# Autonomous Surface Mobility on Small Solar System Bodies with Hopping/Tumbling Rovers


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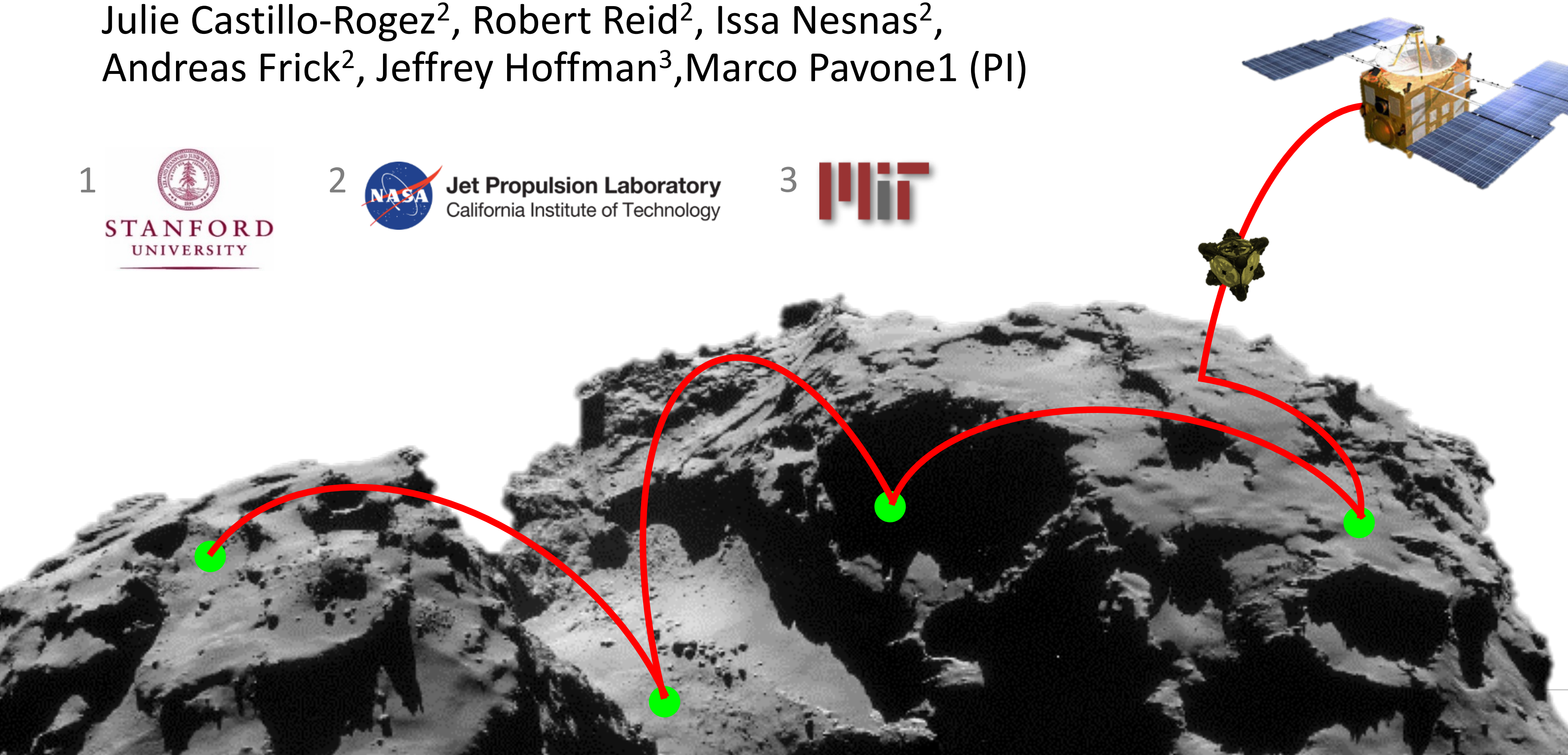
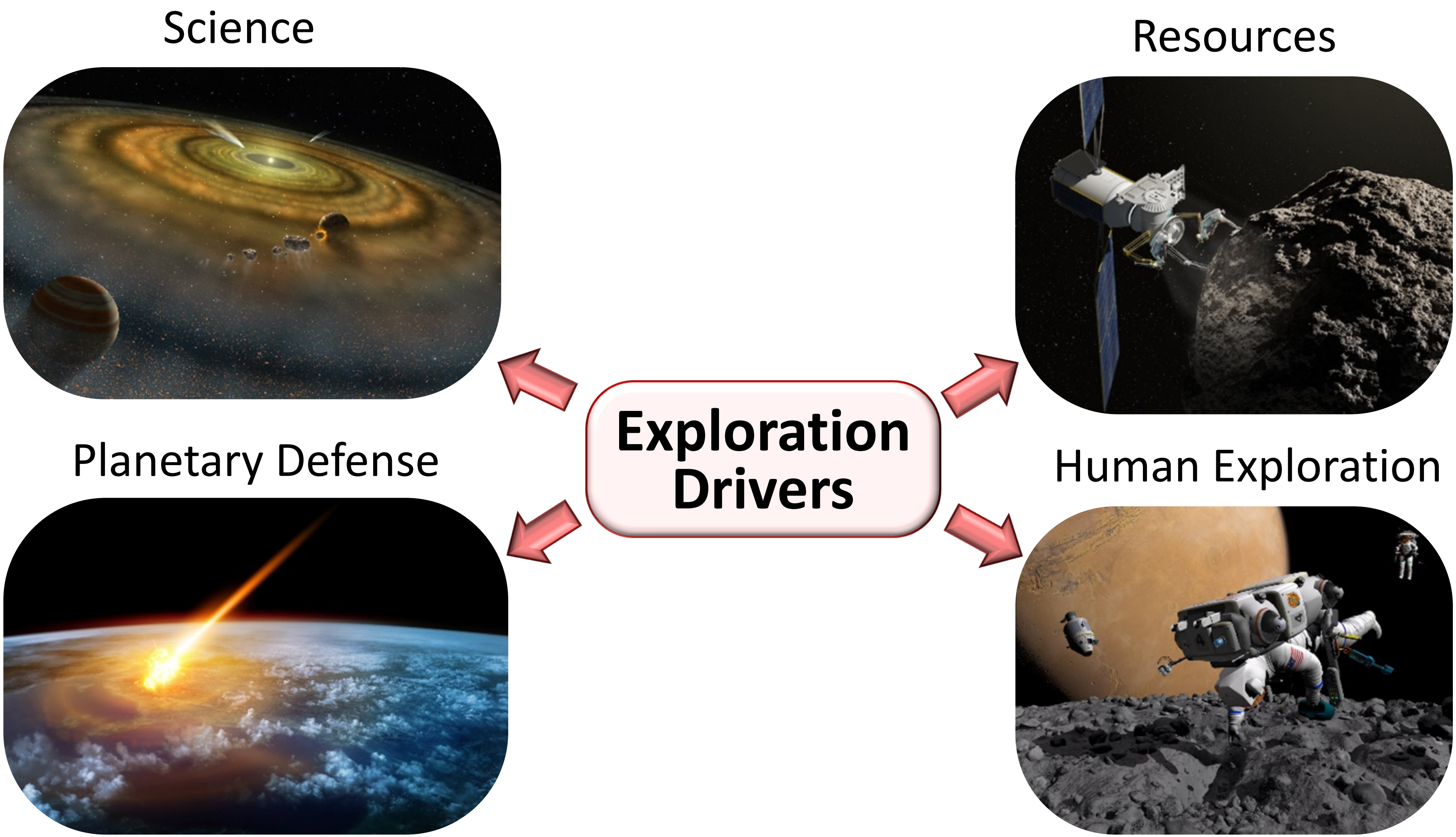
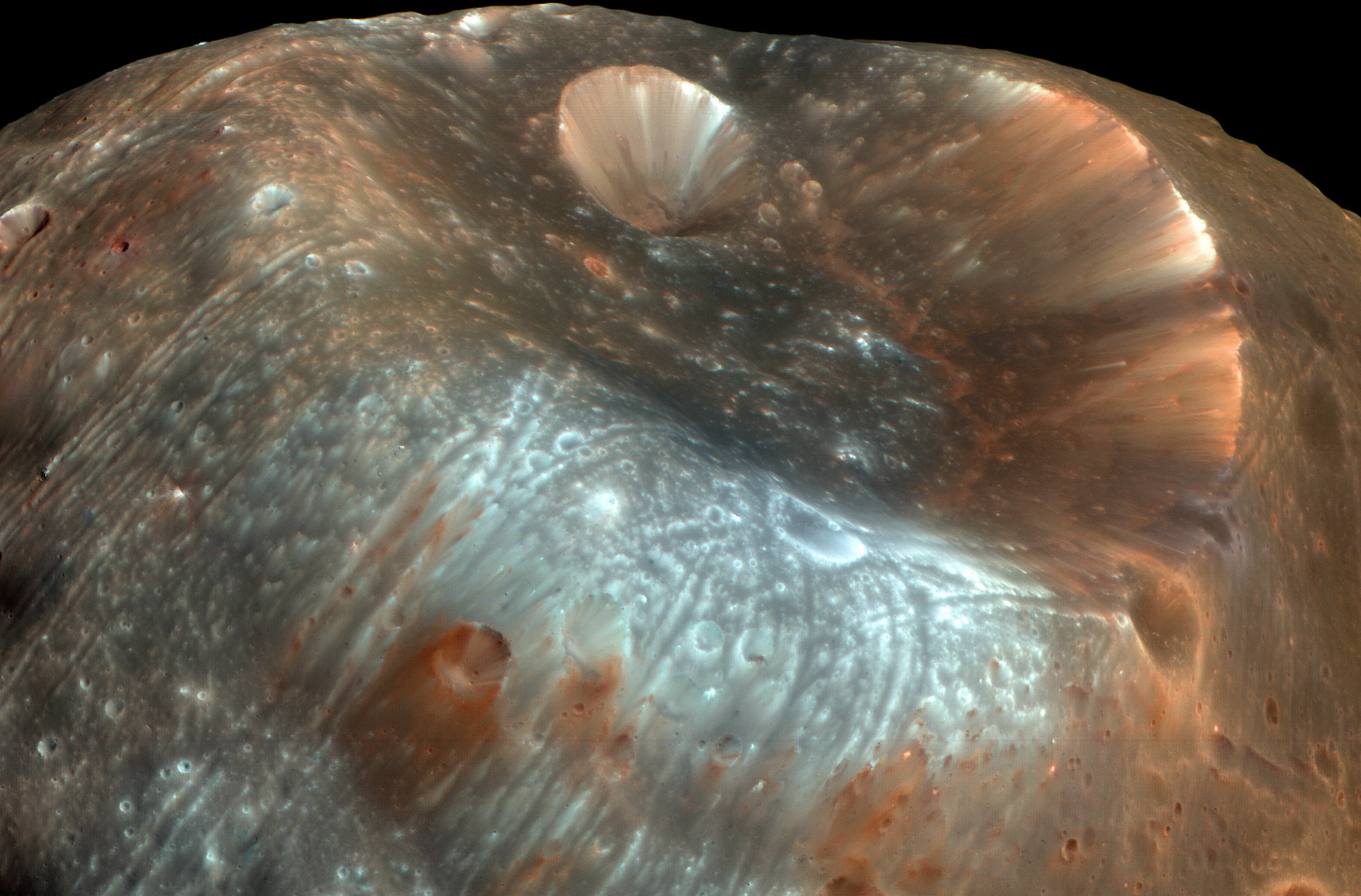
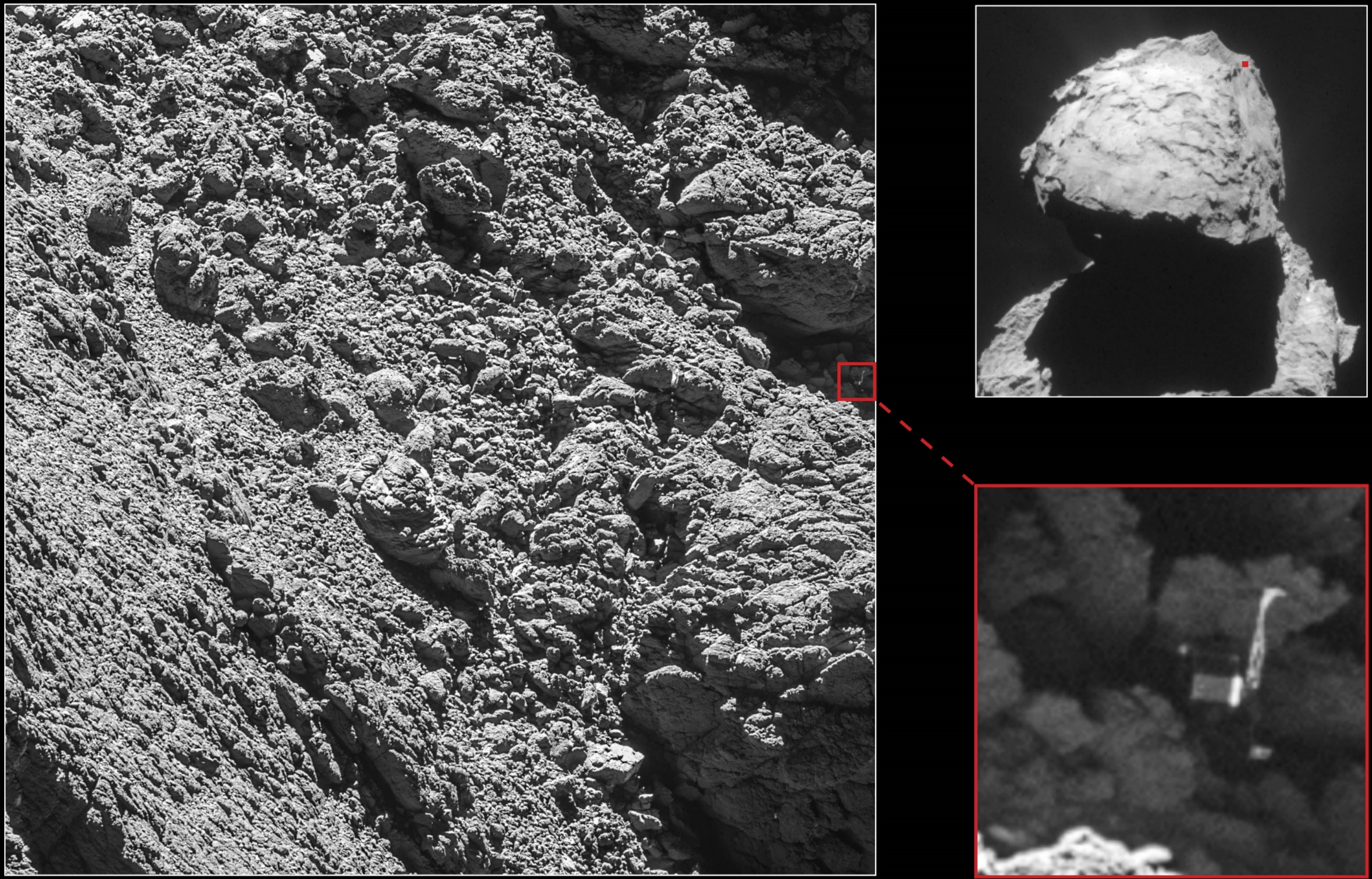


