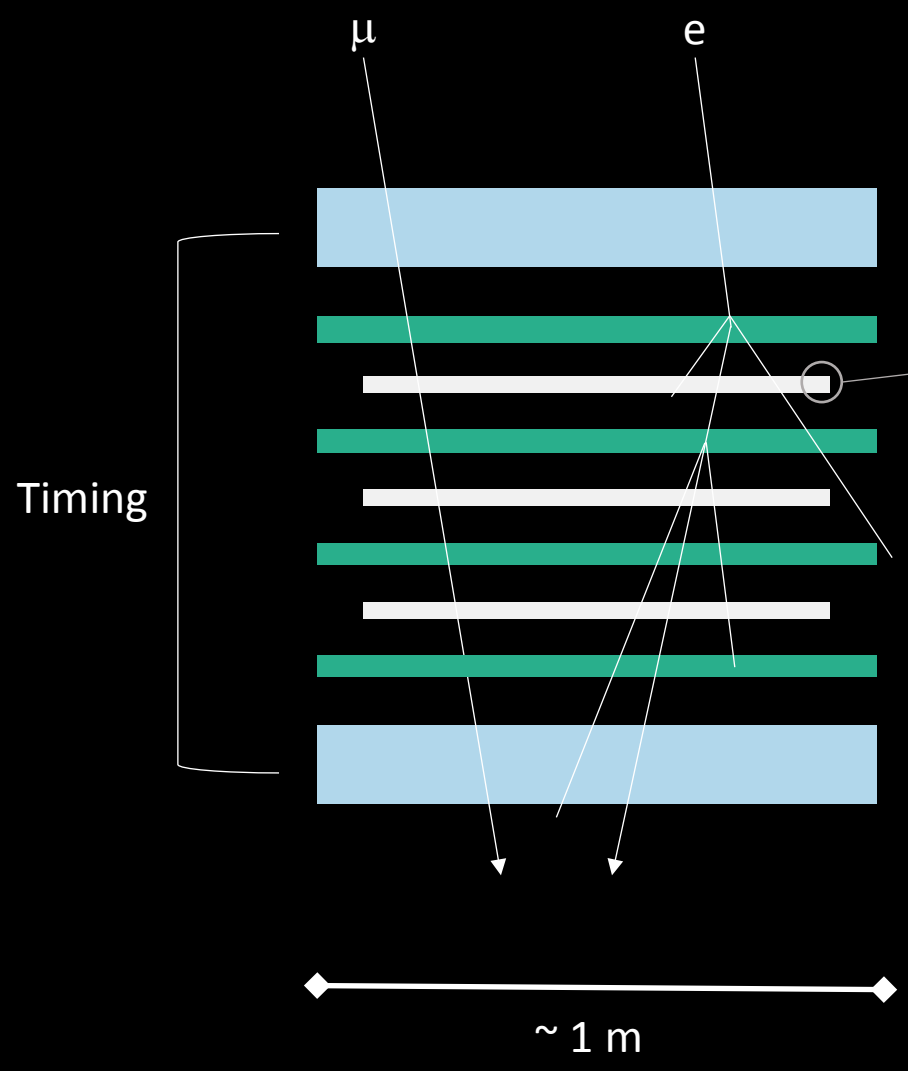
Particle velocity distributions

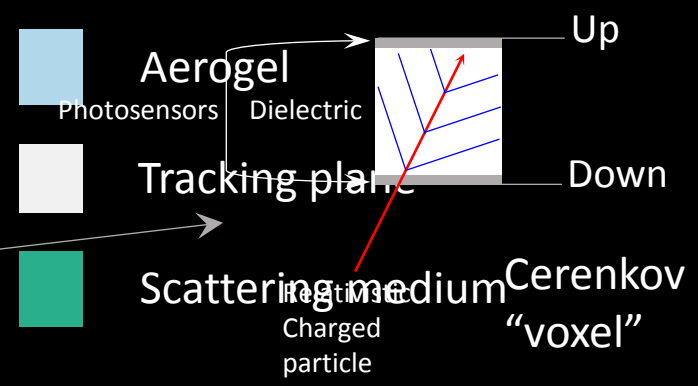
Emission angles less than 30°



Electrons cannot be suppressed using a velocity filter.

