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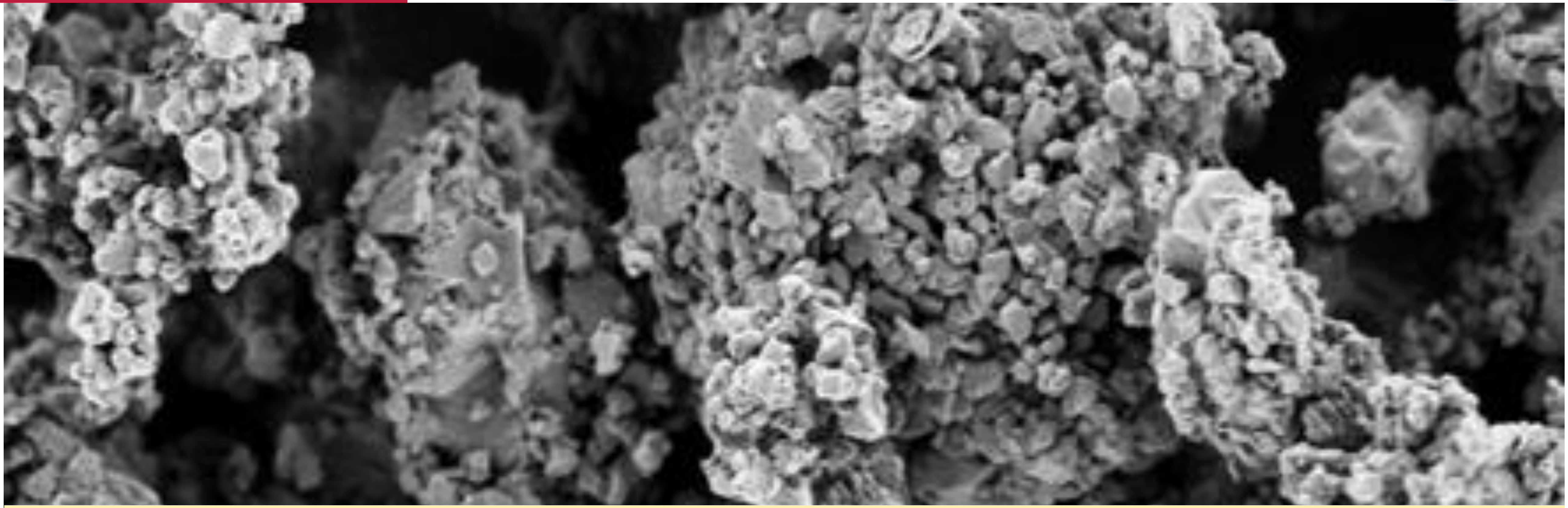

The Stratification of Regolith on celestial objects

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Overview

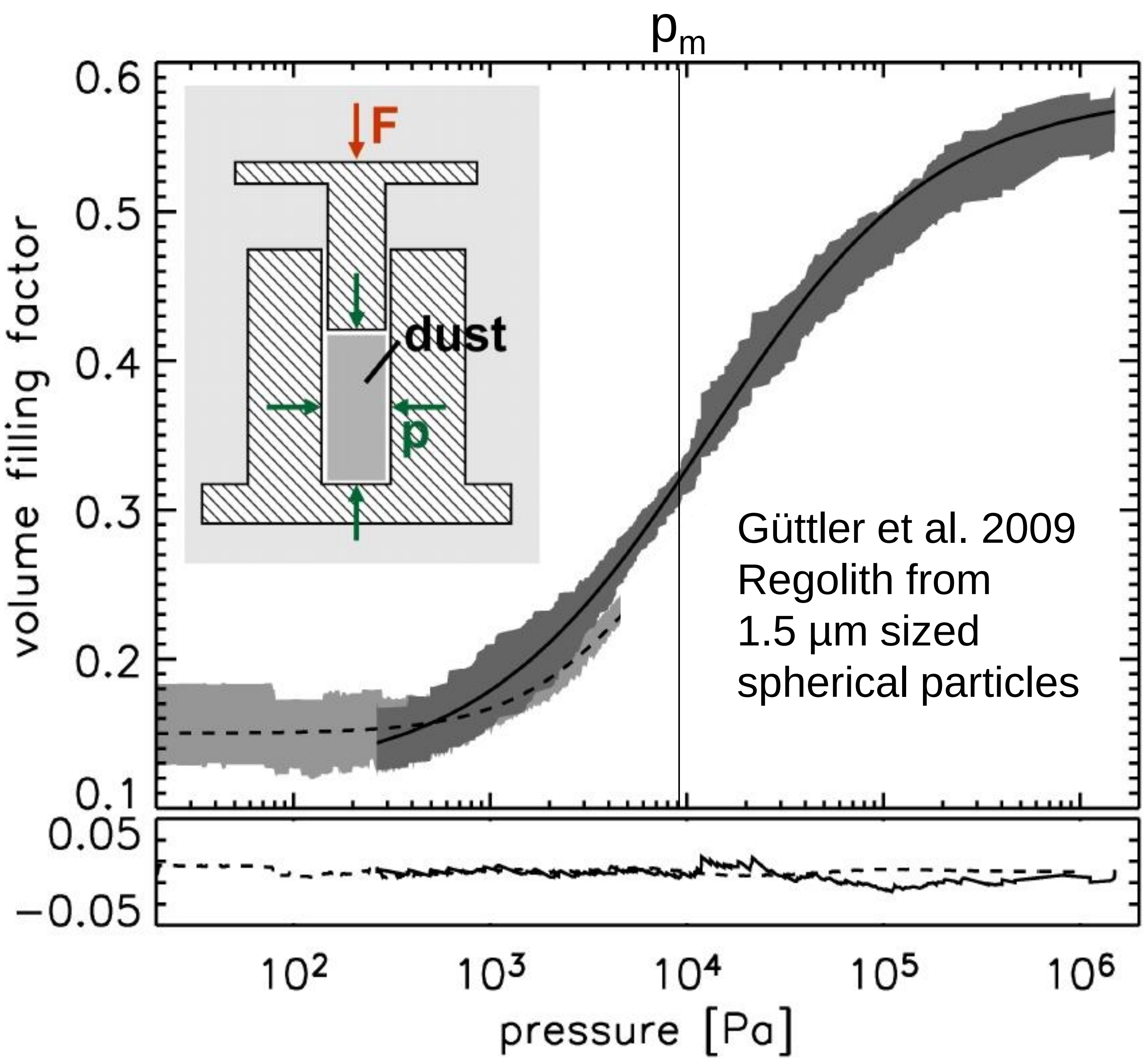
- Model of Regolith
- Application on Asteroids
- Application on Comet 67P (Churyumov-Gersimenco)
- Experimental Setup
- Experimental Results
- Summary

Model

$$\Phi(\Sigma) = \Phi_2 - \frac{\Phi_2 - \Phi_1}{\exp\left(\frac{\lg \Sigma - \lg p_m}{\Delta}\right) + 1}$$

(Güttler et al. 2009)

$\Phi_1 = 0.64$	Random Close Packing
$\Phi_2 = 0.15$	Random Ballistic Deposition
Σ :	Pressure Variable
$\Delta = 0.58$	Logarithmic Transition Width
p_m:	Turnover Pressure



Güttler et al. 2009
Regolith from
1.5 µm sized
spherical particles

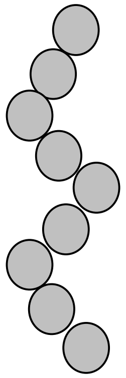
Model

$$\Phi(\Sigma) = \Phi_2 - \frac{\Phi_2 - \Phi_1}{\exp\left(\frac{\lg \Sigma - \lg p_m}{\Delta}\right) + 1}$$

(Güttler et al. 2009)

