National Aeronautics and Space Administration

ARM Observation Campaign

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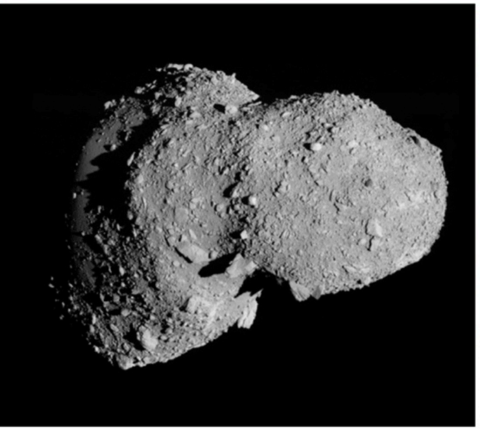
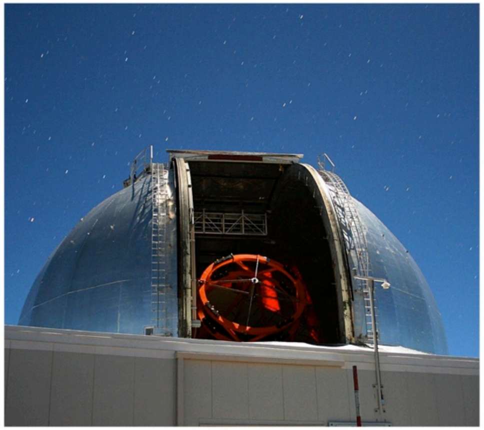
KISS Workshop on Applications of Asteroid Redirection Technology

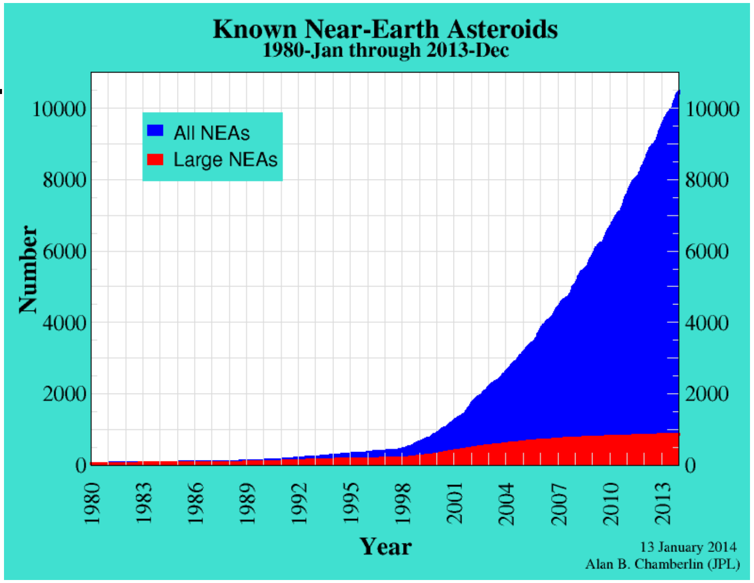
April 7-9, 2014

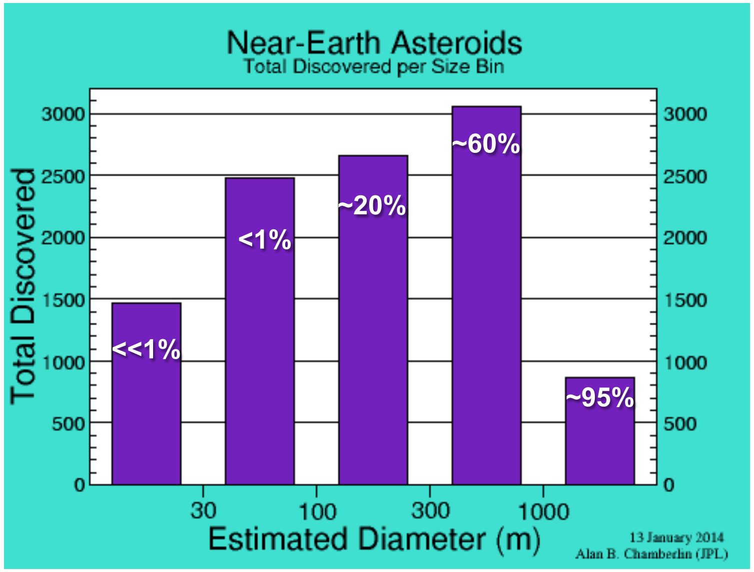



Numbers of Near-Earth Asteroids (NEAs)

- 99% of Near-Earth Objects are asteroids (NEAs).
- Current number of known NEAs: ~10,777, discovered at a rate of ~1000 per year.
- Since 1998, NASA's NEO Observation Program has led the international NEO discovery and characterization effort; this responsibility should continue in the search for smaller asteroids.
- 95% of 1-km and larger NEAs have been found; the completion percentage drops for smaller asteroids because the population increases exponentially as size decreases.
- Numbers for 10-m-class NEAs:

Estimated population:	~30,000,000
Number currently known:	~380
Estimated number that meet Ref. Concept orbital criteria:	~10,000
Number currently known:	~17





