National Aeronautics and Space Administration

Observation Campaign Status

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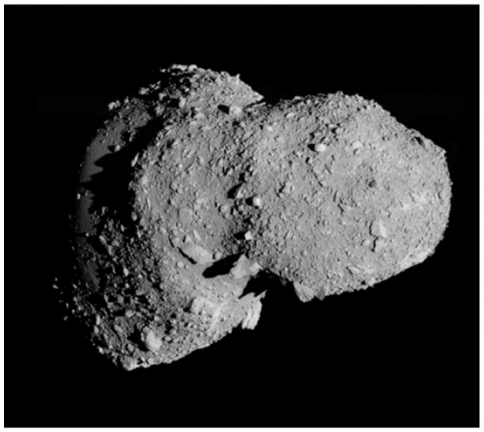
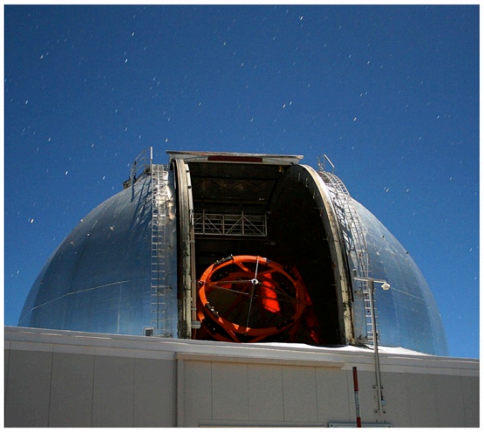
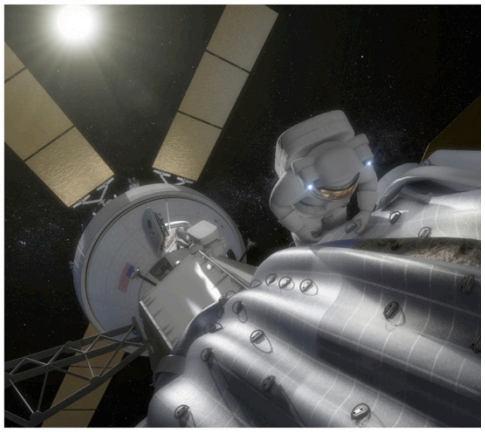





Observation Campaign Status

- Discovery of NEOs continues at the same pace as in the last few years (~1000 per year).
- Observation campaign discovery enhancements are in work but have not yet come online.
  - The DARPA Space Surveillance Telescope (SST) carried out NEO testing in this fall. More tests will be carried out in January, possibly leading to more regular operations starting in March.
- Radar characterization of NEOs continues at a slightly faster pace than last year, due to higher priority for asteroids.
- NEOWISE has been reactivated and is cooling down. The spacecraft will start surveying soon.
- Three new ARM candidates for the Reference Mission were discovered in the last 6 months (2013 LE7, 2013 PZ6, 2013 XY20):
  - First two were too distant for radar characterization; the third was also distant but Arecibo will attempt to characterize it this week.
  - All three were too distant for ground-based IR characterization.
- An attractive potential candidate was found for the Alternate Mission last month (2013 WA44), but it also was too distant for radar characterization.

Observation Campaign Enhancements for Discovery

	Facility	V_{lim}	FOV (deg^2)	In Work or Potential Improvements	Ops Date
Current Surveys	Catalina Sky Survey:			Increase ML field of view 4x	Late 2013
	Mt. Bigelow	19.5	8	Increase MB FOV 2.5x	Late 2014
	Mt. Lemmon	21.5	1.2	Retune observation cadence	Mid 2014
	Pan-STARRS 1	21.5	7	Increase NEO time to 50%	Early 2014
				Increase NEO time to 100%	Late 2014
Future Surveys	DARPA SST	22+	6	Additional NEO detection tests	Early 2014
	Palomar Transient Facility (PTF)	21	7	Improve software to detect streaked objects	Early 2014
	Pan-STARRS 2	22	7	Complete telescope system	Late 2014
	ATLAS	20	40	Entire night sky every night x2	Late 2015

V_{lim} = limiting magnitude , FOV = Field of View

Nomenclature Guide

- **"Potential Candidate":**
  - Orbit parameters satisfy rough constraints on launch date, return date and total mission delta-v.
  - Absolute magnitude indicates size lies roughly in the right range.
- **"Characterizable":**
  - Approaches the Earth (or Spitzer) close enough, and with suitable enough observing geometry, that its physical properties can be adequately characterized.
- **"Valid Candidate":**
  - Physical properties have been adequately characterized and lie within acceptable ranges to achieve mission goals.
  - Detailed mission design has been performed using feasible launch and return dates, and the upper bound on the mass is less than the maximum return mass from the mission design.
- **"Selectable Target":**
  - Meets programmatic constraints (eg. on achievable schedule and minimum return size), and has identified but manageable risks.

