Off Earth Mining Forum

Microgravity Geology: A New Challenge for Human and Robotic Space Exploration

February 20th, 2013
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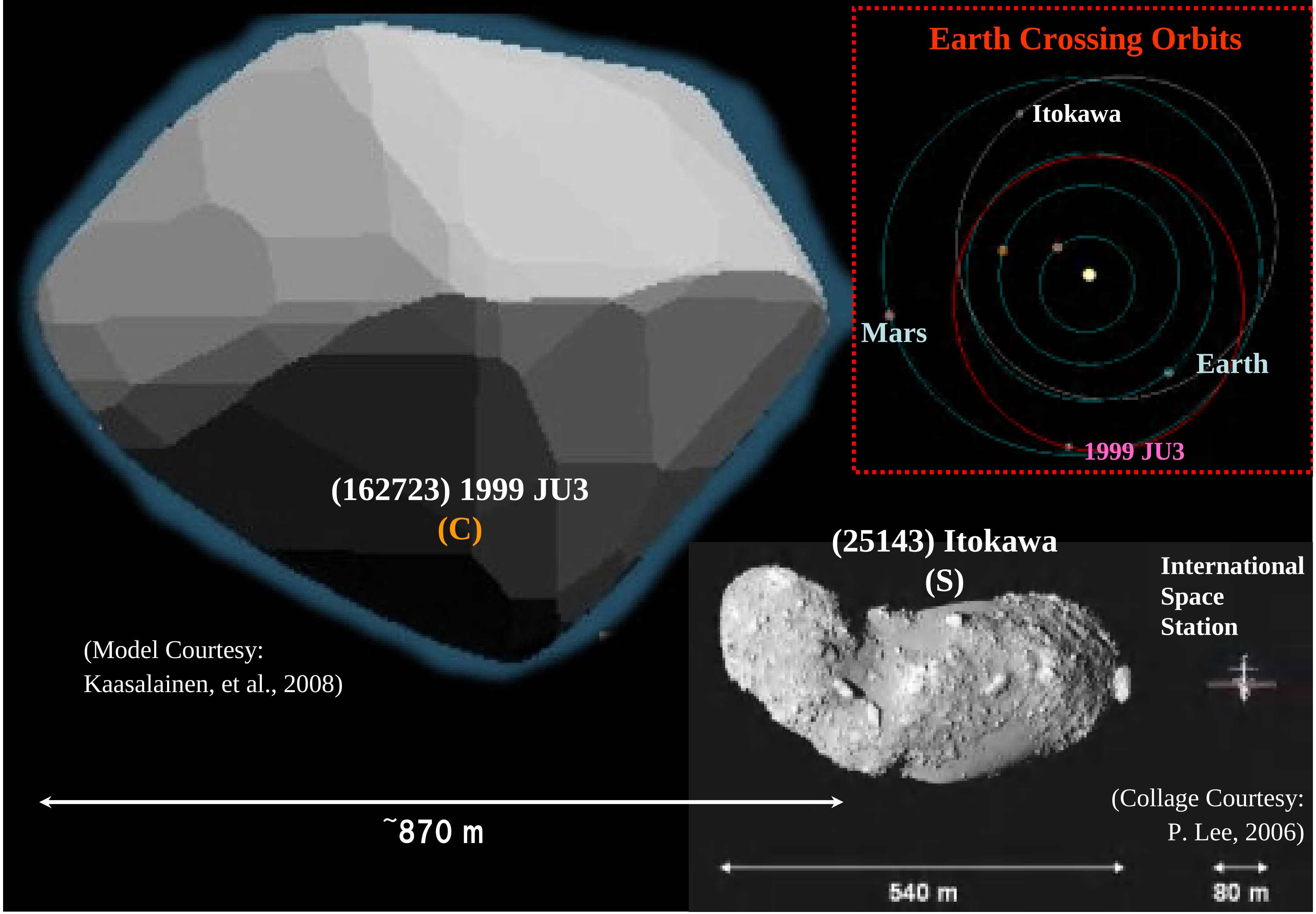
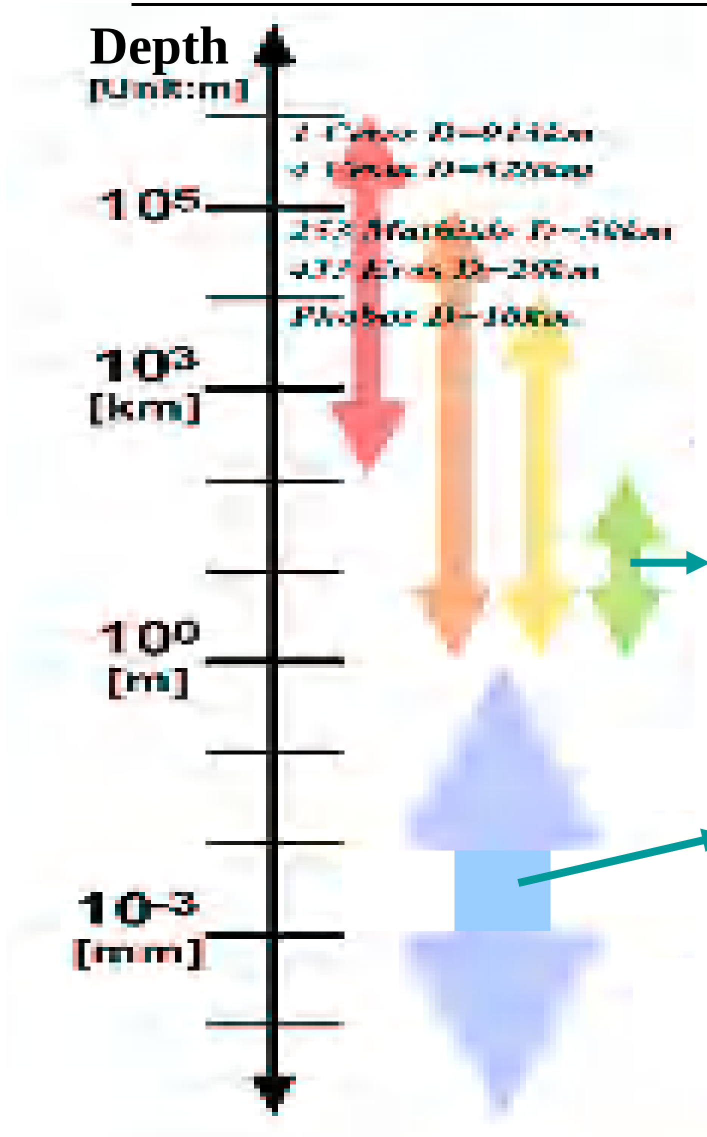
Near Earth Objects: Itokawa vs. 1999 JU3 at a Glance



What You Need for Asteroid Mining: A Typical Case Proposed by Planetary Resources Corp.

(1) Survey
(2) In-situ Remote Sensing
(3) Internal Structure (e.g., Interceptor)
(4) Landing and Mining
(5) Transportation

Asteroid Interior Investigation Techniques Sorted by Depths & Resolutions



Vesta Crater Exploration

Family Asteroid Exploration

Radar Sounder /Tomography

Seismic Network

Boulder & Groove Rover *In-situ*

Fixed Lander *In-situ*

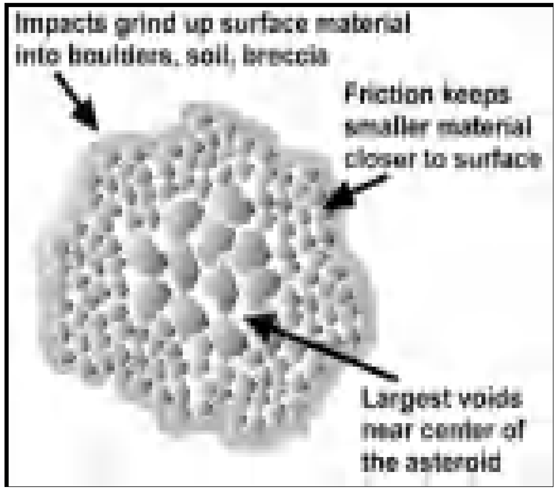
Sample Return (Core Boring)

Sample Return (Regolith)

In-Situ Microscopic Camera

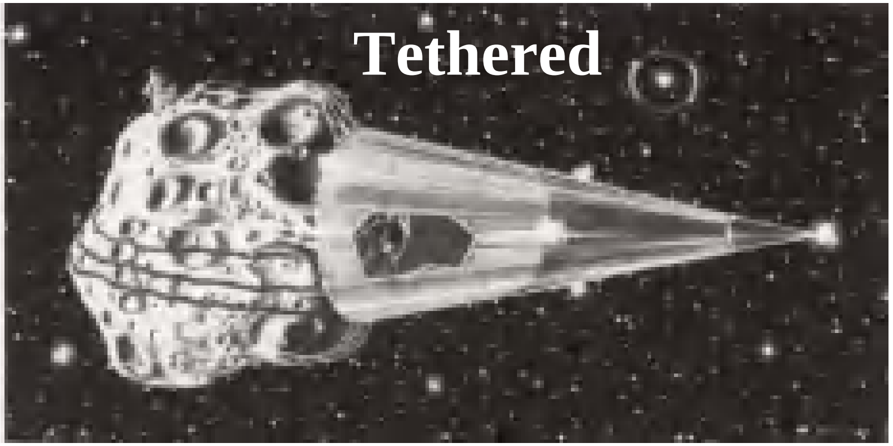
Micro-tomography

To better-understand internal structure of undifferentiated minor body



Key Questions for Technology and Operation for Small Body Mining

How to Reach
How to Descend
How to Land
How to Anchor
How to Excavate
How to Contain
How to Examine
How to Ascend
How to Return

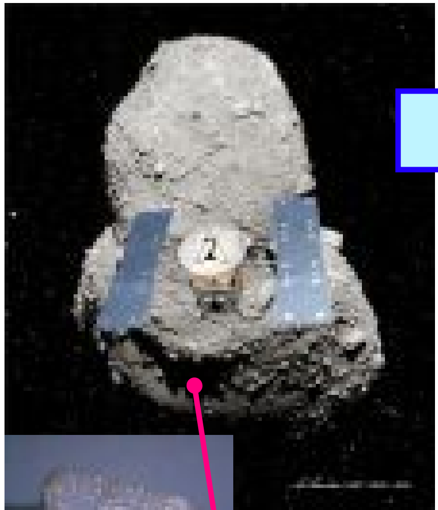


➔“Know Your Enemy”
= Microgravity Geology

"Chicks" of Hayabusa:
Sample Return Missions to sub-km~km Sized Bodies

Post Hayabusa Series

Hayabusa
Itokawa = S type
(1996~/2003-10)



Ordinary
Chondrites

Hayabusa-2
1999 JU3 = C type
Lessons Learned from Hayabusa
(2010~/2014-20)

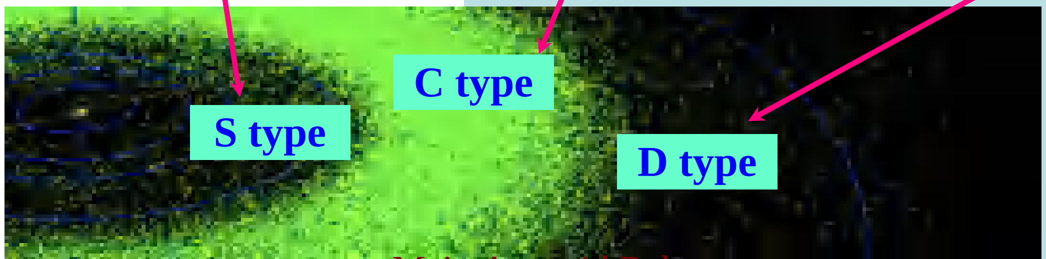
Carbonaceous
Chondrites

OSIRIS-REx
1999 RQ36 = B type
New Frontier Class
(2016-23)

Hayabusa Mk-II
D type, Dormant comet
Advanced, Full Model-change
(Mid 2010's~/Early 2020's)

IDP,
AMMs,
Tagish
Lake?

Marco Polo-R
1999 FG3 = C type
Cosmic Vision-M
(2022-29)



Main Asteroid Belt

Microgravity Geology, a New Research Field of Solar System Science and Engineering

• Current planetary system formation theory has a “black box” in the intermediate state between dust-to-dust aggregation (e.g., Mukai, et al., Blum, et al.,) and planetesimal growth/ disruption (e.g., Kokubo, et al., Michel, et al.) that are never able to learn from exploration of large, differentiated bodies.

• Yet, no one had witnessed geological evolution of small planetesimals or equivalent, until Hayabusa’s in-depth exploration of Itokawa, a sub-km rubble pile asteroid.

• Geological features of Itokawa surprised us about both similarities and differences from larger asteroids like Eros and much larger satellites/planets.

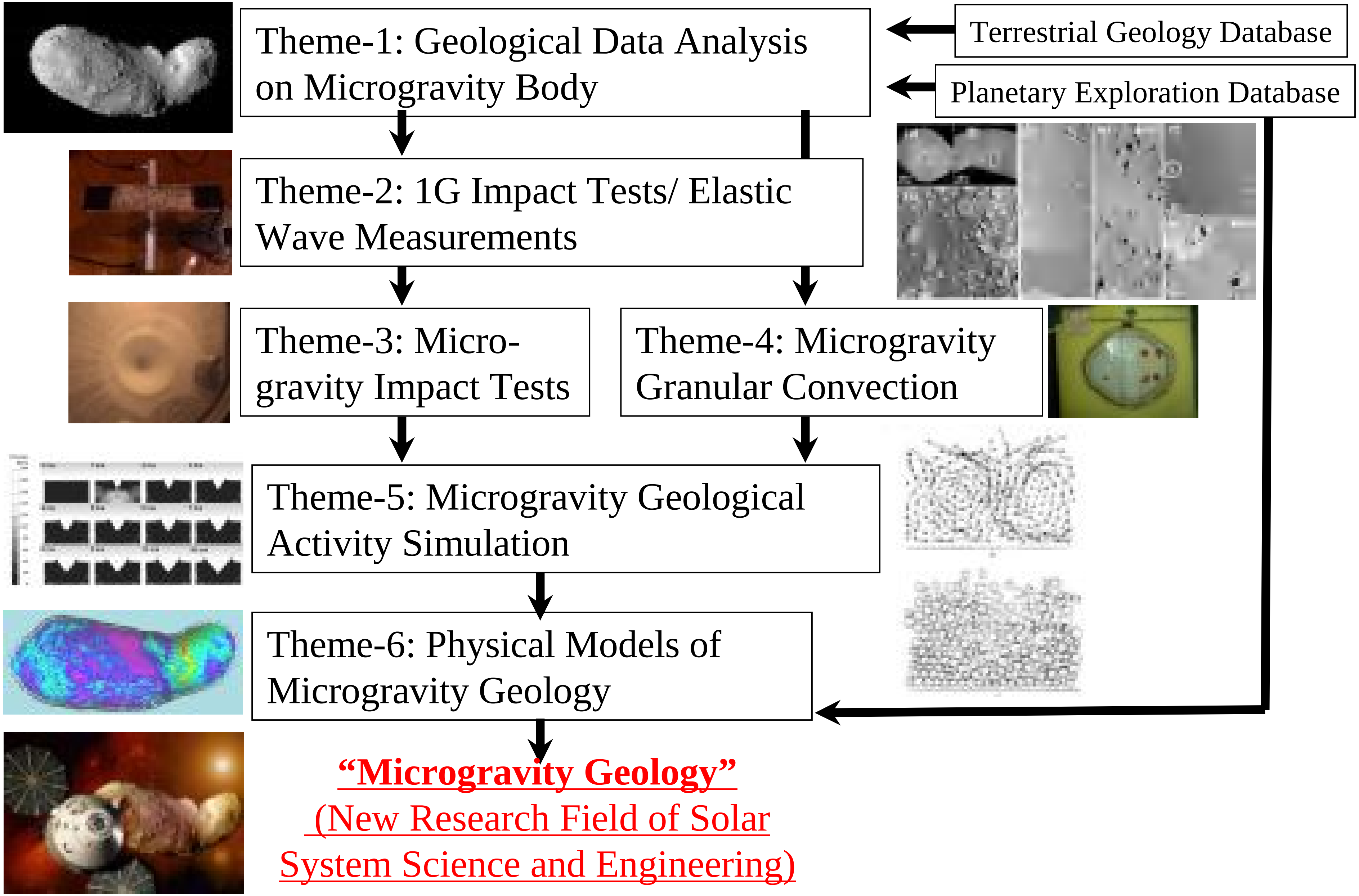
Microgravity Geology, a New Research Field of Solar System Science and Engineering

•Apparent similarities between Itokawa and the Earth (and Mars) are not necessarily due to the same geological processes as the terrestrial geology largely affected by the presence of water in atmosphere, surface and underground, let alone five orders of magnitude difference of G-levels.

➔Thus, a need to create a new research field of "Microgravity Geology" is clear, in order to understand the missing link of the planetary evolution processes, as well as better preparation for future robotic and human exploration of such microgravity bodies, such as off-earth mining.

➔Such knowledge can also be beneficial to natural disaster management on the Earth for better understanding of their triggering mechanisms

Research Theme Flow of "Microgravity Geology"



Main Focuses of Microgravity Geology Experimental Research

<Understanding Physical Processes >

(1) Impacts (*Gravity-strength regime scaling*, Ejecta redistribution, Low density/weak strength *monolithic targets vs. granular targets*, etc.)

(2) Vibration (Wave propagation, *seismic efficiency, diffusivity*, quality factor, etc. in regolith and low density targets)

(3) Granular Mobility (*Brazil Nuts effect, granular convection, dust levitation*, surface mobility, non-gravitational activities such as cometary gas release, etc.)