# Exploring small Solar System bodies

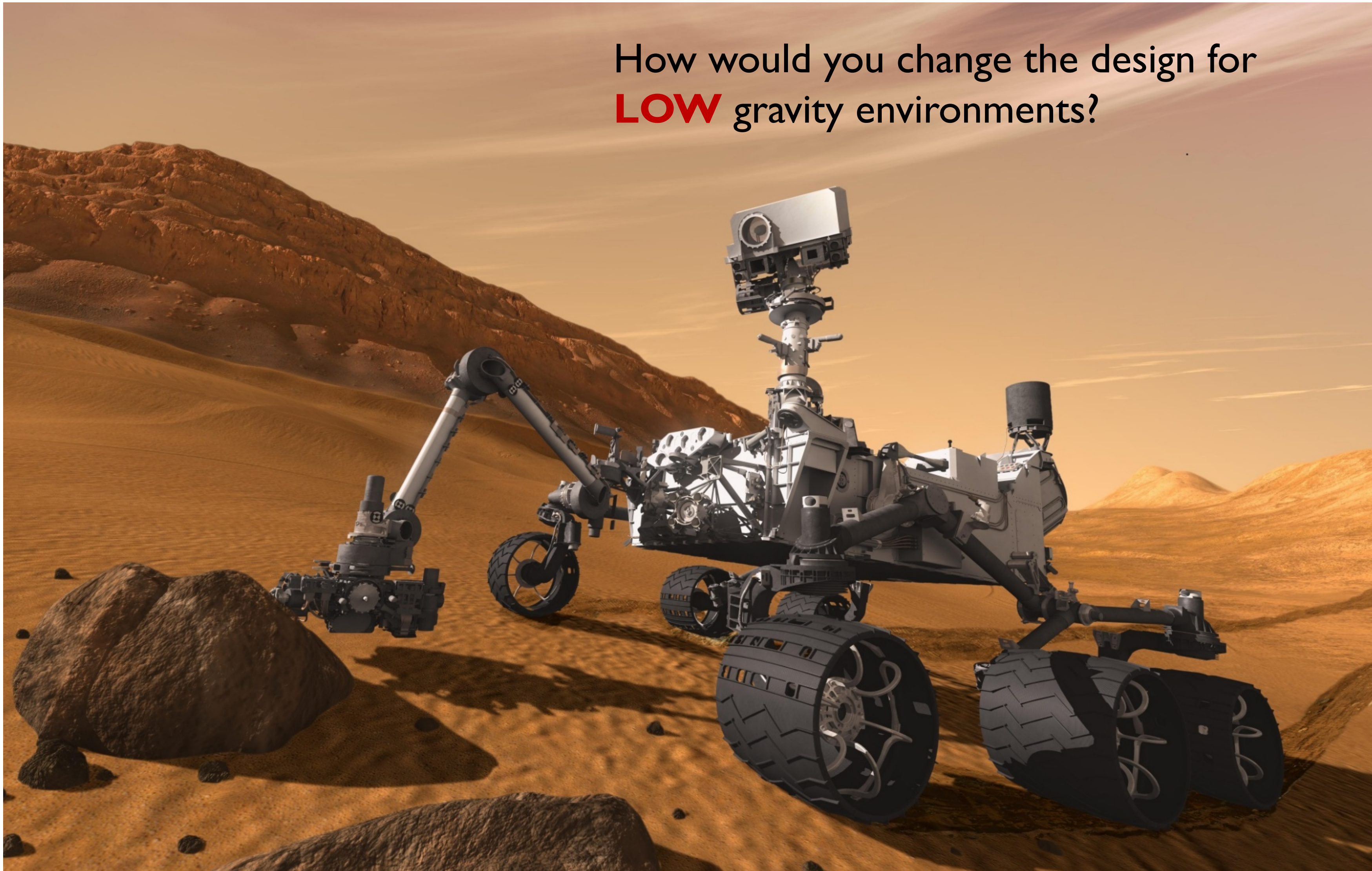


Where would you like to sample? → Need a **Rover**!





# The Big Question

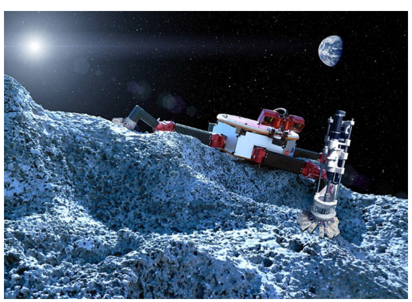


# Micro-Gravity Space Rovers

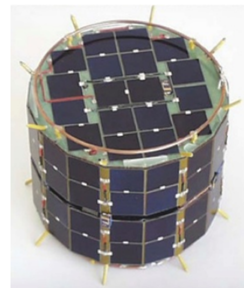
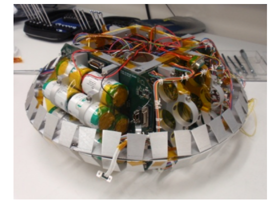
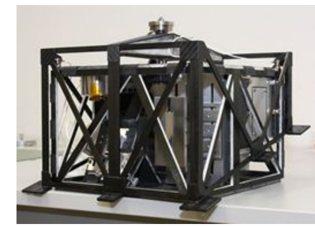
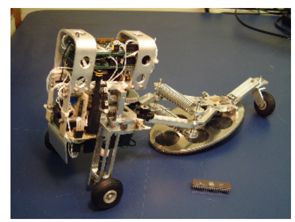
Four classes of mobility:

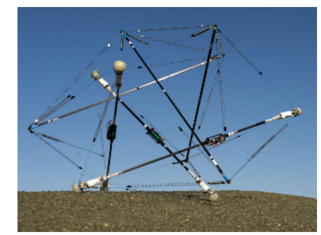
- Wheels

- Legs

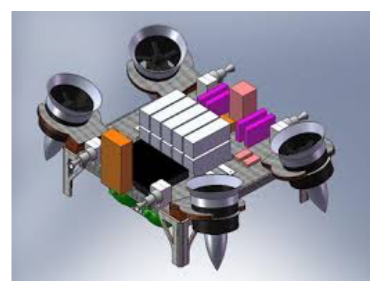


- Hopping

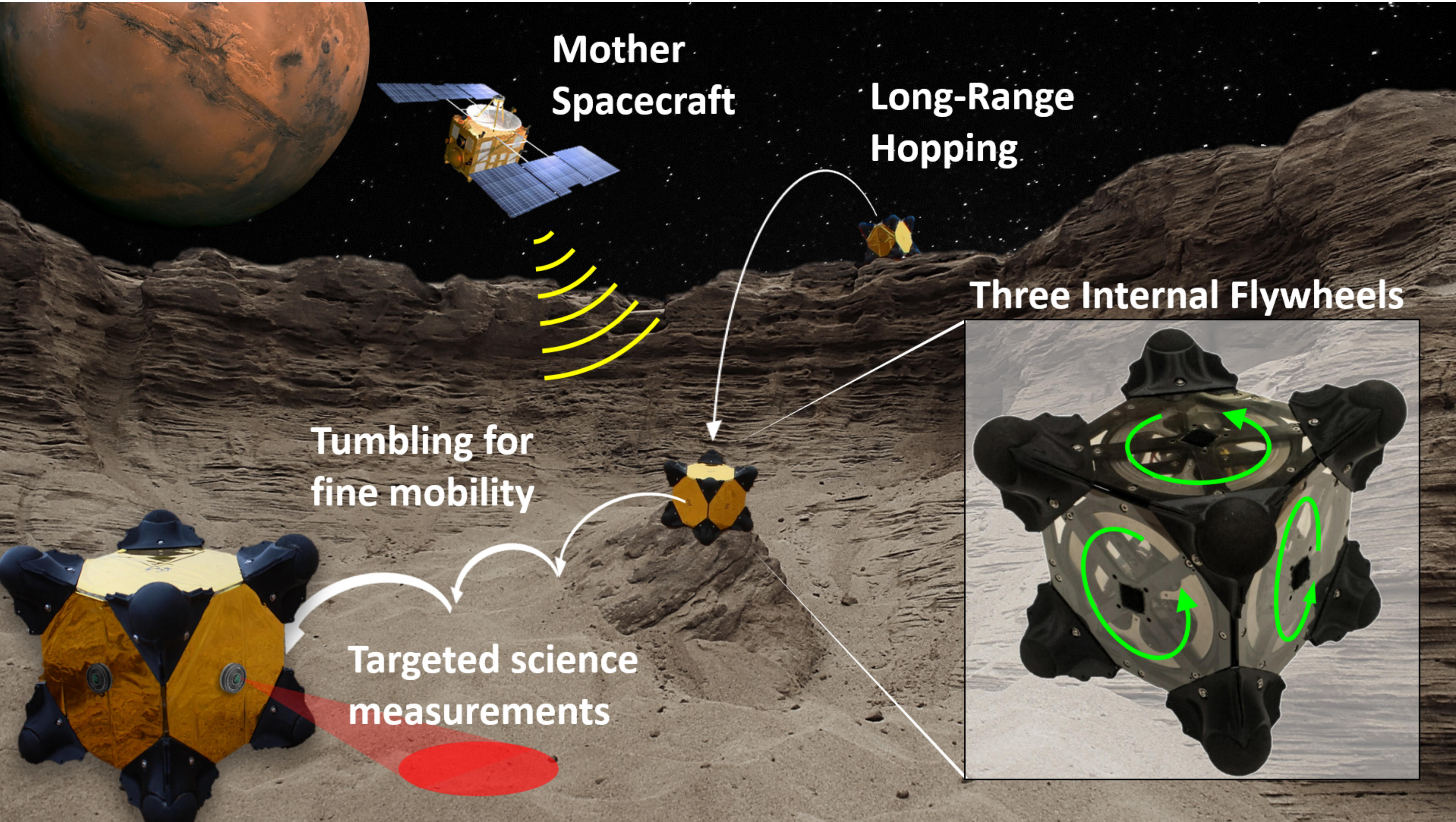


- Thrusters



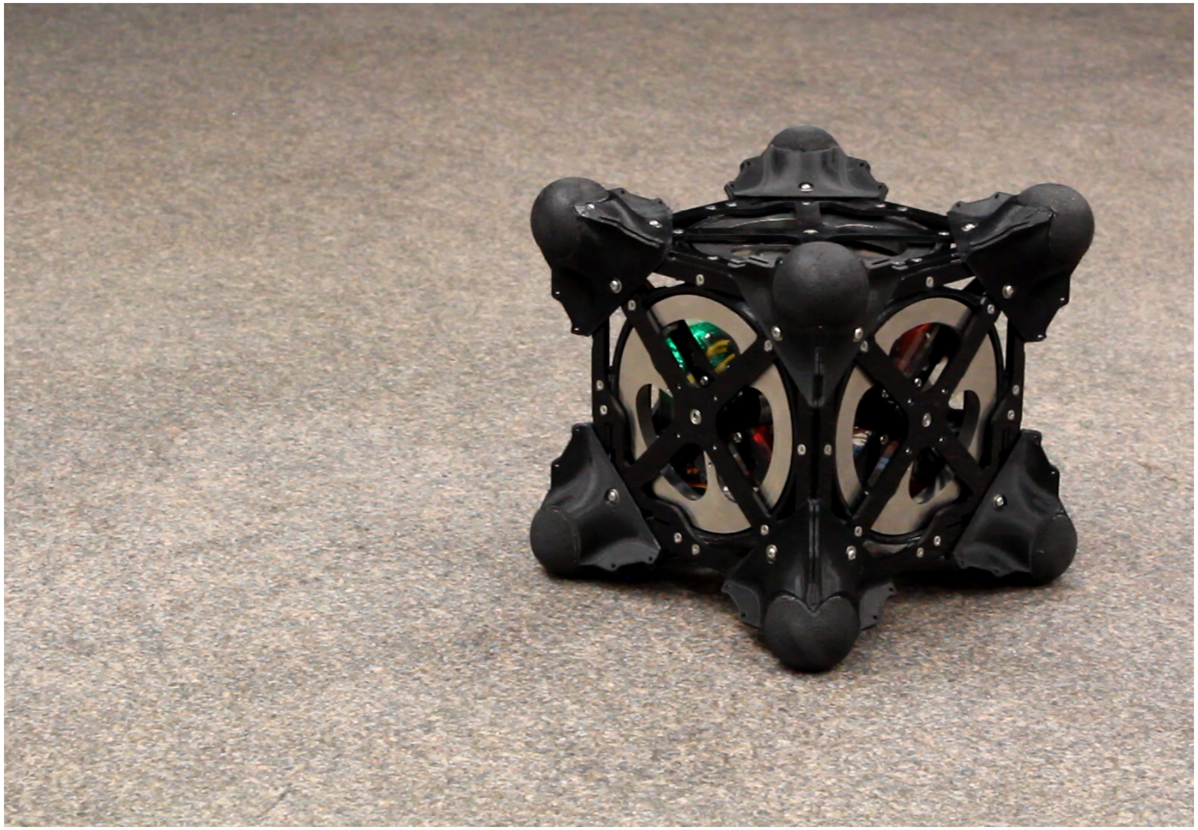

# Hedgehog hopping rovers

A mission architecture that allows the systematic and affordable in-situ exploration of small Solar System bodies.



# Mobility via Internal Actuation

**Key idea:** Swapping angular momentum



Spin up flywheels to desired speed

↓

Hit the brakes!
Generates large torque

↓

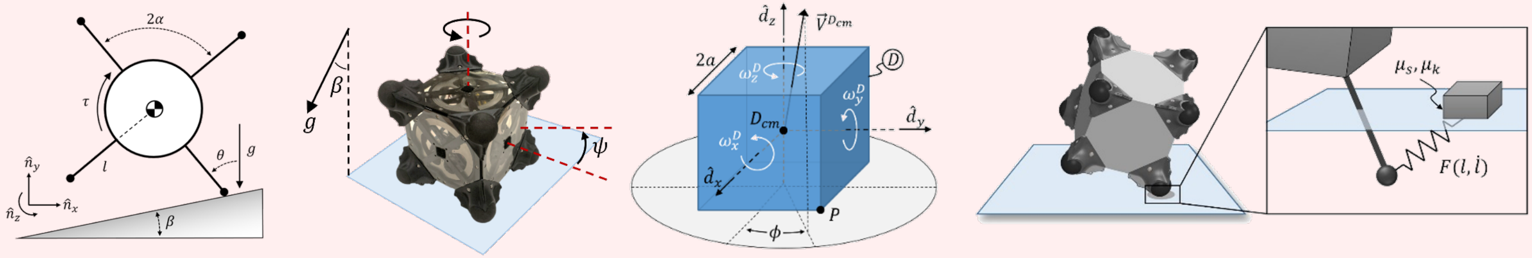
Angular momentum transferred to chassis

↓

Rover hops in a forward ballistic trajectory

# Dynamics and Control

## Analytical and numerical models




[Hockman, et al. JFR, 2016]

## Control Laws

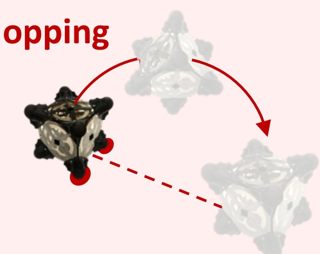
$$\omega_{\mathrm{f}}(d_{\mathrm{h}}) = \sqrt{\frac{d_{\mathrm{h}} g}{\eta^2 l^2 \sin(2(\alpha+\beta))}}$$

$$\begin{bmatrix} I_f & 0 & 0 \\ 0 & I_f & 0 \\ 0 & 0 & I_f \end{bmatrix} \begin{bmatrix} \omega_{F^x} \\ \omega_{F^y} \\ \omega_{F^z} \end{bmatrix} = \begin{bmatrix} I_D + 2m_D a^2 & -m_D a^2 & m_D a^2 \\ -m_D a^2 & I_D + 2m_D a^2 & m_D a^2 \\ m_D a^2 & m_D a^2 & I_D + 2m_D a^2 \end{bmatrix} \begin{bmatrix} \omega_x^D \\ \omega_y^D \\ \omega_z^D \end{bmatrix}$$

$$\omega_f(\mu_k, \psi_d) = \frac{I_p}{I_f} \sqrt{\frac{-2\tau_\mu \psi_d}{I_p}}$$

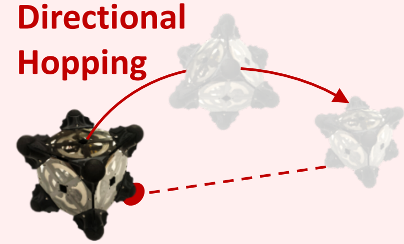
## A suite of *controllable* motion primitives

**Hopping**



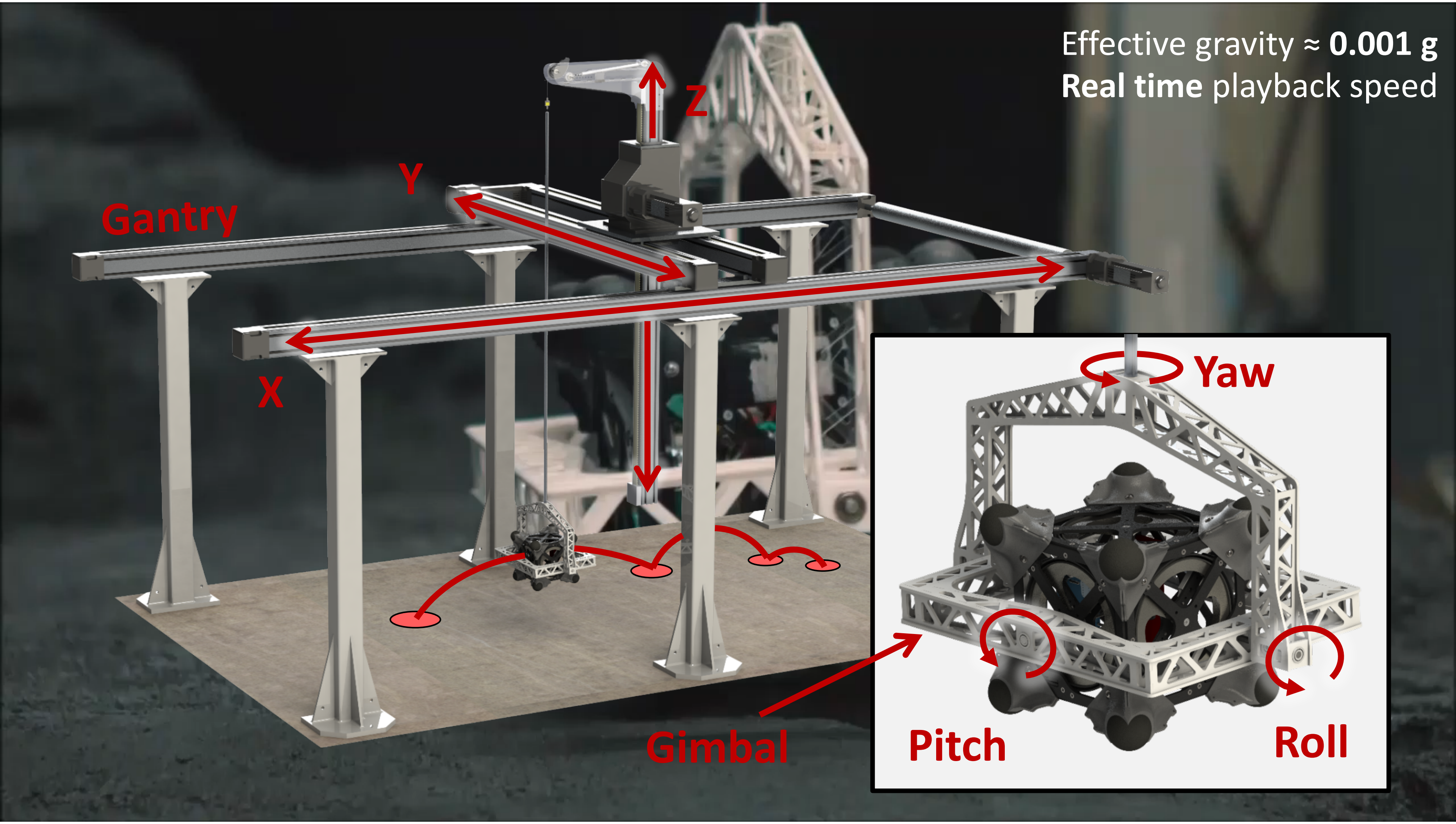
**Tumbling**

**Directional Hopping**

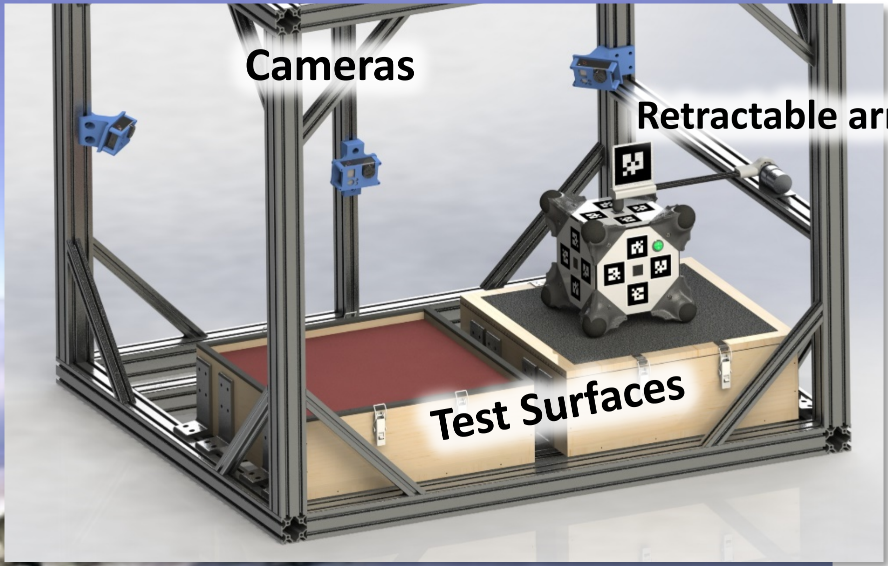


**Twisting**

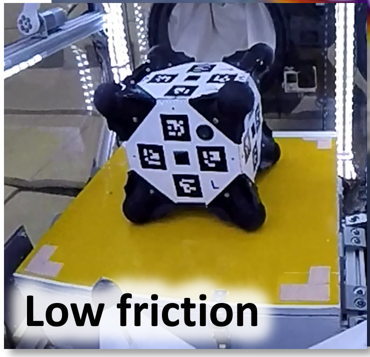
# Experiments in Microgravity Test Bed

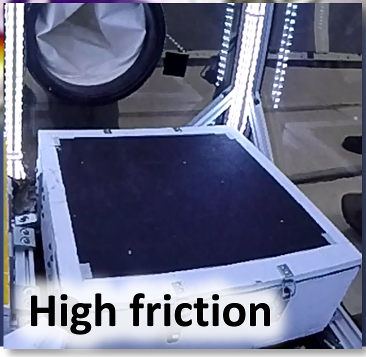


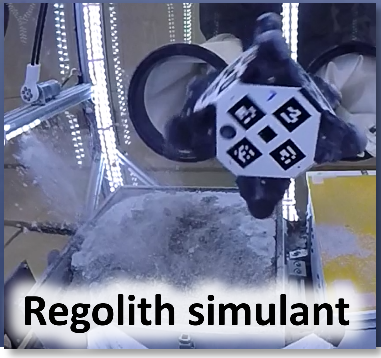
# Parabolic Flight Experiments




Four different test surfaces:

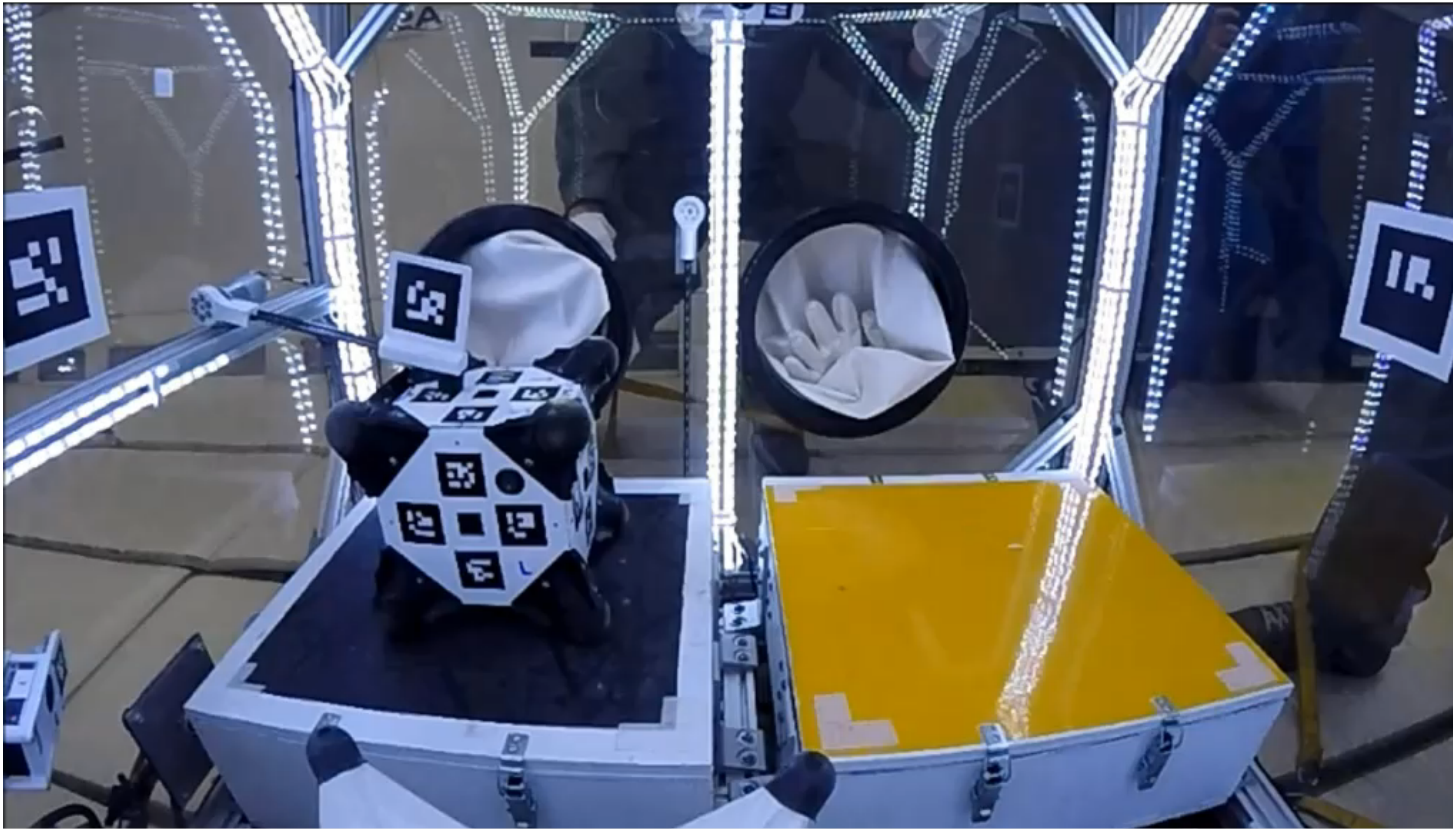



# Parabolic Flight Experiments

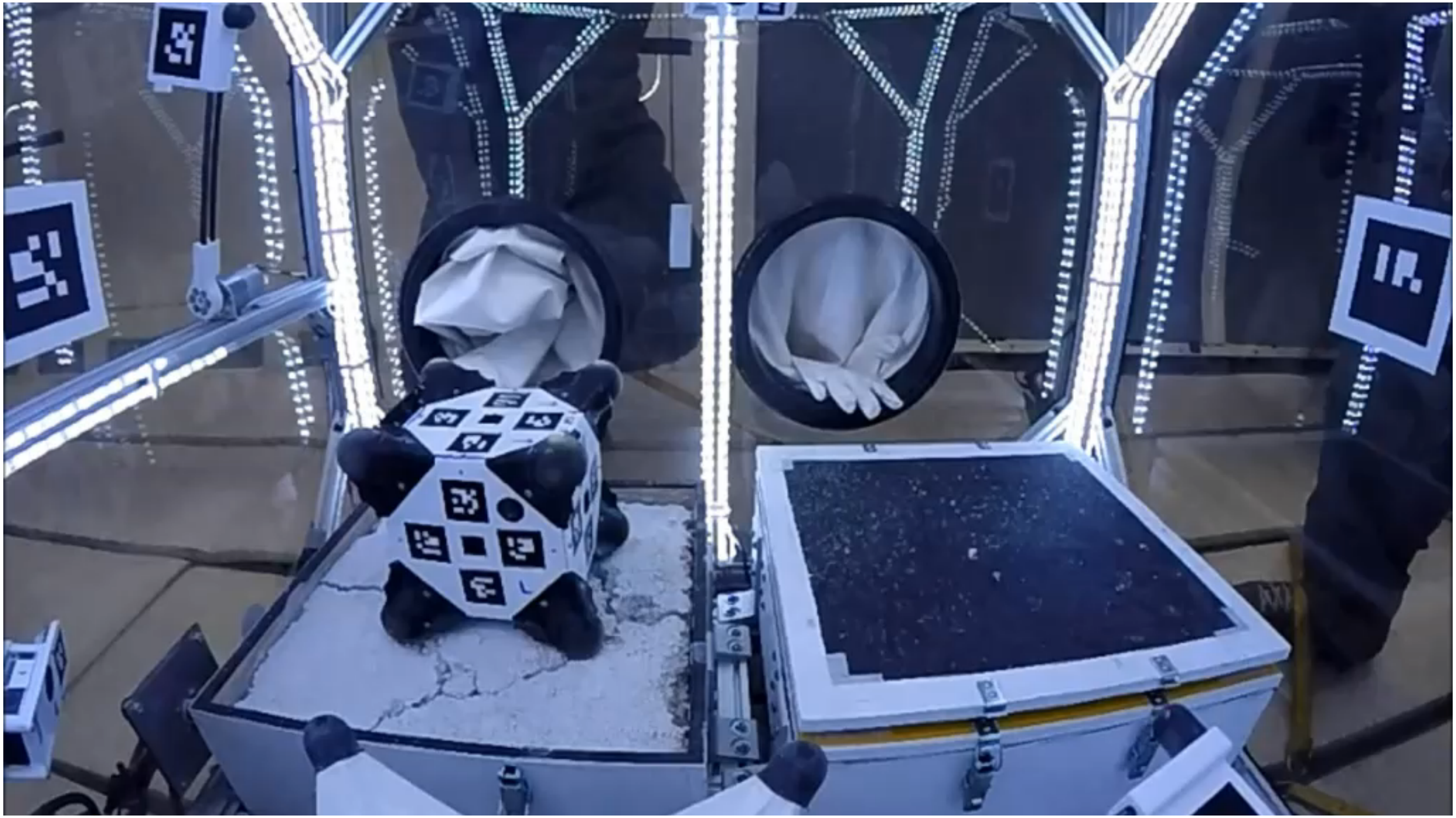
## Hopping on rough surface



[Hockman, et al. ISER, 2016]

# Parabolic Flight Experiments

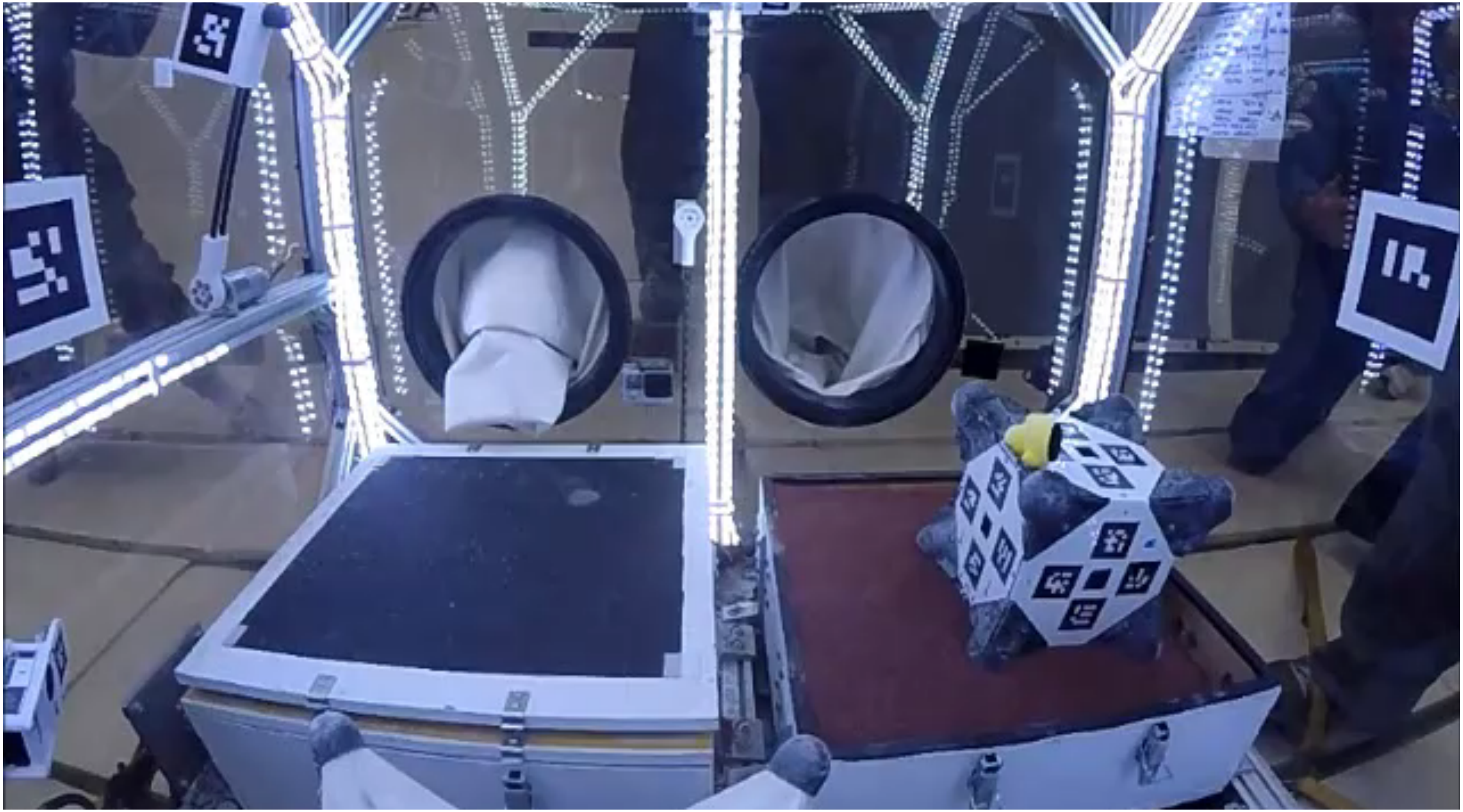
## Hopping on regolith simulant



[Hockman, et al. ISER, 2016]

