National Aeronautics and Space Administration

# Keck Workshop:
# Asteroid Retrieval Mission Potential Targets

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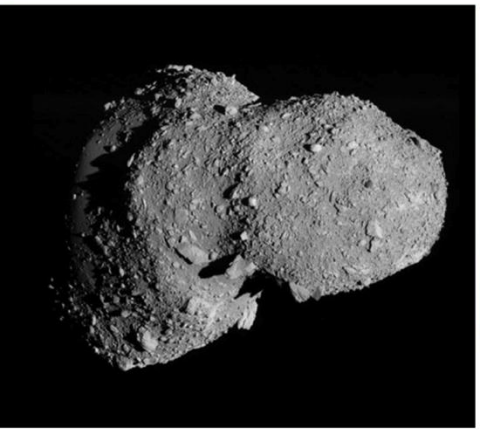
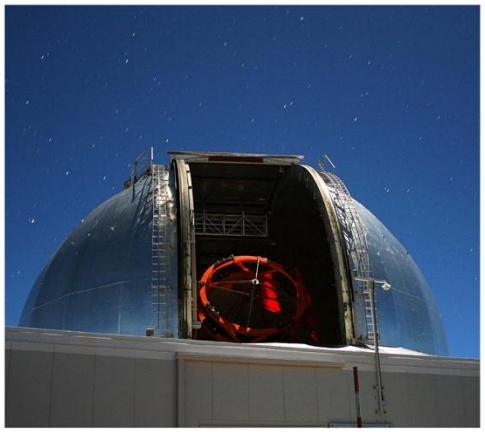



# Candidate Asteroids for Mission Design

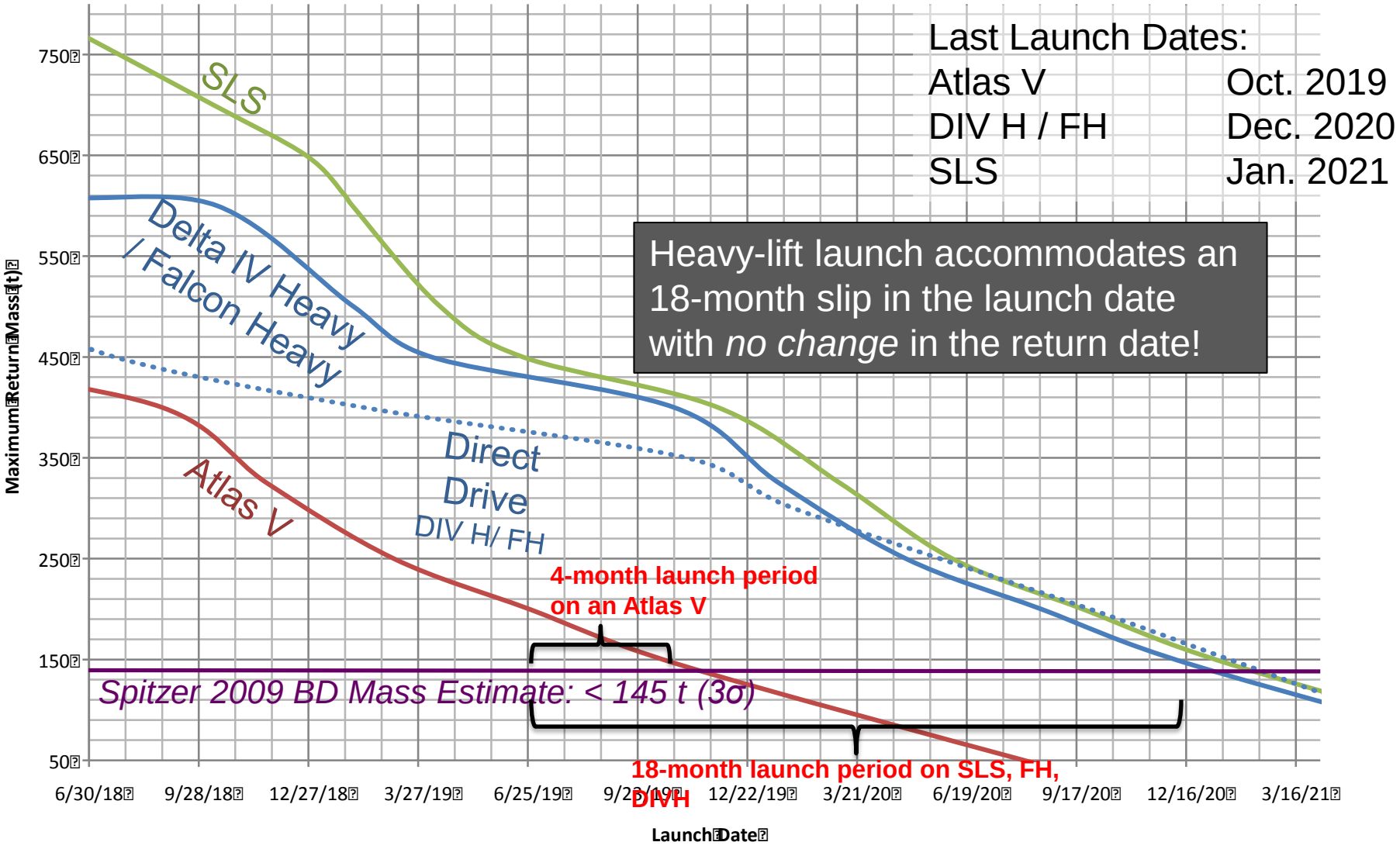
- **Each asteroid's return date is fixed & dictated by natural close approach times**
- **Lower $V_\infty$ allows return of larger objects**
- **Assuming mid-2019 nominal launch**