➔Also investigate other internal/external forces than impacts such as Centrifugal force, YORP, tides, etc.)

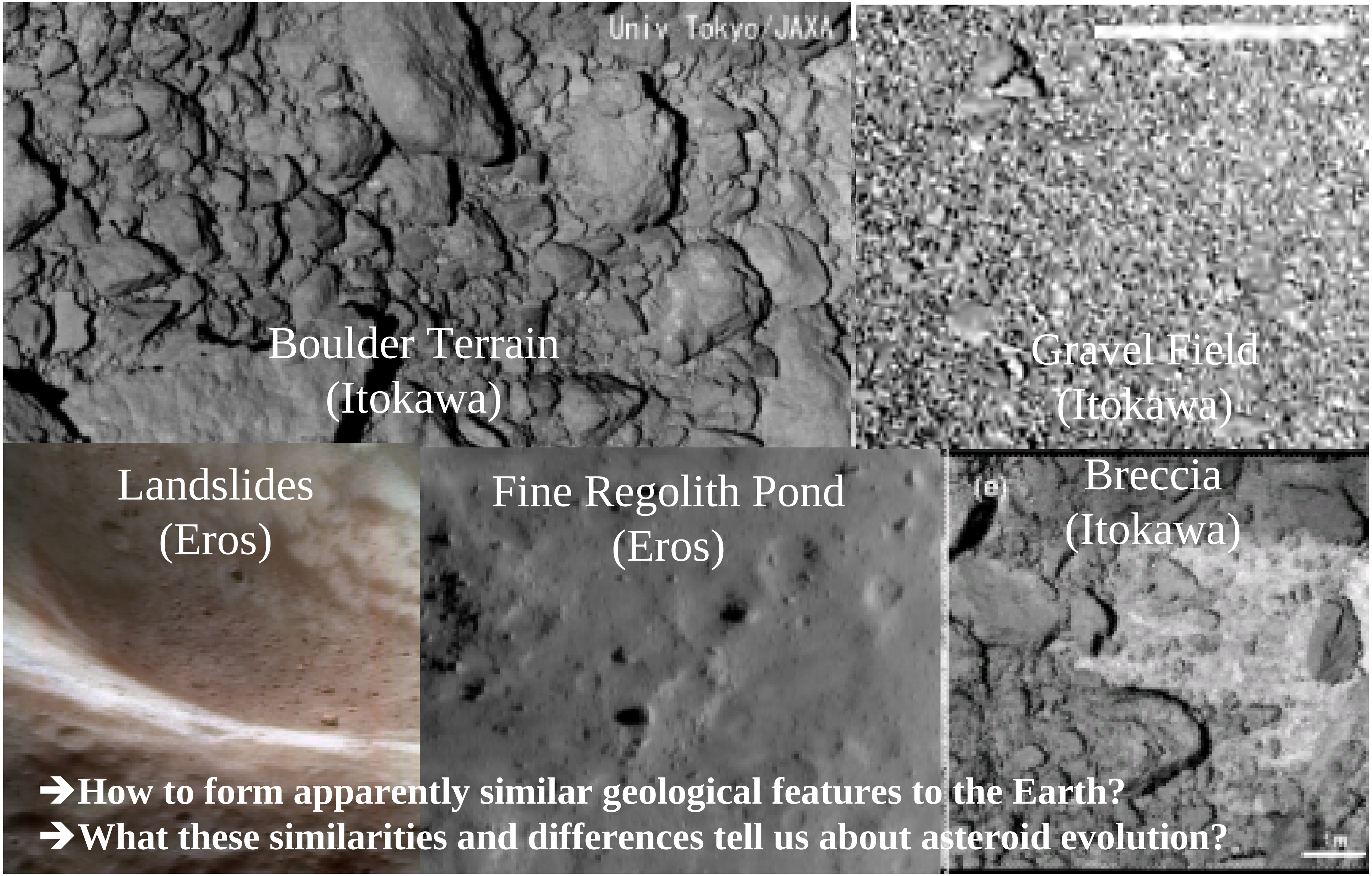
< Applications to Small Body Exploration >

・ *Development of sampling system and landers* for Hayabusa follow-on missions

Understand Geological Features in Microgravity

Terrestrial Geological Features:
Governed by Gravity, Heat, Air and Water

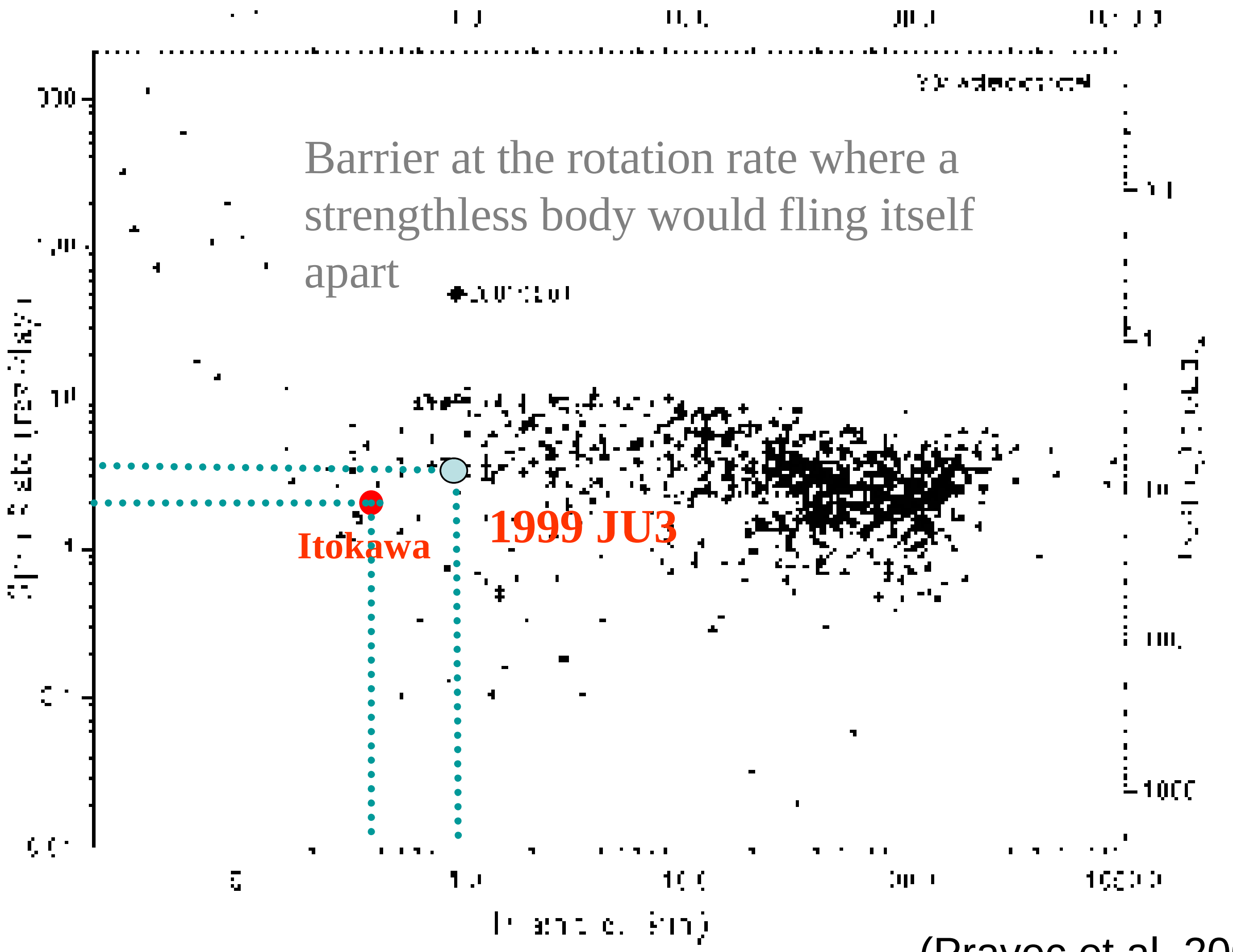
Asteroidal Geological Features: Mainly due to Impacts and Vibrations in Vacuum and Microgravity



➔How to form apparently similar geological features to the Earth?

➔What these similarities and differences tell us about asteroid evolution?

Internal Structure Implied by Rotational Periods and Sizes

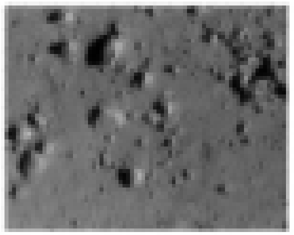
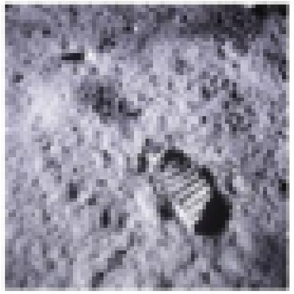
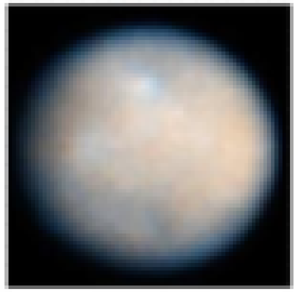


(Pravec et al. 2002)

Thermal Inertia vs. Surface Condition

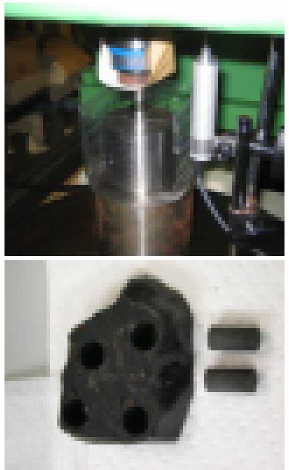
Thermal Inertia: G **$[J\ m^{-2}\ s^{-0.5}\ K^{-1}]$**	**Surface Condition**
~ 10	Very fluffy, high porosity (~80%), Ceres, Martian soils
~ 50	Fine sand : Lunar regolith (d ~ 100 mm or less)
100 ~ 200	Sandy regolith (d ~mm): Eros' Pond
200 ~ 400	Pebbles (d ~cm): Itokawa's Muses-Sea Regio
400 ~ 1000	Boulders, Rock fragments (d < m): Itokawa's rough terrain
1000 ~ 2000	Rocks with high porosity
2000 ~	Monolithic rocks

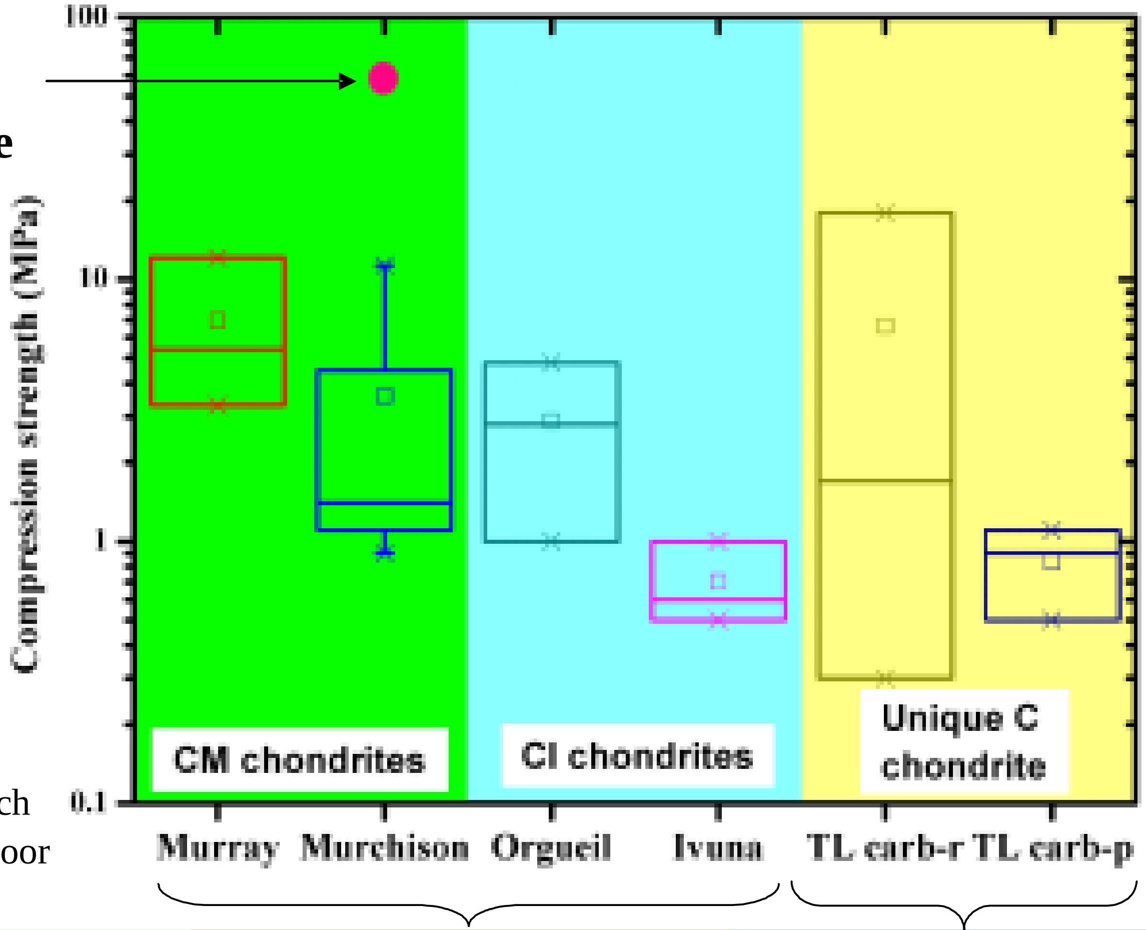
Thermal inertia gives information about the presence (or absence), depth and thickness of regolith, and the presence of exposed rocks on the surface of atmosphere–less bodies (Γ in SI units: $Jm^{-2}s^{-0.5}K^{-1}$).

25143 Itokawa	433 Eros	The moon	1 Ceres
$\Gamma = 600$	$\Gamma = 150$	$\Gamma = 50$	$\Gamma = 10$
			
Coarse regolith and boulders	Finer and thicker regolith	Mature and fine regolith	Very fine regolith ??

Compressive Strength Measurement of Sub-mm Meteorite Powders

5x10 mm Compressive Strength



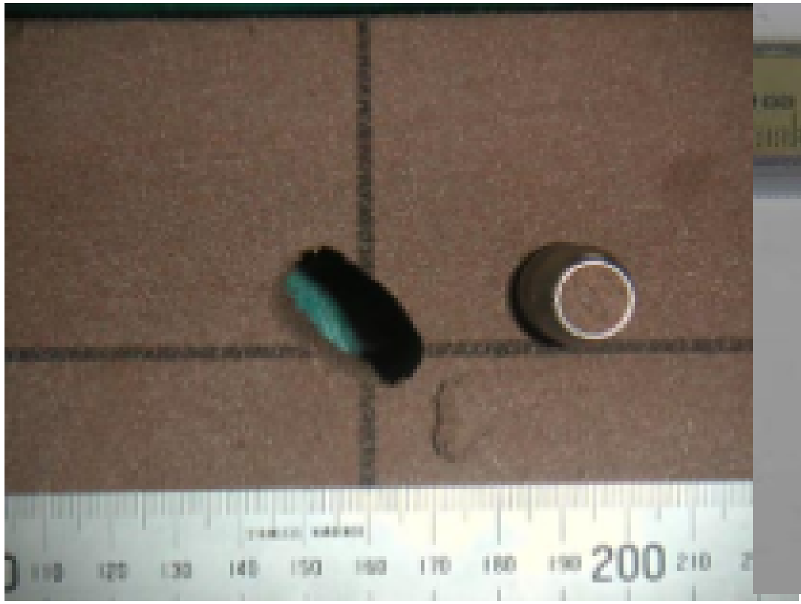


TL: Tagish Lake
carb -r: carbonate -rich
carb -p: carbonate -poor

Probable parental asteroids	C-type asteroids	T- (or D-) type asteroid

(Miura, Tsuchiyama, Noguchi and Yano, 2008)

C-type Asteroid Analog Targets Based upon Meteorite Measurements

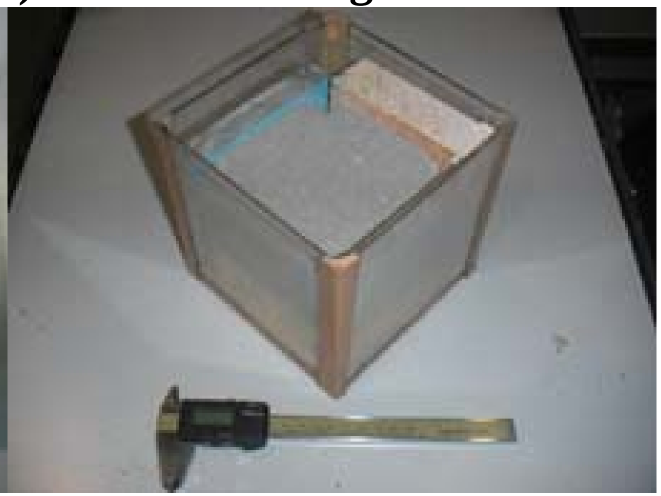


Gravel

Monolith

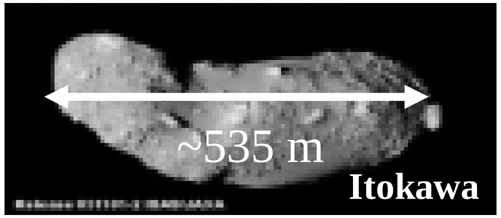
Gravels(Coarse Regolith)