# Parabolic Flight Experiments

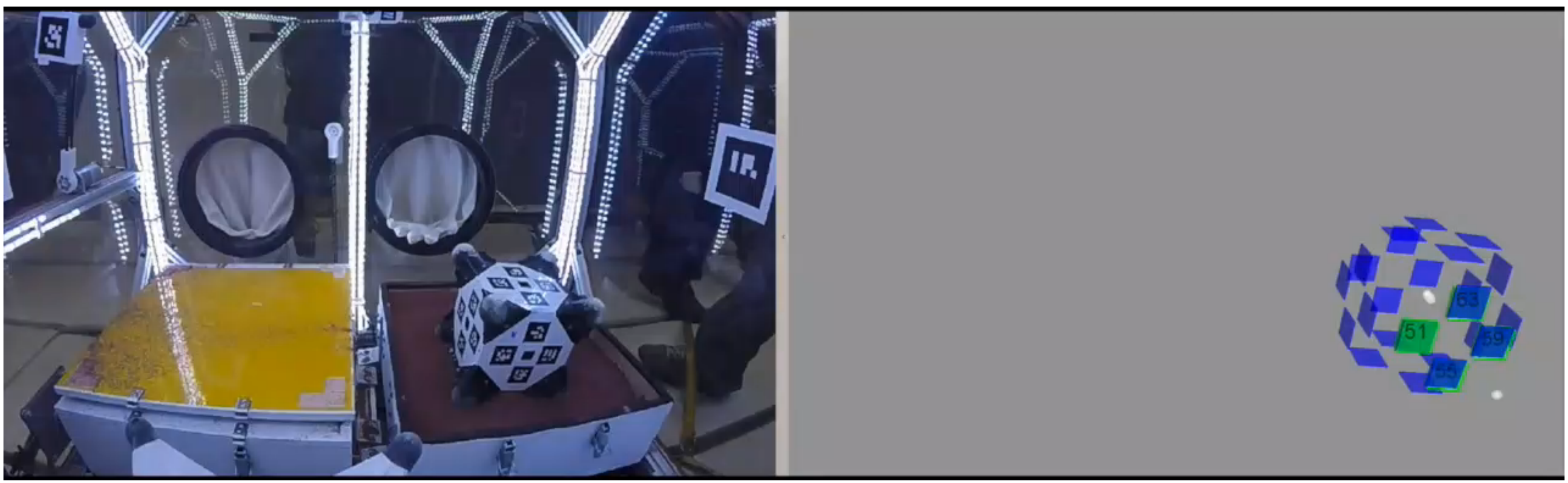
## Hopping on sand



[Hockman, et al. ISER, 2016]

# Experimental Results

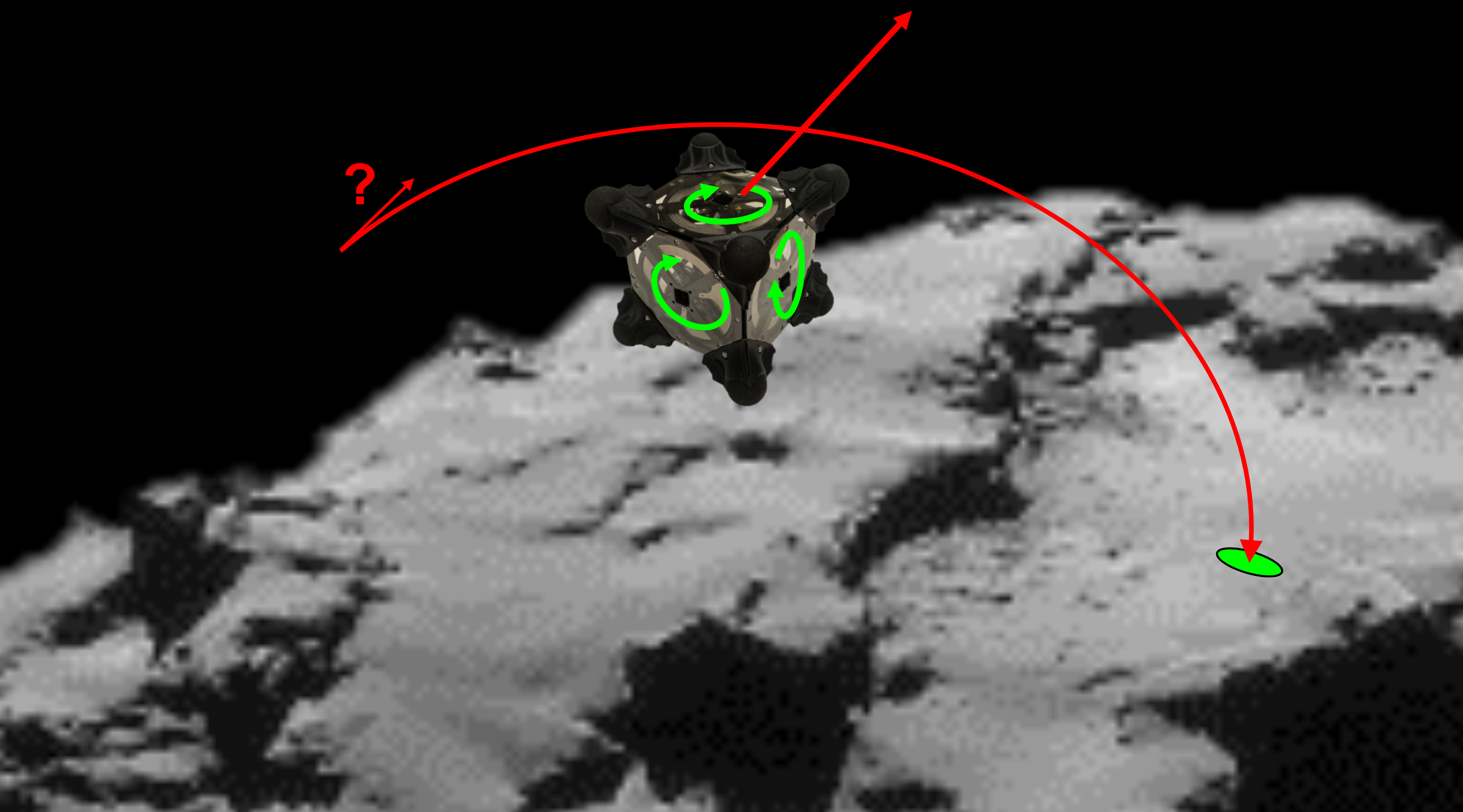
- Extract launch trajectory from imagery and compare with predictions
- Good agreement for rigid surfaces (< 10% error)
- More accurate granular media contact models needed
- Bottom line: Controlled mobility is possible and uncertainty can be characterized



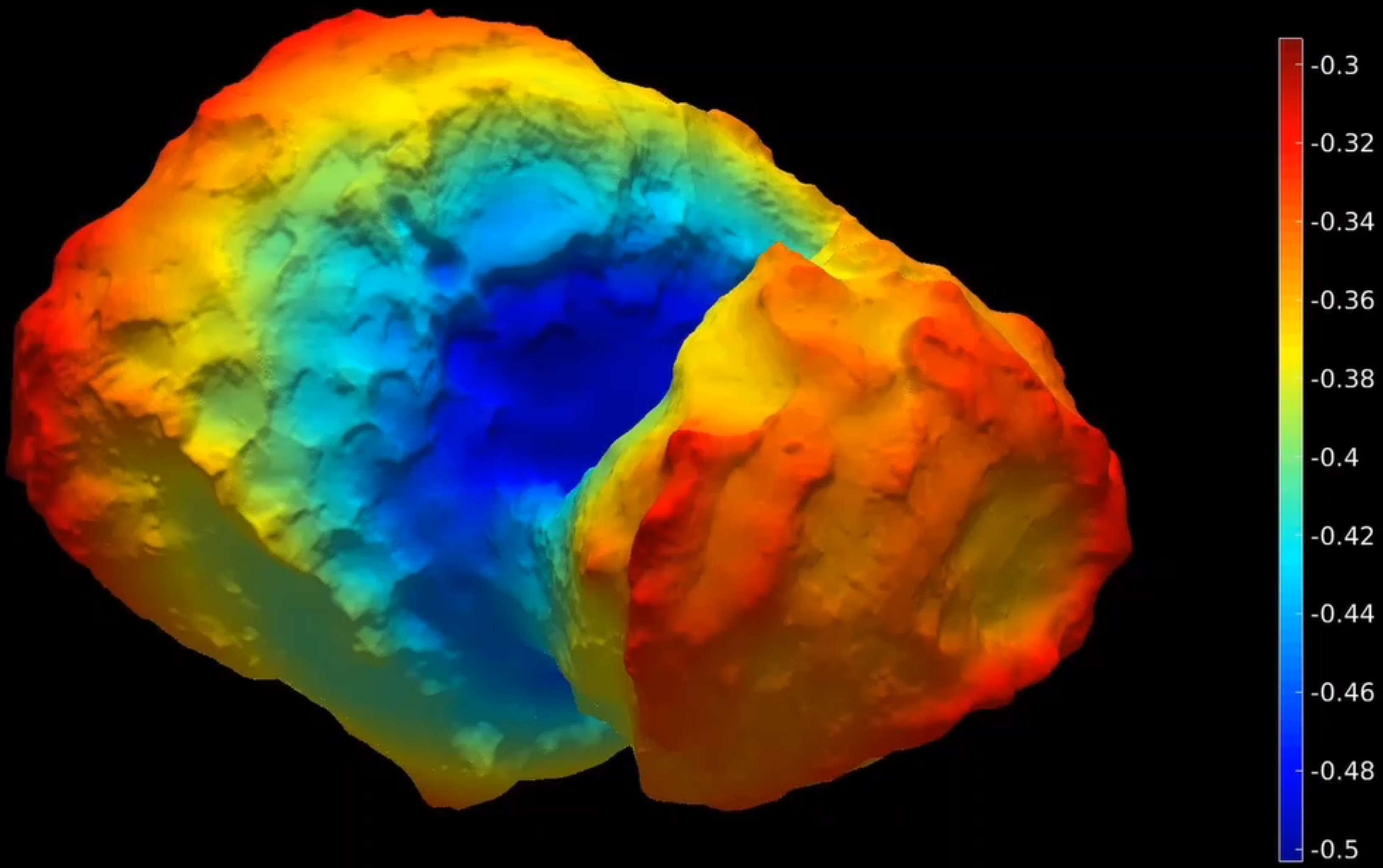
[Hockman, et al. ISER, 2016]