| Asteroid | Asteroid Mass Est. | Asteroid V-infinity | Earth Return Date | Crew Accessible | Notes |
|---|---|---|---|---|---|
| **2009 BD*** | 30-145 t (returnable) | 1.2 km/s | Jun 2023 | Mar 2024 or earlier | Valid mission candidate, rotation period > 2 hrs, Spitzer-based upper bound on mass |
| **2011 MD*** | TBD (max 620 t)** | 1.0 km/s | Jul 2024 | Aug 2025 | Spitzer obs. successful final characterization results pending<br>Rotation period 0.2 hrs |
| **2014 BA3** | TBD (max 500 t)** | 1.8 km/s | Jan 2024 | Early 2025 | Discovered Jan 2014, not detected by Radar<br>Optical characterization pending |
| **2013 EC20** | 4-43 t (returnable) | 2.6 km/s | Sept 2024 | Late 2025 | Discovered March 2013, Radar characterized rotation period ~ 2 min<br>2024 return requires DIV H or FH launch<br>2020 return possible with Feb 2018 launch |
| **2008 HU4** | TBD (max 700 t)** | 0.5 km/s | Apr 2026 | Mid 2027 | Close Earth flyby in April 2016 |

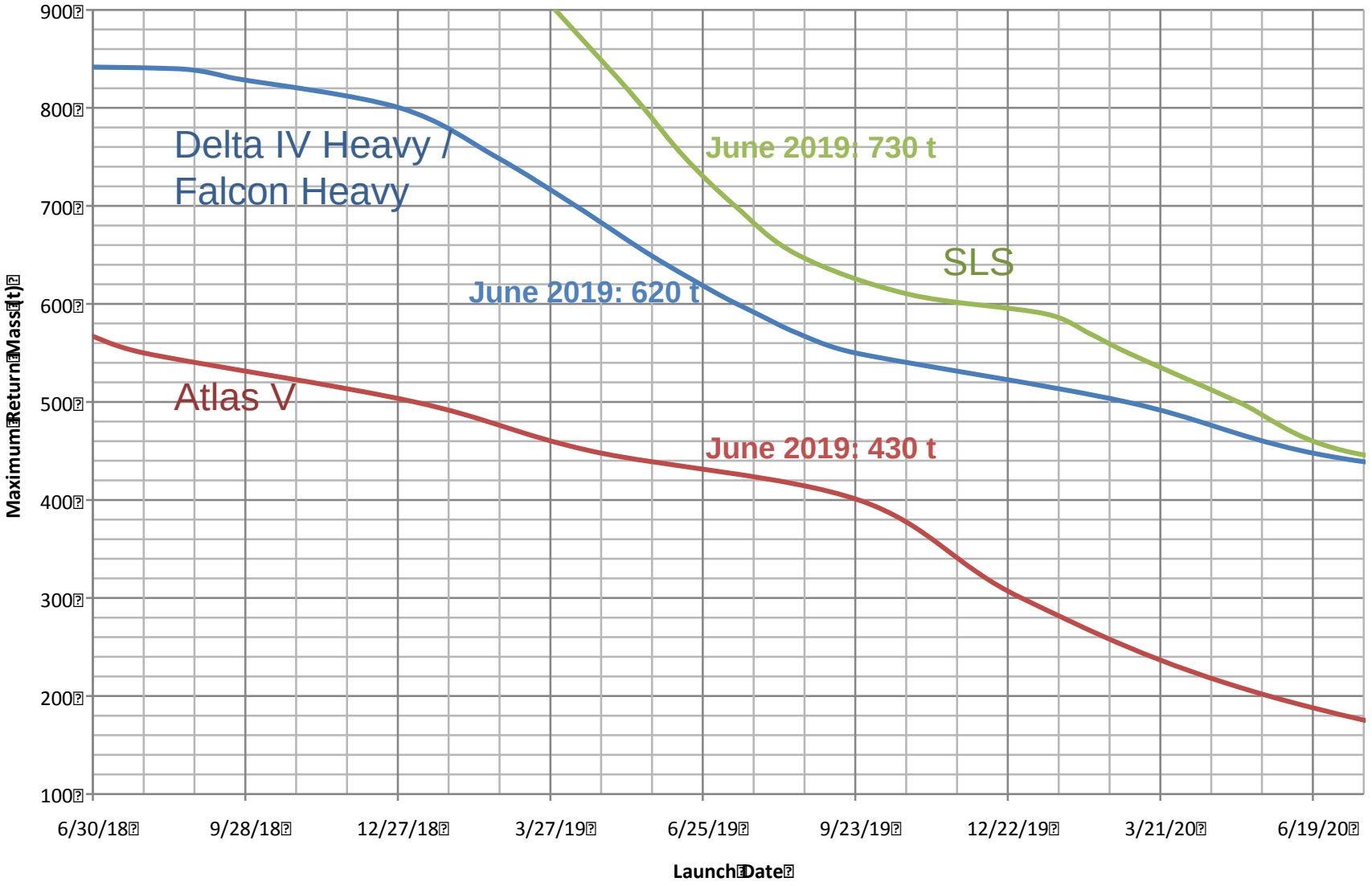
* High-fidelity trajectory analysis performed for 2009 BD and 2011 MD