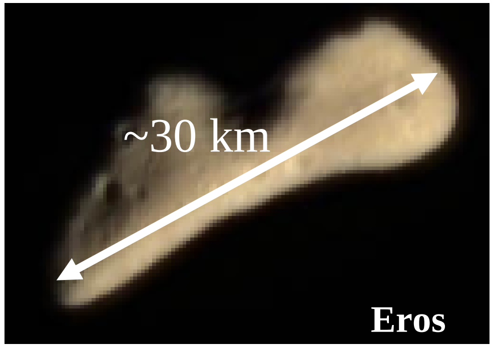
Fine Regolith

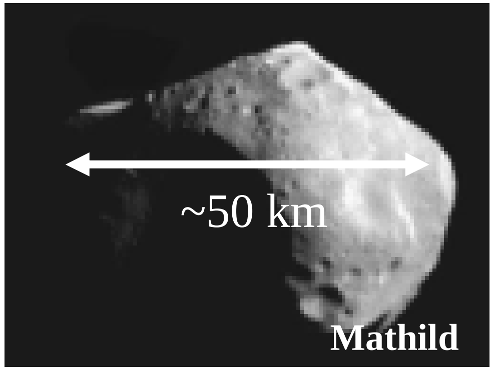


Grain Target Comparison with Asteroids

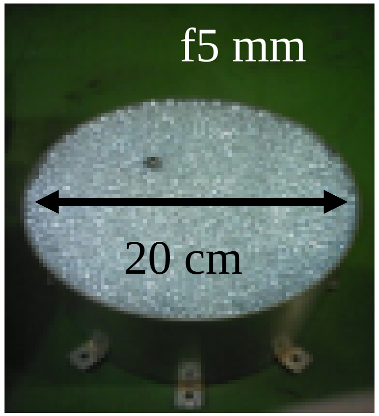
Asteroid	Itokawa (S-type)	Eros (S-type)	Mathilde (C-type)
Bulk density	**1.9 g/cm^3**	**2.4 g/cm^3**	**1.3 g/cm^3**
Porosity	**~40 %**	**~20 %**	
	Fujiwara et al. (2006)_Science	Yeomans et al. (1999)_Science	Yeomans et al. (1997)_Science

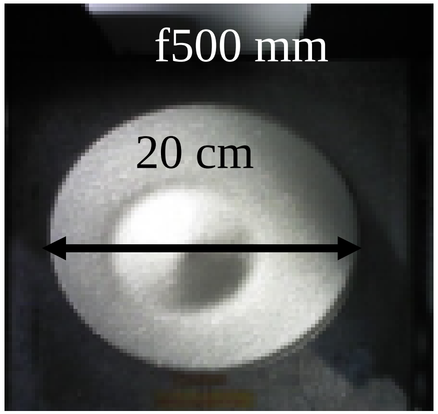






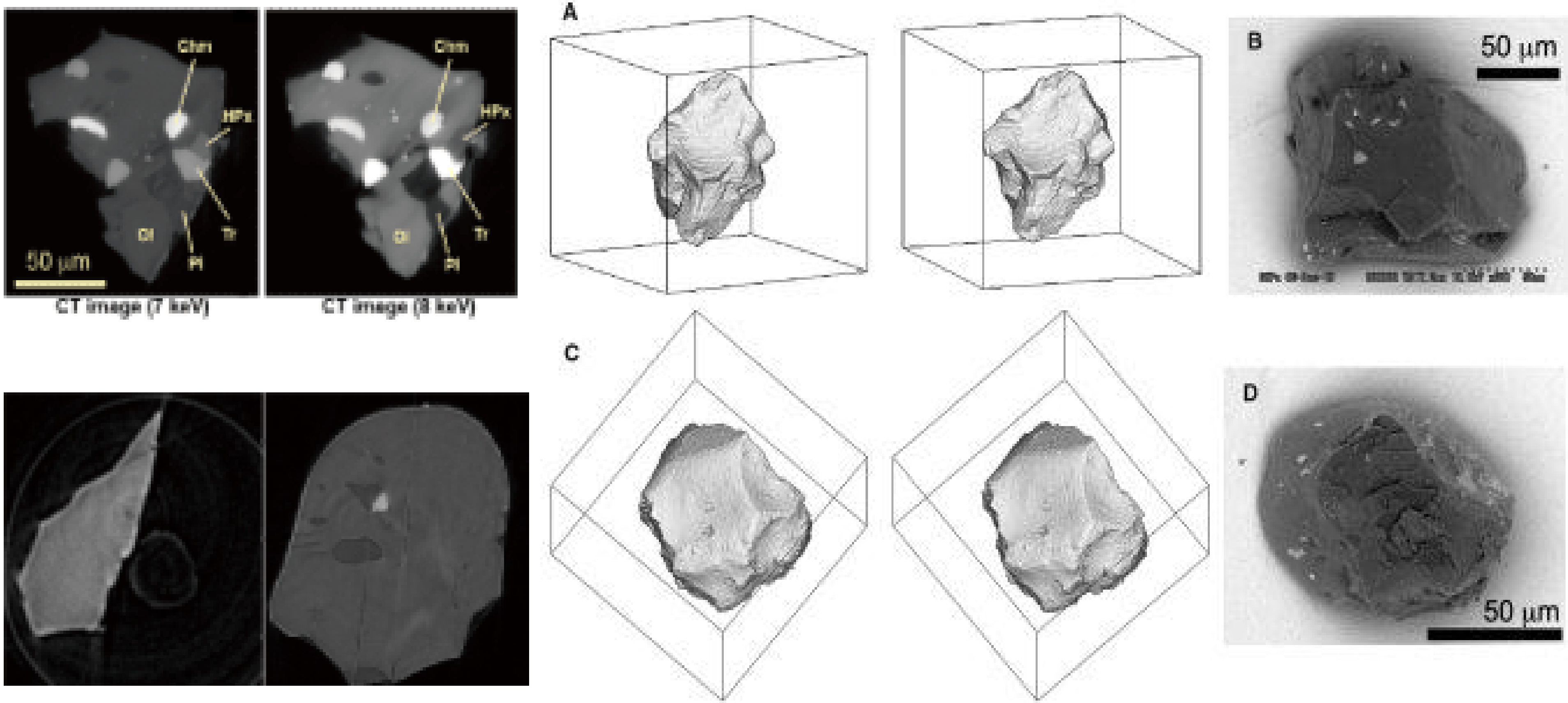
This study	Glass beads f5 mm	Glass beads f0.5 mm
Bulk density	**1.6 g/cm^3**	**1.6 g/cm^3**
Porosity	**36 %**	**36 %**





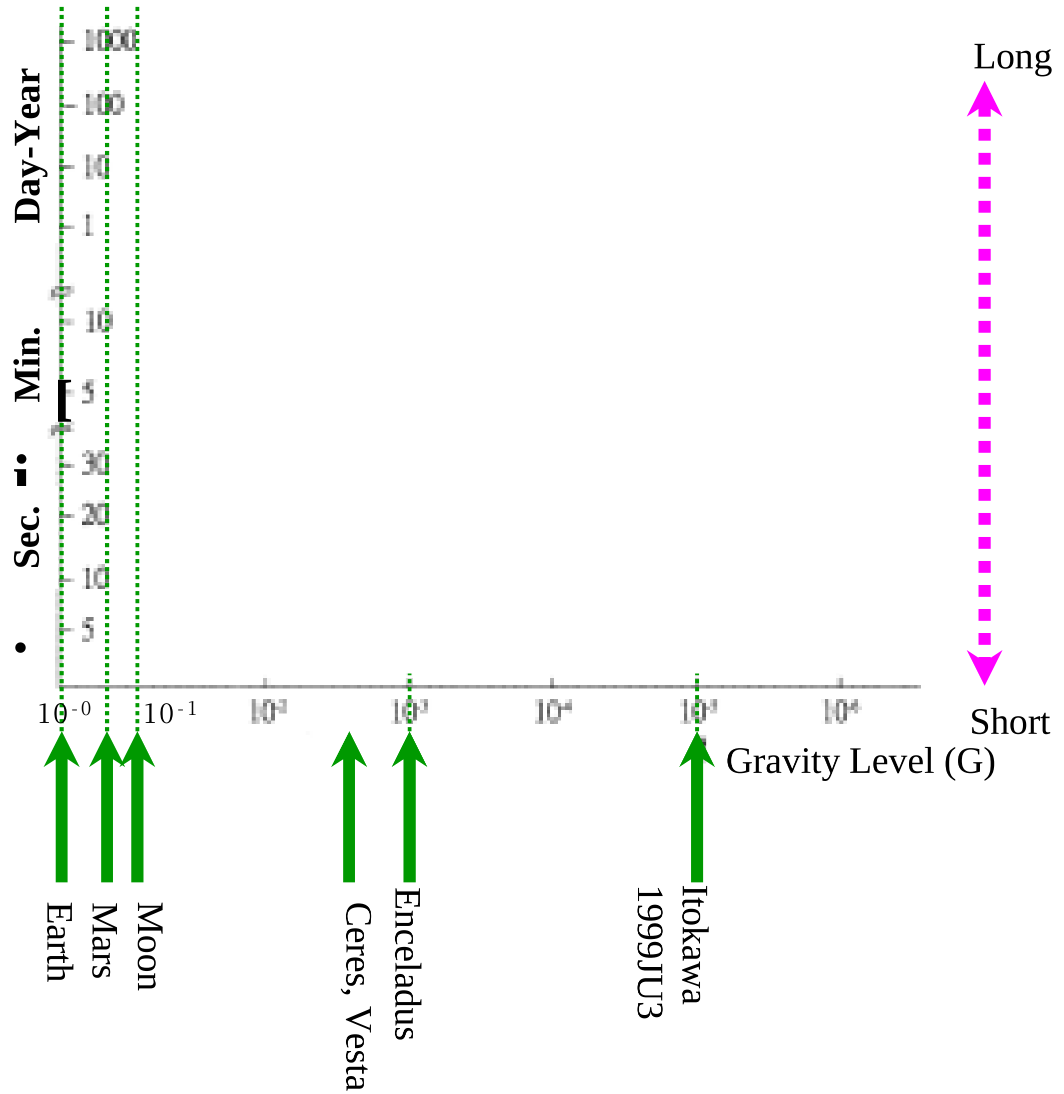
(Makabe and Yano, 2008)

X-ray Tomography of 3D Internal Structure of Asteroid Regolith
(Tsuchiyama, et al., Science, 2011)

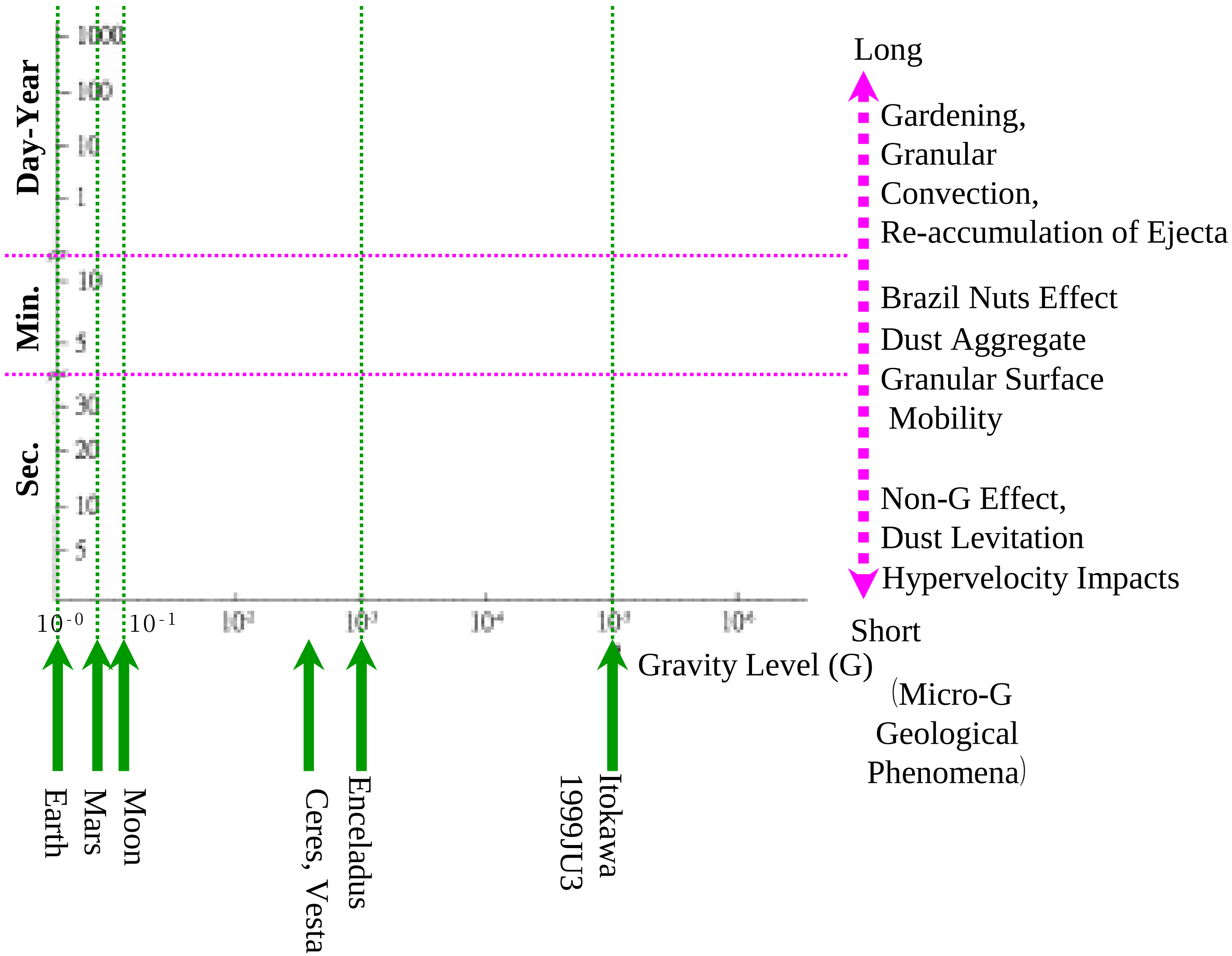


Gravity-Duration Diagram

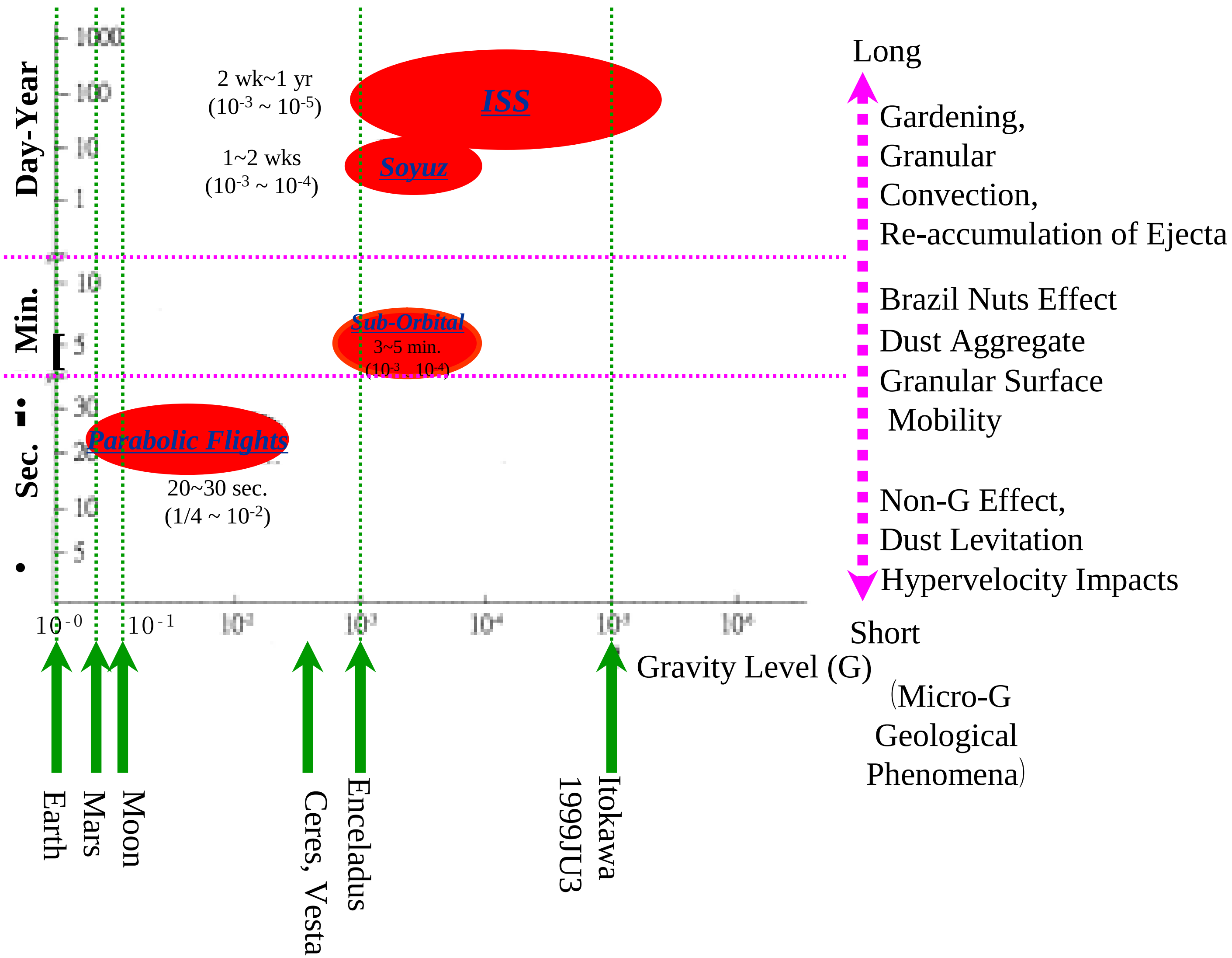
The Gravity-Duration Diagram: Solar System Bodies in Different Gravity Level