NEA Population vs. Absolute Magnitude & Size

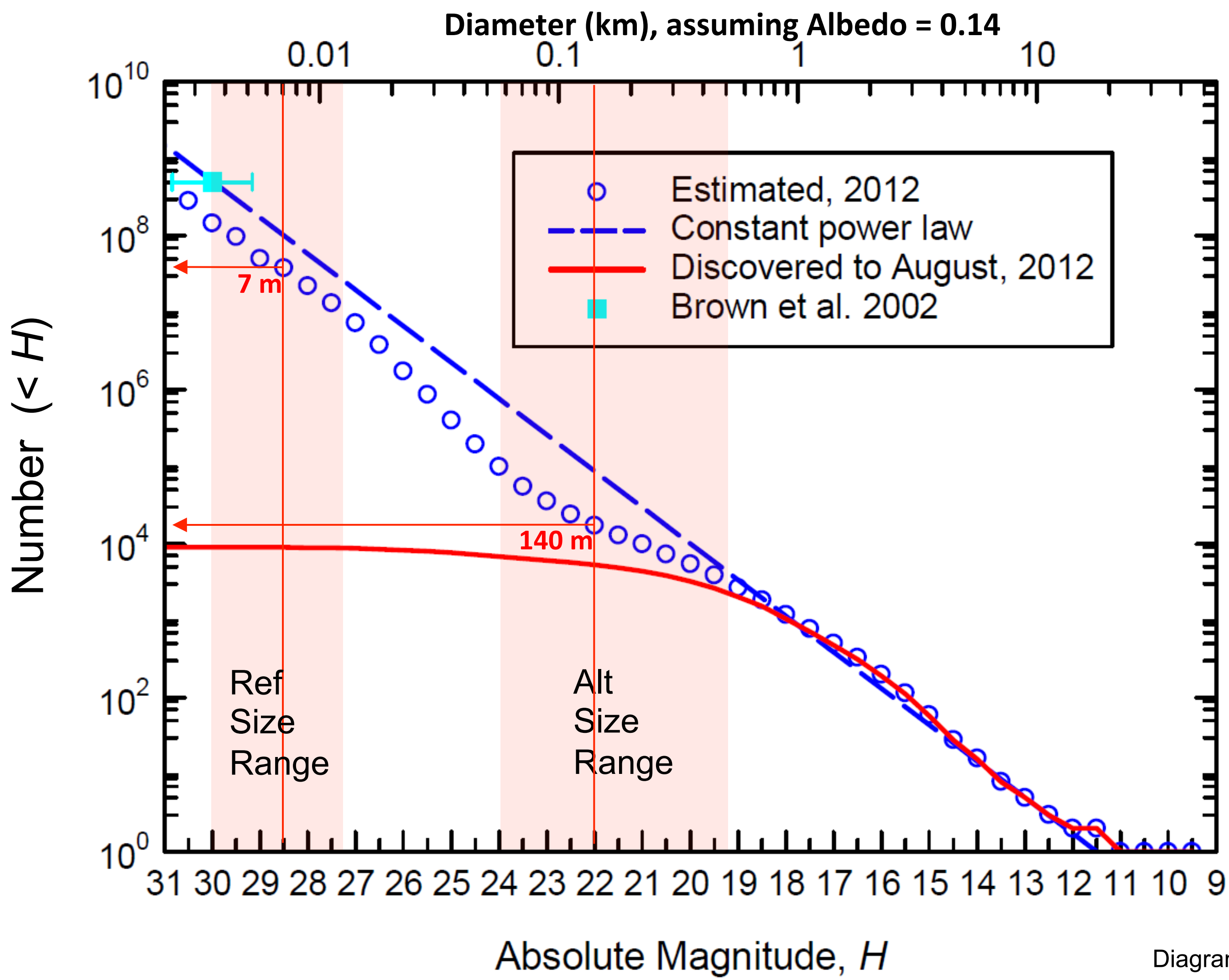
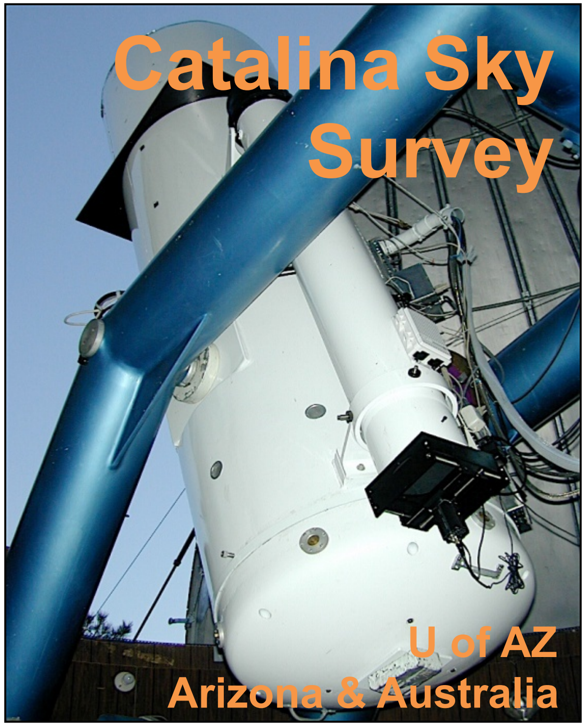