** Max returnable mass using a Delta IV Heavy or Falcon Heavy

# 2009 BD: Max Return Mass vs. Launch Date

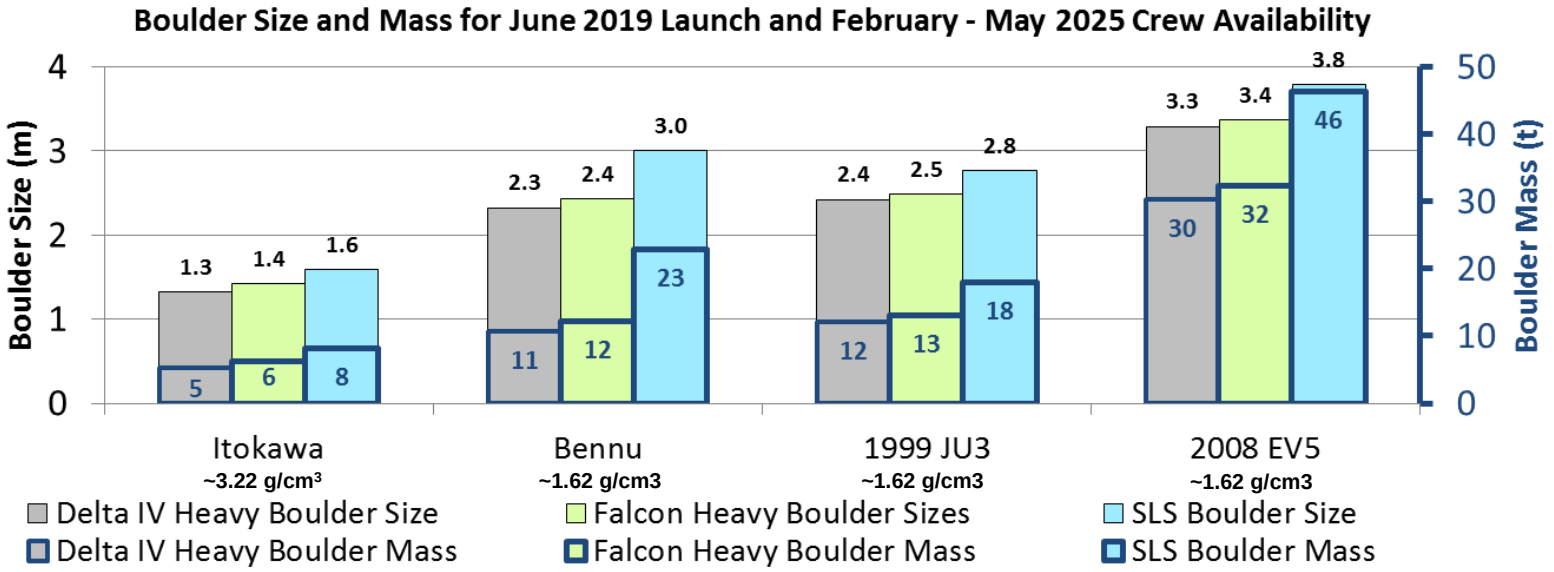


# 2011 MD: Max Return Mass vs. Launch Date



# Target Availability and Boulder Size and Mass

- One Valid Candidate with hundreds of candidate boulders: **Itokawa**
- Two candidates may be characterized by precursors in 2018: **Bennu** (OSIRIS-REx) & **1999 $JU_3$** (Hayabusa 2)
- One candidate characterized by radar at ~6000 SNR: **2008 $EV_5$**[*]
- At least two more candidates may be sufficiently characterized by radar during the next 4 years: **2011 $UW_{158}$**, **2009 $DL_{46}$**