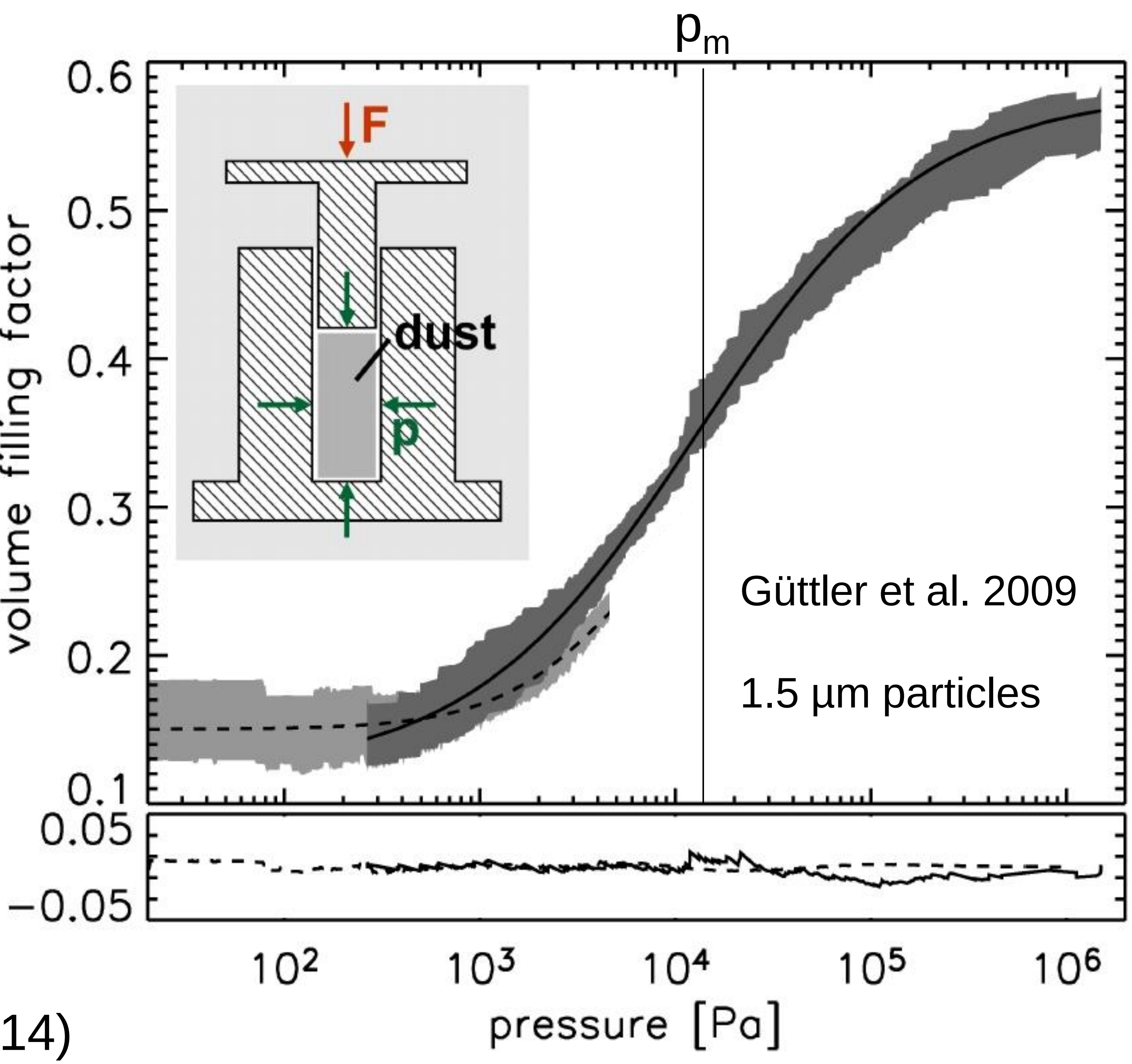
$$p_{0.15} = \frac{F_{roll} 0.15}{r_p^2 \pi}$$

$$\frac{p_m}{p_{0.15}} = 25$$



$$F_{Roll} = F_0 \left(\frac{r_p}{r_0}\right)^{\frac{2}{3}}$$

(Krijt & Dominik 2014)



Güttler et al. 2009

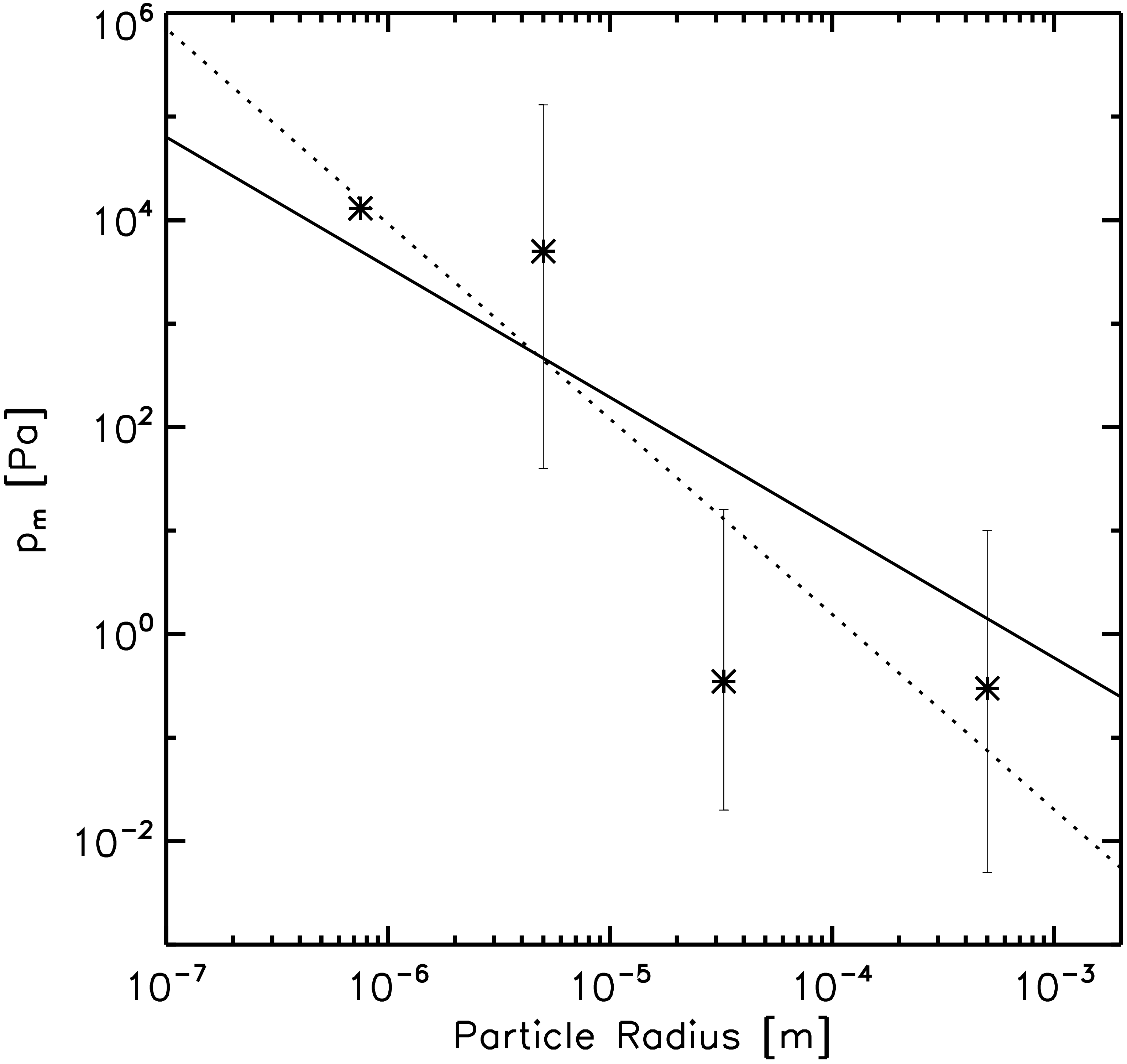
1.5 µm particles

Parameter p_m over Particle Radius

Solid line: Krijt & Dominik (2014)

Dashed line: fit to our measurements

Stars: our measurements



Our model compared to experimental data

$$\Phi(\Sigma) = \Phi_2 - \frac{\Phi_2 - \Phi_1}{\exp\left(\frac{\lg \Sigma - \lg p_m}{\Delta}\right) + 1}$$

△ Spherical monodisperse particles (Feng & Yu 1998)