Typical Duration of Low Gravity Geological Processes

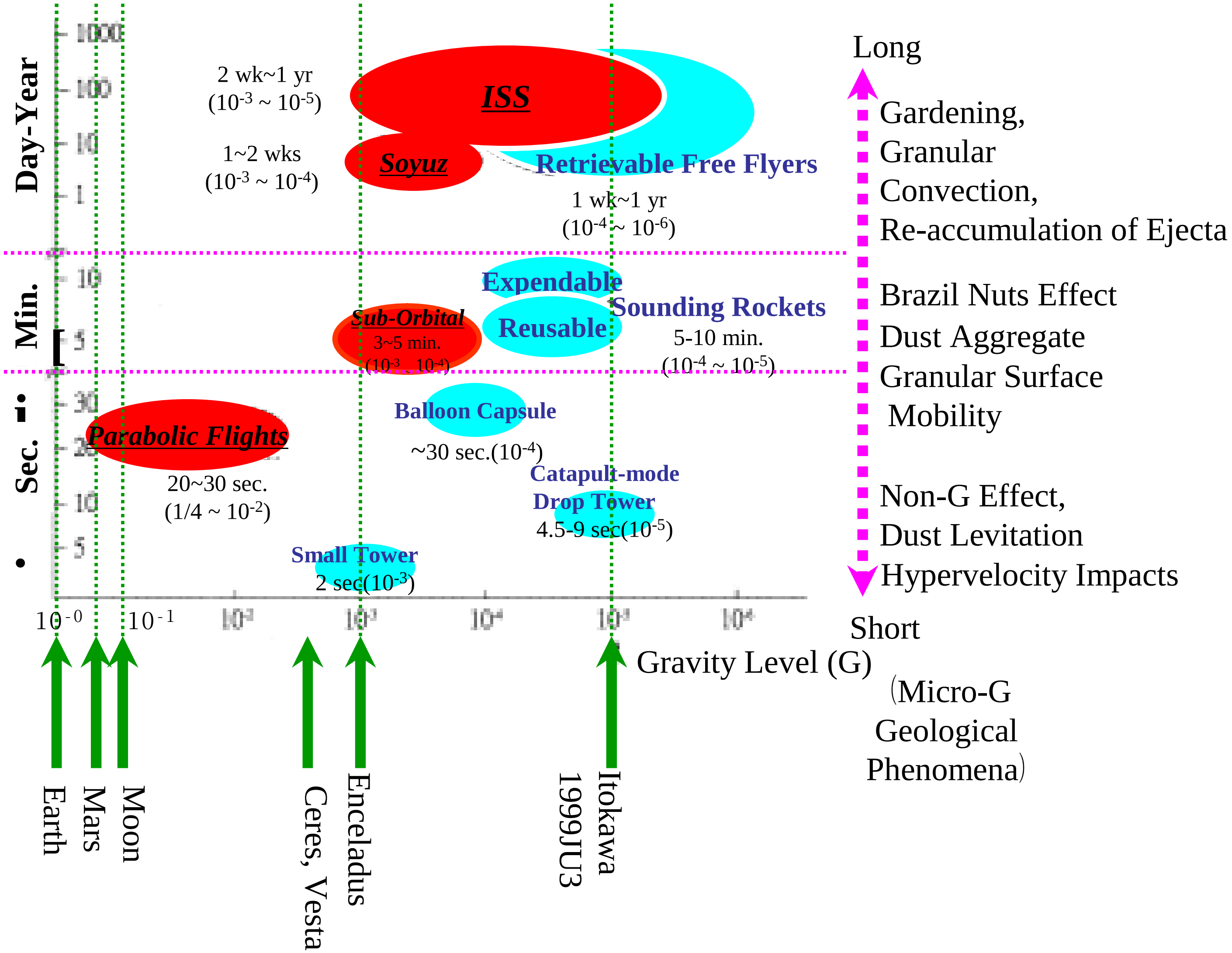


Human-tended Test Facilities for Microgravity



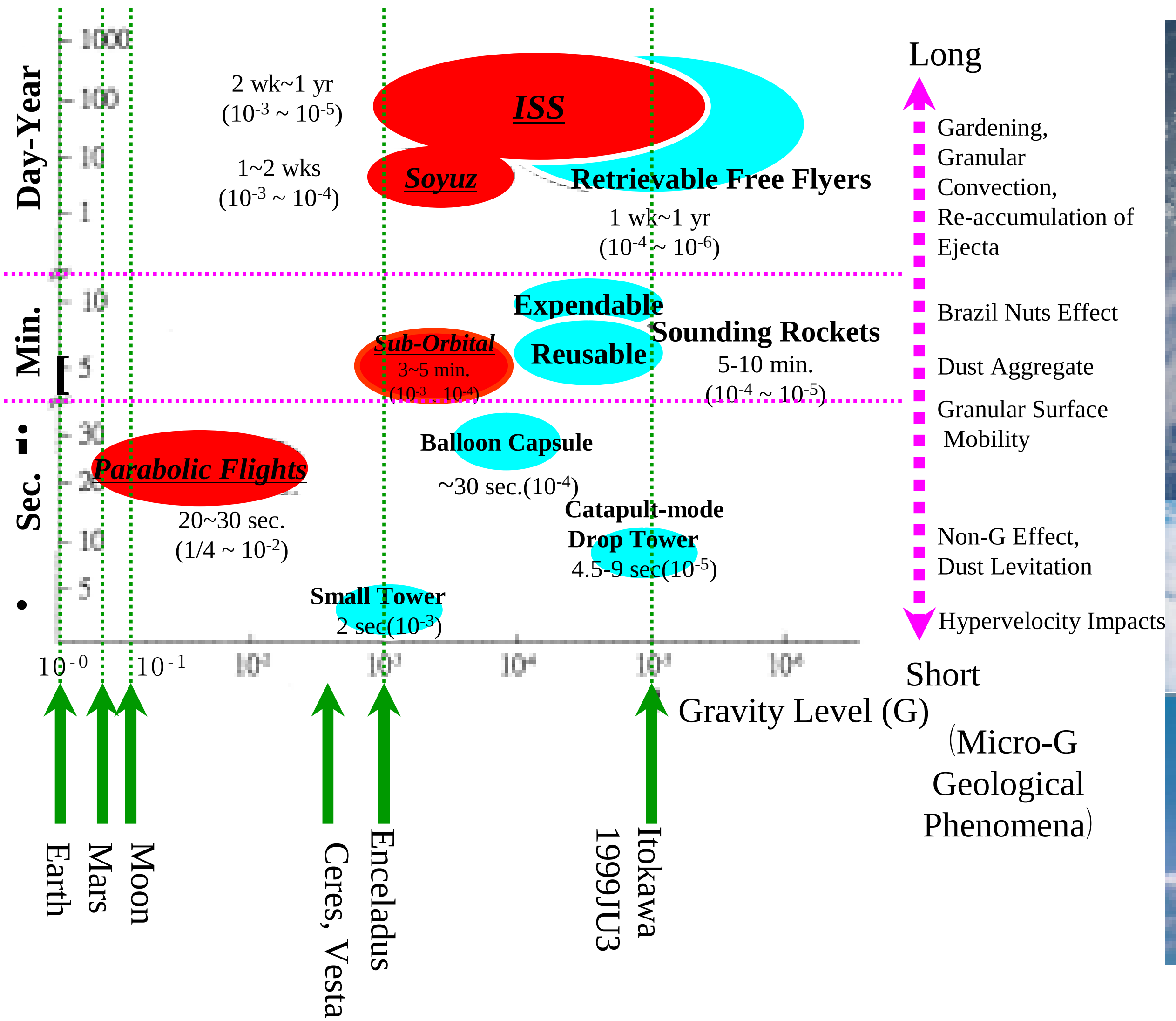
Human-Tended

Unmanned Test Facilities for Microgravity



Unmanned

Summary of the Microgravity Geology Experiments



Human-Tended Unmanned

* Plus counter-mass/low friction stages and underwater analog sites for longer duration

Examples of Past and Current Efforts: Science

High and Slow Velocity Impacts

➔Smaller and slower impacts studied by Blum, Colwell, etc.
➔Hypergravity impact experiments extrapolated to microgravity ranges by Housen & Holsapple

<Major Issues>

•**Disruption ~ Re-accumulation?**
- > Ejecta Behavior
- > Compaction Effect

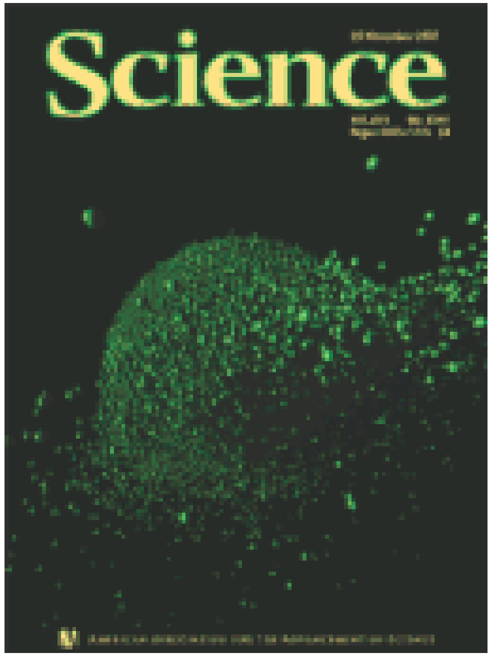
•**Strength Regime vs. Gravity Regime for Cratering**
- > Revisit the Impact Scaling Laws
- > New Dominant Forces in Microgravity?

•**Computer Simulation** (Hydrocodes, DEM)

•**Improve Impact Experiment Apparatus**
- > Vacuum Level, Dry Powders/Grains
- > Microgravity Level and Duration
- > High Speed Imagery

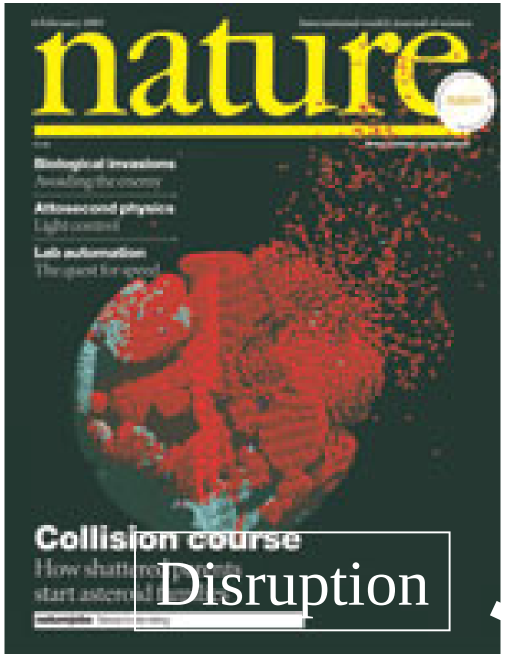
•**Sampling Device Development**

What Is the Boundary between Impact Disruption and Aggregation?: Structure, Size, Material



Simulations of asteroid disruptions suggest that objects >100 m are rubble piles

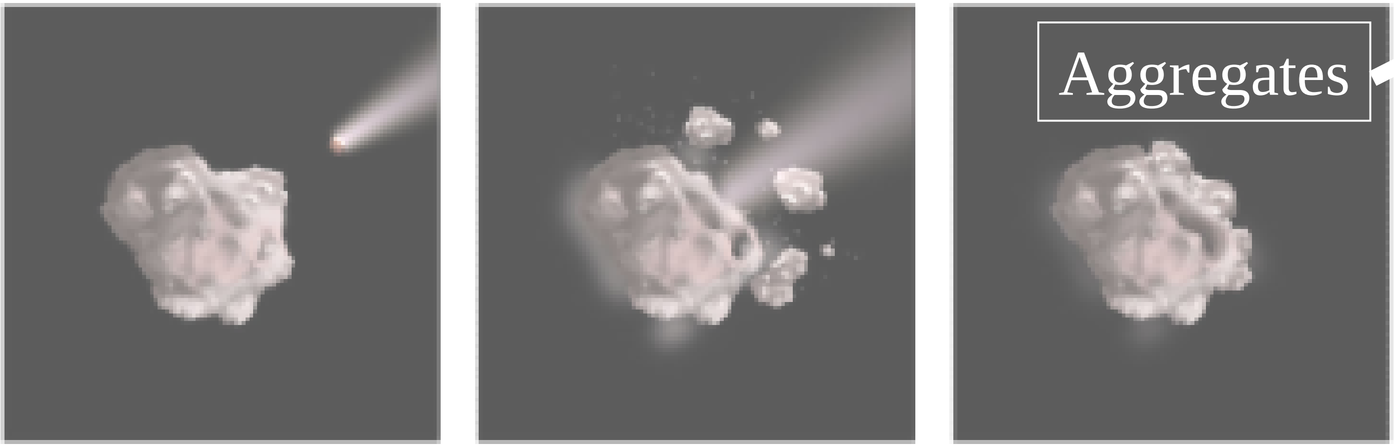
Michel et al., *Science* (2001)



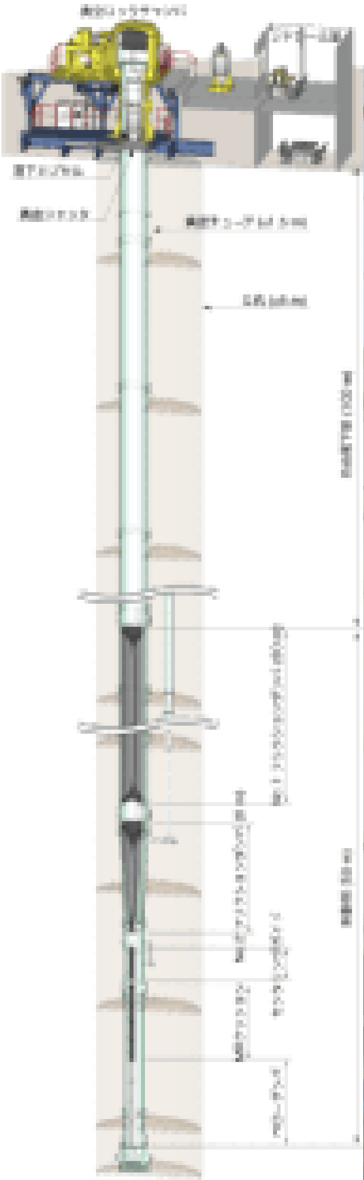
Impact energies and outcome depend strongly on internal structure of asteroids

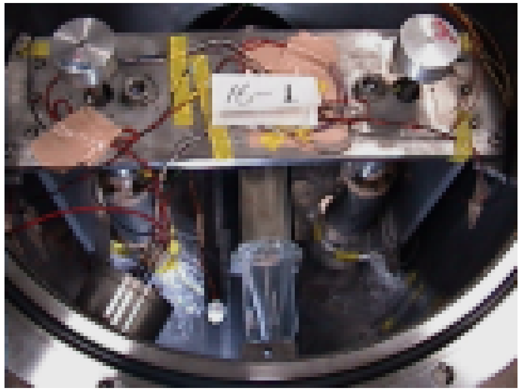
Michel et al., *Nature* (2003)

“Survival of the Weakest”: Asphaug, Scientific American

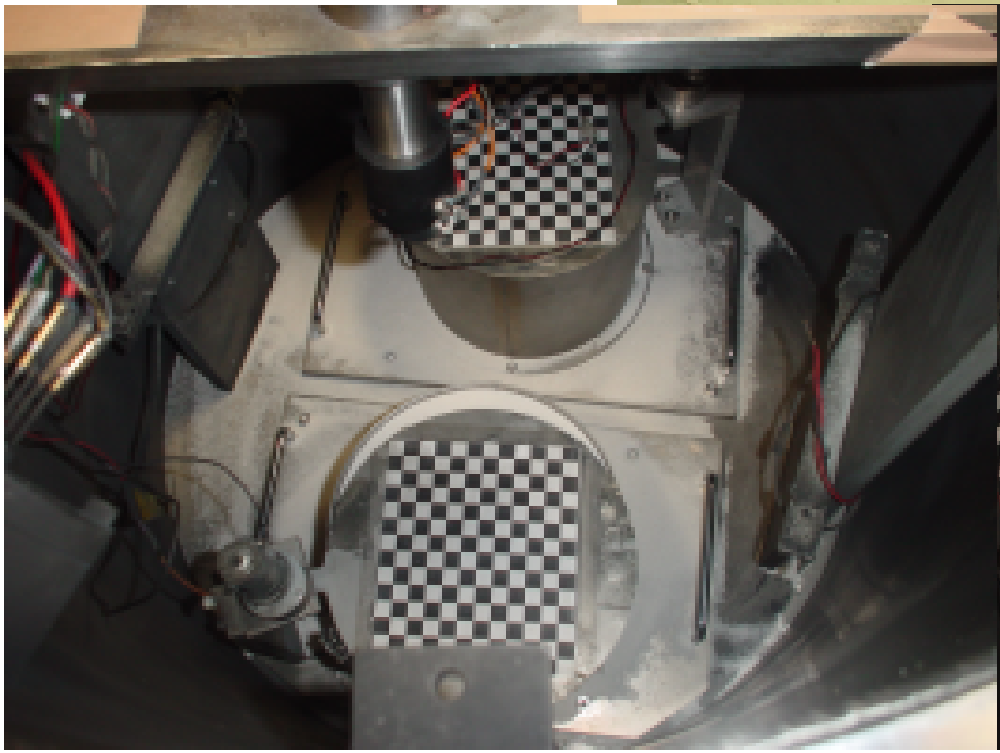


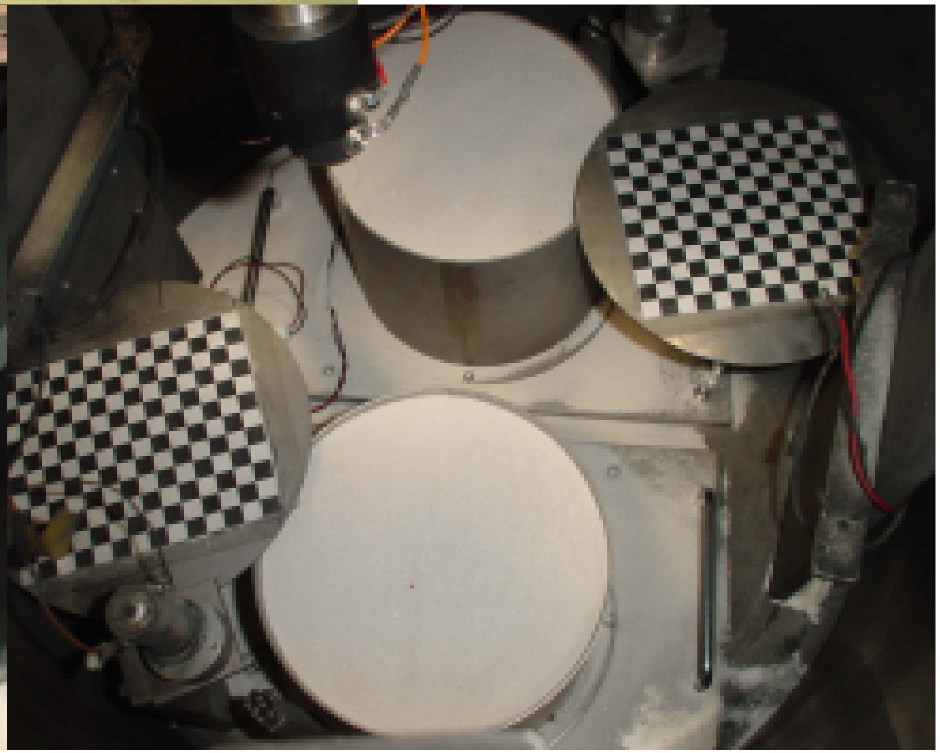
MGLAB at Toki, Japan
(4.5 sec. of 10^{-5} G…. until 2010.)