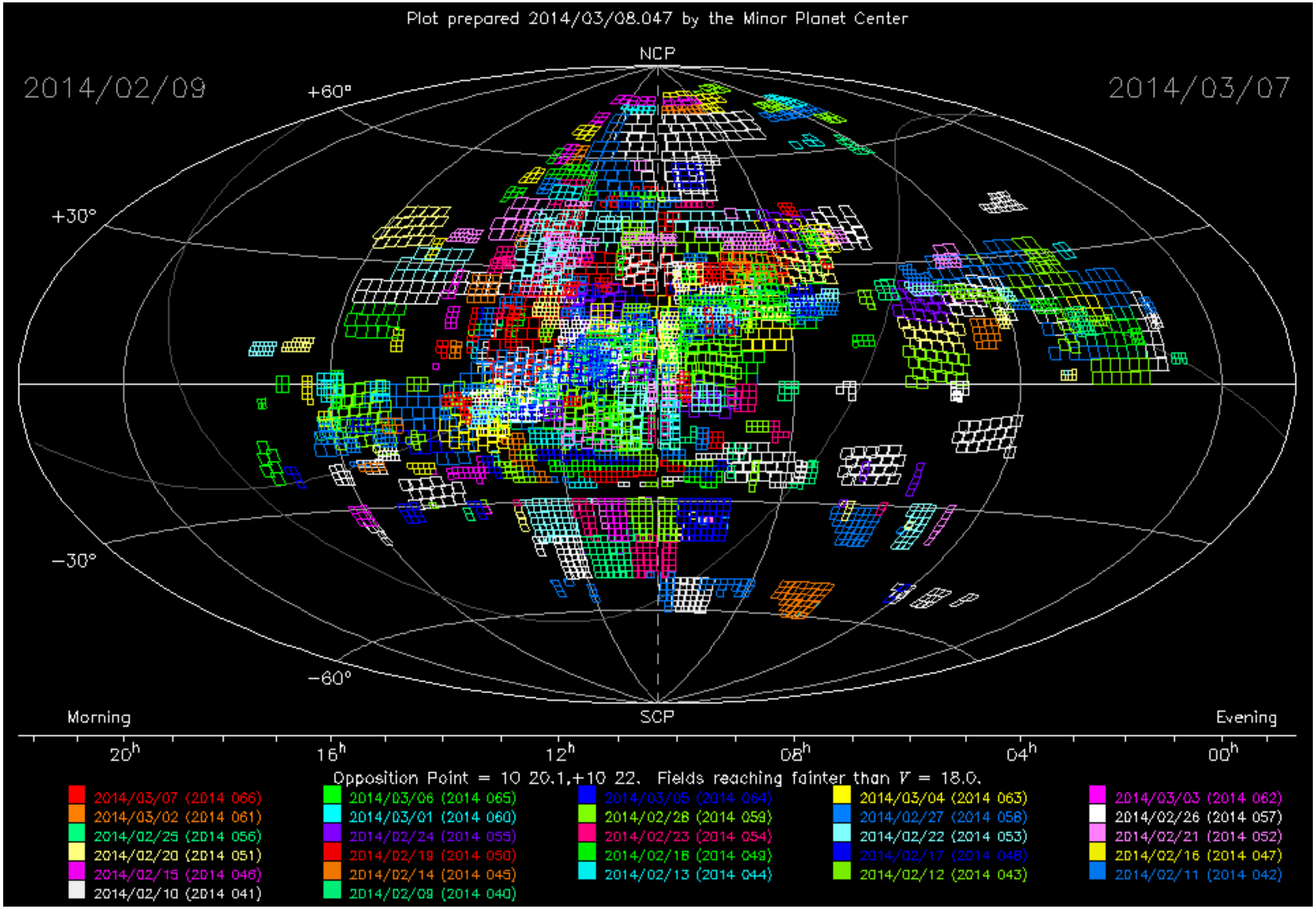
Diagram courtesy of Al Harris

NASA's NEO Search Programs: Current Systems



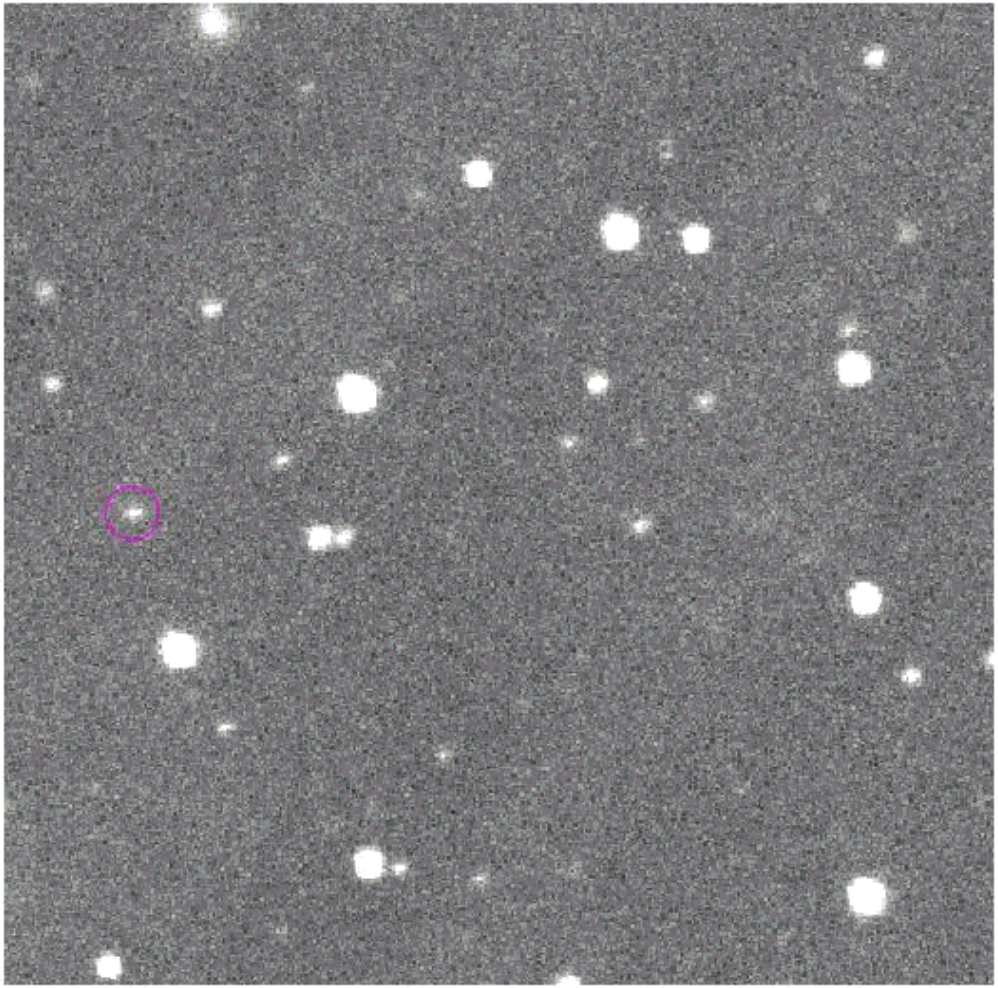
- Currently, most Near-Earth Asteroid discoveries are made by: Catalina Sky Survey (60%), Pan-STARRS-1 (30%), and Spacewatch (2%).
- Enhancements to current surveys and entirely new surveys are coming online now and over the next 2 years.
- These enhancements will increase capabilities to find hazardous asteroids in general, as well as ARM candidate targets.