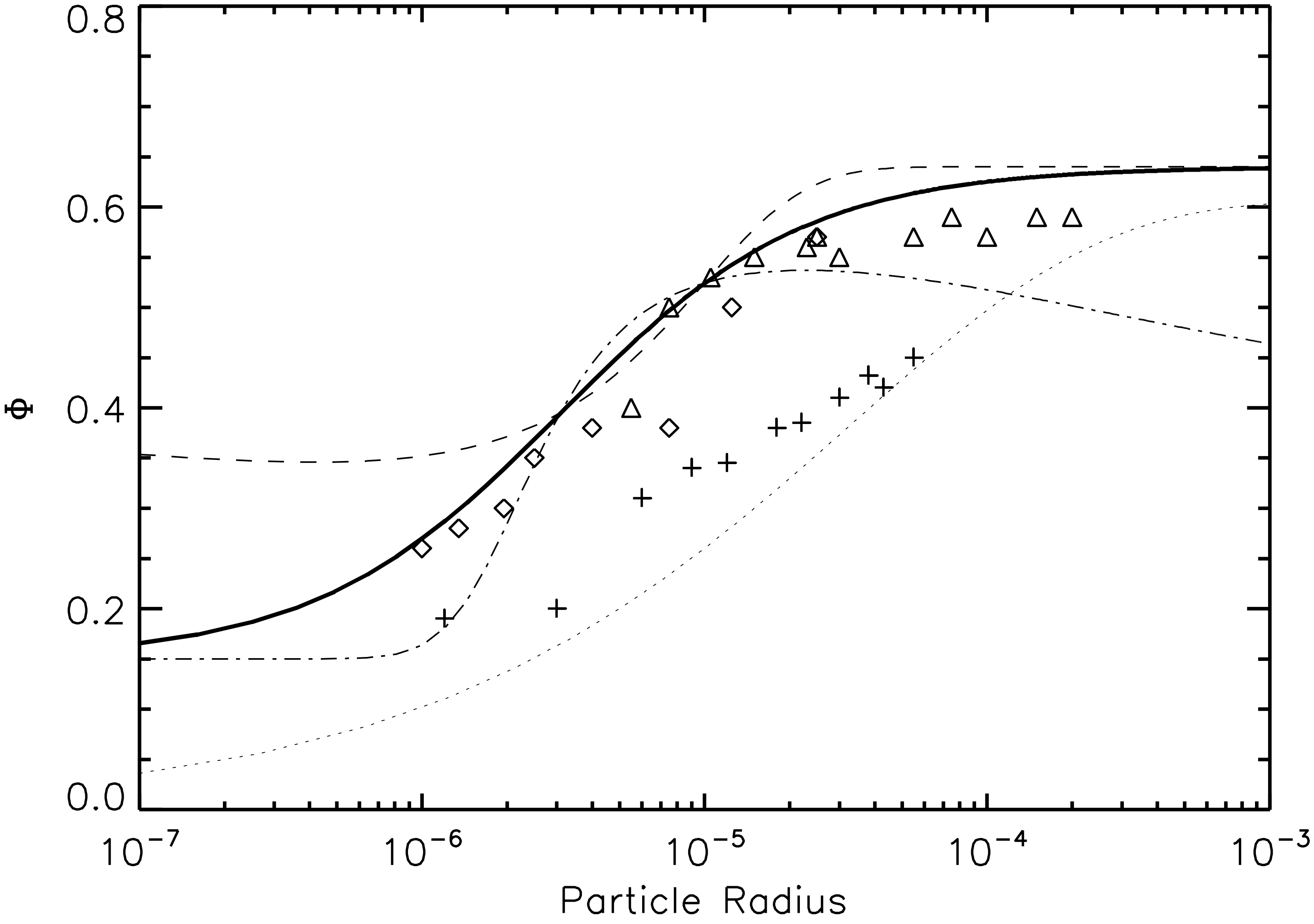
◇ Spherical monodisperse particles (Milewsky & Katz 1987)

+ Irregular monodisperse particles (Yu et al 1997)

----- Best fit of irregular monodisperse particles of several Authors in (Yu et al 2003)

– – - our model in case $\Delta \sim r^{-2}$

–·– our model in case $\Delta \sim r^{2}$

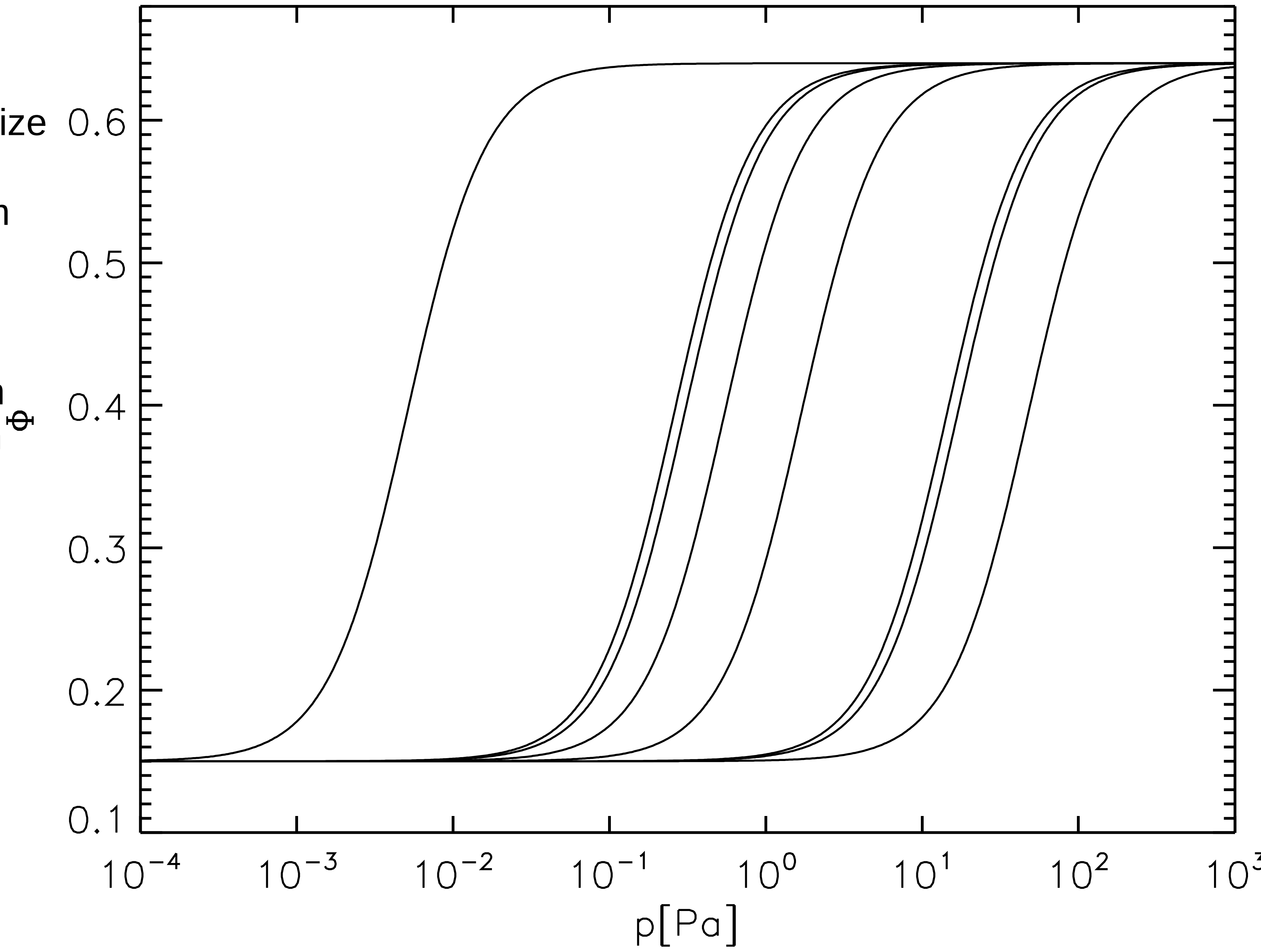


Application: Pressure-Compression Curves for different Radii corresponding to celestial bodies

From left to right:

Body	size	g (ms^{-2})	grain size
Itokawa	300m	9.3E-5	21mm
Phobos	22km	5.8E-3	1mm
1996-FG3	1.69km	3.3E-4	1mm
Steins	5.3km	3.5E-3	0.6mm
Dodona	58.3km	3.8E-2	0.3mm
Vesta	516km	0.26	54µm
Moon	3475km	1.6	48µm
Mercury	4880km	3.7	22µm

(Regolith grain sizes from Gundlach & Blum 2013)



Stratification on celestial bodies from Filling-Pressure Relation

Only ambient gravity considered as pressure source
No impact compaction

Because F (h) is non algebraic
We calculate its inverse function h(F)