# From controlled hopping... to *targeted* mobility

→ Nonlinear two-point boundary value problem

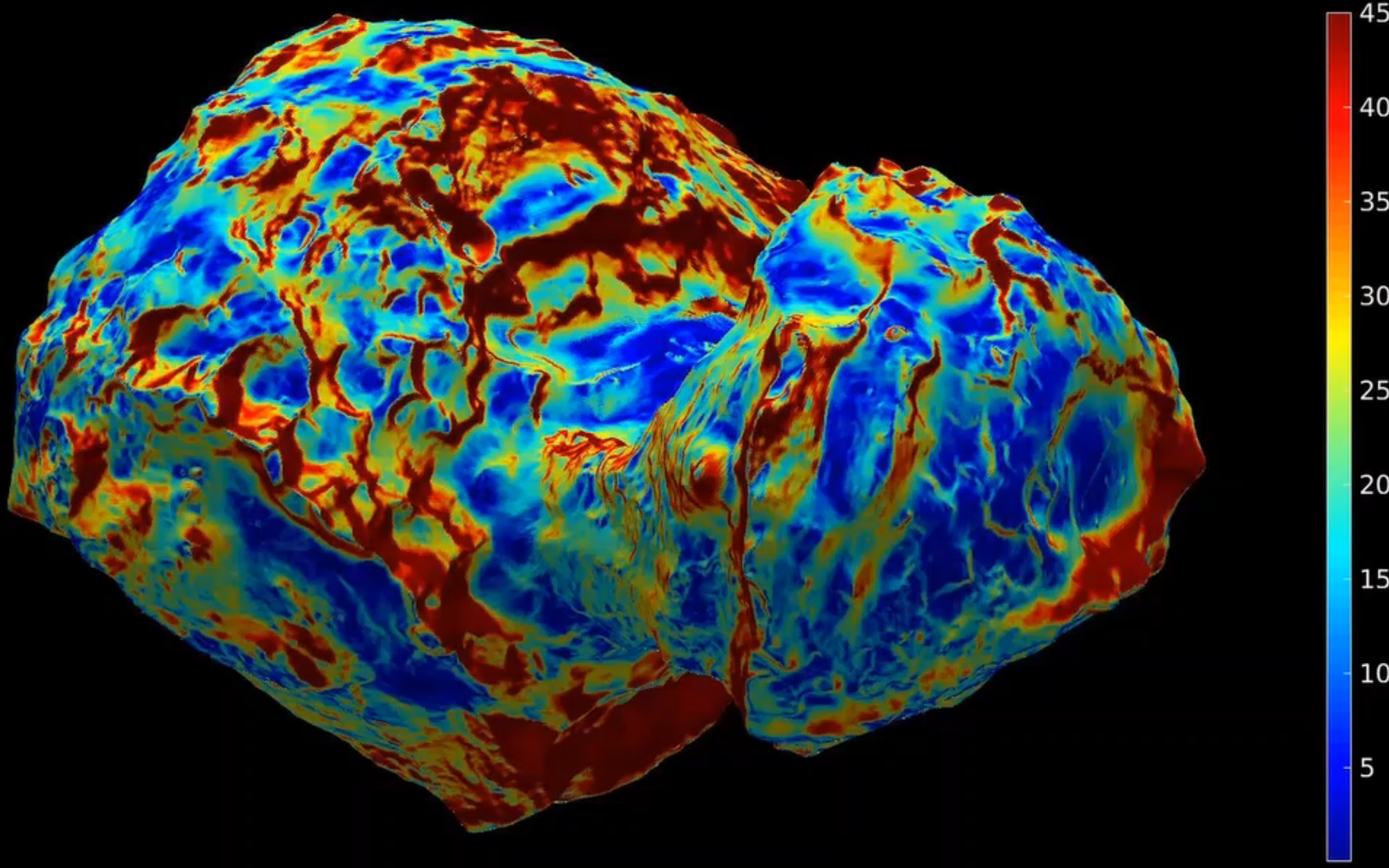


# Which way is up?




Geopotential map of comet 67P

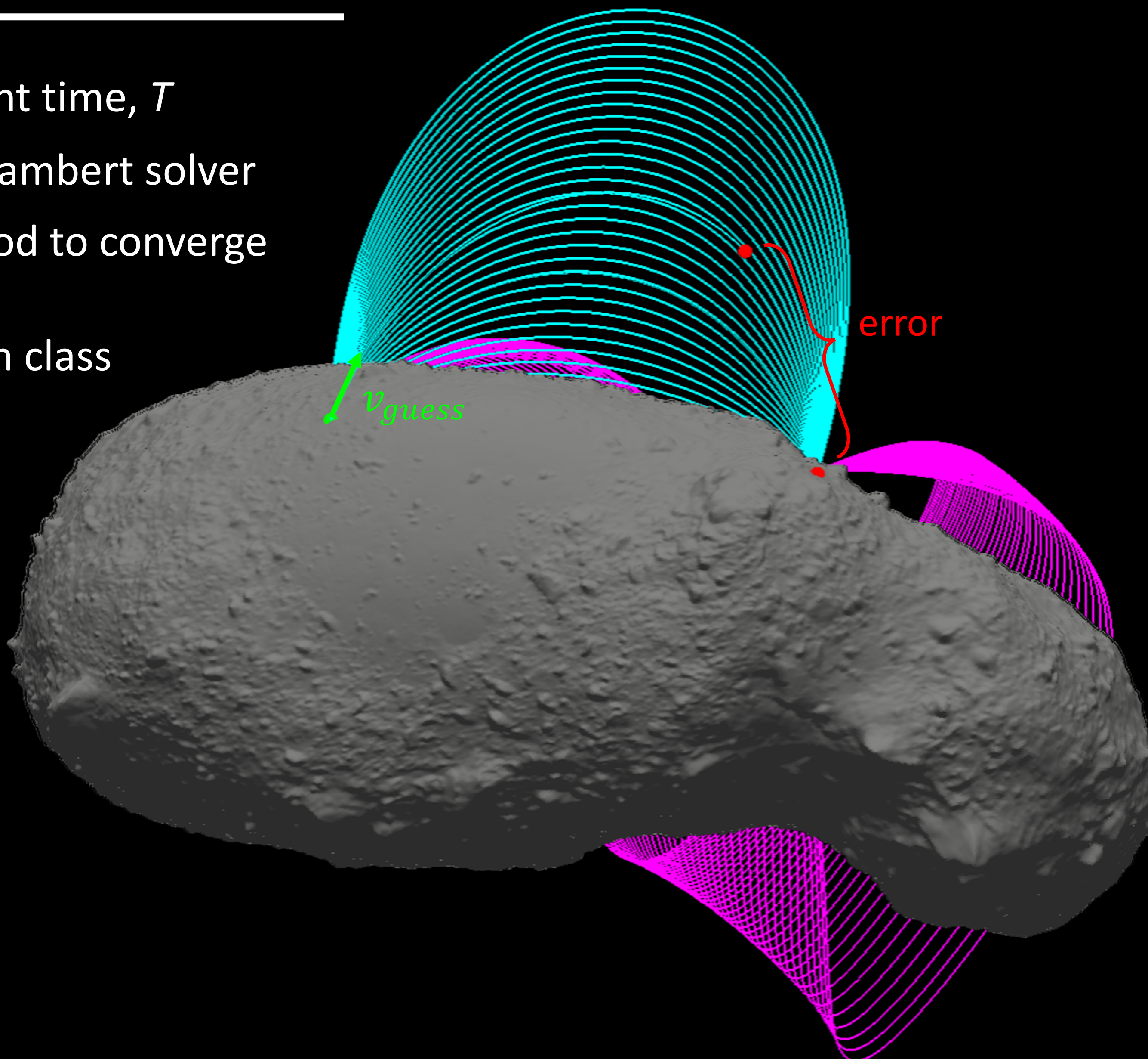
# Where can the rover go?




Surface slope map of comet 67P

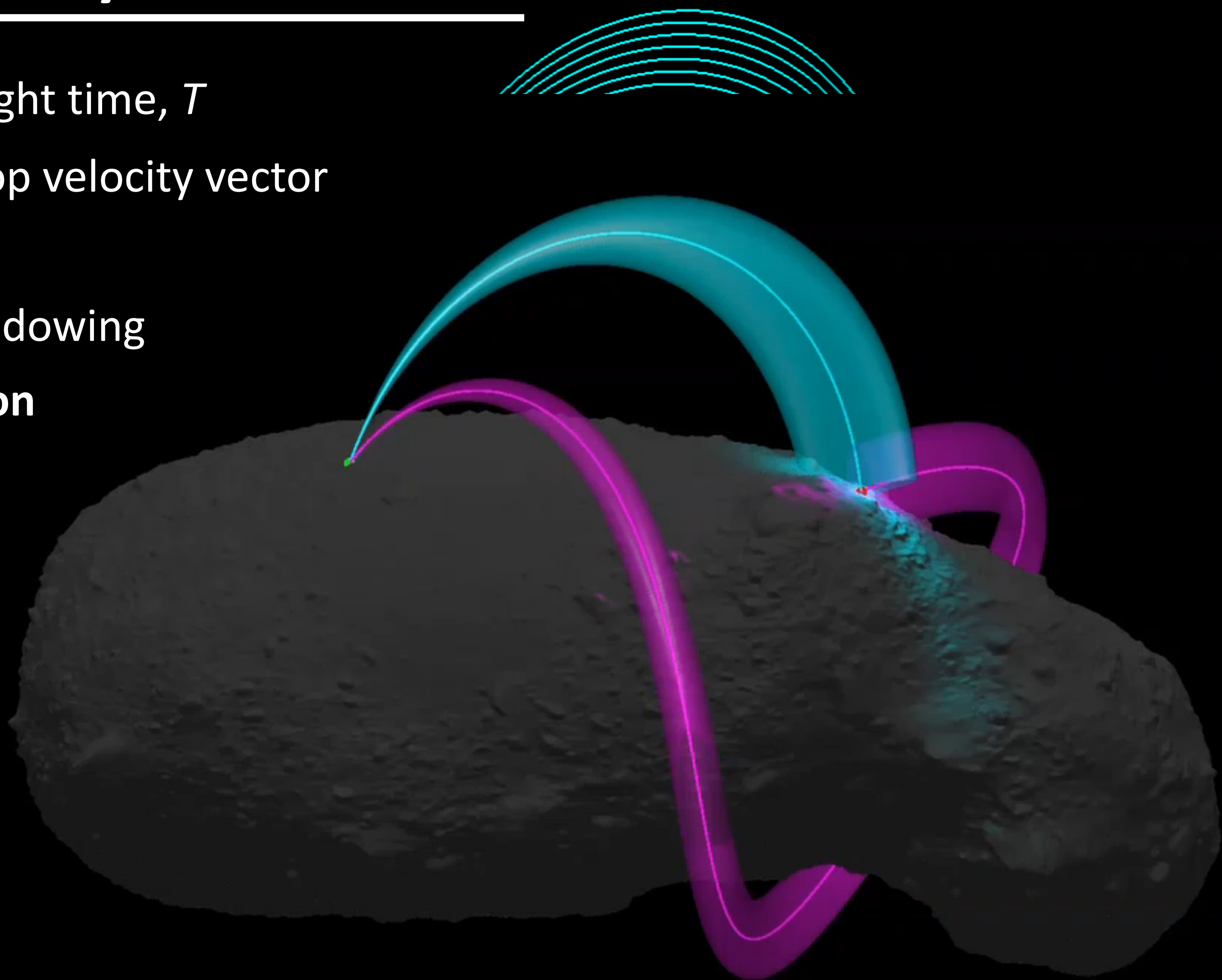
# Going from A to B

- Choose desired flight time, *T*
- Initial guess using Lambert solver
- Use shooting method to converge on true solution
- Extrapolate solution class
- Search for other classes of solutions



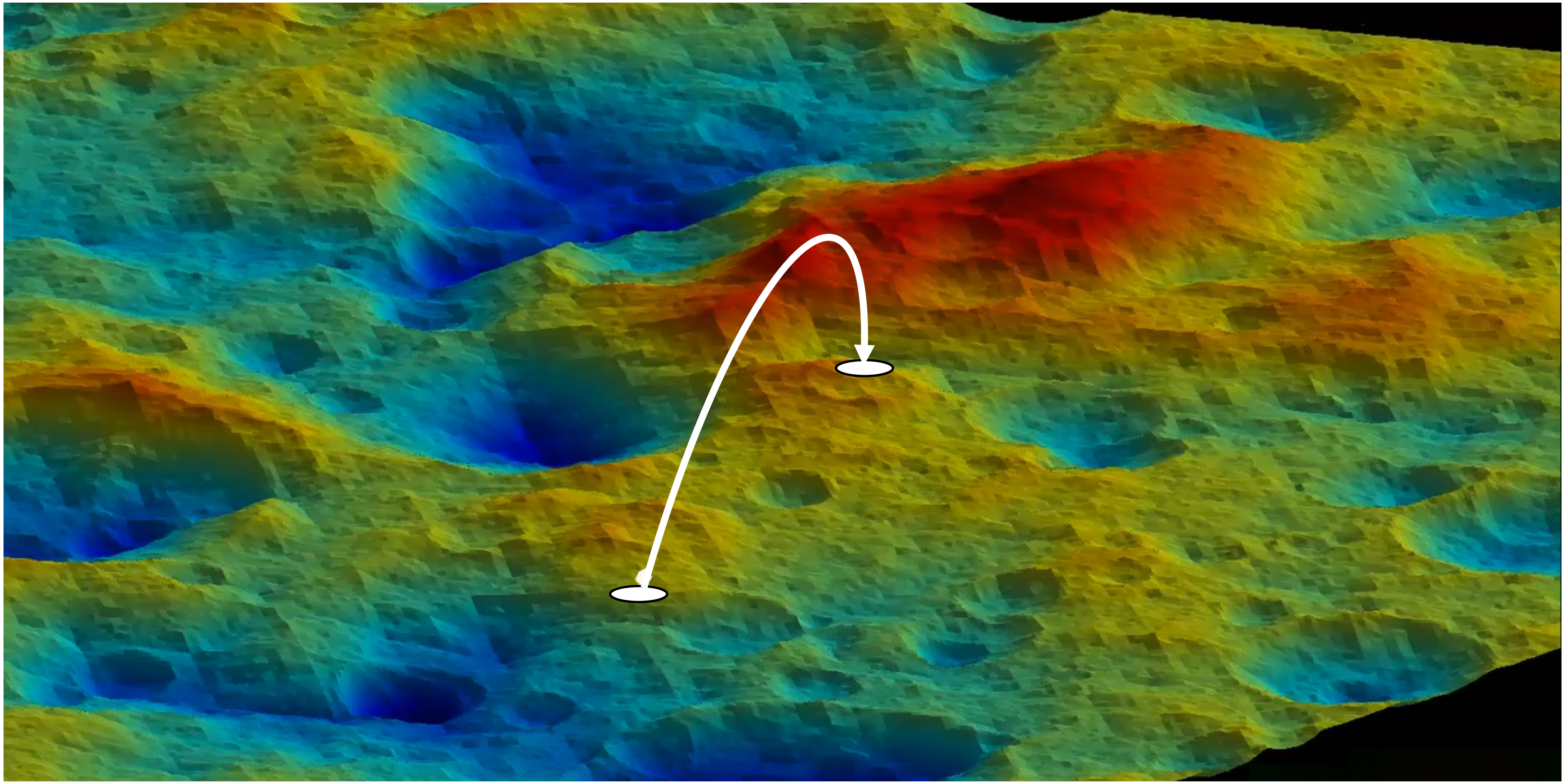
# Which trajectory to choose?