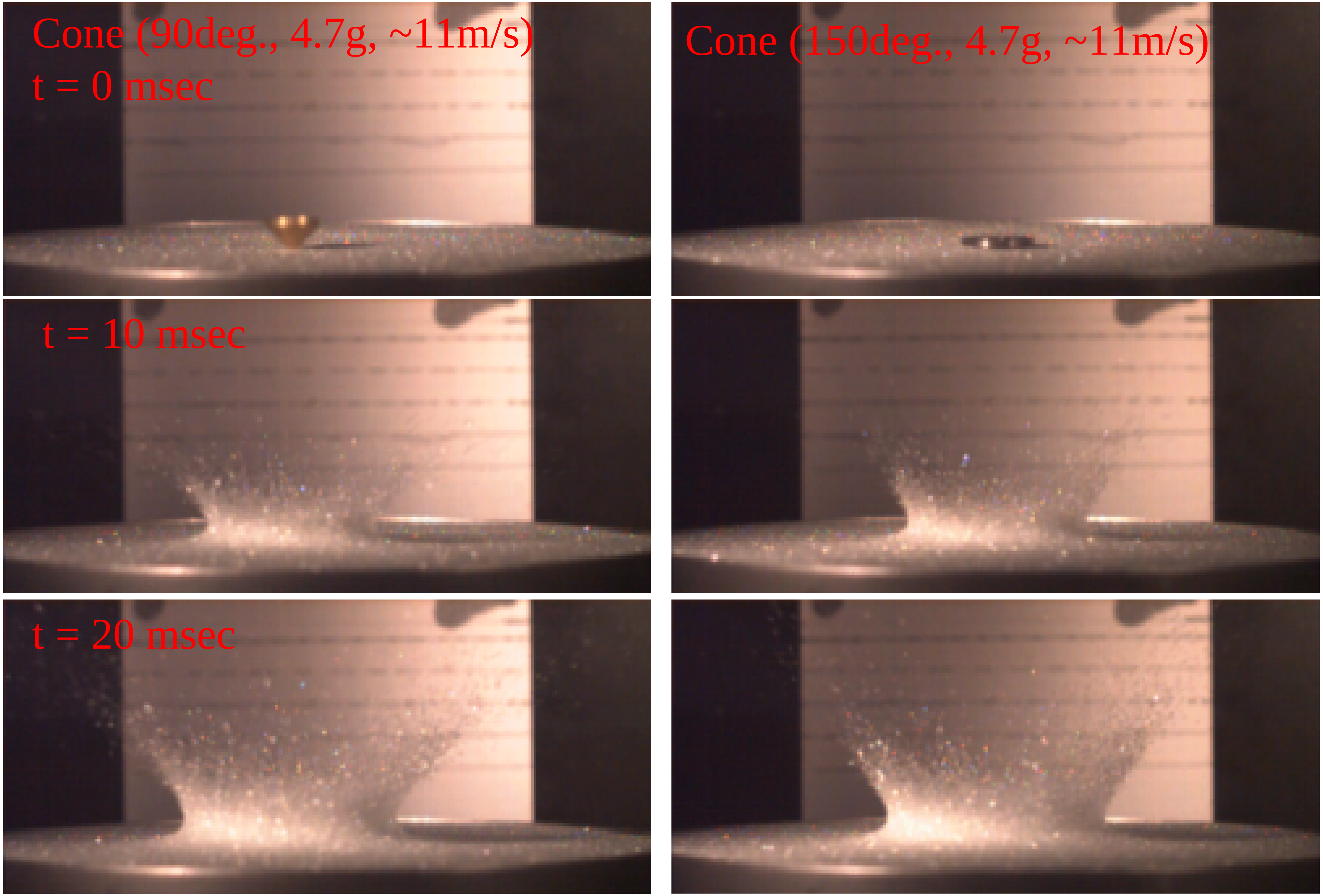


Inside the Microgravity Vacuum Chamber

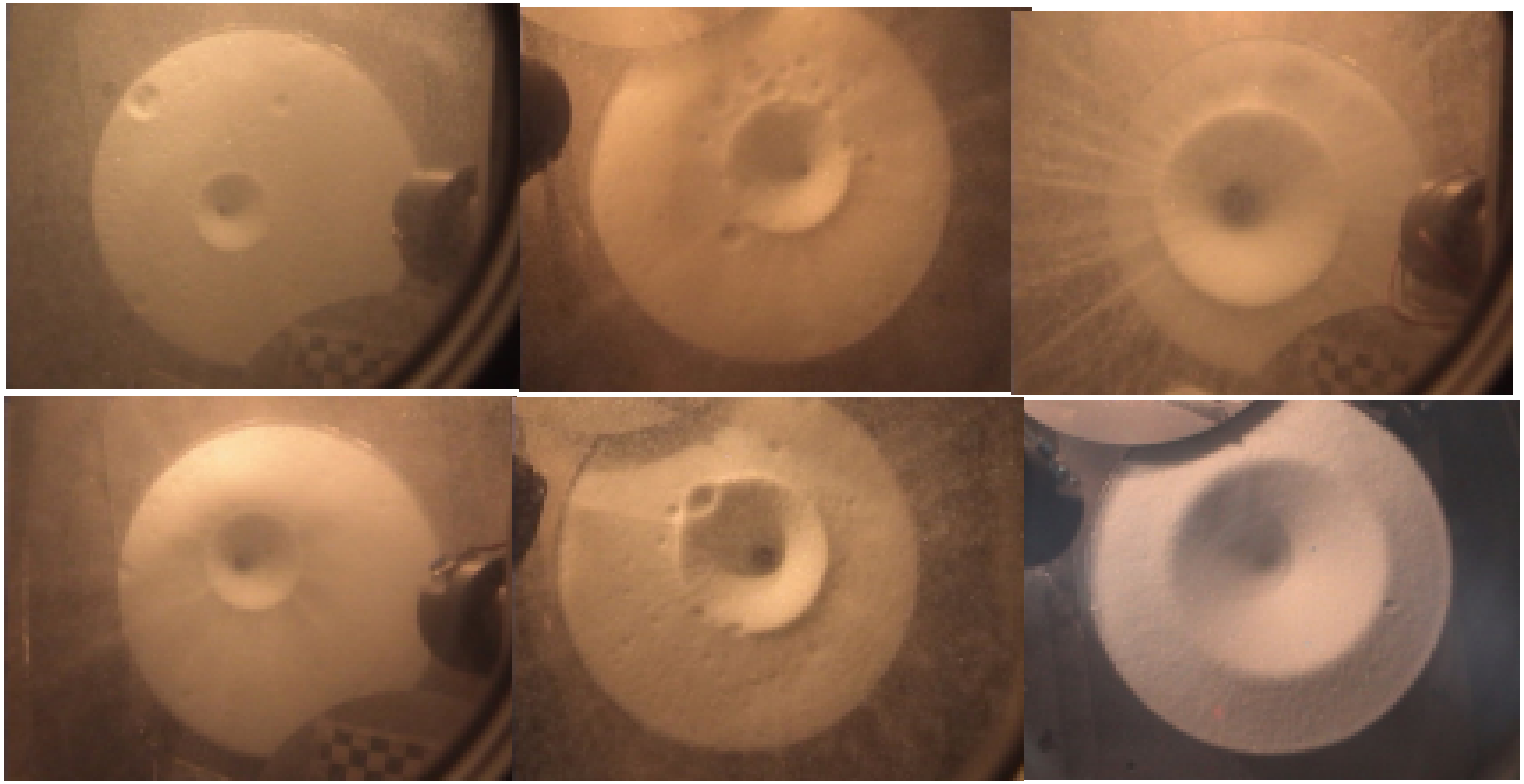




High-speed Imagery of Projectile Impacts onto Glass Beads of 500 μmφ



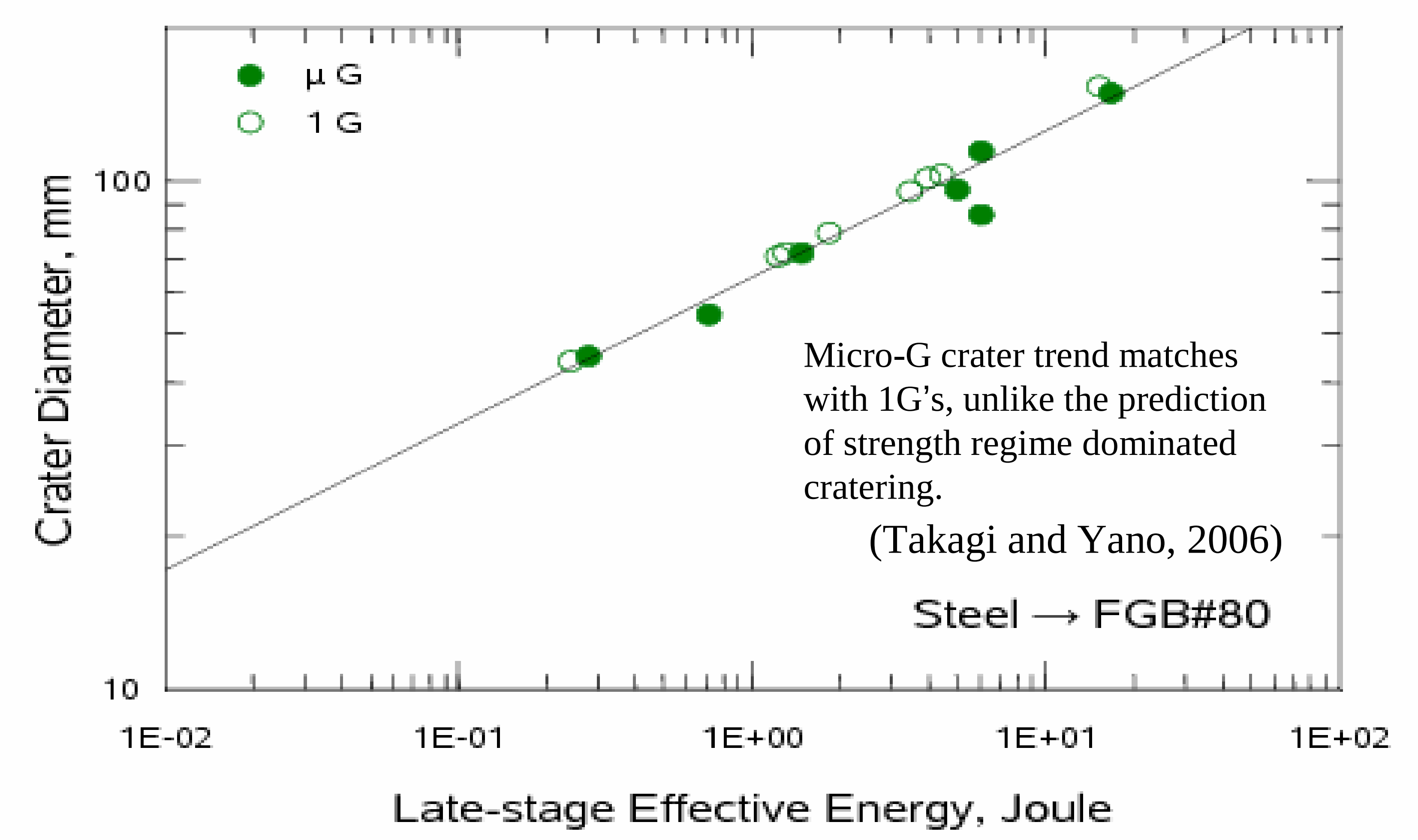
Examples of Impact Cratering on 100-500 Micron Glass Beads in Vacuum Microgravity



➔Gravity-strength regime formula predicts a long expansion of a large crater in microgravity

➔ Crater formation mostly ends in the first second during a 4.5-seconds free fall in MGLAB drop tower.

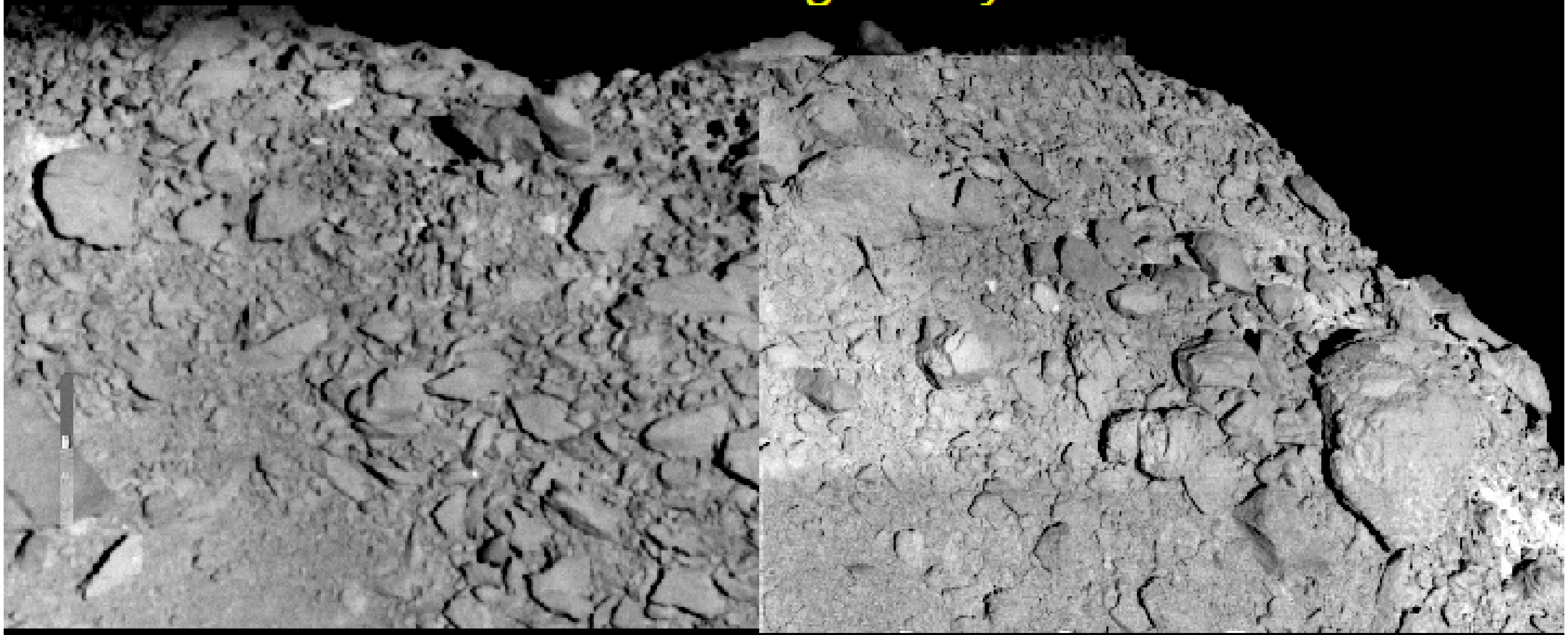
Granular Impacts in Gravity Regime without Gravity?