Instrument sketch



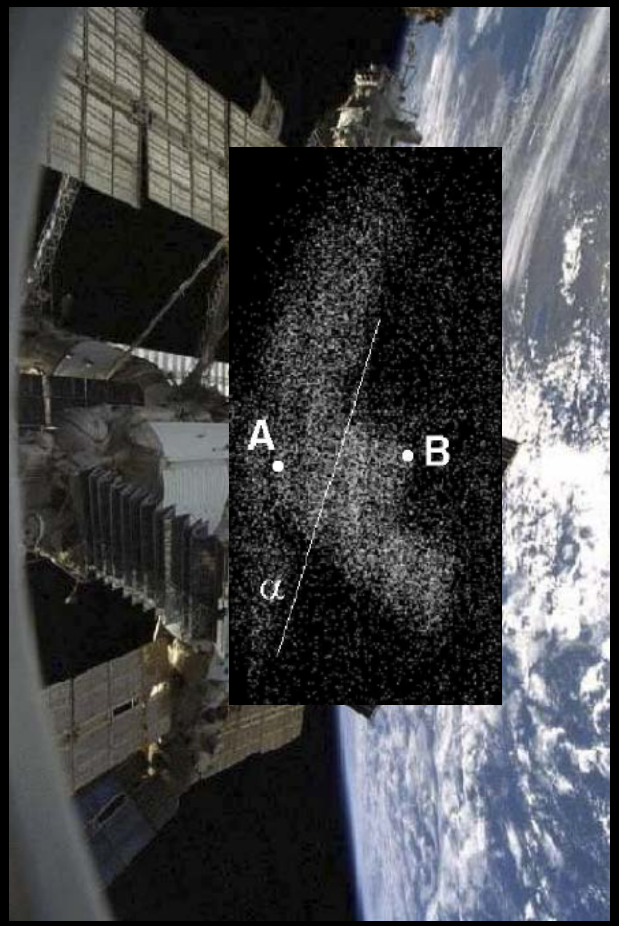


Coarse requirements:

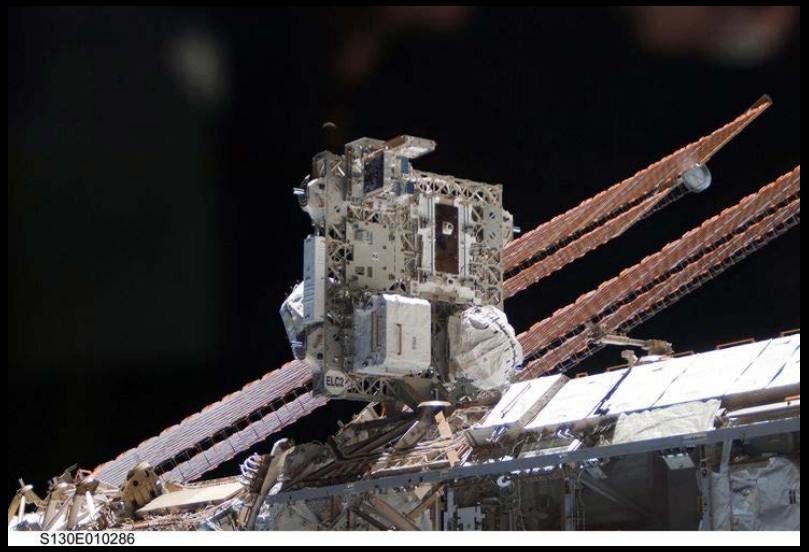
- High β filter
- Up-down discrimination
  - Direction of Cerenkov light
  - Timing
- Scattering medium for electrons
  - # of radiation lengths TBD
  - At lest three tracking planes
- Wide area
  - A few m^2-steradian etendu

Beyond NIAC

A prototype hodoscope could be tested on the International Space Station (ISS) or on balloon flights.