Target Nomenclature for Reference Mission

Proposed nomenclature for describing Reference Mission ARM candidates:

1) **Potential Candidate**: A Near-Earth Asteroid in the open source Small Bodies Data Base whose:
   - Rough orbit satisfies the approximated expected ARRM mission constraints on V-infinity and return Earth close approach date and distance;
   - Rough size, as estimated from absolute magnitude and a range of possible albedos, potentially satisfies capture size constraints.
2) **Valid Candidate**: A potential candidate whose:
   - Physical properties have been characterized by accepted processes, with vetted results, and size and rotation state meet capture design constraints with estimated mass less than the maximum mass returnable for its orbit.
   - Orbit is of sufficient accuracy (eg. condition code ≤ 4), and meets expected mission design constraints for a range of feasible launch dates, return dates, launch vehicles and possible target masses;
3) **Selectable Target**: A valid candidate which:
   - Meets the technical and programmatic constraints of the implemented ARRM project and has identified but manageable risks
4) **Selected Target** (by HQ management team): based on acceptable risks.

Current Potential Candidates for Reference Mission

- Selected list of Potential Candidates for the Reference Mission:

	Name	Estimated Size (m)	V_∞ (km/s)	Earth Approach Date	Maximum Returnable Mass (t)†
	2008 EA9	5 - 22	1.9	5/6/2021	45
	2007 UN12	3 - 14	1.2	12/7/2021	90
	2010 UE51	4 - 17	1.2	12/12/2022	90
	2013 LE7	7 - 30	2.5	5/21/2023	100
Current baseline	2009 BD	2.6 - 7	1.2	6/26/2023	430
	2013 PZ6	5 - 20	n/a	8/11/2023	100
	2011 MD	4 - 20	1.0	8/10/2024	620
	2013 EC20	2 - 3	2.6	9/20/2024	45
	2013 GH66	5-18	2.0	4/18/2025	100
	2013 EC20	2 - 3	2.6	4/24/2025	90
	2013 XY20	11 - 55	1.8	12/15/2025	310
KISS baseline	2008 HU4	4 - 18	0.5	4/26/2026	800

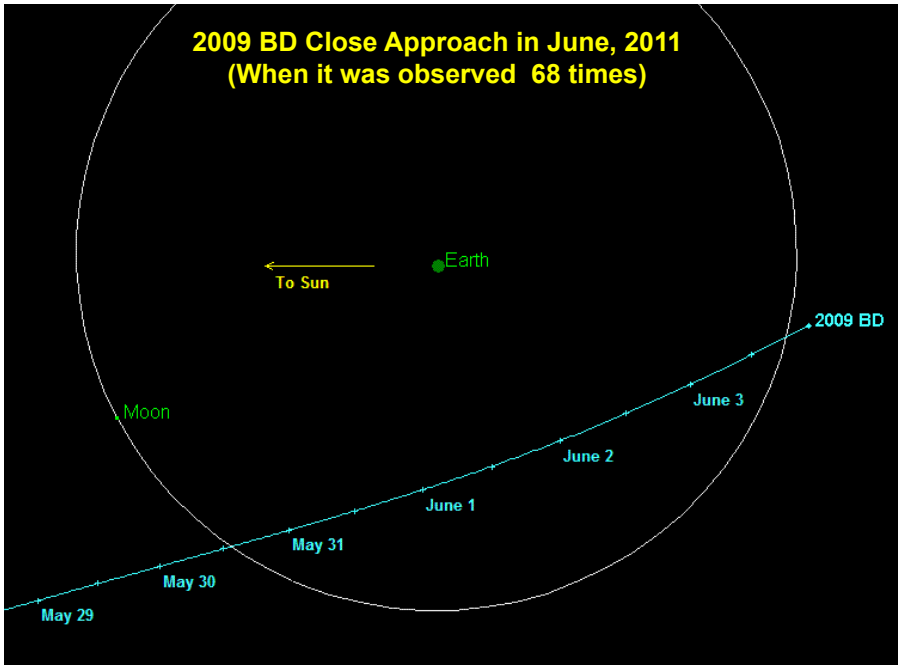
†Assumes Falcon Heavy and launch dates no earlier than June 2019.