Sky Coverage, Feb.-Mar. 2014



Courtesy of Tim Spahr, Minor Planet Center

The Asteroid Search Process & An Interesting Find

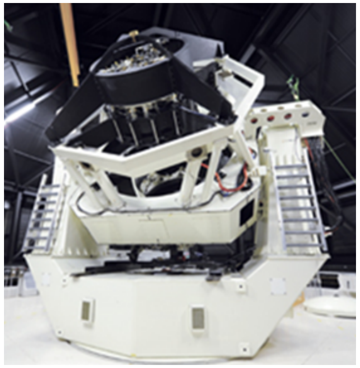


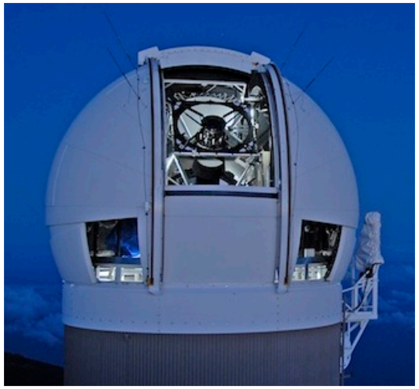
Discovery images of 2008 TC3 from Catalina Sky Survey

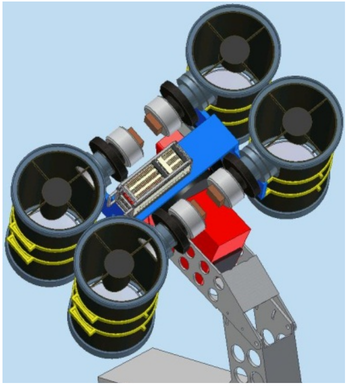
- Each region of sky is imaged 3-4 times over ~80 minutes.
- The images are compared to look for moving objects.
- On October 7, 2008, the Catalina Sky Survey found a very interesting object: 2008 TC3, headed for impact.
- Discovered at 1.3 lunar distances, 19 hr before impact.
- Impact location was predicted 11 hours before impact.
- The object was clearly very small and would likely break up on entry.

Primary Enhancements for ARRM Candidate Discovery

- **NEO Time on DARPA Space Surveillance Telescope**
  - Large 3.6m telescope, first light: Feb 2011, now in testing.
  - Developed for DoD Space Situational Awareness.
  - Testing of NEO detection capability: Winter 2013-14
  - Routine NEO observing is planned to start in **April 2014.**
- **Enhancing Pan-STARRS 1, Completing Pan-STARRS 2**
  - Increase NEO search time to 50% on PS1: **March 2014**.
  - Complete PS2 (improved copy of PS1): **Late 2014**.
- **Accelerated Completion of ATLAS**
  - Set of small telescopes with extremely wide fields of view covering the entire night sky every night, but not as deeply.
  - Final design completed. 1st system completion: **Late 2015**.
  - Prototype being set up at Mauna Loa NOAA site.