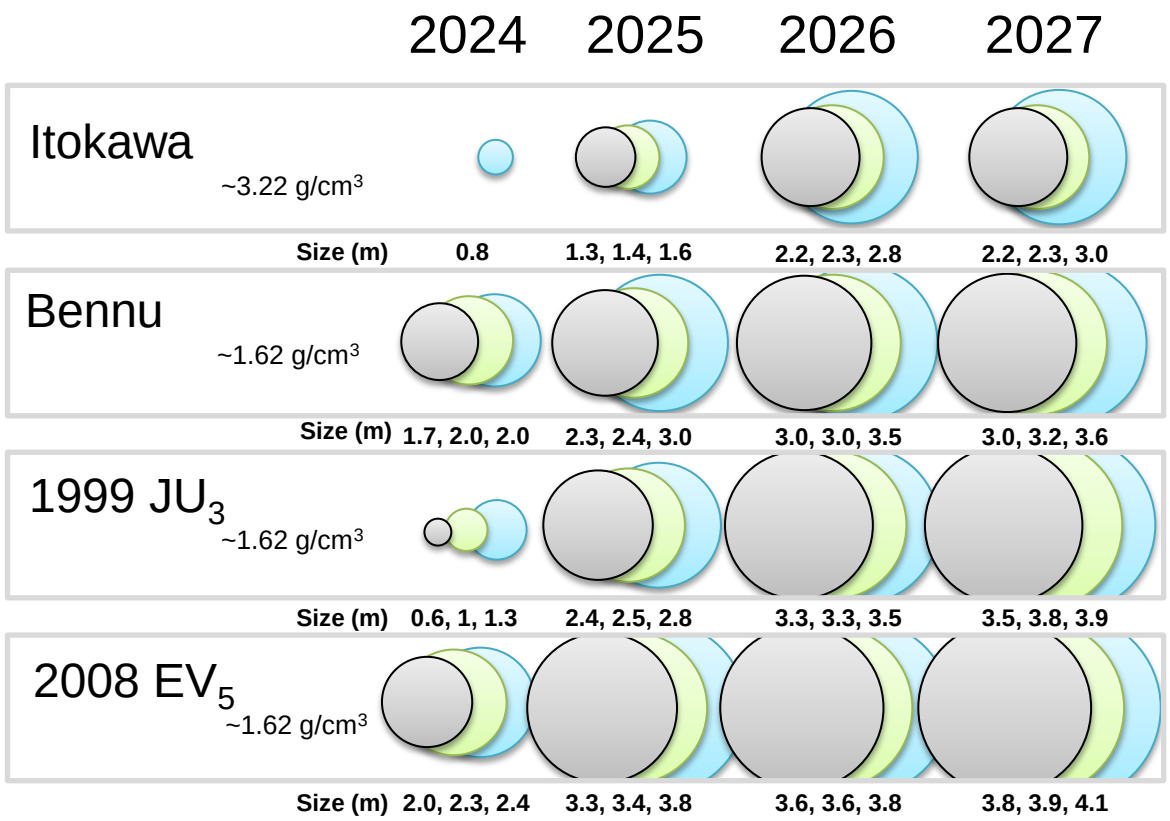

**Spherical maximum returnable boulder size ranges from 1.5 m to 4 m enabling a large range of boulder size for retrieval.**

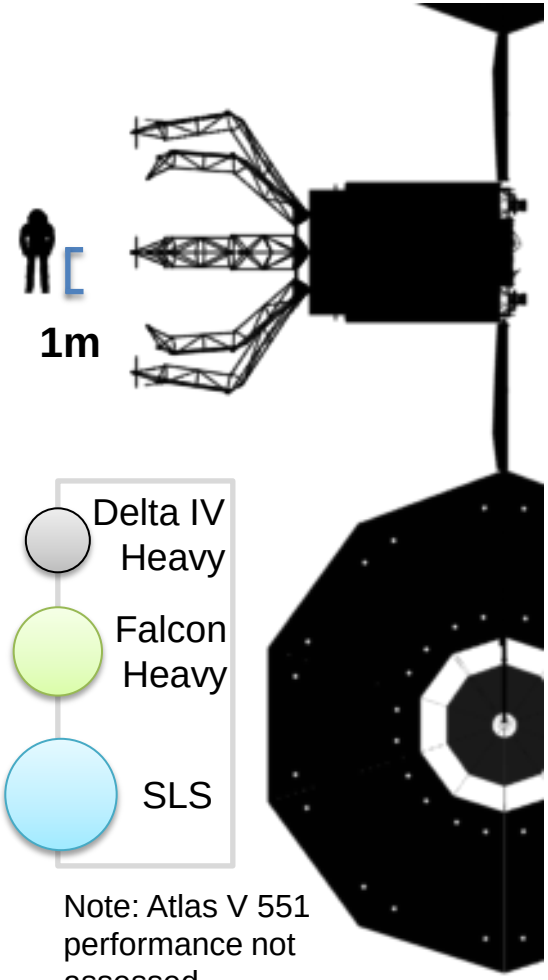
* Personal communication Michael Bush (ref. Busch et al., Icarus Volume 212, Issue 2, April 2011, Pages 649–660)

# Candidate Target Boulder Return Sizes

**Launch no earlier than June 2019**

**Crew Availability in stable LDRO in February - May of:**




Note: Atlas V 551 performance not assessed.