- Two (2009 BD and 2013 EC20) have been accurately characterized; two others (2011 MD and 2008 HU4) are characterizable.
- **Currently, there is one Valid Candidate: 2009 BD**
- Potential candidates are discovered at a rate of **2-3 per year**.
- Enhancements to discovery assets, when they come online, will likely lead to a doubling in the discovery rate.

Reference Mission Candidate 2009 BD

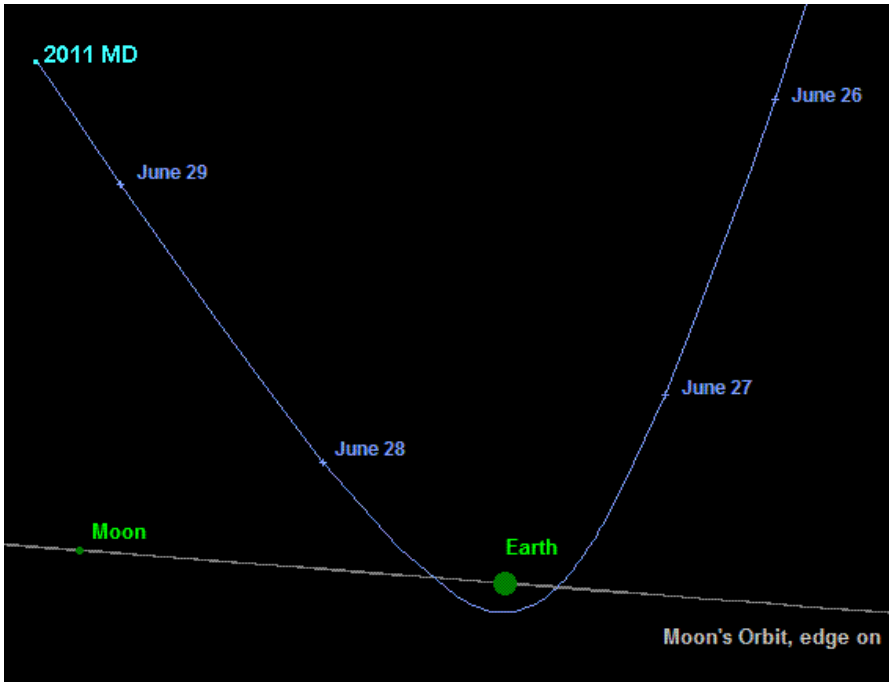
- Spitzer observed 2009 BD in Oct. 2013 but did not detect it because it is smaller than expected: **2.6 to 7 meter** mean size (3σ), and likely smaller than 5 meters.
- If it had been >~8 meters in size, 2009 BD would have been detected (Spitzer's pointing was correct, as confirmed by several independent methods).
- BD's intrinsic optical brightness is accurately known from hundreds of observations from 2 dozen observatories; to be smaller than expected, its optical albedo must be higher than expected, in the range of 25% to 80%.
- More importantly, the Spitzer observation tells us the mass of 2009 BD is in the range ~30 – ~85 tons, with a **3σ upper bound of 145 t**.
- This upper bound on mass is well within the maximum return mass capability for 2009 BD's orbit, for launches through the end of 2020.

2009 BD is considered a Valid Candidate for the Reference Mission



Reference Mission Candidate 2011 MD

- 2011 MD will be observed by Spitzer in Feb. 2014.
- Its intrinsic optical brightness is similar to 2009 BD's, only slightly brighter.
- It will be at a greater distance from Spitzer and observed for 25% fewer hours: If it has a albedo similar to 2009 BD's, 2011 MD will probably not be detected.
- But the true albedo is unknown, so the Spitzer observation is still valuable for constraining the size of 2011 MD, which is currently in the range ~4 to ~20 m.
- The current wide size range leads to a very wide mass range: ~50 to ~50,000 t; the Spitzer observation will help constrain the mass.
- The maximum return mass for a mid-2019 launch to 2011 MD is ~620 t, which is more than for 2009 BD.
- Over 500 observations of 2011 MD have been made, even more than for 2009 BD.