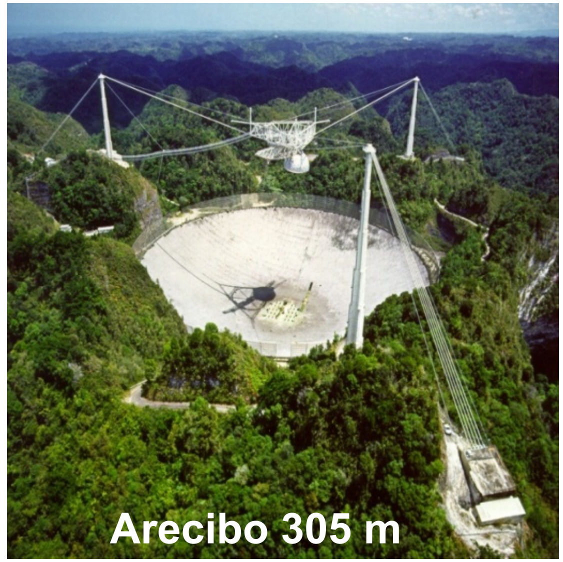
Observation Campaign Enhancements for Discovery

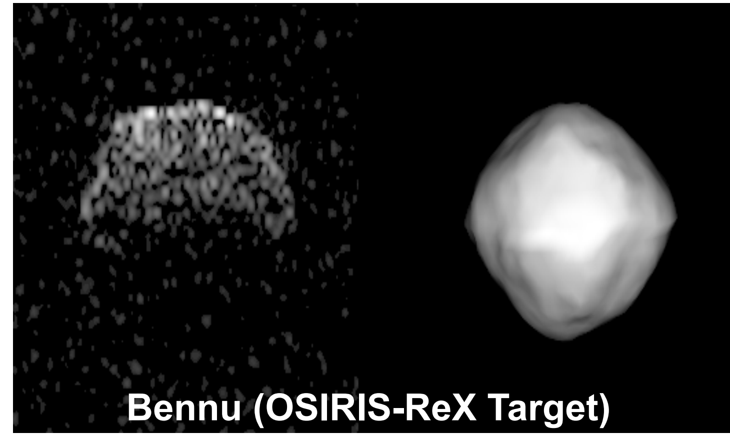
	Facility	V_{lim}	FOV (deg^2)	In Work or Potential Improvements	Ops Date
Current Surveys	Catalina Sky Survey:			Retune observation cadence	Late 2014
	Mt. Bigelow	19.5	8	Increase FOV to 19.4 deg^2	Late 2014
	Mt. Lemmon	21.5	1.2	Increase FOV to 5.0 deg^2	Mid 2014
	Pan-STARRS 1	21.5	7	Increase NEO time to 50%	Mar 2014
				Increase NEO time to 100%	Apr. 2014
Future Surveys	DARPA SST	22+	6	Begin bulk data delivery - MPC	Apr. 2014
	Palomar Transient Facility (PTF)	21	7	Improve software to detect streaked objects	Mid 2014
	Pan-STARRS 2	22	7	Complete telescope system	Late 2014
	ATLAS	20	40	Entire night sky every night x2	Late 2015

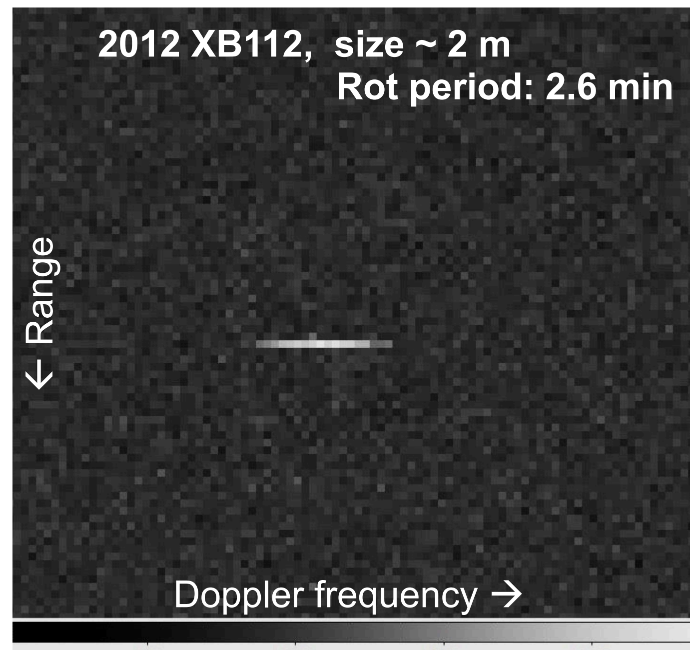
V_{lim} = limiting magnitude , FOV = Field of View

Radar Observations of ARRM Candidates


Goldstone 70 m


Arecibo 305 m


Bennu (OSIRIS-ReX Target)

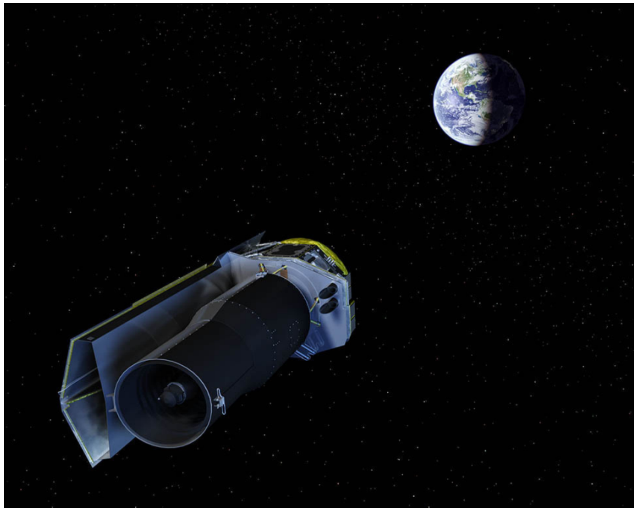


- For the Reference Concept, a candidate must pass < ~6 lunar distances to be detected; ~75% of current candidates could have been detected.
- For the Alternate Concept, a candidate must pass < ~8 lunar distances to have a high enough SNR to detect boulders.
- Radar observations can provide:
  - Size and shape to within ~2 meters.
  - High precision range/Doppler orbit data.
  - Spin rate, surface density and roughness.