- How to grow an impact crater on grains in microgravity, presumably in strength regime?
- <u>Frictional / VdW force may play an important role to determine crater size in microgravity</u>

Gravels on Itokawa were reallocated after depositions

→ *shaken globally* (Miyamoto et al., 2007)

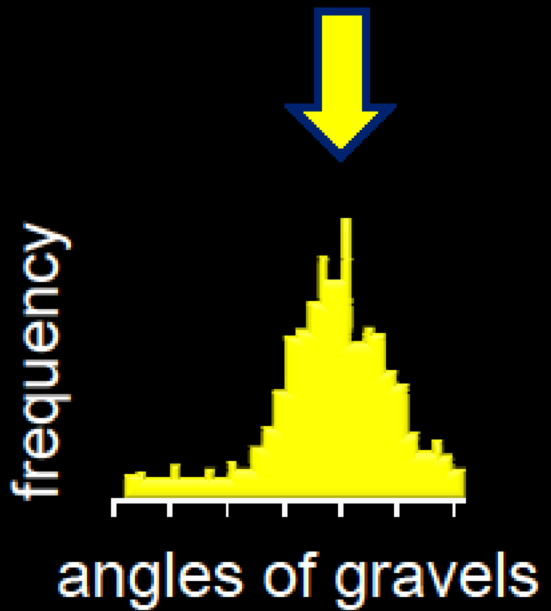


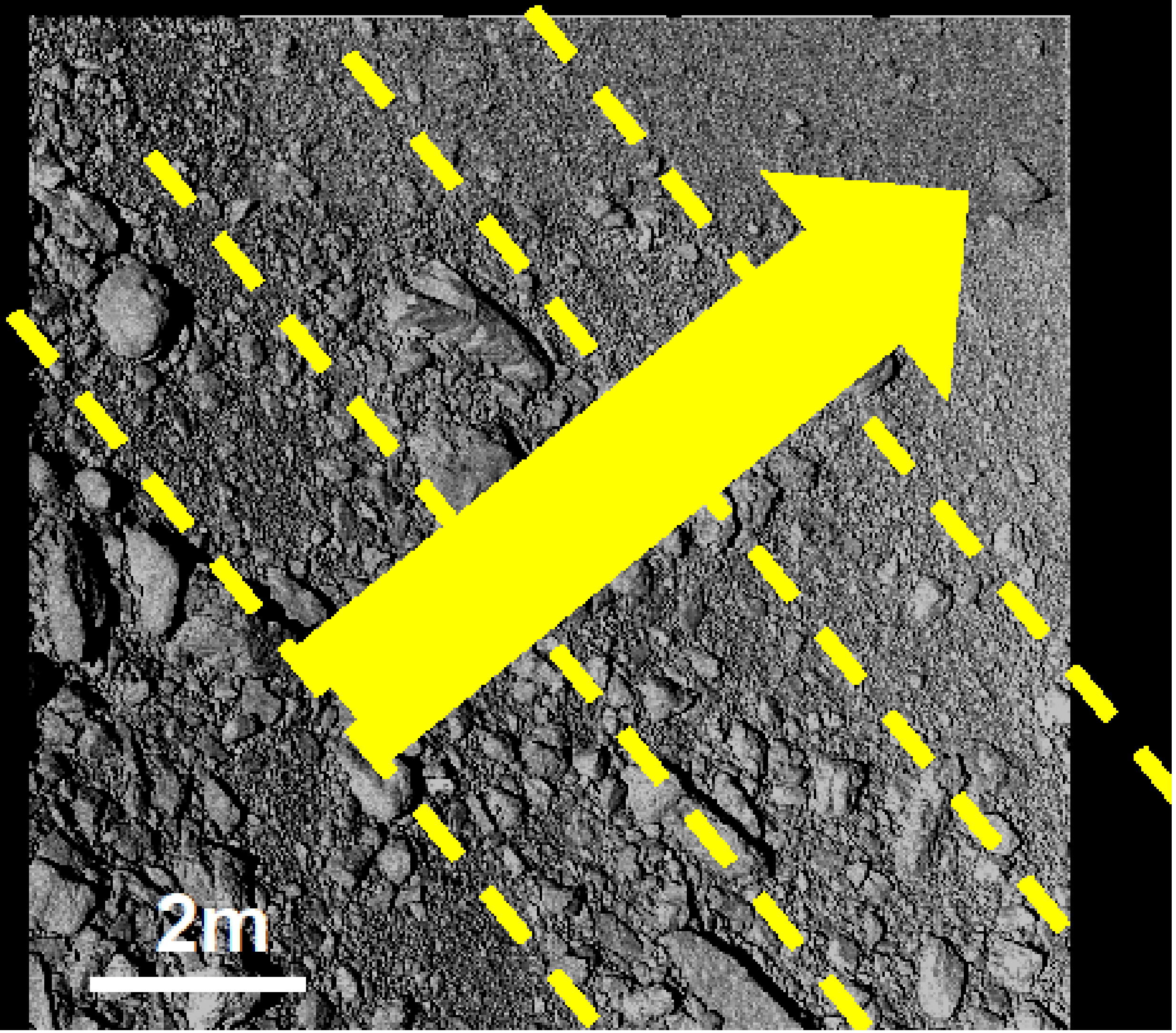
No small gravels are on the surfaces of boulders

Orientations of (larger) gravels appear to be gravitationally stable

Gravel migrations in rough terrains are evidenced by a range of morphological characteristics similar to terrestrial landslides:

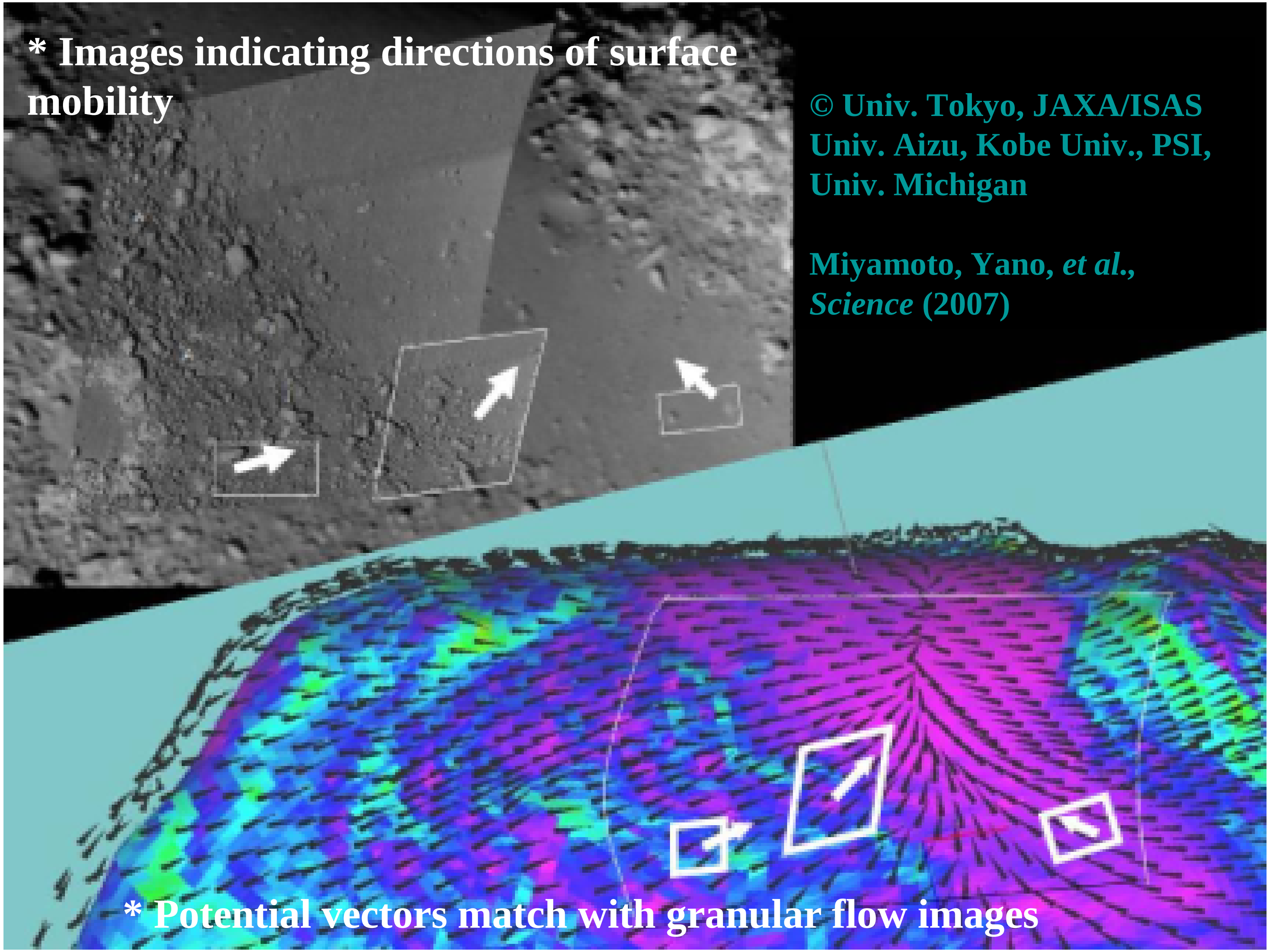
- Piles of gravels exclusively on the uphill sides
- Boulder alignments / Imbrications of boulders



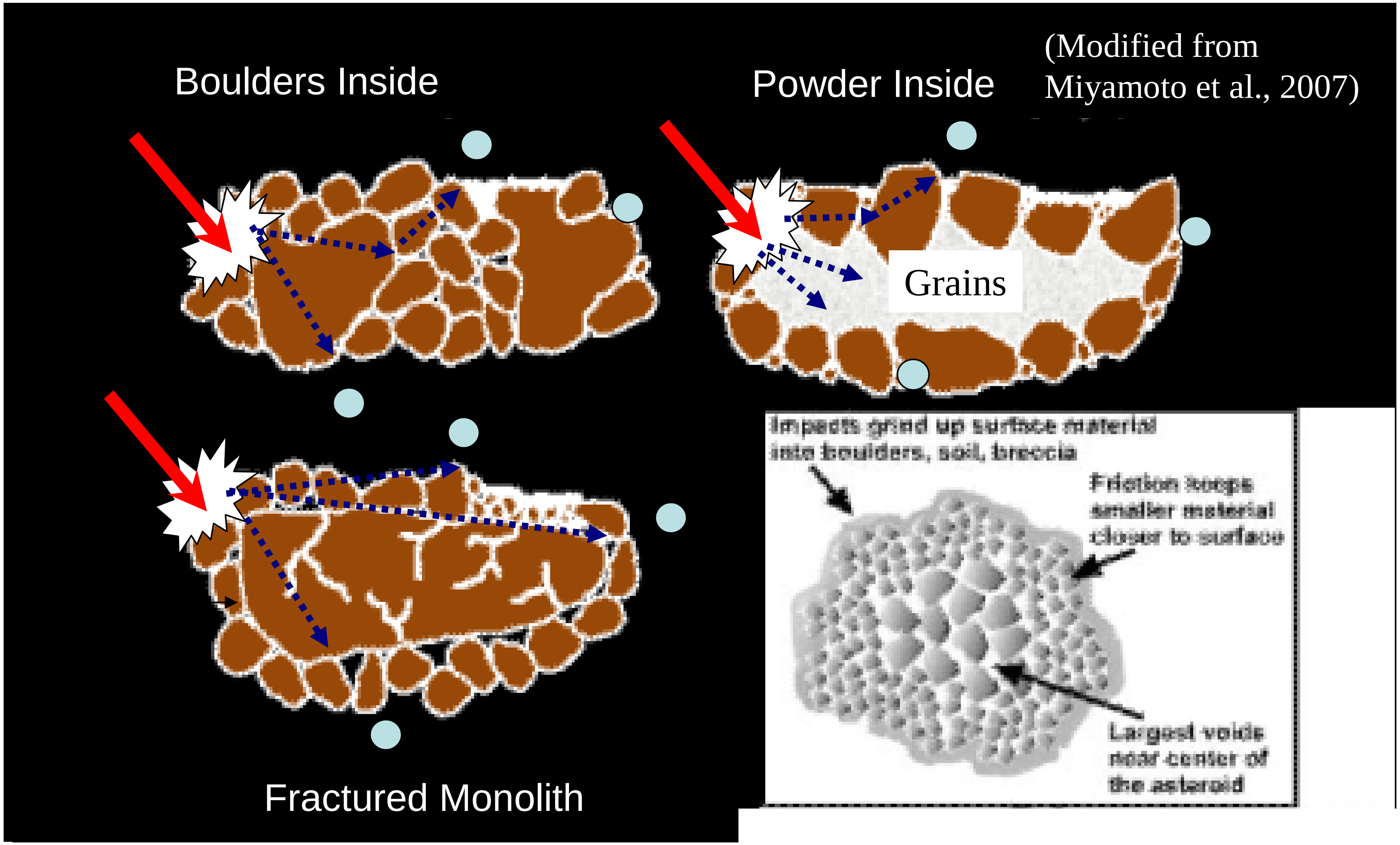


(Miyamoto, Yano, et al., Science, 2007)

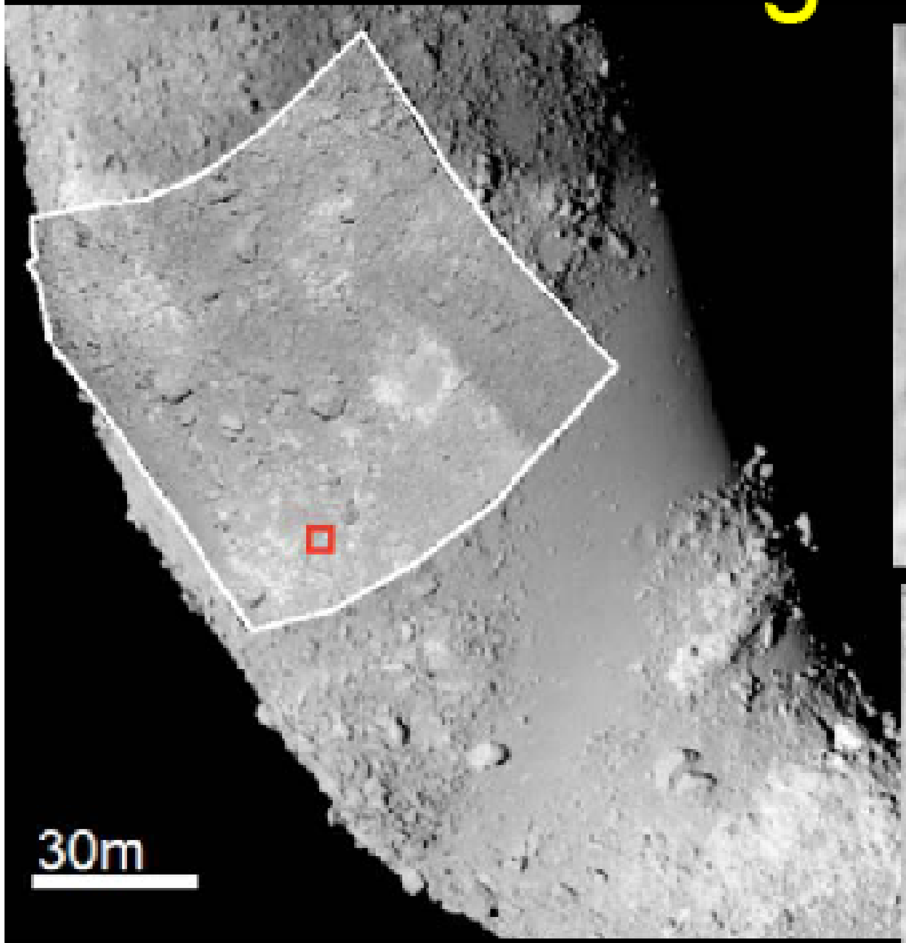
Image-Model Comparison of Granular Flow and Surface Potential on Itokawa