Target Nomenclature for Alternate Mission

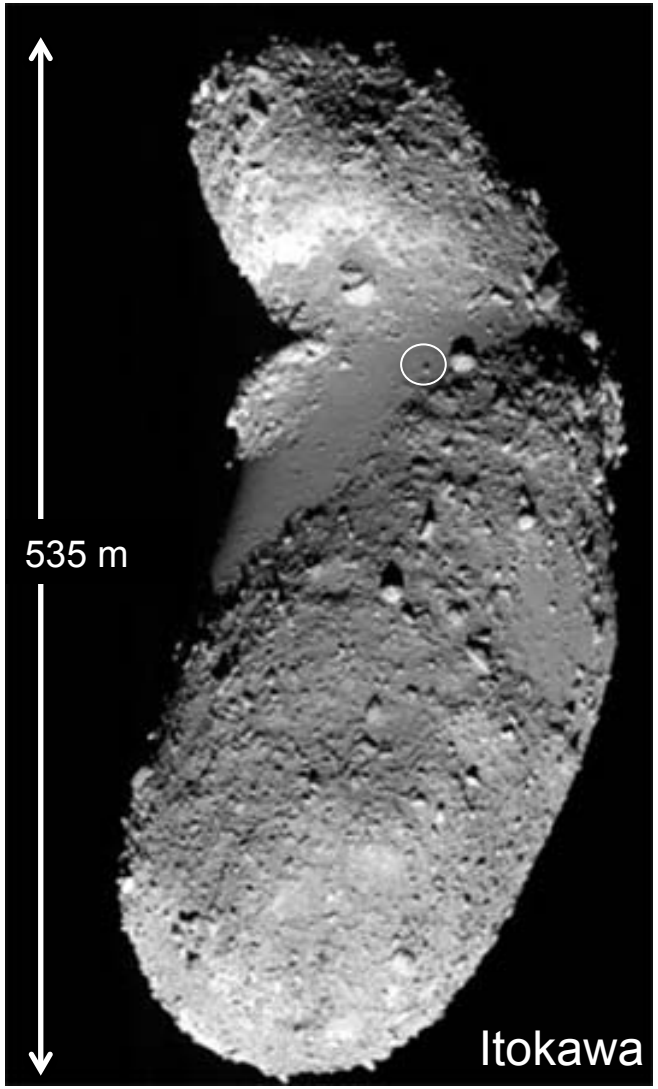
Proposed nomenclature for describing candidates for Alternate Mission:

1) **Potential Candidate**: An NEA in the JPL Small Bodies Data Base whose:
   - Rough orbit satisfies the expected ARRM mission constraints on V-infinity or total mission ΔV.
   - Rough size of ~50-500m as estimated from absolute magnitude and a range of possible albedos.
2) **Valid Candidate**: A potential candidate whose:
   - Asteroid surface has been characterized by accepted processes, and the existence of boulders of the size which can be returned can at least be inferred.
   - Orbit meets expected mission design constraints: feasible launch date, desired return date, available launch vehicle and acceptable return mass.
   - Rotation state of the asteroid permits successful proximity operations.
3) **Selectable Target**: A valid candidate which:
   - Meets the technical and programmatic constraints of the implemented ARRM project and has identified but manageable risks.
4) **Selected Target** (by HQ management team): based on acceptable risks.