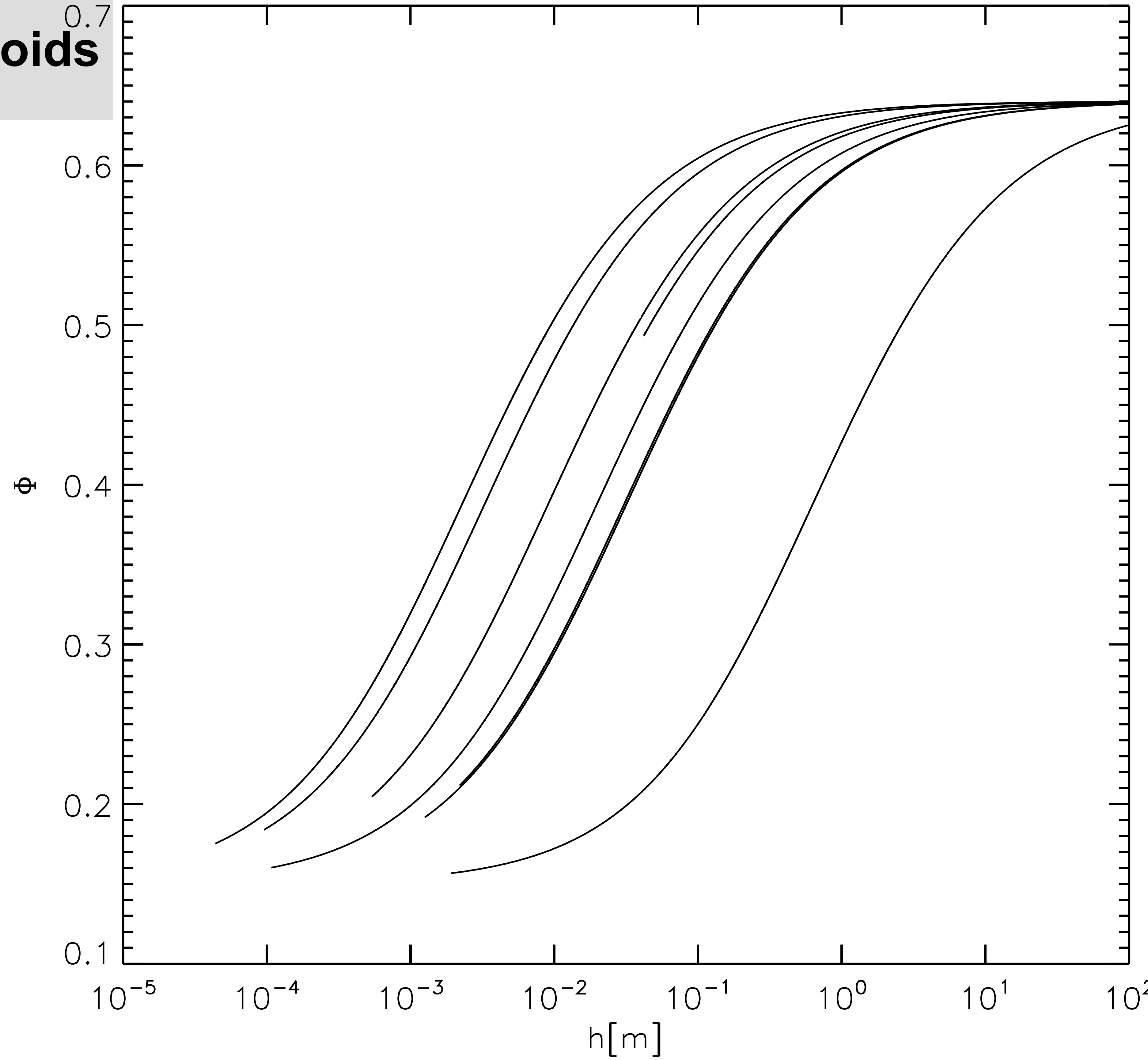
$$\mathrm{d}h = \frac{\mathrm{d}\Sigma}{\rho_b g \Phi(\Sigma)}$$

$$h = \frac{\Sigma}{g\rho_B(\Phi_1\Phi_2 - 2\Phi_2^2)} \Big\{ \Phi_1 - 2\Phi_2 + (\Phi_2 - \Phi_1) \times \mathrm{H2F1}\left[\Delta \lg(10), 1, 1 + \Delta \lg(10), \frac{\Phi_2 \Sigma^{\frac{1}{\Delta \lg(10)}} p_m^{-\frac{1}{\Delta \lg(10)}}}{\Phi_1 - 2\Phi_2} \right] \Big\}$$

Stratification on Asteroids

From top to bottom:

Mercury (44 µm)
Moon (96 µm)
Dodona (0.6 mm)
Itokawa (4.2 cm)
Vesta (108 µm)
Phobos (2.2 mm)
Steins (1.3 mm)
1996FG3 (2.0 mm)



Comparison of our Model with Apollo 14-16 Core Tubes (*) (Lunar Sourcebook)

Depth Range (m)	F (Our Model)	F (Measured at Apollo 14-16 missions)
0 - 0.15	0.57	0.60
0 - 0.30	0.59	0.64
0.3 – 0.60	0.62	0.70
0 - 0.60	0.60	0.68

Regolith from polydisperse irregular grains has a RCP of 70% (Desmond & Weeks, 2013)

Calculation of the Yield of an Astronaut of 100 kg standing on one Foot ($0.07 m^2$)

All reasonable loads are an order of magnitude above the pressures that lead to RCP (on all celestial bodies except comets)

$$h_{yield} = \int_0^{H_\infty} \mathrm{d}H - \frac{1}{\Phi_{RCP}} \int_0^{H_\infty} \Phi(H)\mathrm{d}H$$

Transforming the rhs Integral: Substitution $H = h(\mathrm{F})$ and partial integration

Method: Stemfunction of the inverse function

$$h_{yield} = \int_{\Phi_0}^{\Phi_\infty} h(\Phi)\mathrm{d}\Phi$$

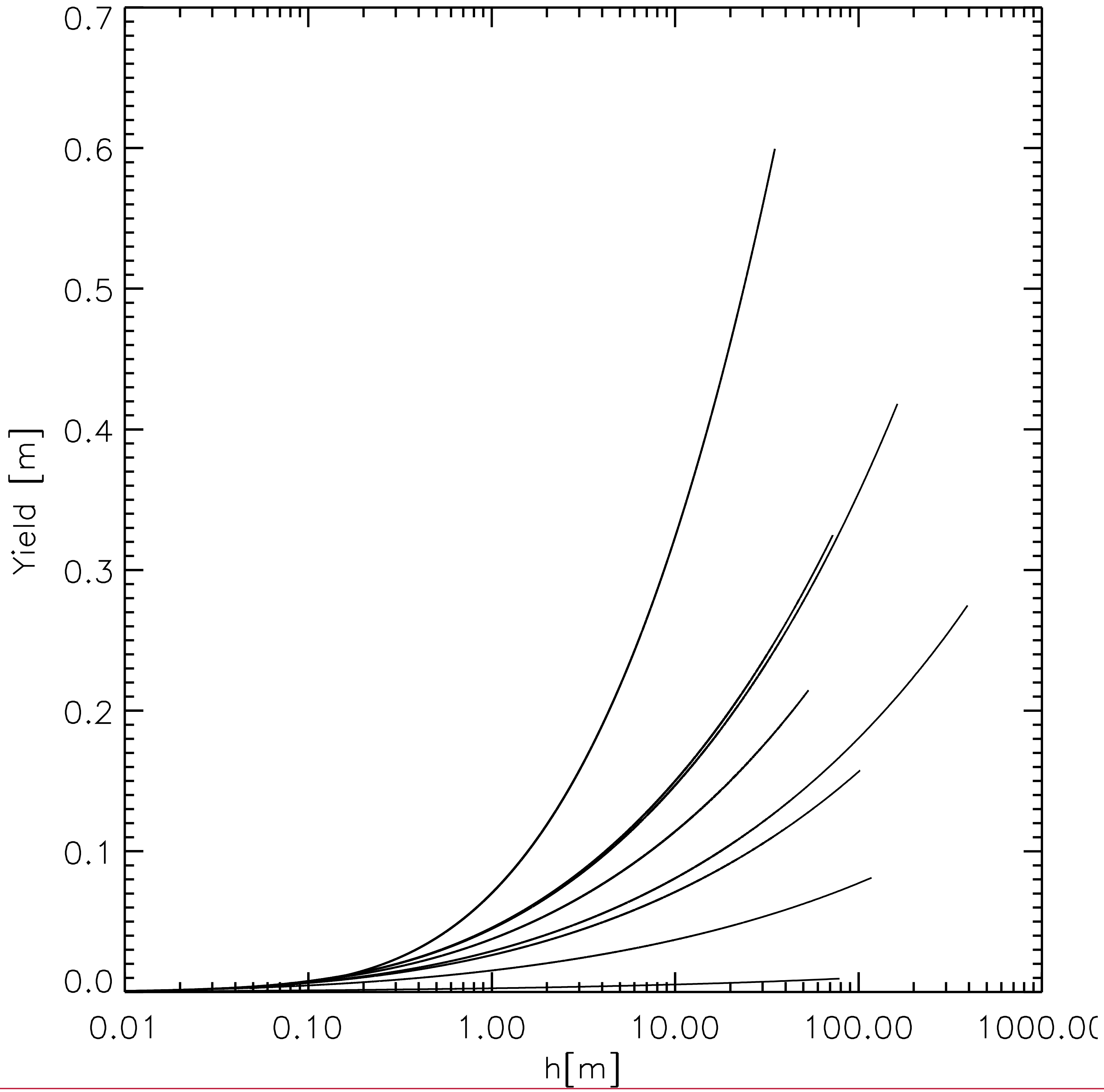
The integral converges very slowly -> The yield depends on the Regolith Depth

Friction angle important

Yield of an astronaut on diverse celestial objects depending on regolith depth

From top to bottom:

- 1996FG3
- Steins
- Phobos (almost identical to Steins)
- Vesta
- Itokawa
- Dodona
- Moon
- Mercury



Stratification on Comets

A model of Comet formation (Skorov and Blum 2012):

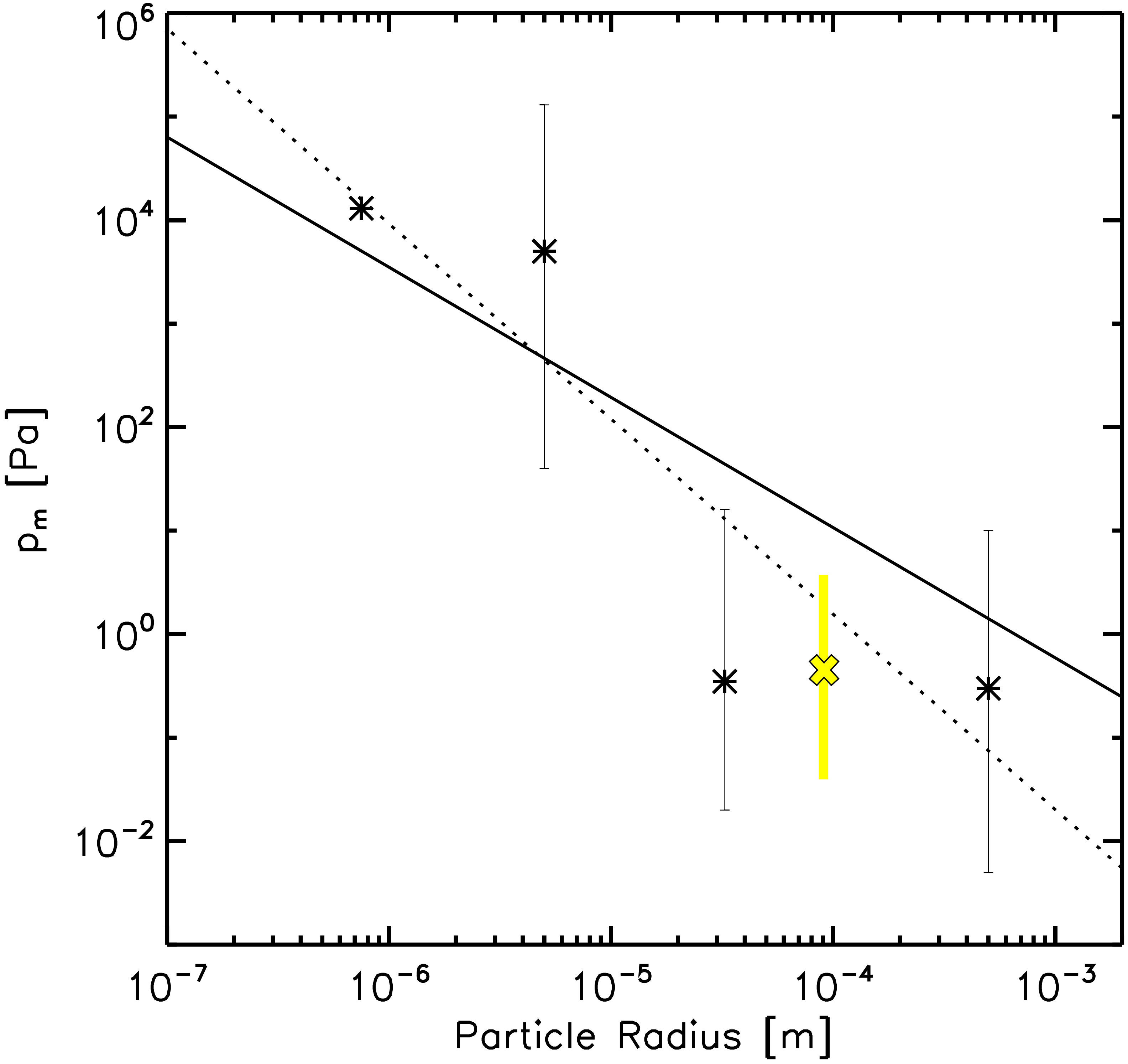
1. Formation of dust and ice aggregates from 0.1mm – 1m in the inner and outer solar nebula from µm-sized particles (Wilner et al.2005, Zsom et al. 2010, 2011)

2. Transport of refractory–dust agglomerates to the outer solar nebula (McKeegan et al. 2006, Zolensky et al. 2006)

3. Formation of comet precursors by gravitational instability (e.g. Johanson et al. 2007)

4. Skorov and Blum (2012) found that the aggregates should have a size of at least 10 mm to explain dusty jets.

Parameter p_m over Particle Radius



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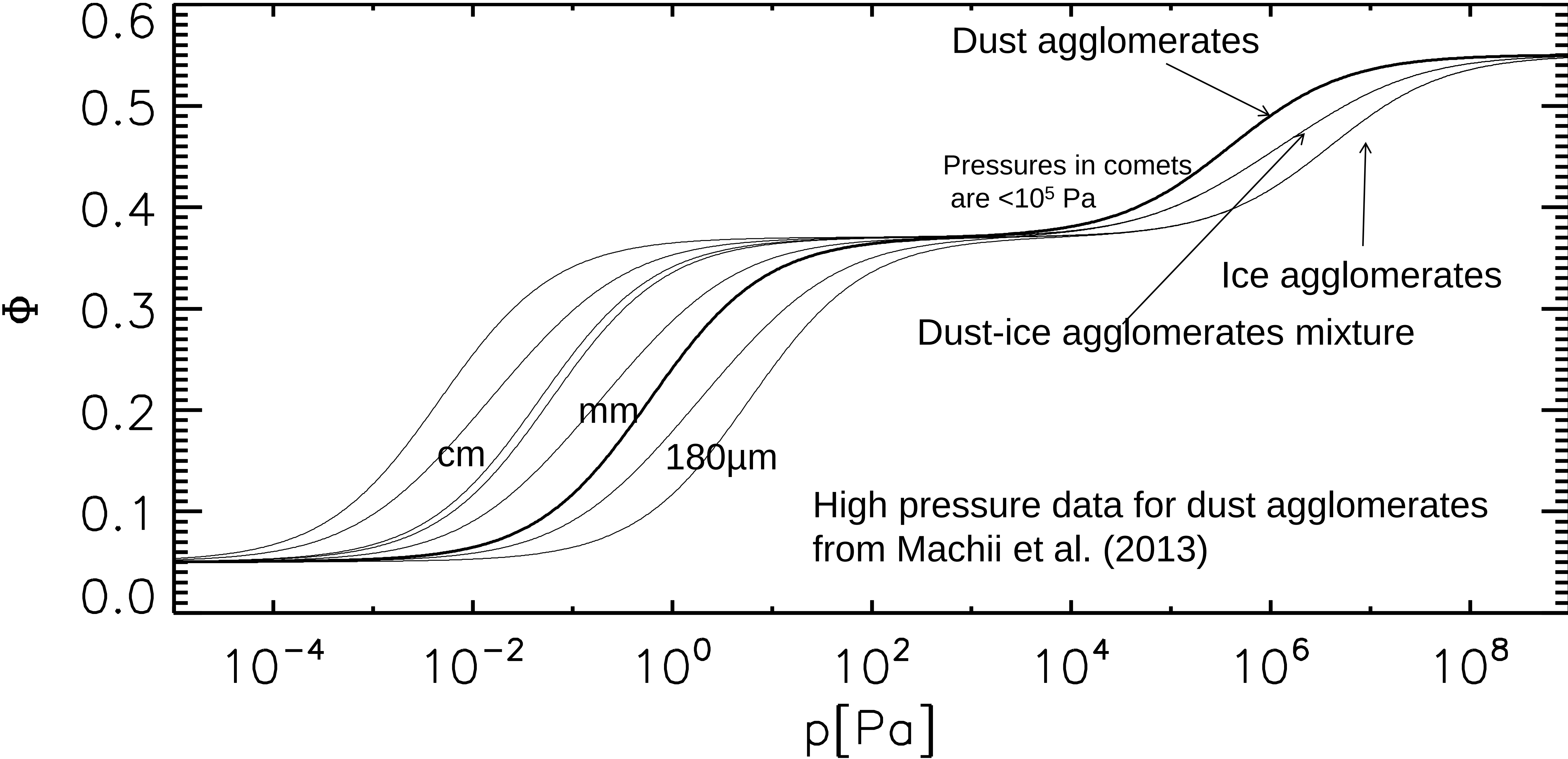
Assumptions

- Comets consist of a 1:1 mixture of dust and ice agglomerates (Skorov & Blum 2012)

- p_m of ice agglomerates is an order of magnitude larger than the p_m of dust agglometates (Gundlach et al. 2011)