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

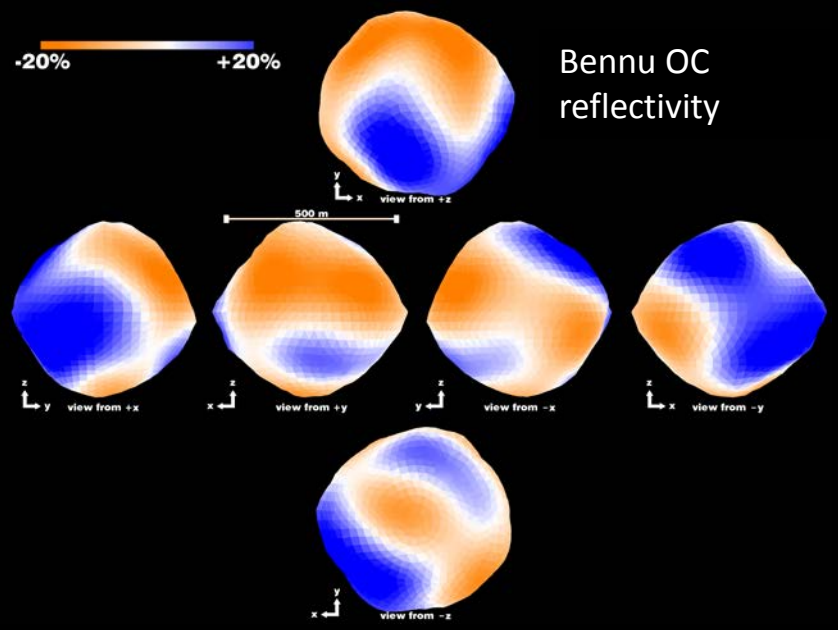


ISS Express Logistic Carriers

Pilot Mission

- Target: < 1 km asteroid observable by ground-based radar
- Payload
  - Muon telescope, up to 1 m^2
  - Shape data from camera or laser altimetry
  - Optional radar system
  - 3-6 months in close proximity to target

Radar observations constrain surface density and, consequently, muon production



Bennu OC reflectivity

The Fresnel reflectivity is a measure of the bulk density (relative) in the top about 2 π wavelengths.

Spacecraft-based 12-cm wavelength systems have been flight-tested (Mini-RF on LRO).