Infrared Characterization of NEOs

NASA InfraRed Telescope Facility (IRTF)

- Dedicated Planetary Science Observatory
- Spectroscopy and Thermal Signatures
- On-call for Rapid Response on Discoveries



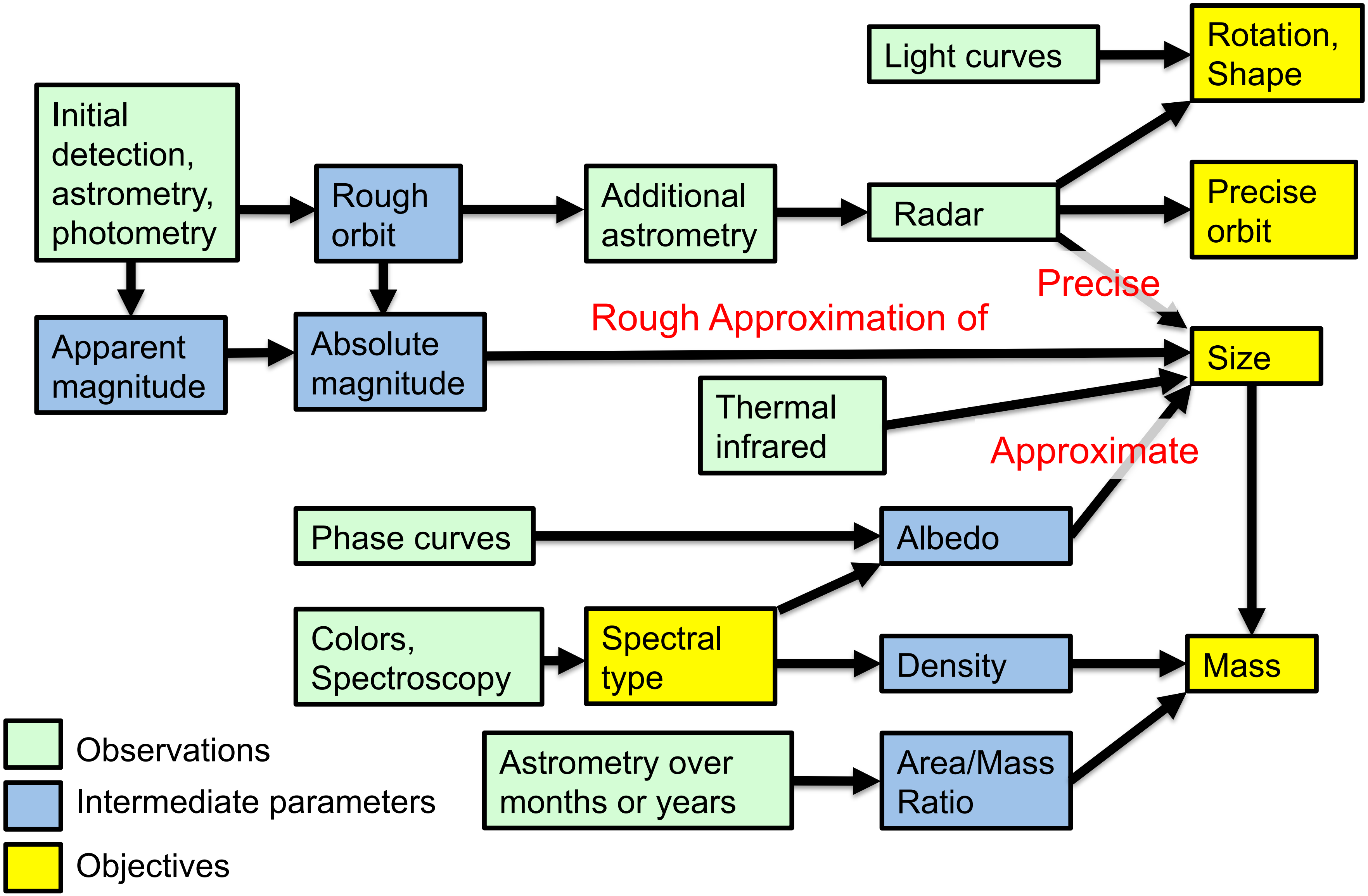
Spitzer Infrared Space Telescope

- Orbit about Sun, ~180 million km from Earth
- In extended Warm-phase mission
- Thermal Signatures, Albedo/Sizes of NEOs
- Longer time needed for scheduling