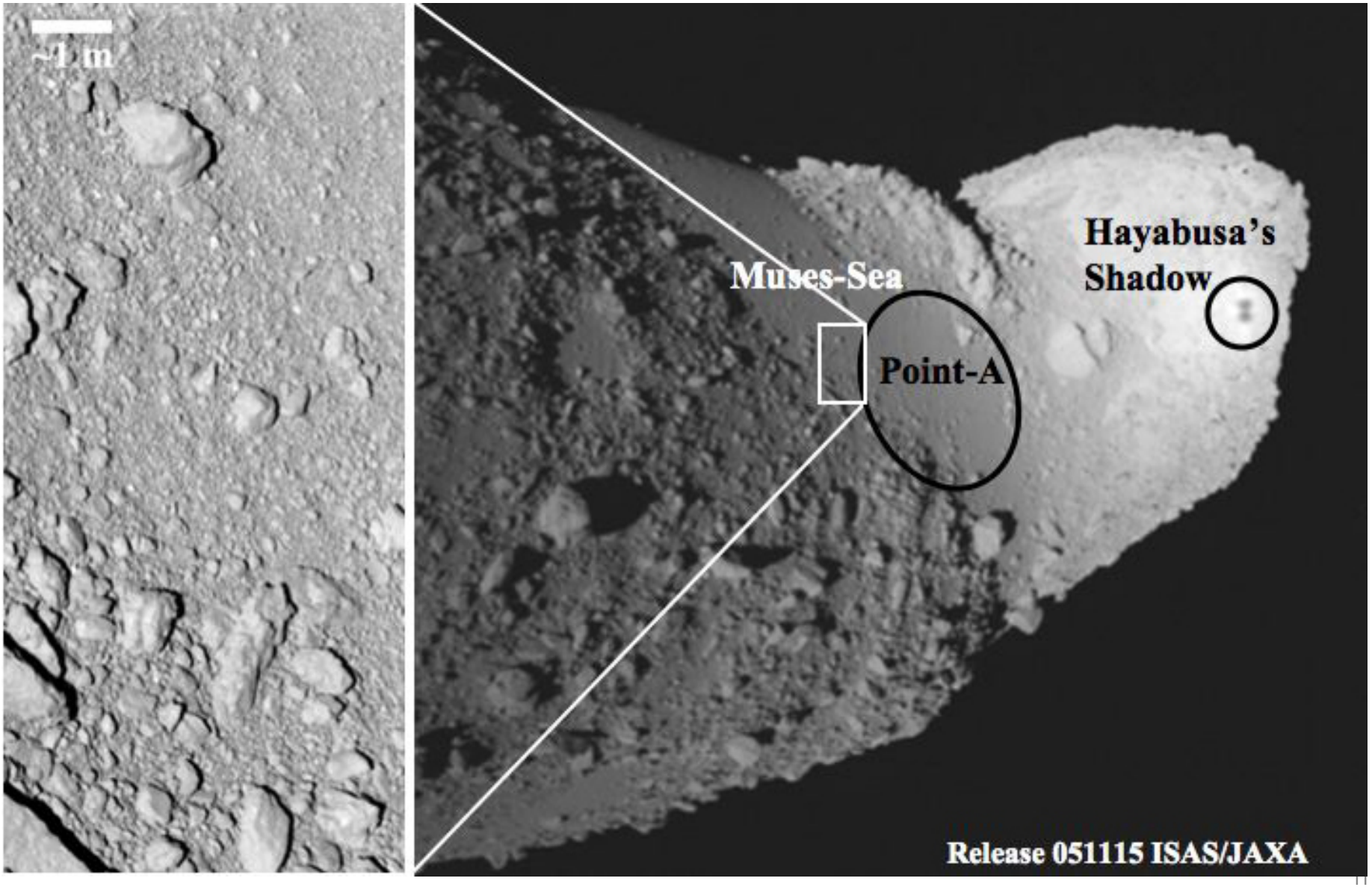
Characterization for the Alternate Mission

- For the Alternate Mission, the surface of a 50 – 500m mission candidate must be characterized to establish the presence of returnable boulders.
- There are two possible means of characterizing the surface – imaging from a prior mission and ground-based radar with high enough SNR.
- The amount of mass which can be returned from known large and characterizable candidates is <~25 t, which corresponds to boulder sizes of <~2.8 m.
- Only 1 asteroid in the 50 – 500m size range has been visited by a spacecraft and characterized well enough to detect <3 m boulders: **Itokawa**, visited by Hayabusa in 2005.