- Assumption: $p_m(r_p)$ for agglomerates follows the same power law as for compact particles

Filling factor over pressure of cometary material



Pressures in comets are $<10^5$ Pa

High pressure data for dust agglomerates from Machii et al. (2013)

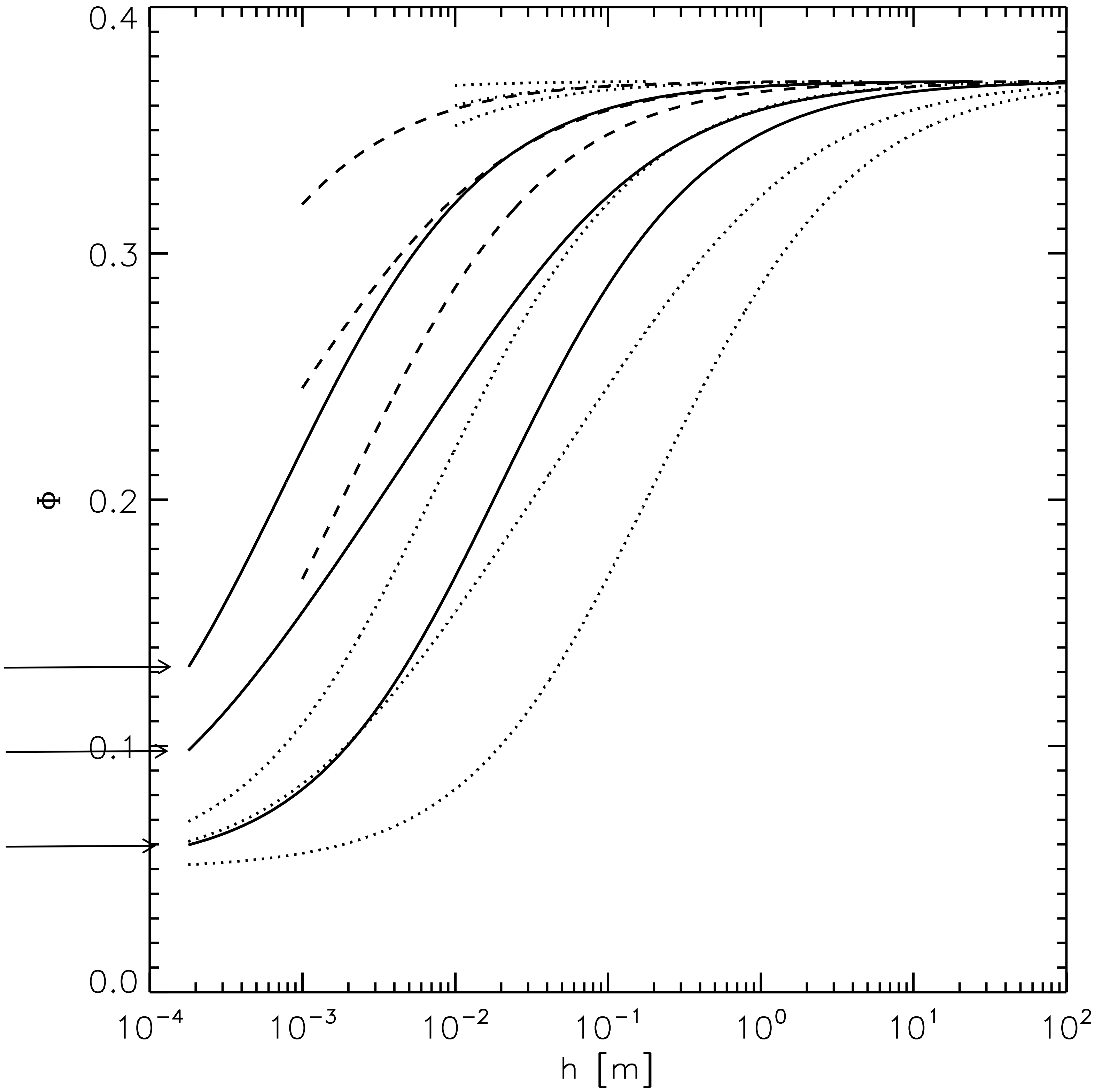
Stratification of Comet 67P (Churyumov-Gersimenco)

Upper …. : cm sized agglomerates

- - -: mm-sized agglomerates

___:180µm-sized agglomerates

Lower …..:180µm-sized agglomerates
at maximal p_m measured



Dust agglomerates

Dust-ice agglomerates mixture

Ice agglomerates

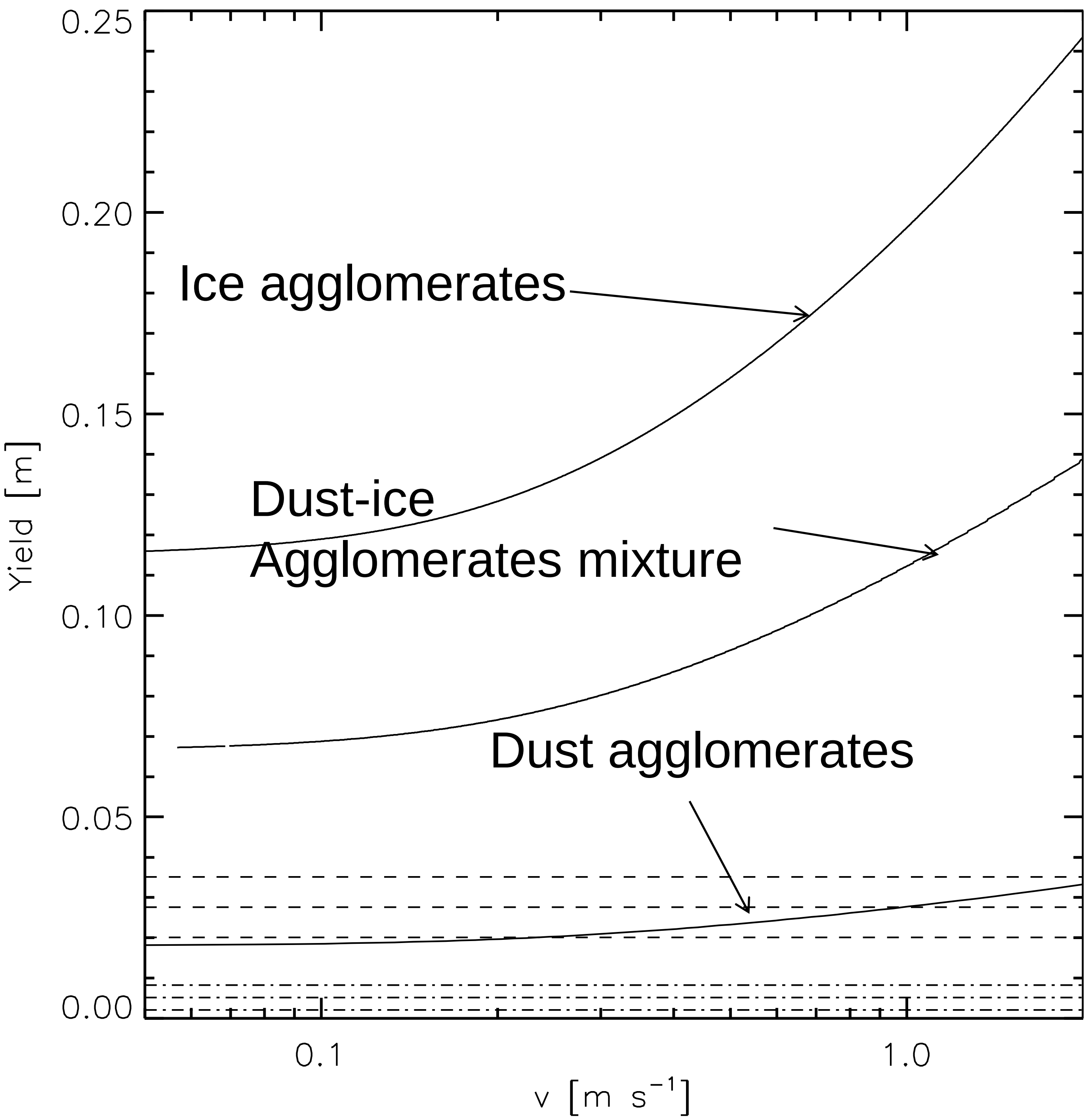
Yield of the Rosetta Lander (assuming 100 kg and 0.07 m^2 feet area)

Impact force generated by a constant deceleration of the spacecraft over 10 cm caused by the damping system of the landing gear.