- Constraint on flight time, $T$
- Constraint on hop velocity vector
- Surface imaging
- Illumination/shadowing
- **Error propagation**



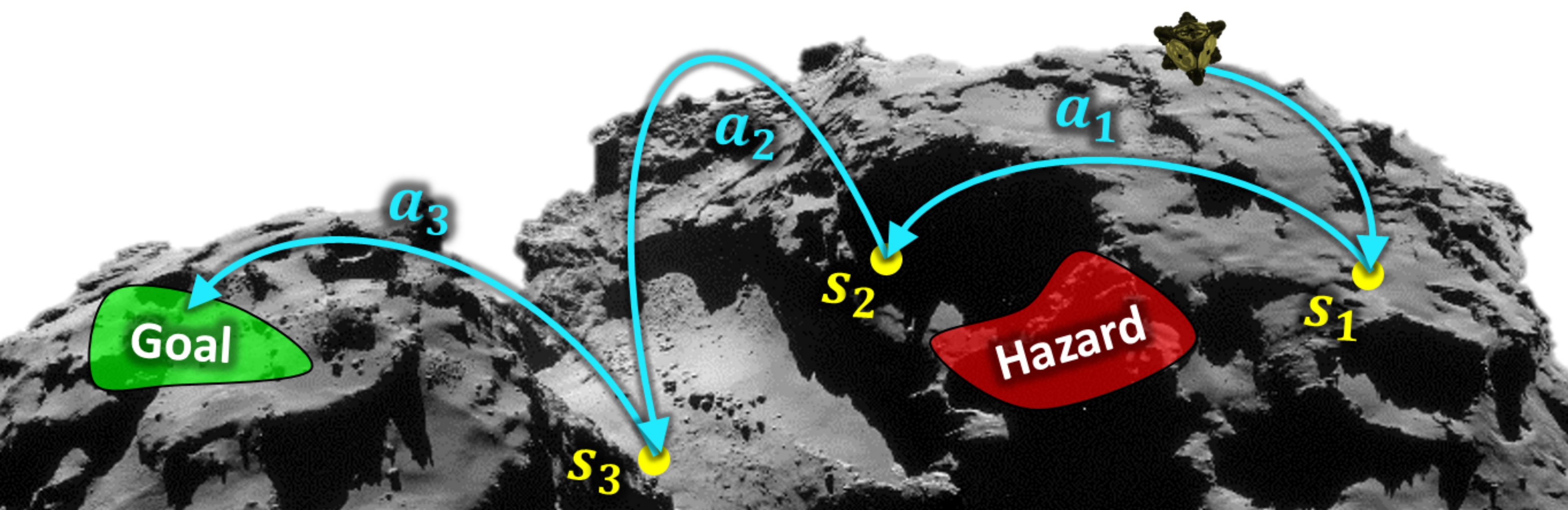
# But what about bouncing?

- Impact on the surface is likely to be somewhat *elastic*
- Series of bounces produces chaotic scattering



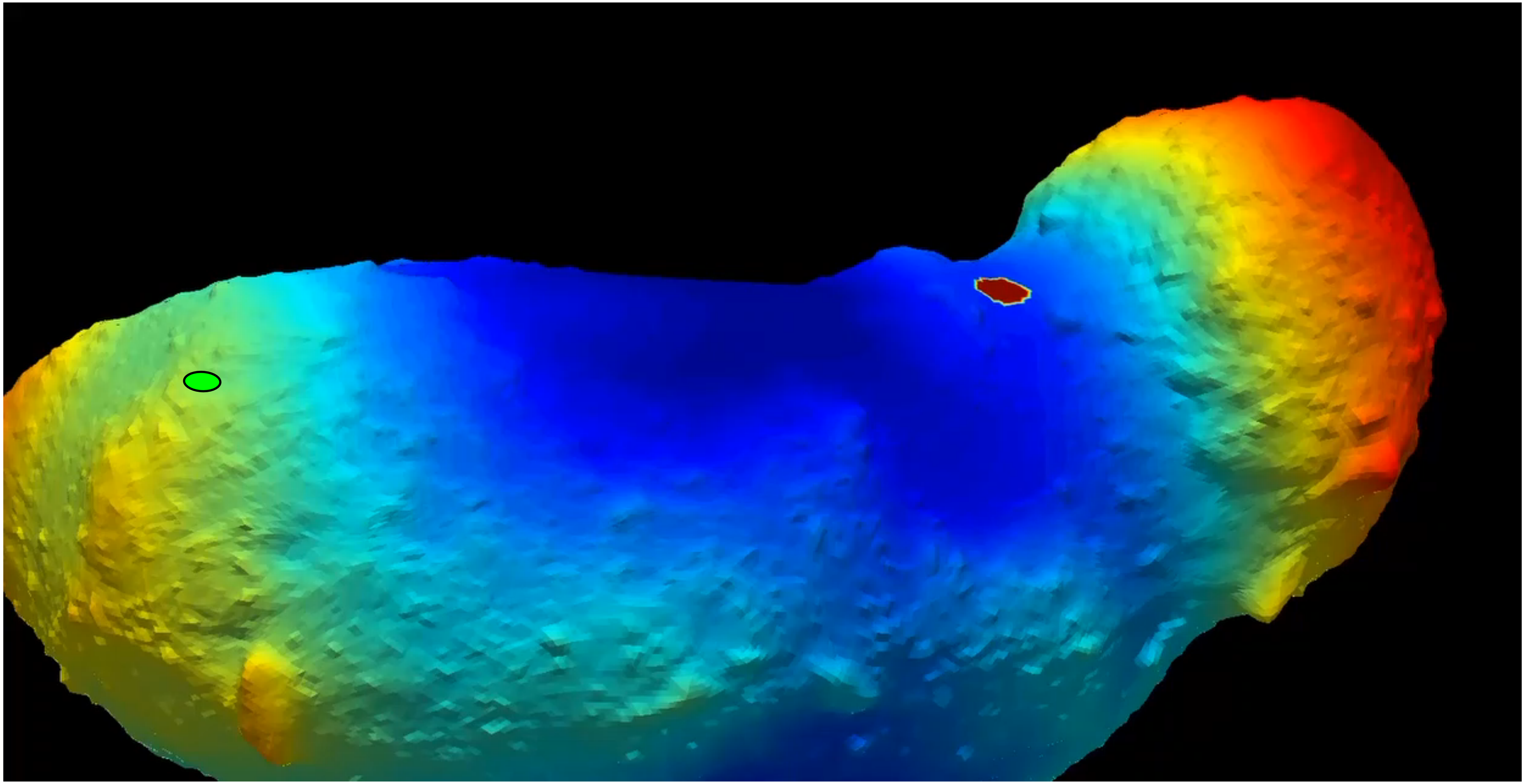
## Autonomous mobility as a *sequential* decision process

**Localization**: where am I? → **Planning**: where should I go? → **Execution:** how do I get there? → Ballistic flight and bouncing → (back to Localization)



# "Learning" a control policy

- Tools from *Reinforcement Learning* to compute approximately optimal control policies from simulation data



# Conclusions

- Hopping rovers are a promising solution for targeted mobility in microgravity.
- Models, simulations, and experiments suggest motion accuracy of ~10%.
- Autonomous navigation requires very different tools than for wheeled rovers.

## Ongoing and Future Work

- Develop more realistic contact models for granular media and friable regolith
- Extend planning algorithms to be "adaptive" and account for localization uncertainty
- Impact damping strategies to mitigate bouncing
- High-fidelity GPU-based framework for integrated planning and localization simulations

# Questions

## Publications


B. Hockman, R. Reid, I. A. D. Nesnas, and Marco Pavone. Experimental Methods for Mobility and Surface Operation of Microgravity Robots. International Symposium on Experimental Robotics, October 2016 (in review)

B. Hockman, A. Frick, I. Nesnas, and M. Pavone. Design, control, and experimentation of internally-actuated rovers for the exploration of low-gravity planetary bodies. In Conf. on Field and Service Robotics, Toronto, Canada, June 2015. **Best Student Paper Award**

R. Reid, L. Roveda, I. Nesnas, and M. Pavone. Contact dynamics of internally-actuated platforms for the exploration of small Solar System bodies. In Proc. International Symposium on Artificial Intelligence, Robotics and Automation in Space, Montreal, Quebec, June 2014.

A. Koenig, M. Pavone, J. Castillo, and I. Nesnas. A dynamical characterization of internally-actuated microgravity mobility systems. In Proc. IEEE Int. Conf. Robotics and Automation, Hong Kong, China, June 2014.

R. Allen, M. Pavone, C. McQuin, I. Nesnas, J. Castillo, T. N. Nguyen, and J. Homan. Internally-actuated rovers for all access surface mobility: Theory and experimentation. In Proc. IEEE Int. Conf. Robotics and Automation, Karlsruhe, Germany, May 2013.

M. Pavone, J. Castillo, I. Nesnas, J. Homan, and N. Strange. Spacecraft/rover hybrids for the exploration of small Solar system bodies. In Proc. IEEE Aerospace Conference, Big Sky, Montana, March 2013.

J. Castillo, M. Pavone, I. Nesnas, and J. Homan. Observational strategies for the exploration of small Solar system bodies. In Proc. IEEE Aerospace Conference, Big Sky, Montana, March 2012.



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# System Architecture

- Baselined for Phobos mission
- Leverages subsystems designed for JPL's interplanetary CubeSats (~TRL 6)
- 8U (20cm) design, scalable from 1U to 27U

### 1. C&DH/Avionics

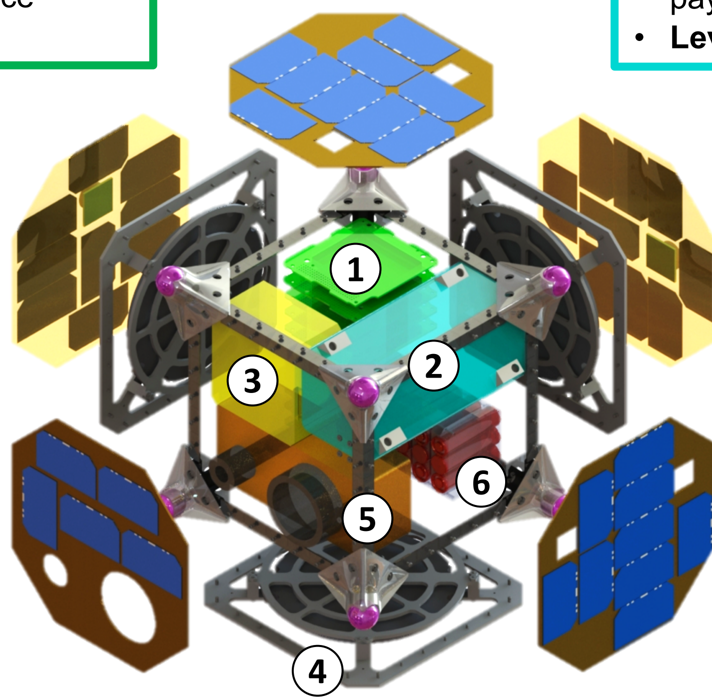
- JPL Interplanetary CubeSat C&DH Board
- Processing capability for semi-autonomous ops and agile science
- **Leverages: NEA Scout**

### 2. Cold Gas Propulsion (Optional)

- For soft landing from ~20m/s deployment
- Alternatively, volume can be used for payload or more batteries
- **Leverages: INSPIRE, MarCO, NEAS**

### 3. Telecom

- UHF or S band Relay to Mothership
- antennas embedded in frame
- **Leverages: INSPIRE**




### 4. GNC Sensors/Actuators

- 3 flywheels
- 3+ wide angle cameras
- Sun Sensors + IMU
- Star Tracker
- **Leverages: JPL Visual Odometry frameworks & VSLAM algorithms**