Itokawa is considered a Valid Candidate for the Alternate Mission

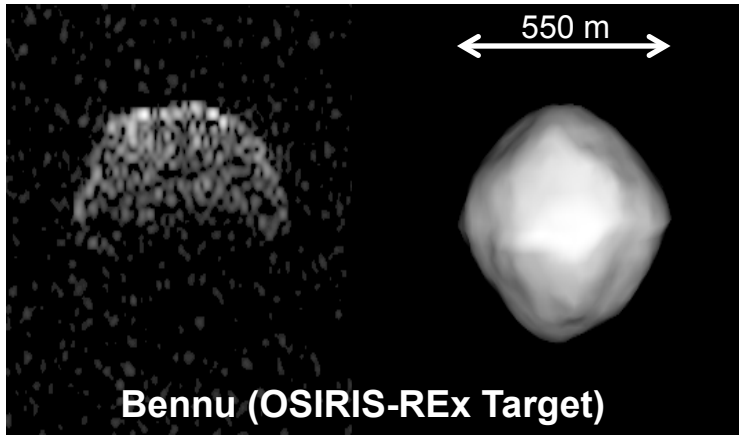


Boulders on Itokawa



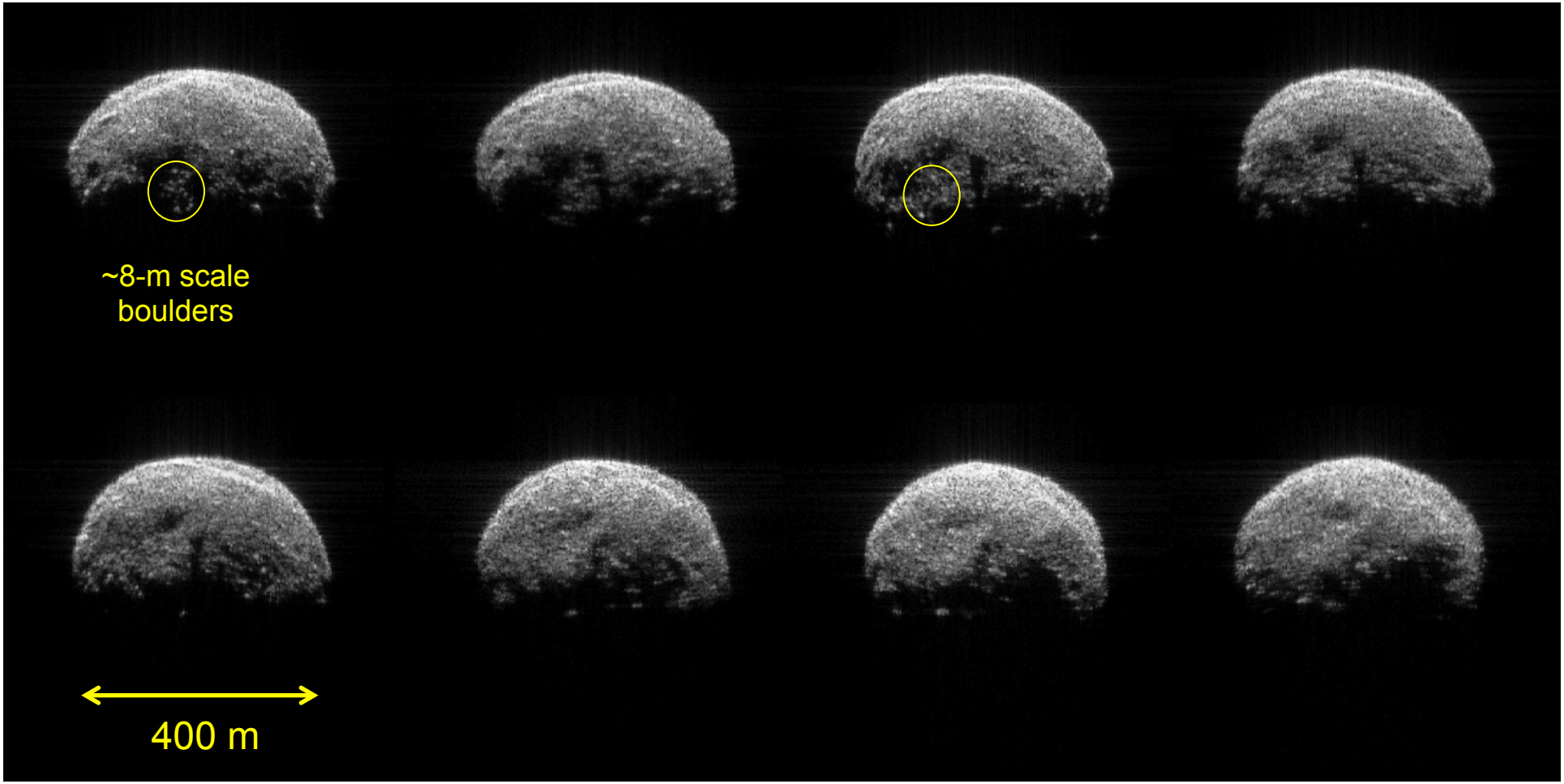
Radar Characterization of Boulders on Asteroids