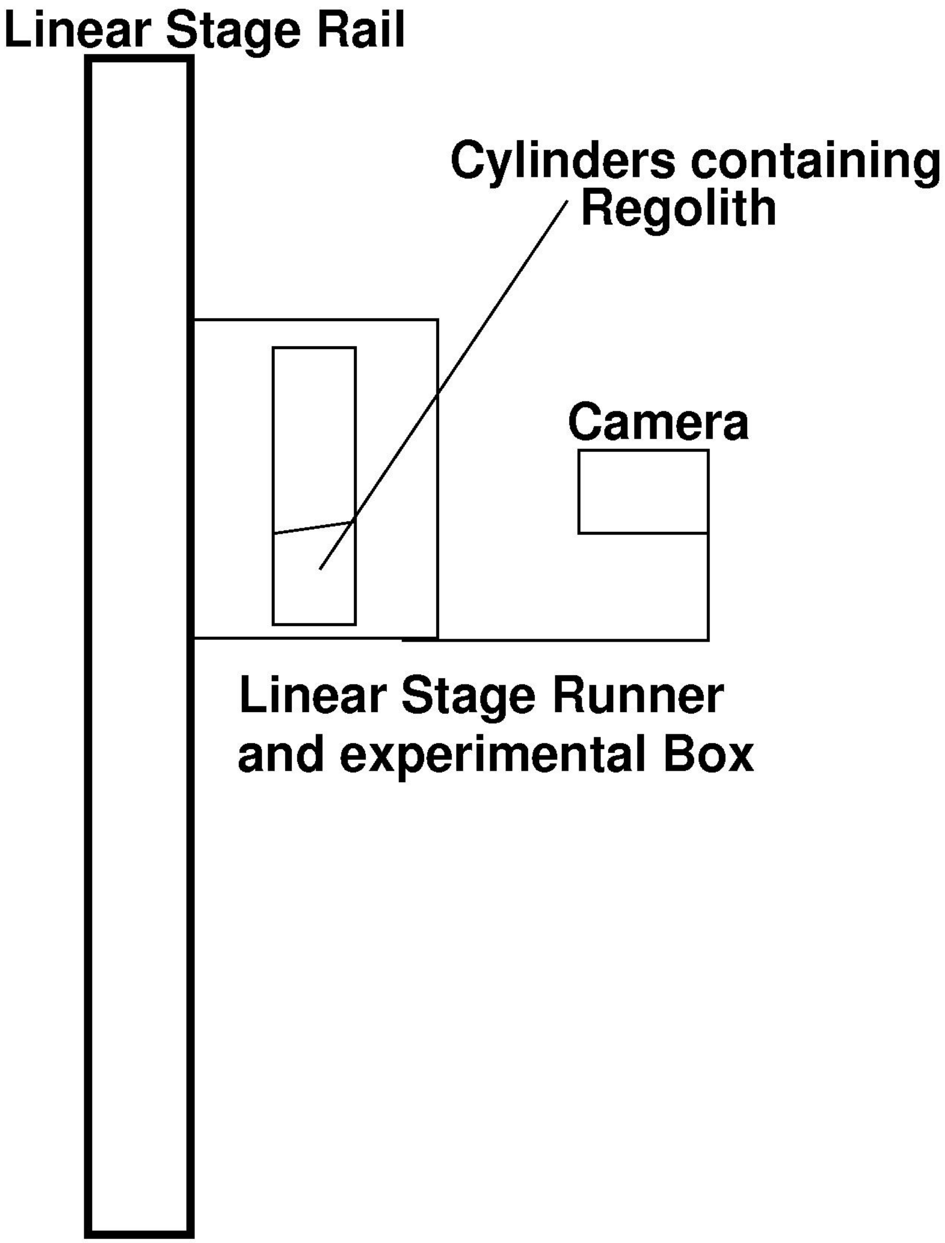
___:180µm-sized agglomerates

- - -: mm-sized agglomerates

…. : cm sized agglomerates



Experimental: Setup

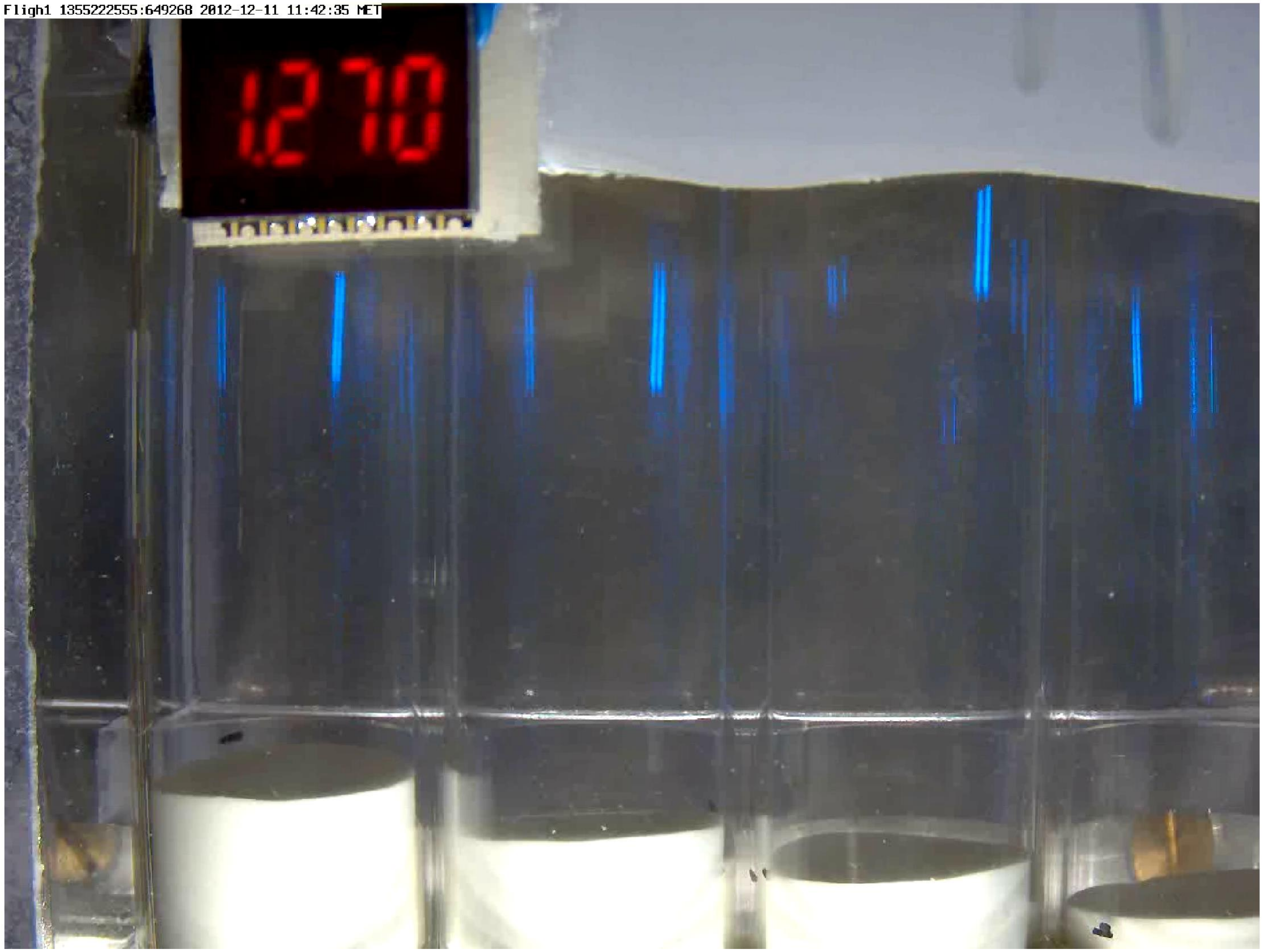


Linear Stage Rail

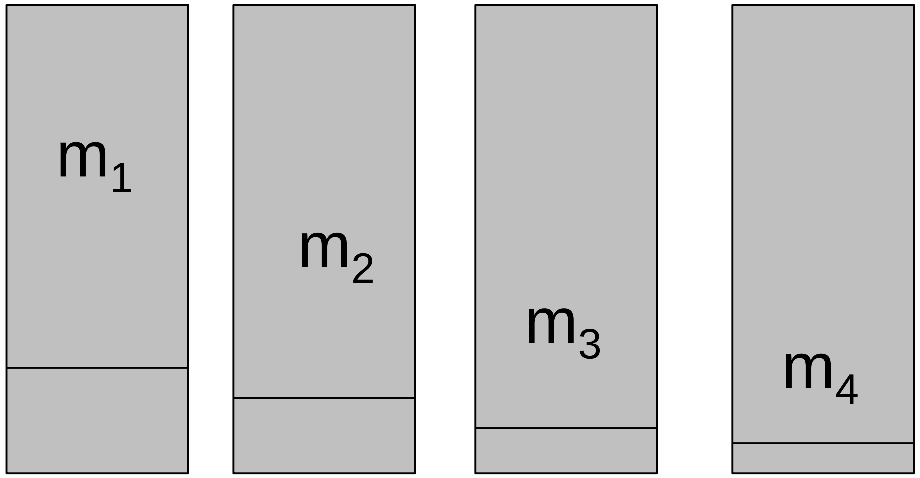
Cylinders containing Regolith

Camera

Linear Stage Runner and experimental Box



Packing Densities in different layers



$$\Phi_4 = \frac{m_4}{V_4 \rho_b}$$

$$\Phi_3 = \frac{m_3 - m_4}{(V_3 - V_4)\rho_b}$$

i

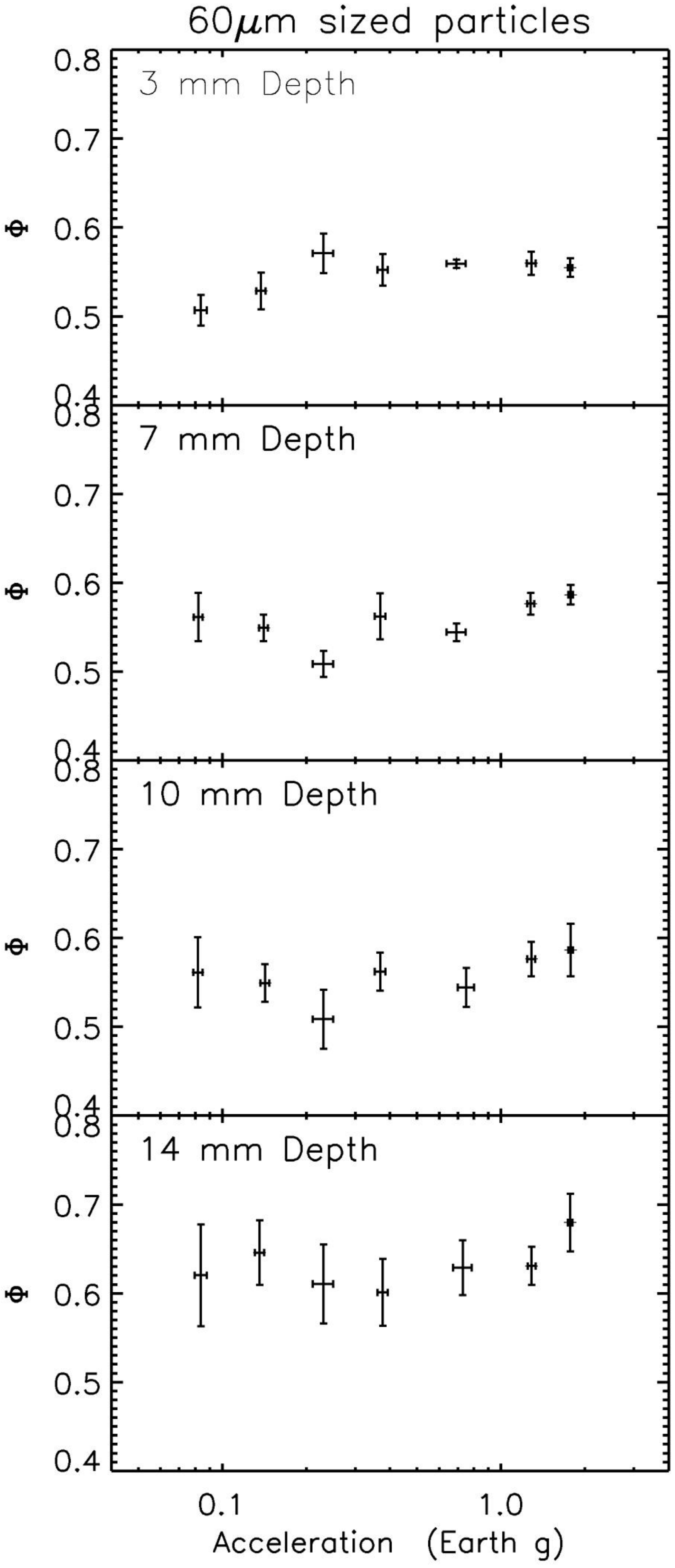
$$\Phi_i = \frac{m_i - m_{i+1}}{(V_i - V_{i+1})\rho_b}$$

Packing Density over
Layer Thickness and Gravitation