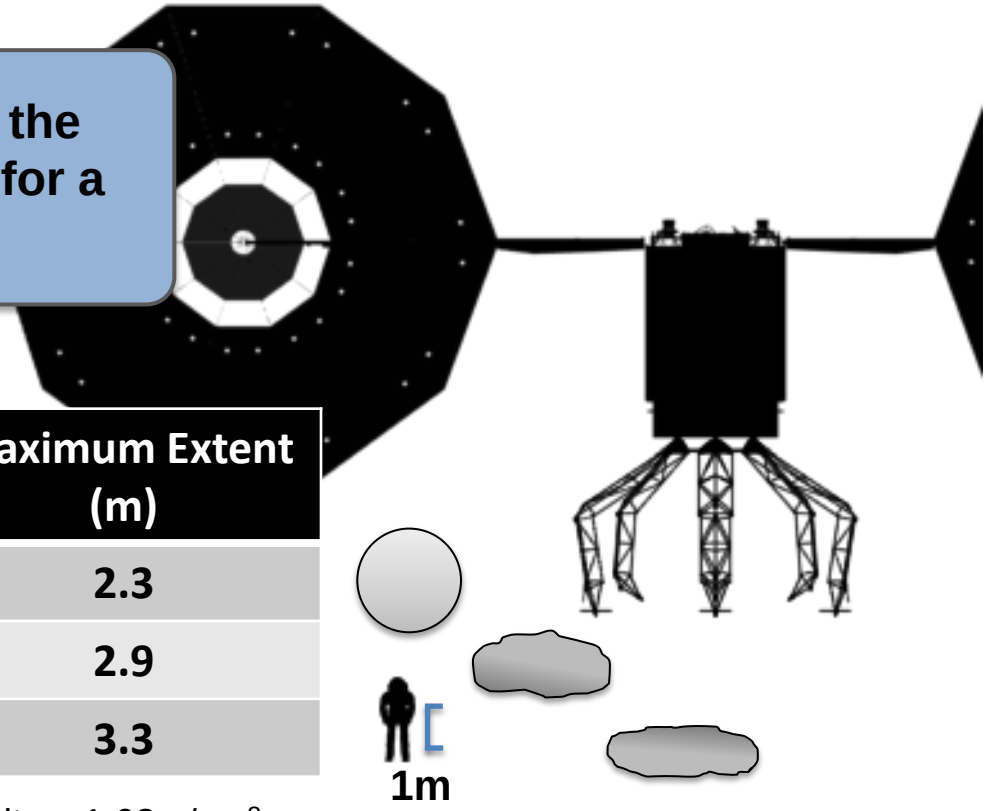
**Robotic Boulder Capture Option has a set of candidates that are robust to changes in return dates.**

**Masses and additional data for June 2020 and June 2021 launches in backup**

# Boulder Aspect Ratio

- Spherical boulder sizes in this presentation assume represent the smallest maximum extent for a given mass and density. For example:
  - A 10 t carbonaceous boulder with density of 1.62 g/cm$^3$ has a 2.3 m spherical extent.
  - This mass and density would have a maximum extent of ~3.3 m for 3:3:1 aspect ratio.

**Spherical boulders represent the minimum possible size extent for a given mass and density.**




| Aspect Ratio | Mass (t) | Volume (m$^3$) | Maximum Extent (m) |
|---|---|---|---|
| 1:1:1 | 10 | 6.14 | **2.3** |
| 2:2:1 | 10 | 6.14 | **2.9** |
| 3:3:1 | 10 | 6.14 | **3.3** |

Assumes carbonaceous material with density = 1.62 g/cm$^3$

# Summary of NEA Targets Analyzed

**Configuration and operations are robust to a wide range of NEA sizes, masses, and rotation rates beyond Itokawa.**

| | Itokawa | Bennu | 1999 $JU_3$ | 2008 $EV_5$ |
|---|---|---|---|---|
| Mass | 3.15 x $10^{11}$ kg | 7.79 x $10^{10}$ kg | 1.55 x $10^{12}$ kg | 1.05 x $10^{11}$ kg |
| Dimensions | 535 x 294 x 309 m | Mean Dia.: 492 m | Eff. Dia.: 870 m | 420 x 410 x 390 m |
| Rotation Period | 12.132 hours | 4.297 hours | 7.627 hours | 3.725 hours |
| 50 m Sun Angle | 45 degrees | 60 degrees | 37.5 degrees | 60 degrees |
| Contact Sun Angle | 30 degrees | 15 degrees | 15 degrees | 15 degrees |
| Dry-Run 1 Dur. | 5.25 days | 5.13 days | 5.25 days | 5.13 days |
| Dry-Run 2 Dur. | 5.28 days | 5.26 days | 5.28 days | 5.26 days |
| 20 m Descent Dur. | 12.73 min | 11.37 min | 4.51 min | 7.96 min |
| Contact Velocity from 20 m | 5.237 cm/s | 5.861 cm/s | 14.788 cm/s | 8.371 cm/s |