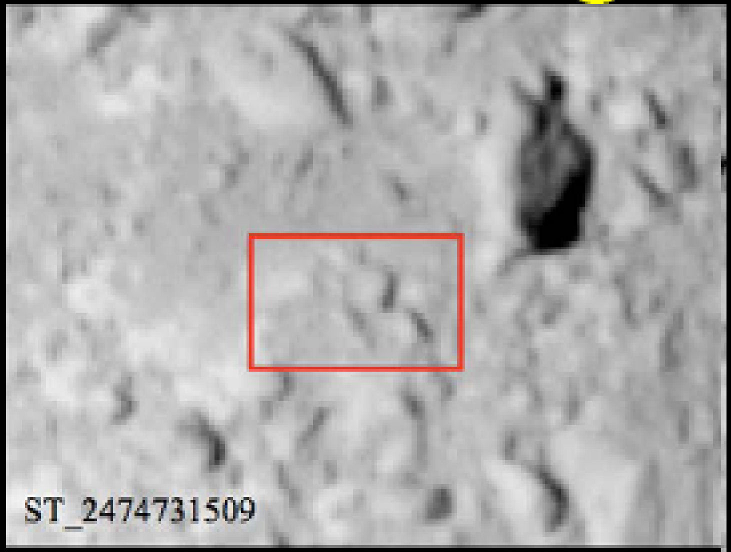


How the Interior Might Affect Surface Morphology

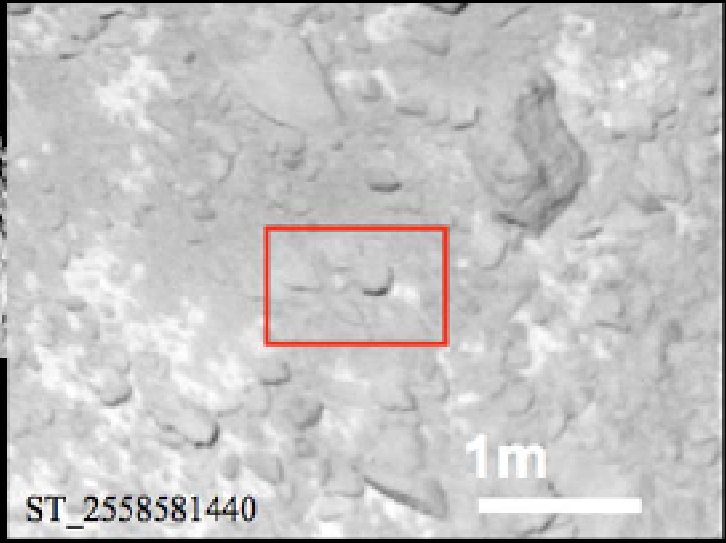


The only suspicious case: a boulder might be missing





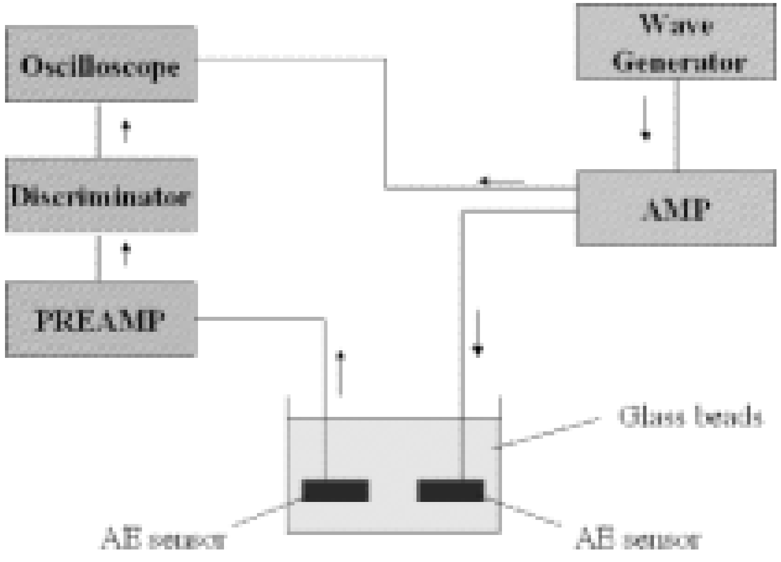
Oct. 20th, 2005



Nov. 19th, 2005

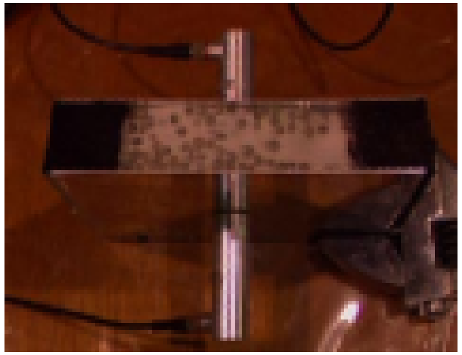
(Miyamoto et al., 2009)

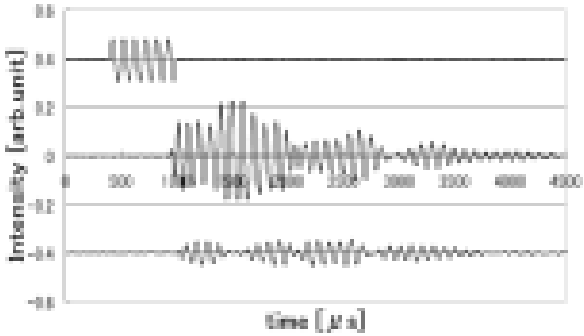
Experimental Work on Wave Attenuation inside Regolith and Porous Materials

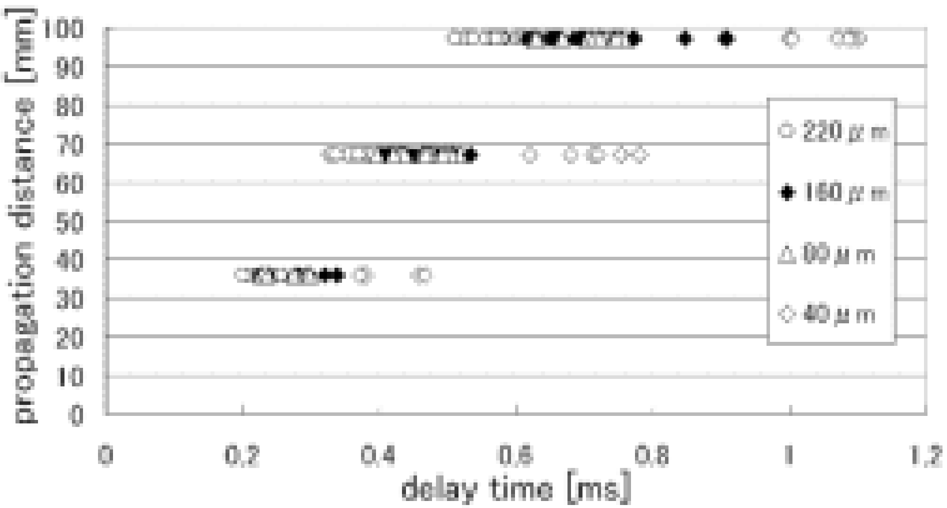


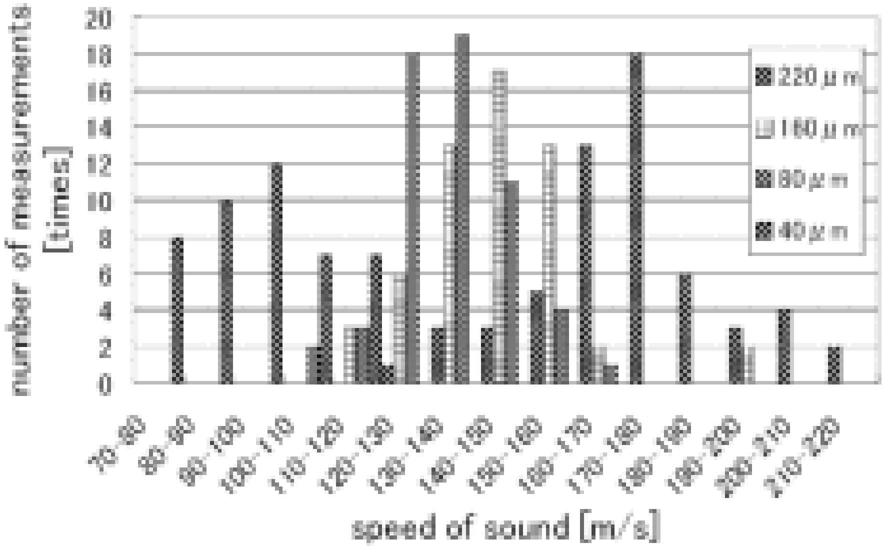
(Teramoto & Yano, 2005)

- How effectively can impact energy contribute to <u>global and local mobility of surface materials</u>?
- What can we learn about <u>sub-surface, internal structure of rubble piles and regolith layers</u>?









Brazil Nuts Experimental Work: Granular Behaviors in Variable Gravity

- Parabolic flight by GS-II (1G=> 2G=> micro-G=> 2G=>1G) proved that <u>granular convection speed greatly varied with gravity level</u>

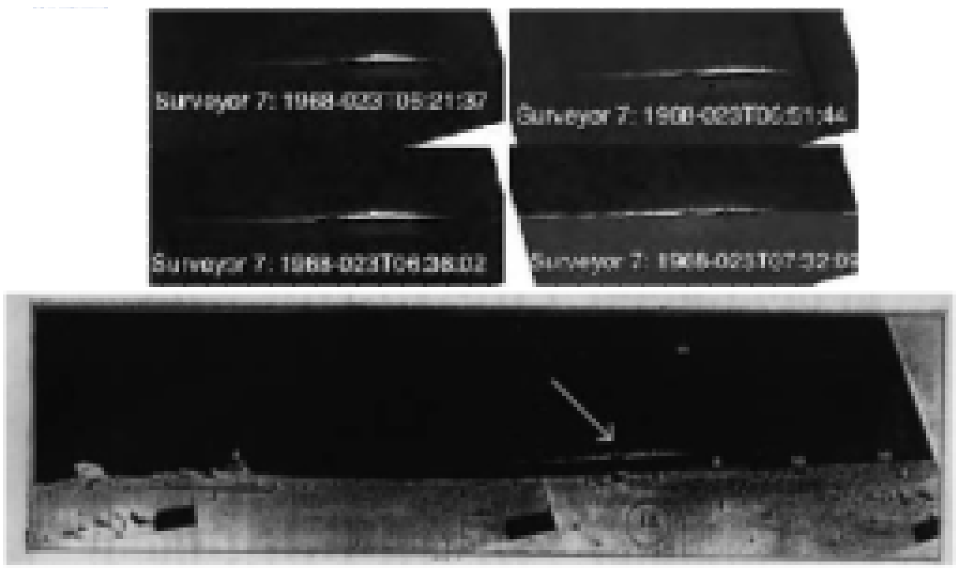
- Currently following up in 1G, 1-axis vibration experiments with computer simulation

(Yano and Makabe, 2007, Miwa, 2009)

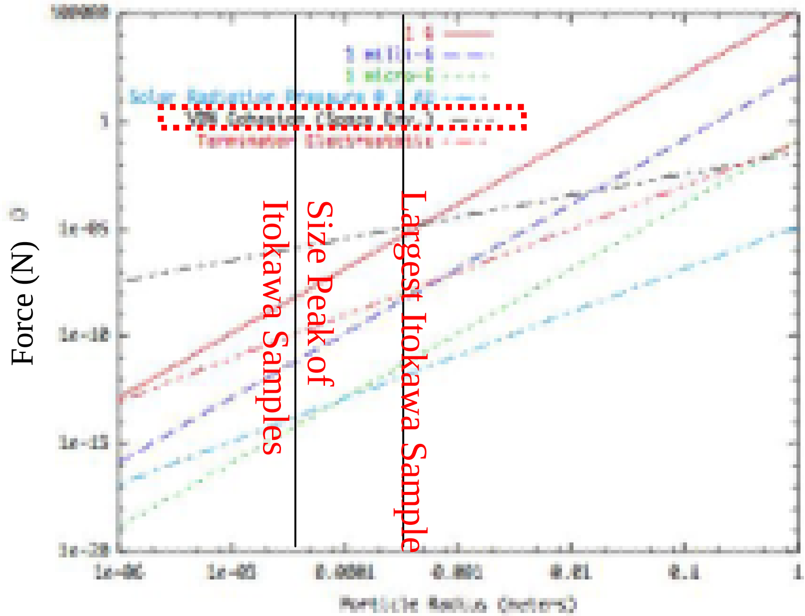
Dust Levitation

➔A few lunar studies
➔Recently revisited by Lee et al. for asteroids and Martian satellites
➔Chou et al. started vacuum chamber plasma sputtering to lunar regolith

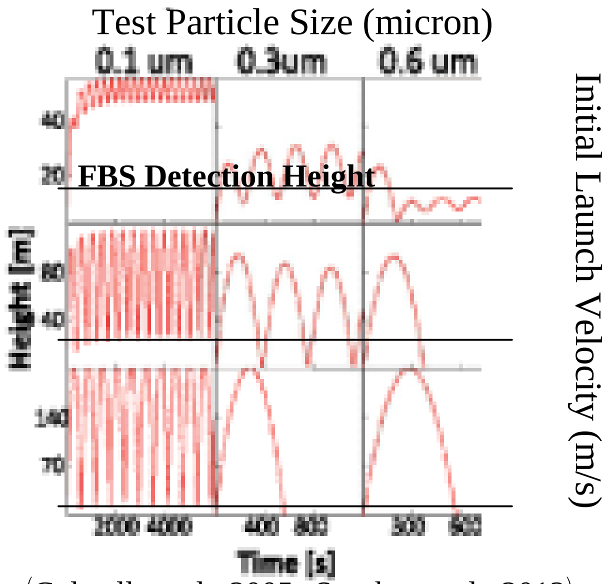
<Major Issues>
- Discover the Evidences
- Understanding Its Mechanism and Conditions
- Simulate in Laboratories
- Evaluate Macro-scale, Geological Effects
- Spacecraft / Lander Safety Assessment



Numerical Simulation of Levitation Dust



(Scheeres, et al., 2010)



(Colwell, et al., 2005、Senshu, et al., 2012)

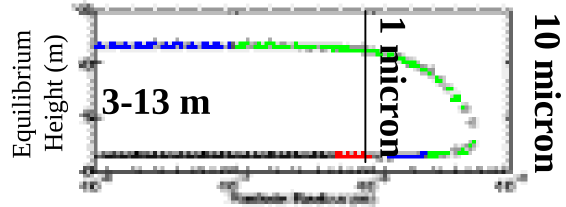


Figure 1: Equilibrium states as a function of particle size above the asteroid Itokawa at the subsolar point. Points are colored according to the number of electrons of the equilibrium charge: [0,1)e, black; [1,10)e, red; [10,100)e, blue; ≥ 100e, green. Solid circular points show the stable equilibria. Others are unstable.

(Hartzell and Scheeres, 2011b)

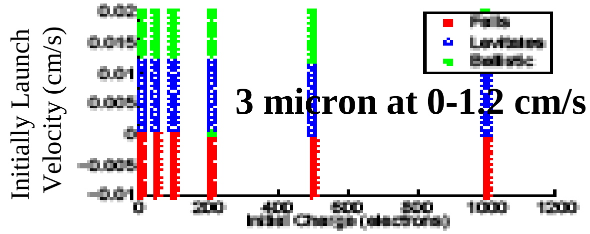


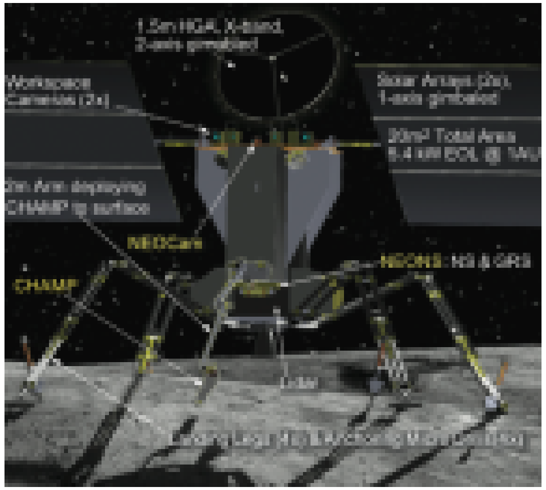
Figure 3: Fate of 3.05 micron radius particles near Itokawa as a function of initial conditions. The initial altitude for all trajectories is the equilibrium altitude at the unstable equilibrium (~ 1 m).

Landing or Tough & Go or Blast?

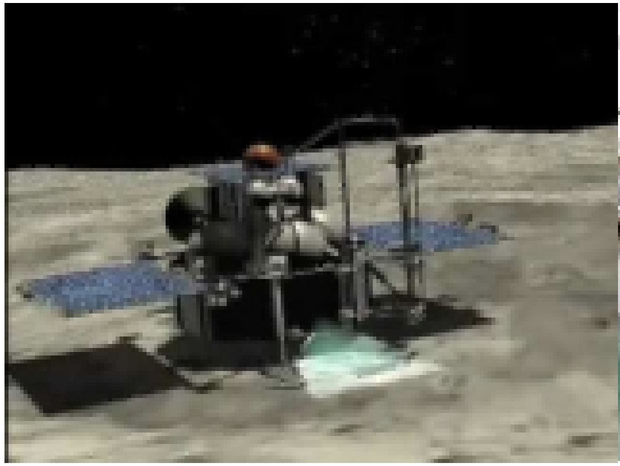
Rosetta/Philae:
Cometary Nucleus Rendezvous & Landing（2004~）

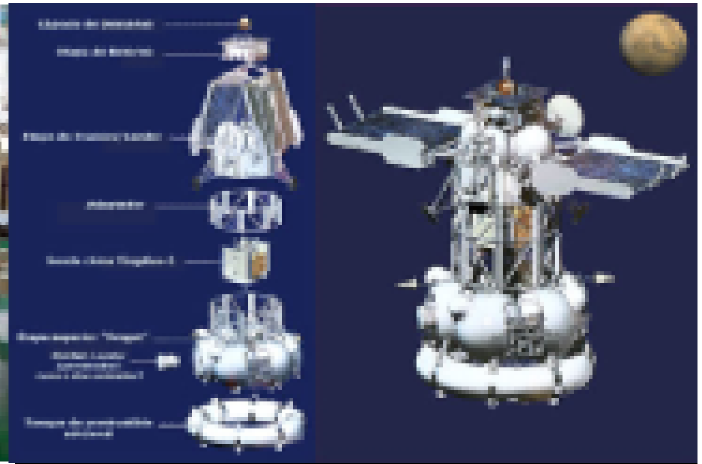
Harpoon and Anchoring Legs

AMOR Concept
(T.Jones, et al.)