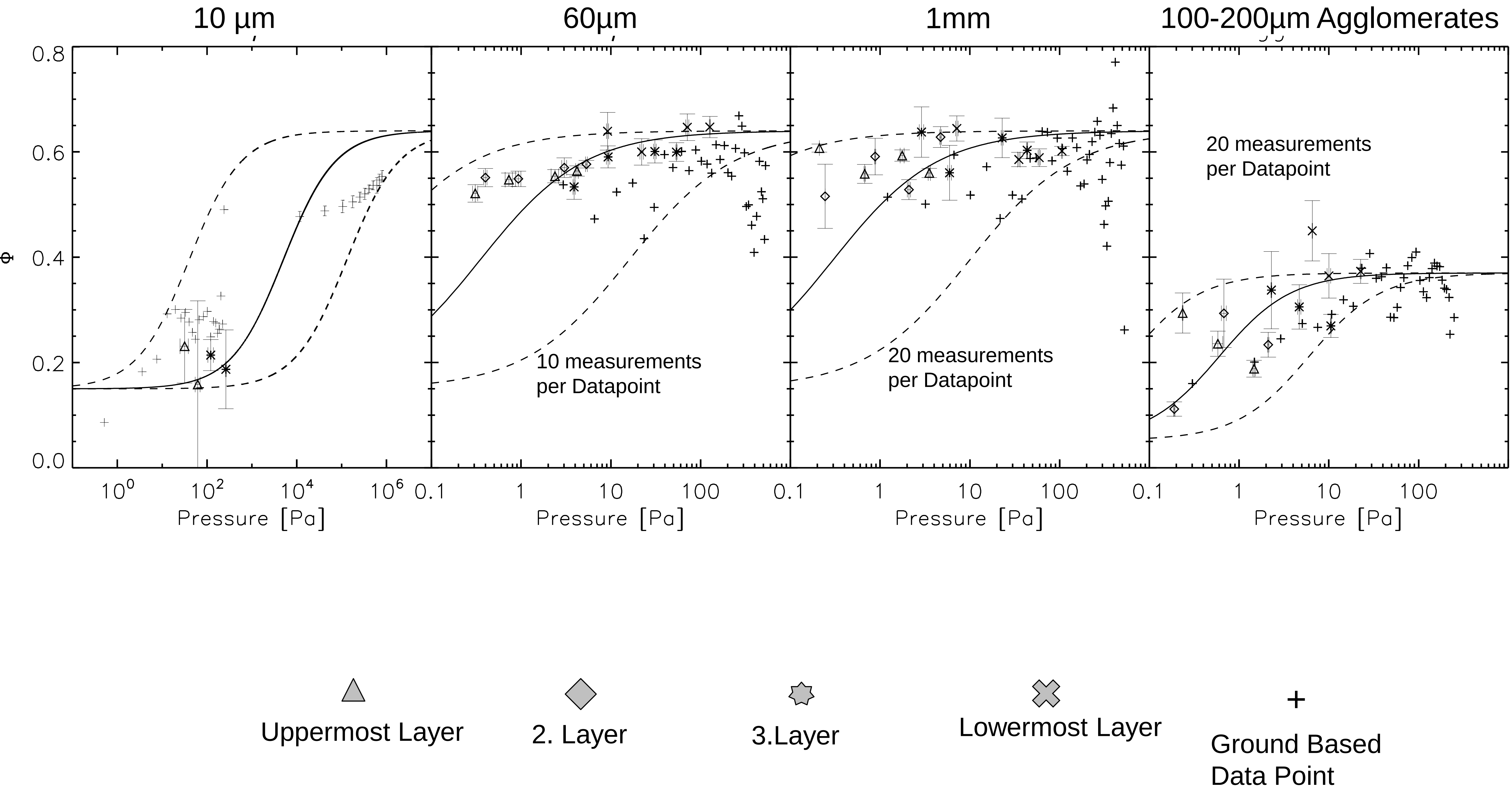
Jansen Equation (1895)

$$p = \frac{mg}{4Kr^2\pi}\left[1 - \mathrm{Exp}\left(-4K\frac{x}{2r}\right)\right]$$

K=0.2 : ratio of horizontaland vertical component of the stress tensor
m : Dust mass at a given Fill Height x
r: Radus of the cylinder



Packing Density over Pressure



Summary

- Model for the Regolith pressure-compaction curve (pressure from rolling force and Fermi Function)
- Application:

  Asteroids (stratification)

  Comet 67P/Churyumov-Gerasimenko
- Experimental Part

This research was supported by:
Deutsches Zentrum für Luft und Raumfahrt
Grant no.: 50WM1236