- Current ground-based radar range resolution: 8 m (Arecibo), 4 m (Goldstone).
- Currently, radar cannot definitively detect boulders <4-m, regardless of the SNR, but the presence of boulders might be inferred from radar observations.
- If the radar SNR exceeds ~5000, radar could detect ~4-m-scale features that are probably boulders, and it can also determine *average surface roughness* at a scale of ~10 cm. Current radar observations can provide confidence in the presence or absence of <4-m-scale boulders.
- The characterization challenge is verifying, or being able to infer with sufficient confidence, the presence of boulders of the appropriate size (<~3 m) available to be captured and removed from the surface.
- About 10 potential candidates for the alternate mission have been observed by radar with high enough SNR; evidence for 10-m-scale boulders was seen on 2 of them: Bennu and 2008 EV5, both C-types.
- These two would be considered valid candidates if we are confident enough to infer the presence of <3-m-scale boulders.



2005 YU55 observed by Goldstone Radar in 2010

- **A C-type asteroid, but not an ARM candidate.**
- **Indicative of how ~8m-scale boulders can be seen at very high radar SNR.**



Current Candidates for Alternate Mission:
Mid-2019 Launch & 2023-24 Return

- There are ~200 potential candidates for the Alternate Mission with return mass >~10 t and return date before the end of 2024; there are ~700 Potential Candidates with return mass >1 t.
- The current list of valid or characterizable candidates for the Alternate Mission is:

Target	Type	Asteroid V_∞ (km/s)	Earth Escape	Earth return	Max Return mass (t)	Boulder max diam (m)[c]	Characterization
Itokawa[a]	S	5.7	3/22/2019	10/7/2023	7	1.6 - 1.9	Visited by Hayabusa in 2005
Bennu[b]	C	6.4	5/13/2019	11/8/2023	10	1.9 - 2.1	OSIRIS-REx, mid-2018
1999 JU3	C	5.1	6/19/2019	7/2/2023	14	2.1 - 2.4	Hayabusa 2, mid-2018
2008 EV5[a]	C	4.4	1/10/2020	1/10/2024[d]	24	2.5 - 2.8	Radar in Dec. 2008, SNR= 240,000
2011 UW158	?	5.3	7/19/2018	7/11/2024[d]	10	1.8 - 2.1	Radar in Jul. 2015, SNR = 280,000
2009 DL46[a]	?	5.7	11/6/2019	8/12/2024[d]	11	1.9 - 2.2	Radar in May 2016, SNR= 48,000

[a]Earth gravity assist ~1yr prior to capture
[b]Falcon Heavy with 13.2 t to C_3 = -2 km^2/s^2
[c]Assuming densities in the range 2.0 to 3.0 g/cm^3
[d]2024 return

- This table assumes a Falcon Heavy L/V, Earth departure in mid-2019, 100-day stay, and return in mid-2023, unless otherwise noted.
- Green rows indicate characterization by imaging from a prior mission.
- Grey rows indicate characterization by radar and inference of appropriate-sized boulders.
- Candidates are being characterized by radar at an average rate of ~1 per year.

Current and Possible Future Valid Candidates

- **Reference Mission:**
  - Currently, 1 valid candidate: **2009 BD**.
  - Possibly another valid candidate in 2 months: **2011 MD**.
  - Possibly another valid candidate in 2016: **2008 HU4**.
  - Potentially future valid candidates, at a rate of a few per year.

- **Alternate Mission:**
  - Currently, 1 valid candidate: **Itokawa**.
  - 2 more valid candidates expected in 2018 (after characterization by other missions): **Bennu** and **1999 JU3**.
  - 1 possibly valid candidate with inferred boulders: **2008 EV5**.
  - Potentially future valid candidates with inferred boulders, at a rate of ~1 per year.