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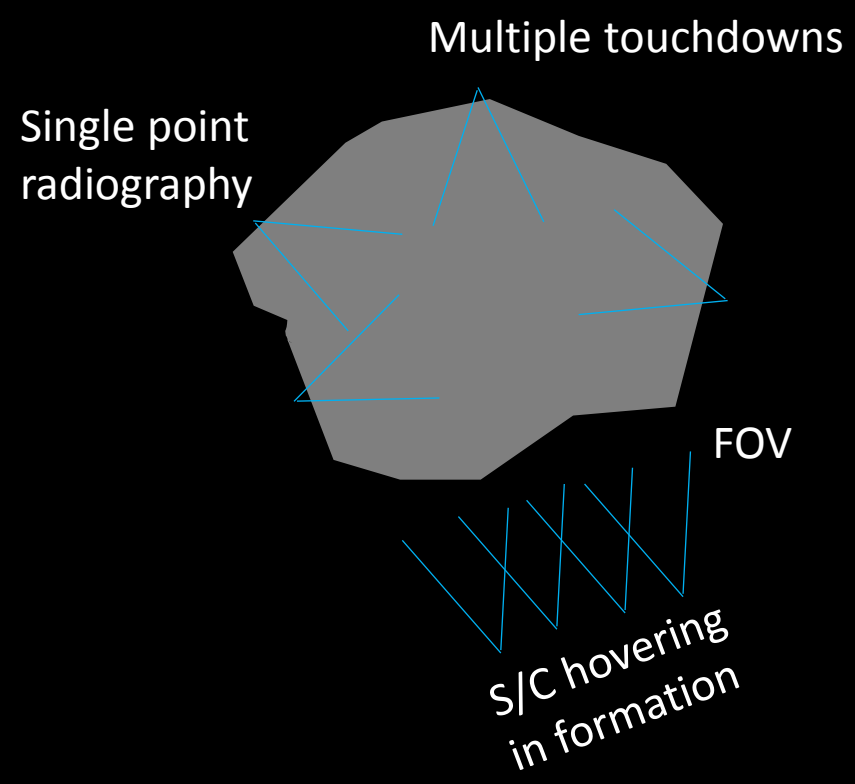
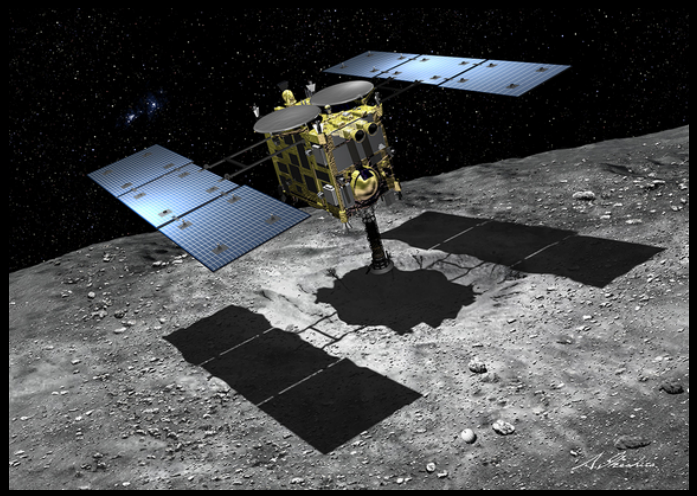
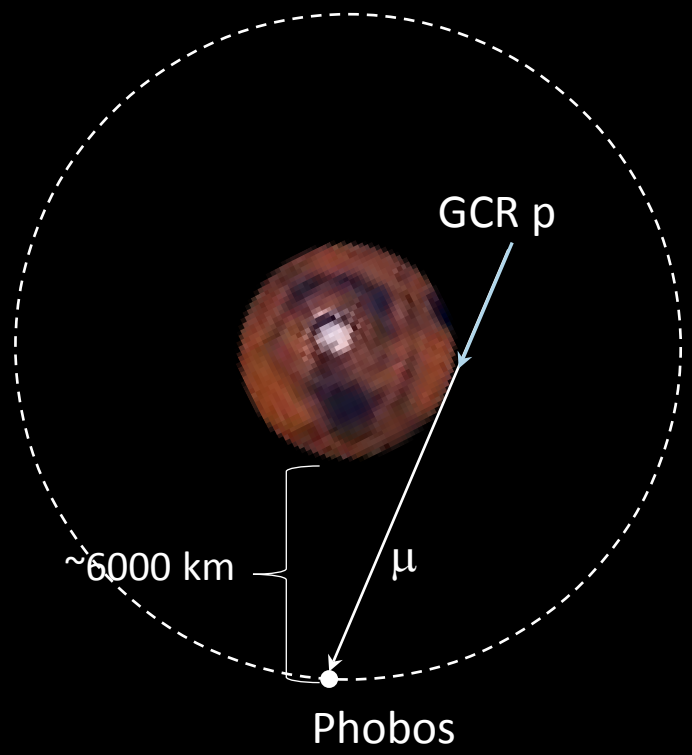