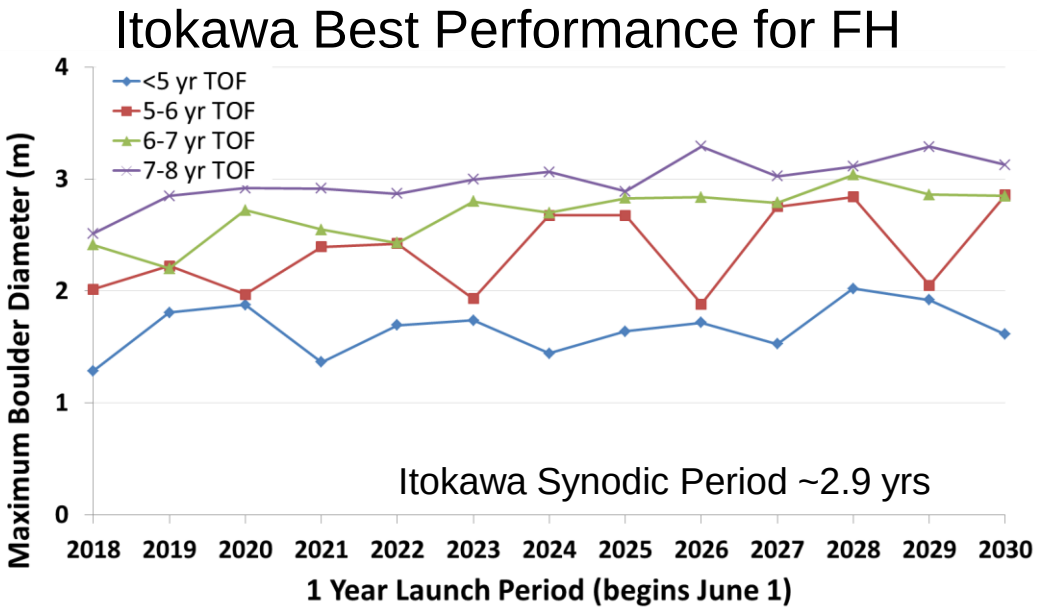
# Returnable Boulder Size Trends

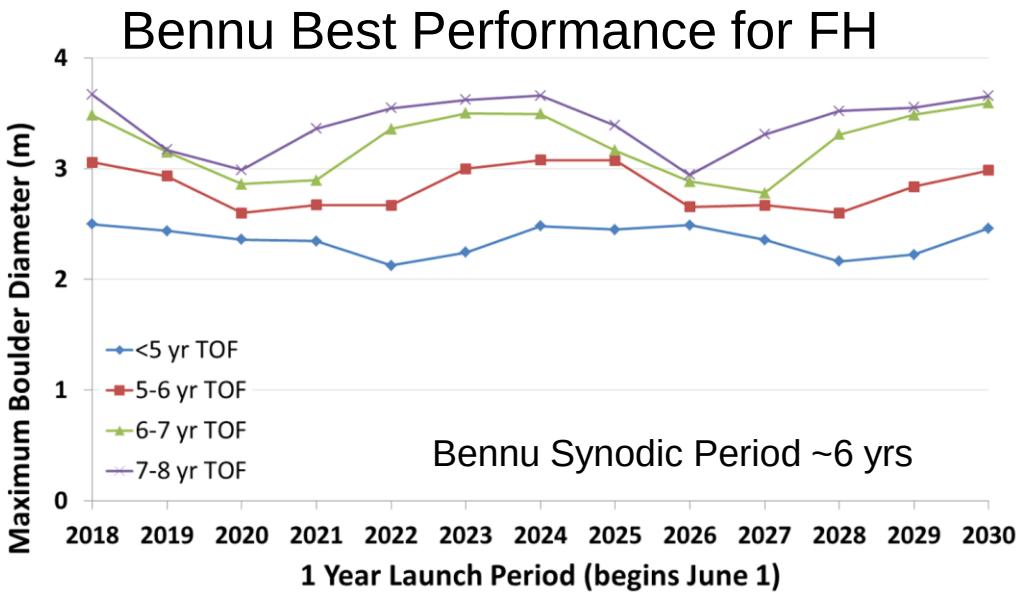
**Missions with duration >5 years can launch any year and return a ~2+ meter boulder from Itokawa or Bennu providing mission robustness to schedule changes.**

Similar performance expected for:

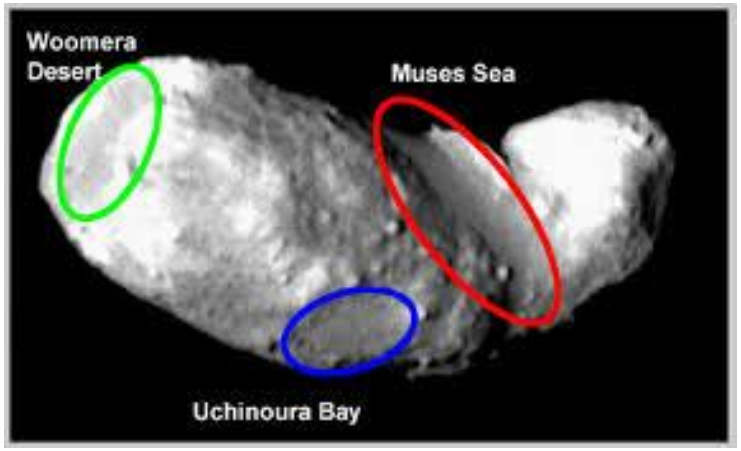
1999 $JU_3$ synodic period ~4.3

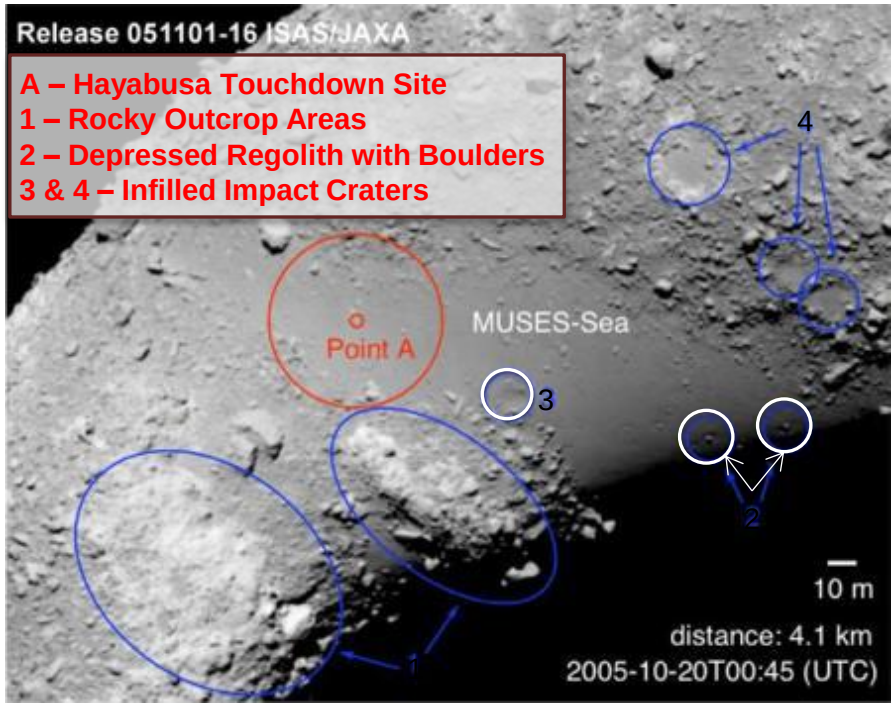
2008 $EV_5$ synodic period ~15.7



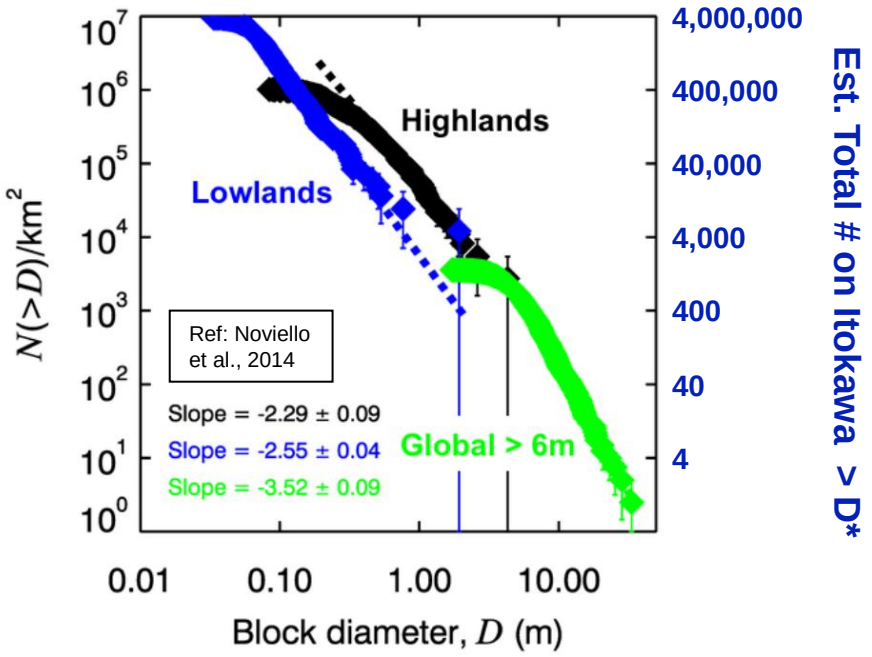



# Itokawa's Boulder Rich Surface



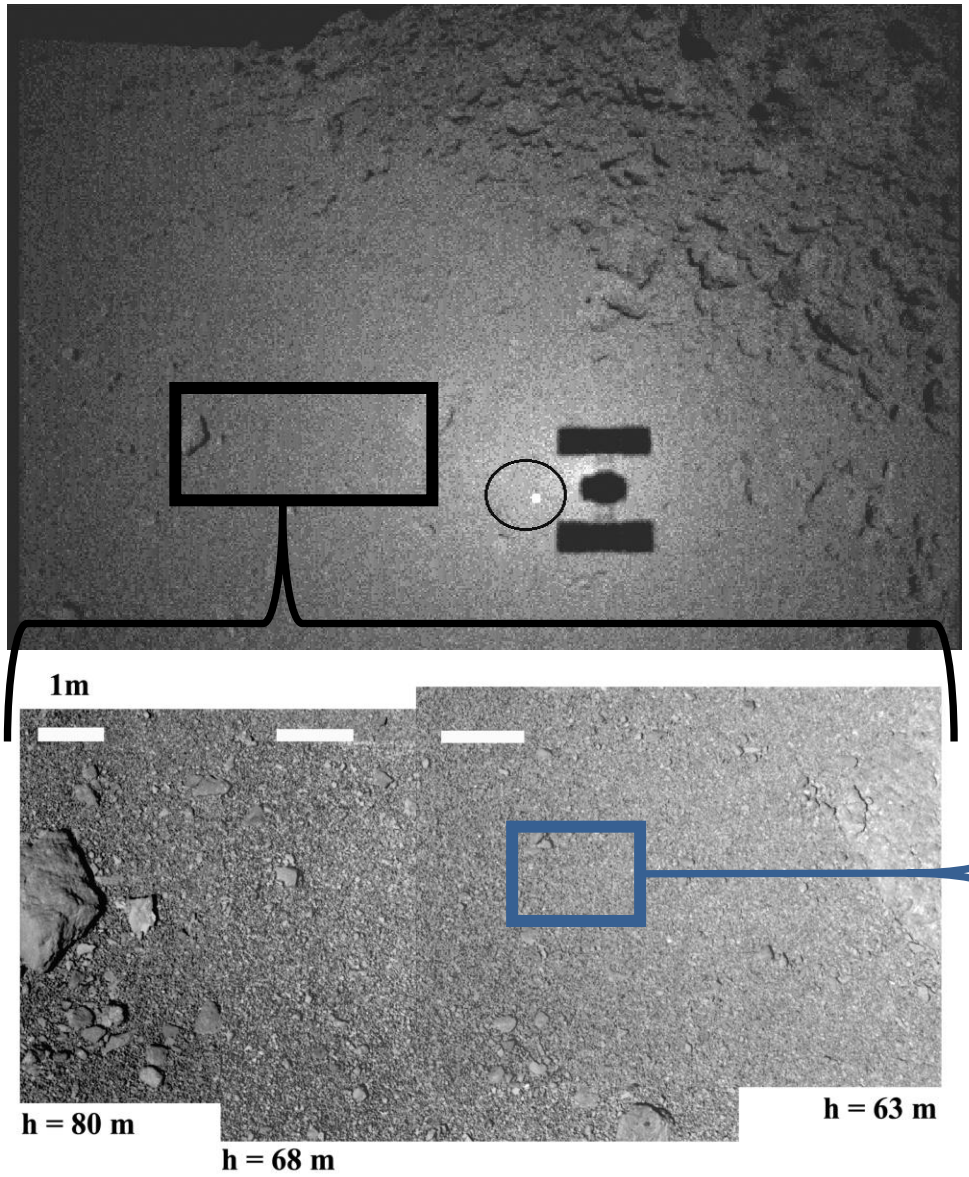




- Hayabusa mission confirmed the presence of many boulders on Itokawa's surface.
- Data from images suggest that several thousand 2 to 5 m boulders exist on Itokawa.
- ~20% of the entire asteroid's surface contains smooth areas (flat terrain with few hazards and wide access) – hundreds of boulder targets
- Boulders are believed to be generated by impacts and appear to be common on NEAs.




*** Added axis based on Itokawa surface area of 0.4011 km²**

# Hayabusa Touchdown Site Approach




- Smooth areas have boulders sitting on a surface dominated by gravels and pebbles. Stereo image analysis indicates a high probability that some boulders are not embedded.
- Highest resolution of the images during the Hayabusa touchdown are 6 to 8 mm/pixel.
- Evidence from Hayabusa and ground-based radar suggests that boulders may be relatively common on near-Earth asteroids (e.g., Bennu and 2005 YU55).
- This evidence is supported by theoretical and laboratory analysis of asteroid rubble pile formation and impact processes.