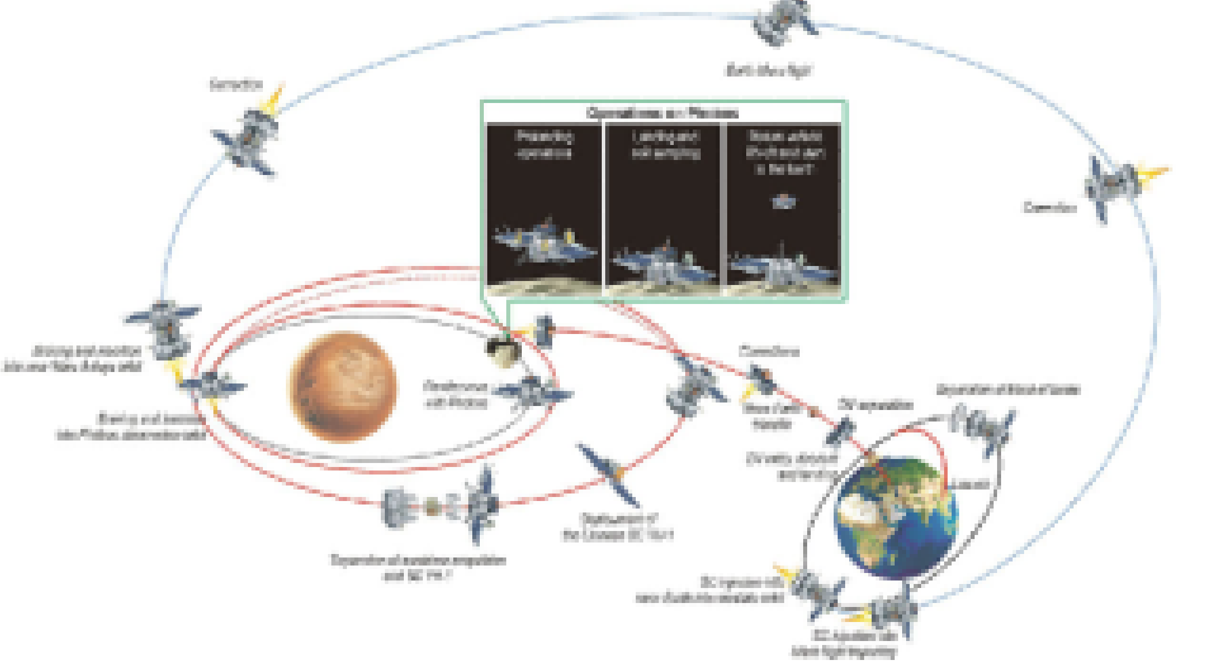


Phobos-Grunt：
Martian Satellite Landing & Sample Return (2011X)





Descent Firing Landing to Flat Places (Well Mapped Area)



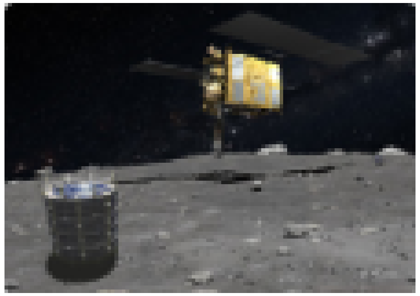

Hayabusa-2's Landers and Other Elements to Be Left at 1999 JU3

<Robotic Landers>

* MASCOT (to be provided by DLR) (x1)

• MINERVA-II1, 2 (x2) and their covers (x1)

➔ **Bouncing and Hopping**



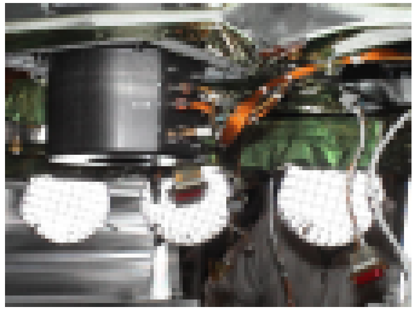
<Sampling Instruments>

• Target Markers (x up to 5)

➔ **Non-bouncing**

• 5-g, Ta Projectiles (x up to 3)

➔ **1-second Touch & Go**



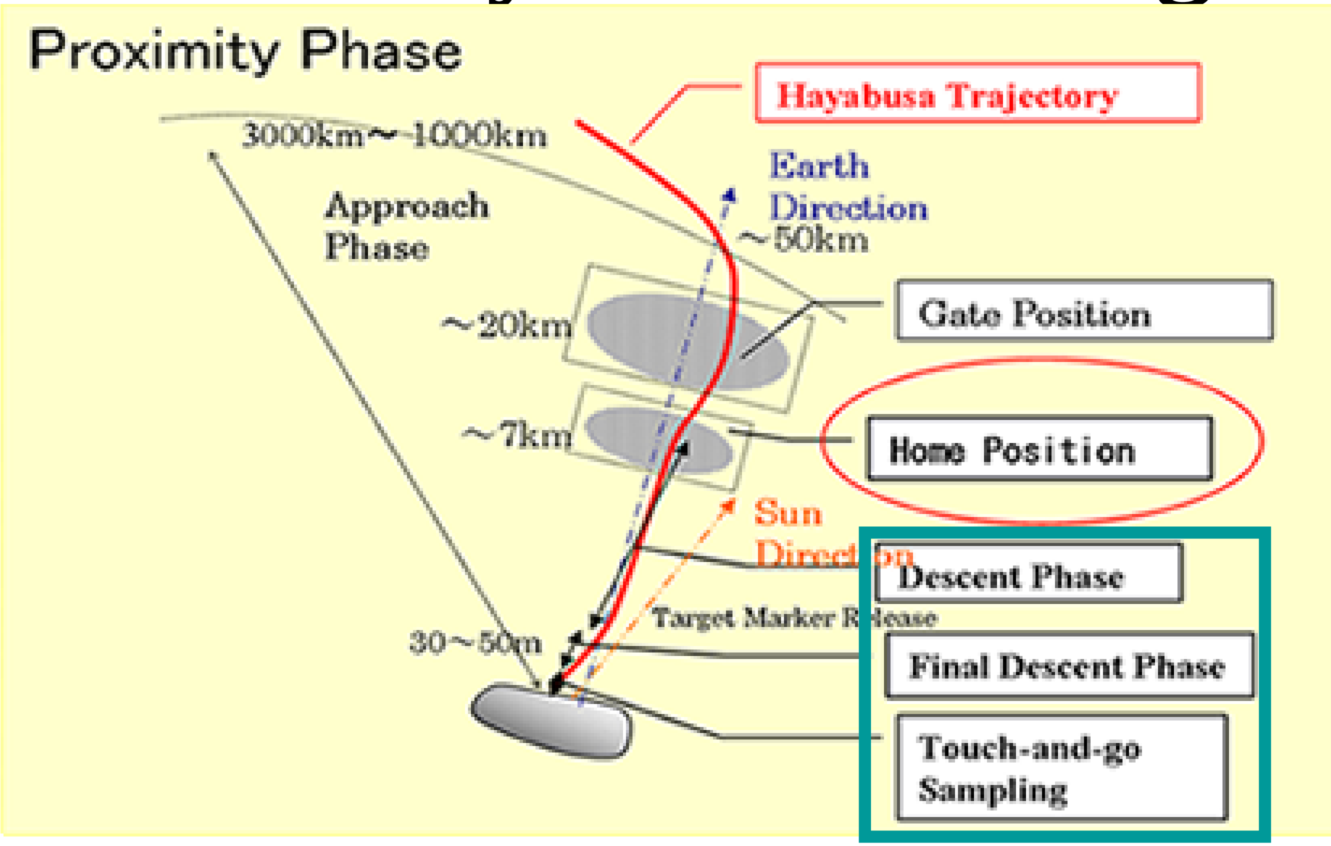
<Artificial Impact Experiments>

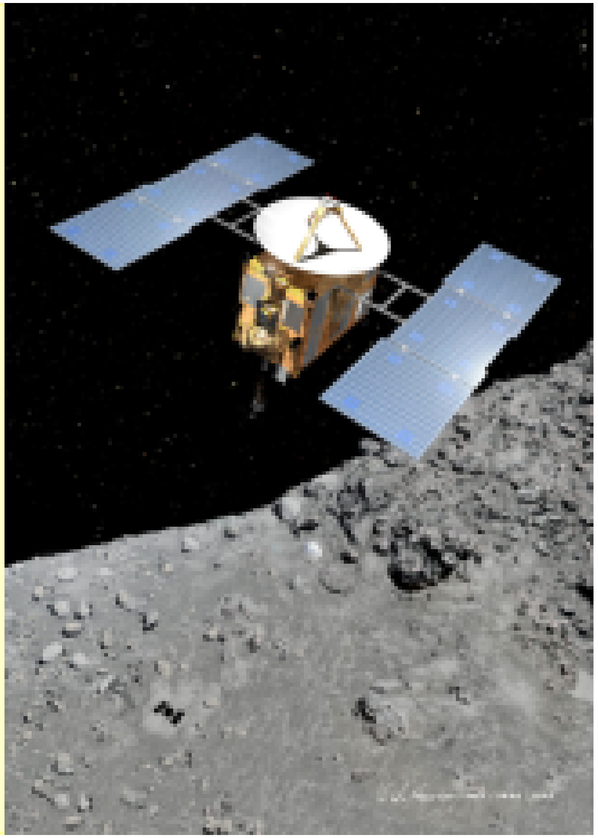
* Deployable Camera (DCAM) (x1)

•Small Carry-on Impactor (SCI): Metal projectile and fragments of exploded module (x1)

➔ **Self Explosive**

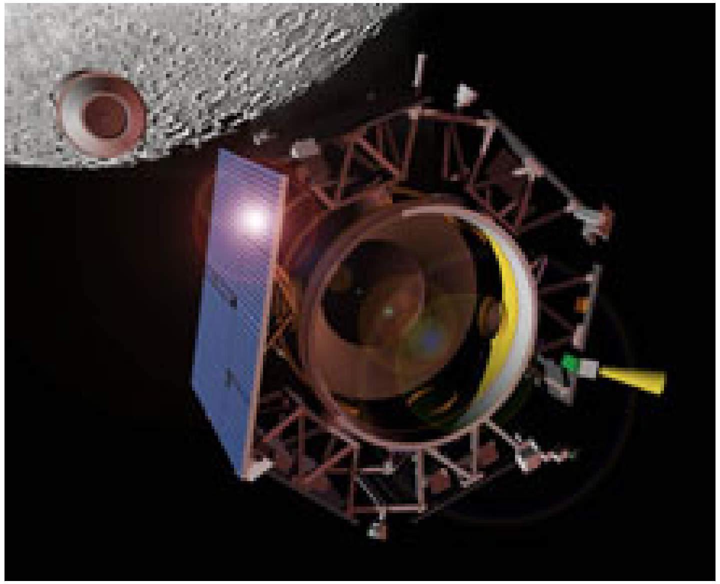
Hayabusa's Tough & Go

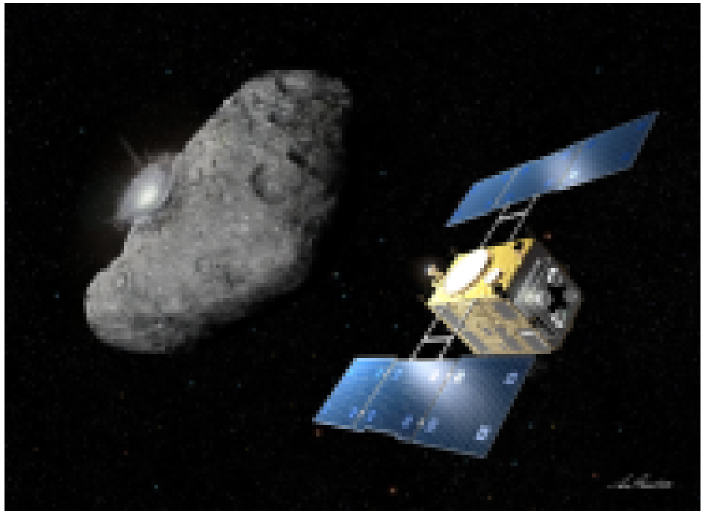




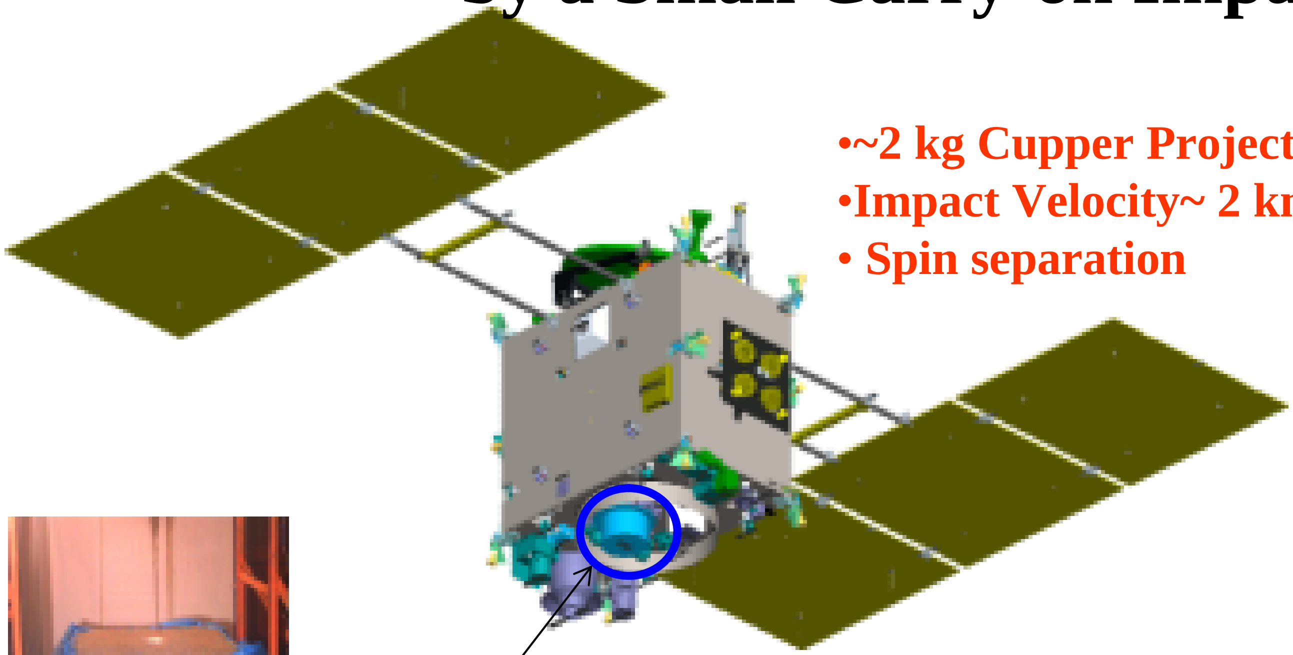
Gate Position (2005/09/12~09/27)
Home Position (09/27~10/05)
Science Tour (10/05~10/21)
Site Selection (10/28)
Touch Downs (2 Rehearsals, 1 Image Navigation Test & 2 TDs) (11/04, 09, 12, 19, 25)

Solar System Exploration
by Physical Interactions, i.e.
Impacts, Excavations, Blasts

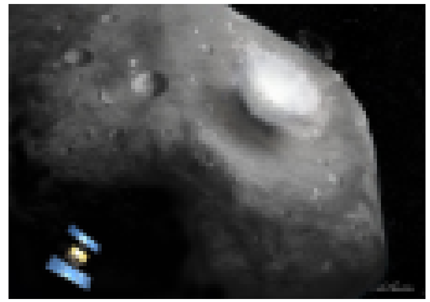



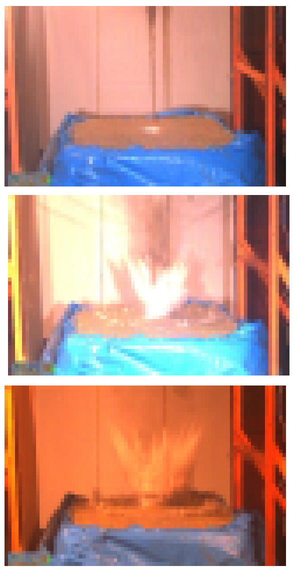


Hayabusa-2's New Challenge: Observe and Sample Excavated, Sub-Surface Materials by a Small Carry-on Impactor



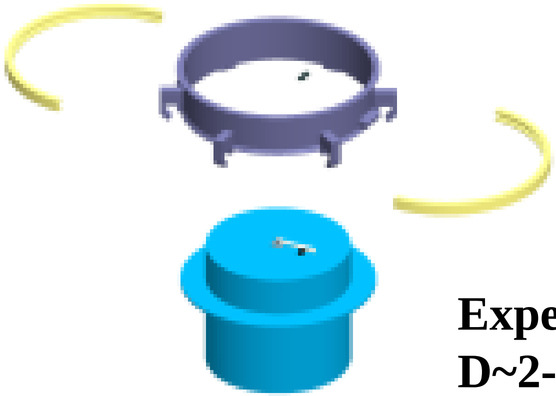
- ~2 kg Cupper Projectile
- Impact Velocity~ 2 km/s
- Spin separation





Impactor

EFP (Explosively Formed Projectile) Demonstration



Expected Crater Size:
D~2-3m: Autodyn Simulation
D~4 m: Takagi et al.
D~7.4 m: Housen & Holsapple

Conclusion

Microgravity Research Is a Critical Element of Small Body Research, Missions and Future Mining

< Spacecraft Data >

* Sub-km Asteroids： Itokawa, 1999 JU3, 1999 RQ36
* Large Asteroids: Eros, Phobos, Deimos, Vesta, Ceres, etc.
• Cometary Nuclei: Halley, Tempel-1, Wild-2, Hartley-2,C-G, etc.
• Small Satellites: Jovian Retrograde Satellites, Enceladus, etc.

←→ *Comparative Data (High-G Bodies): Earth, Moon, Mars*

< Experimental Facilities >

* Drop Tower (ZARM): 4.5-9.0 sec., 10- 5 G
* Vacuum Drop Capsule (ISAS): 2 sec., 10-3 G
* Parabolic Airplane (DAS, Nove Space, Zer-G Corp, etc.): 20-30 sec., 10-2 G
* High-Altitude Balloon (ISAS)： ~30sec., 10-3~-4 G
* Sounding Rocket (Reusable/Expendable) (ISAS): ~180sec., 10-5 G
* Suborbital Flight (NASA Suborbital EX): ~180sec., 10-5 G

< Modeling >

* Shape Model←→Gravitational Potential Simulation
* Micro-G Impact Hydrocodes (Autodyn 3-D, DEM), etc.