### 5. Science Instruments

- X-Ray Spectrometer
- Thermocouple
- Microscope
- Cameras + Accelerometers
- **Leverages: APXS (Pathfinder/MER/MSL)**

### 6. Electrical Power System

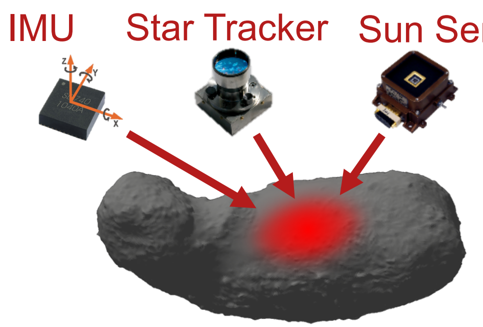
- Lithium primary and secondary batteries ( >1000 W-h @12V)
- Optional solar panels
- **Leverages: INSPIRE, MarCO, NEA Scout**

# Collaborative Localization and Mapping

A hybrid localization approach is being explored:

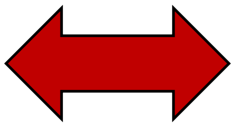
## Coarse / Global Estimation

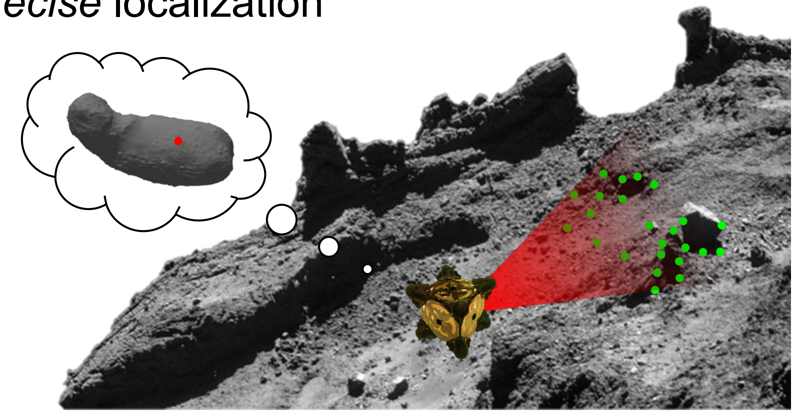
Inertial and optical sensors provide *approximate* localization.




## Fine / Local Estimation

Collaborative visual SLAM allows more *precise* localization



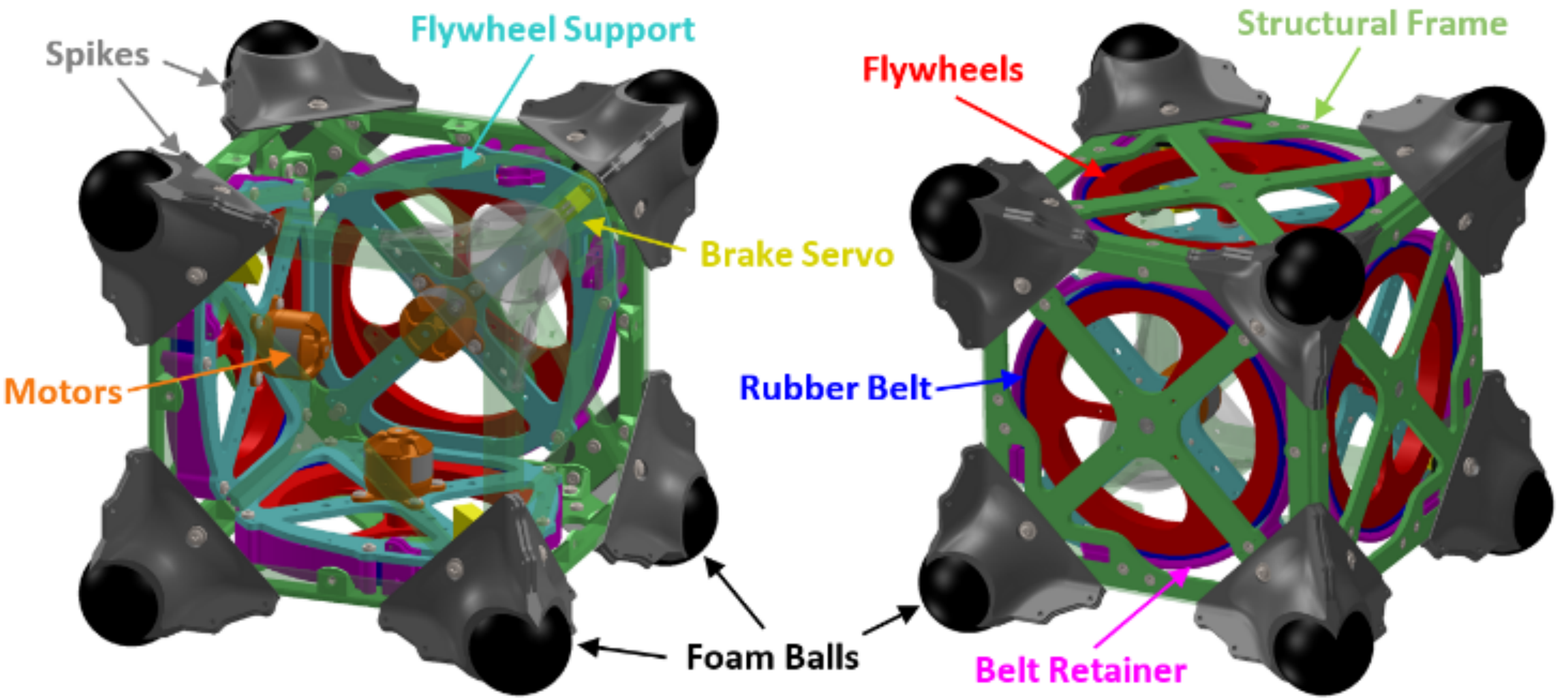


Two phases of visual localization:

I. Prior mapping by mothership: logs visual features at various illumination angles to build a global map of the body

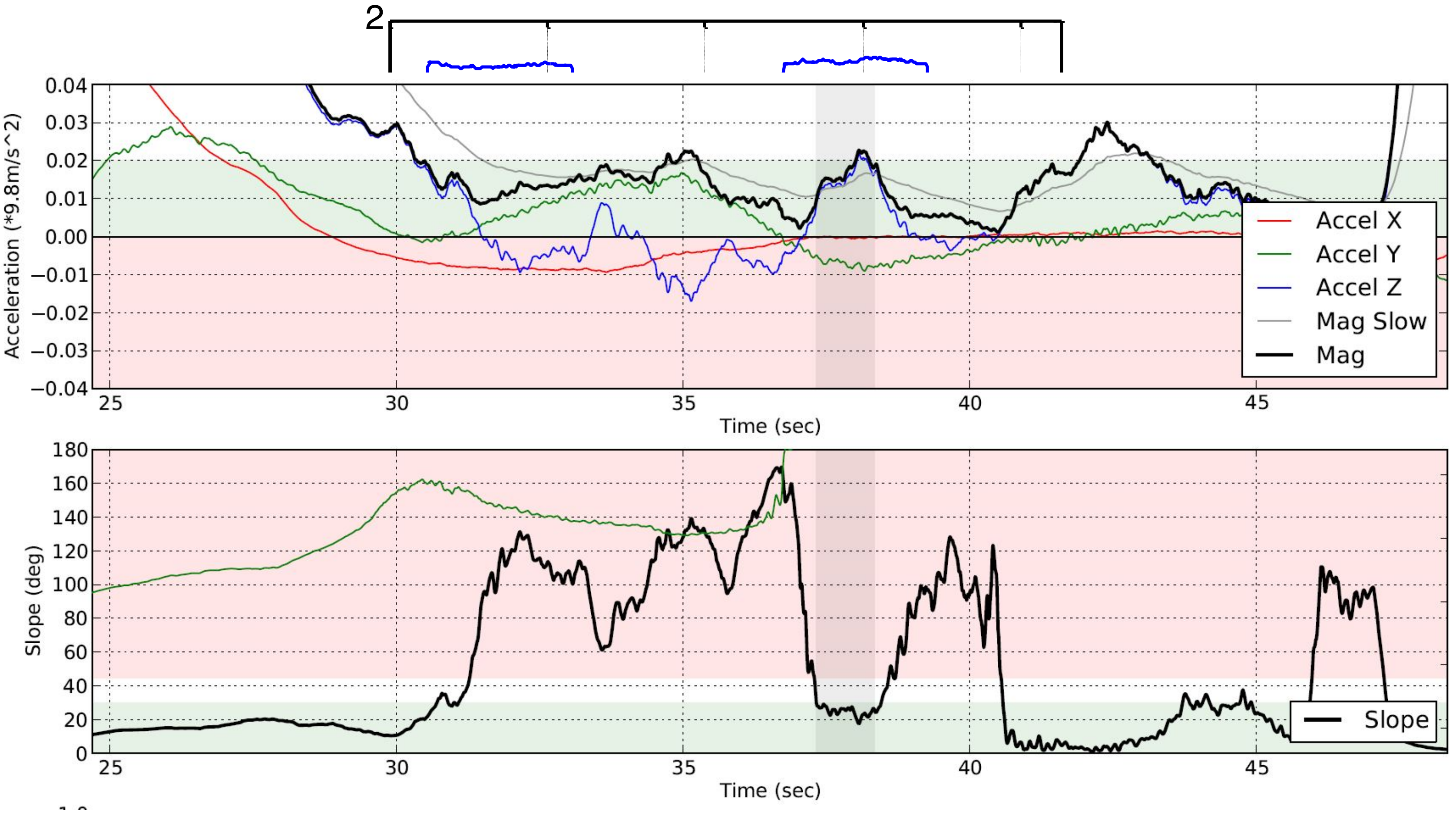
II. Localization onboard deployed hybrid: Builds *internal* map during proximity operations and cross-references with global map during large hops.

# Mechanical Design



# Typical gravity measurements

**Key insight**: Many parabolas yield brief periods of "positive" microgravity

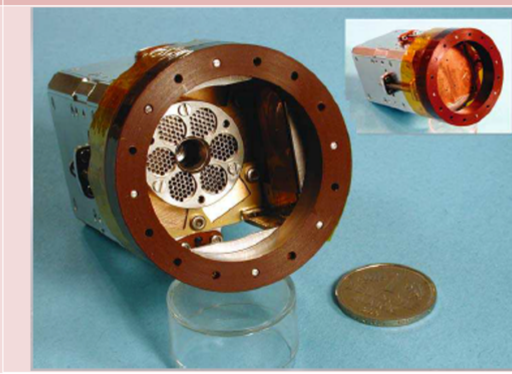
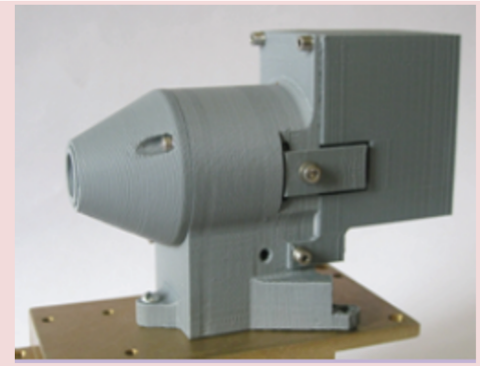


# Results

Mean Absolute Errors (MAE)

| | | Speed | | Elevation | | Azimuth | |
|---|---|---|---|---|---|---|---|
| | # | Analytical | Numerical | Analytical | Numerical | Analytical | Numerical |
| Grip Tape | 9 | 17.7 % | 9.6 % | 6.2° | 4.8° | 7.8° | 5.0° |
| Kapton Tape | 15 | 24.3 % | 16.5 % | 9.8° | 2.3° | 7.2° | 6.6° |
| Simulant | 33 | 16.7 % | 5.1 % | 5.1° | 1.5° | 3.7° | 3.3° |
| Rough Simulant | 3 | 22.2 % | 11.2 % | 4.6° | 1.6° | 13.2° | 12.2° |
| Sand | 5 | 17.1 % | 5.7 % | 9.7° | 6.9° | 1.9° | 1.8° |
| **Total** | **65** | **18.4 %** | **7.8 %** | **6.6°** | **2.4°** | **5.3°** | **4.7°** |

- Generally good agreement between models and measured data
- Low friction surfaces violate pin joint pivoting assumption
- Numerical models are better but require estimates of surface elasticity properties

| Instrument | IntelliCam | APXS | Microscope |
|---|---|---|---|
| Science Objective | Context imaging, surface navigation | Elemental composition | Regolith physical properties |
| Mass | 500 gm | 640 gm | 500 gm |
| Power | 2.5 W (peak) | 1.5 W (peak) | 2 W |
| |  |  |  |