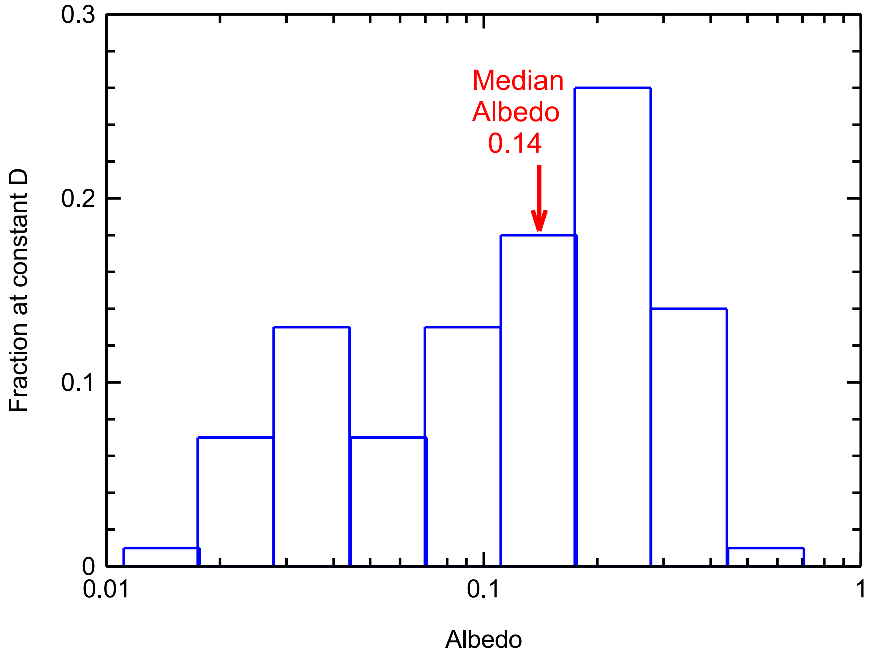
Reactivated NEOWISE

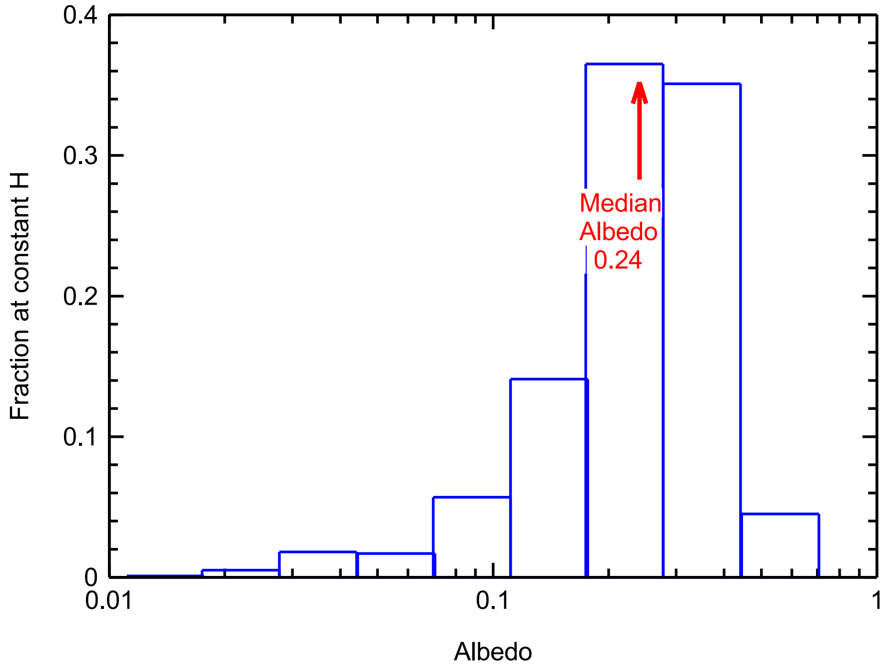
- ~3 year warm phase dedicated to NEO Search/Characterization data collection.

NEA Characterization Process



NEA Albedo Distribution





Albedo distribution at a given diameter vs. Albedo distribution at a given *H* mag.

Data from NEOWISE (Mainzer et al.), diagram courtesy of Al Harris

ARM Candidate Nomenclature Guide

- **"Potential Candidate":**
  - An NEA whose orbit parameters satisfy rough constraints on launch date, return date and total mission ΔV.
  - Absolute magnitude indicates size lies roughly in the right range: < 10 m for the Reference Concept and ~50-500 m for the Alternate Concept.
- **"Characterizable":**
  - Approaches the Earth (or Spitzer) close enough, and with suitable enough observing geometry, that its physical properties can be adequately characterized; or a robotic precursor mission is available.
- **"Valid Candidate":**
  - For the Reference Concept, a Potential Candidate whose physical properties have been adequately characterized (size, mass, rotation rate) and lie within acceptable ranges to achieve mission goals.
  - For the Alternate Concept, a Potential Candidate whose surface has been characterized so that the existence of boulders of the size which can be returned can at least be inferred.
  - Detailed mission design has been performed using feasible launch and return dates, and the upper bound on the mass (entire NEA or boulder) is less than the maximum return mass from the mission design.
- **"Selectable Target":**
  - Meets programmatic constraints (e.g., achievable schedule and acceptable return size), and has identified but manageable risks.

Characteristics of Reference Concept Candidates

Characteristic	Reference Value
$V_{infinity}$ relative to Earth	< 2 km/s desired; upper bound ~2.6 km/s (roughly, 0.85 < a < 1.25, e < ~0.17, i < ~6 deg, → synodic period > ~3.75 years)
Natural return to Earth	Natural return to Earth in 2020-2026 timeframe ("Return" means close approach within ~0.3 au)
Mass	<1,000 metric tons (Upper bound varies according to $V_{infinity}$)
Rotation State	Spin rate < 2 rpm, < 0.5 rpm desired Non-Principal-Axis rotation: OK
Size and Aspect Ratio	7 m < mean diameter < 10 m (roughly, 27 < *H* < 31) Maximum dimension <~13 m, aspect ratio < 2:1
Spectral Class	Known Type preferred, but not required (C-type with hydrated minerals desired)

Candidates for the Reference Concept

- Simulations suggest there are thousands of potential candidate targets suitable for the Reference Concept; the challenge is to find and characterize them.
- Current discovery rate of potential candidates: **2-3 per year**.
- When the discovery enhancements come online, this rate is expected to increase to **~5 per year**.
- Rapid response after discovery is critical for physical characterization of potential candidates. The process has already been successfully exercised for a difficult-to-characterize candidate (2013 EC20).
  - Large aperture optical telescopes: Rotation rate, colors, photometry, area-to-mass.
  - Goldstone and/or Arecibo radar: Size, albedo and rotation state.
  - Ground-based or space-based IR: Size, albedo and spectral type.
  - Candidates must approach within ~6 lunar distances to be adequately characterized.
- Number of Valid Candidates expected to increase at a rate of **1-2 per year**.