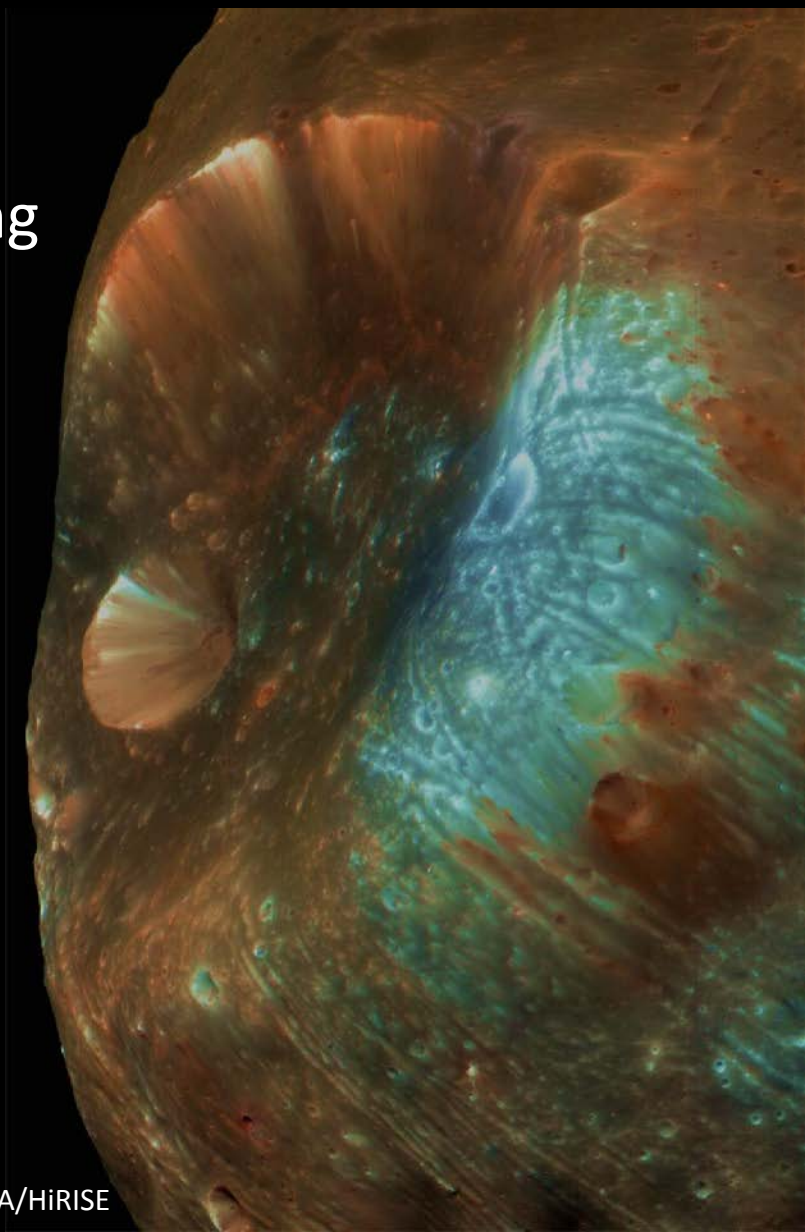


JAXA/Hayabusa

Phobos via Mars' atmosphere?

- High angular flux of atmospheric muons expected at Phobos
- May enable characterization/imaging of large surface features





Miyamoto, H. et al. (2016), LPSC #1684.

NASA/MRO/UoA/HiRISE

Deep mapping summary

Image credit: JAXA

- Muon imaging is a promising method for probing asteroid & comet interiors:
  - Sensitive to bulk density & macroporosity
  - Spatial resolution depends on integration time and contrast
- Potentially powerful tool for planetary science, defense, and in situ resource utilization
- We have identified potential limiting factors & strategies for mitigation
- We will identify prospective targets and document science goals & requirements for instruments and operations for future missions

Image credit: NASA