Physical Characterization of Small ARM Candidates

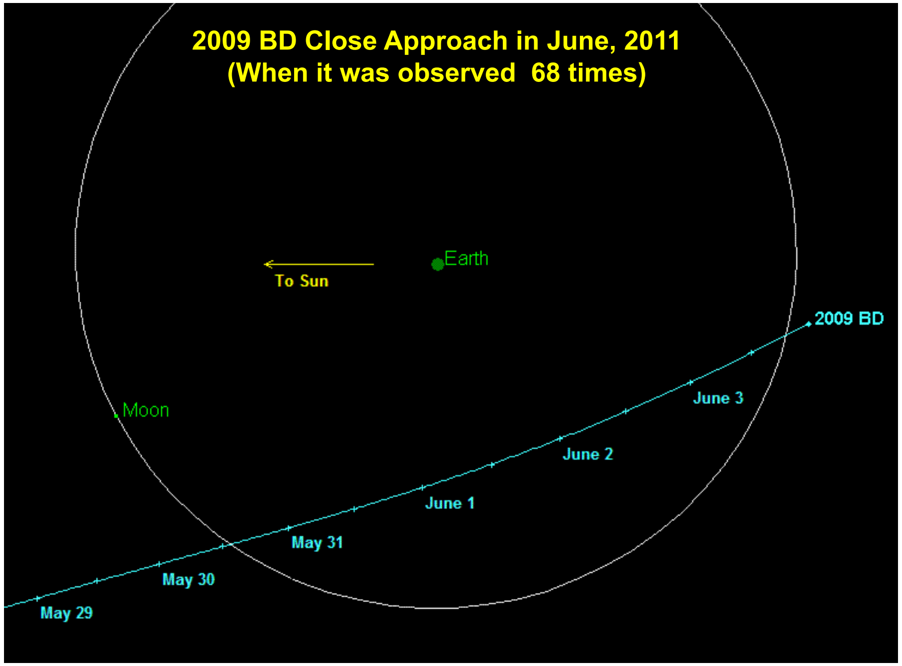
- Radar is essential for obtaining an accurate estimate of size and shape to within ~2 m, as well as rotation state.
- Ground-based and space-based IR measurements are important for estimating albedo and spectral class, and from these an approximate density can be inferred.
- Light curves are important to estimate shape and rotation state.
- Long-arc high-precision astrometry is important for determining the area-to-mass ratio.
- Mass is estimated from size and shape using an inferred or assumed density, and it can be constrained by the estimate of the area-to-mass ratio. Even so, mass may only be known to within a factor of 3 or 4.
- Final ARM target selection may depend largely on how the estimated upper bound on the mass of each candidate compares with the return mass capability for that candidate.

Assumed albedo $p_v = 0.04$

Assumed albedo $p_v = 0.34$

Reference Concept Candidate 2009 BD [1]

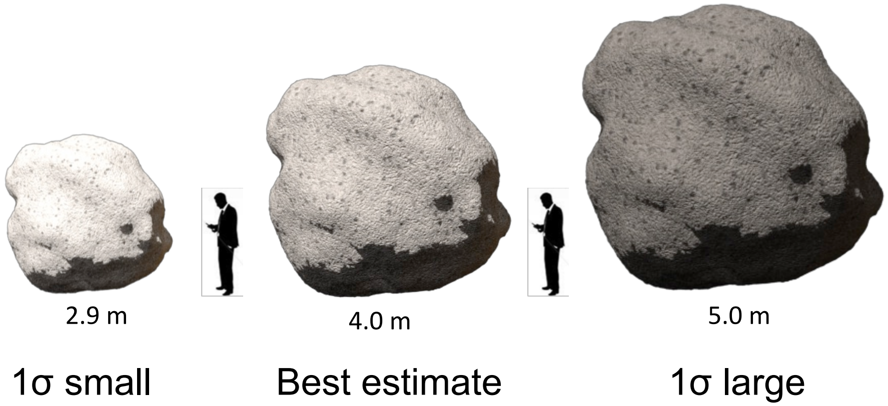
- Reference Concept candidate 2009 BD, discovered in January 2009, is one of the most well observed small asteroids in the catalog.
- Its orbit and optical brightness are extremely accurately known, from hundreds of observations made at 2 dozen observatories.
- 2009 BD's area-to-mass ratio (AMR) and Yarkovsky effect are well measured.
- 2009 BD passed very close to the Earth in May-June 2011; it could easily have been observed by radar, but was not, due to equipment problems.
- Without radar, the estimated size spanned a large range: 4 – 19m.
- 2009 BD passed in the vicinity of the Spitzer Space Telescope twice in 2013; observations were attempted.
- First observation in May 2013 was unsuccessful because of an error in predicting the asteroid's position.



Reference Concept Candidate 2009 BD [2]

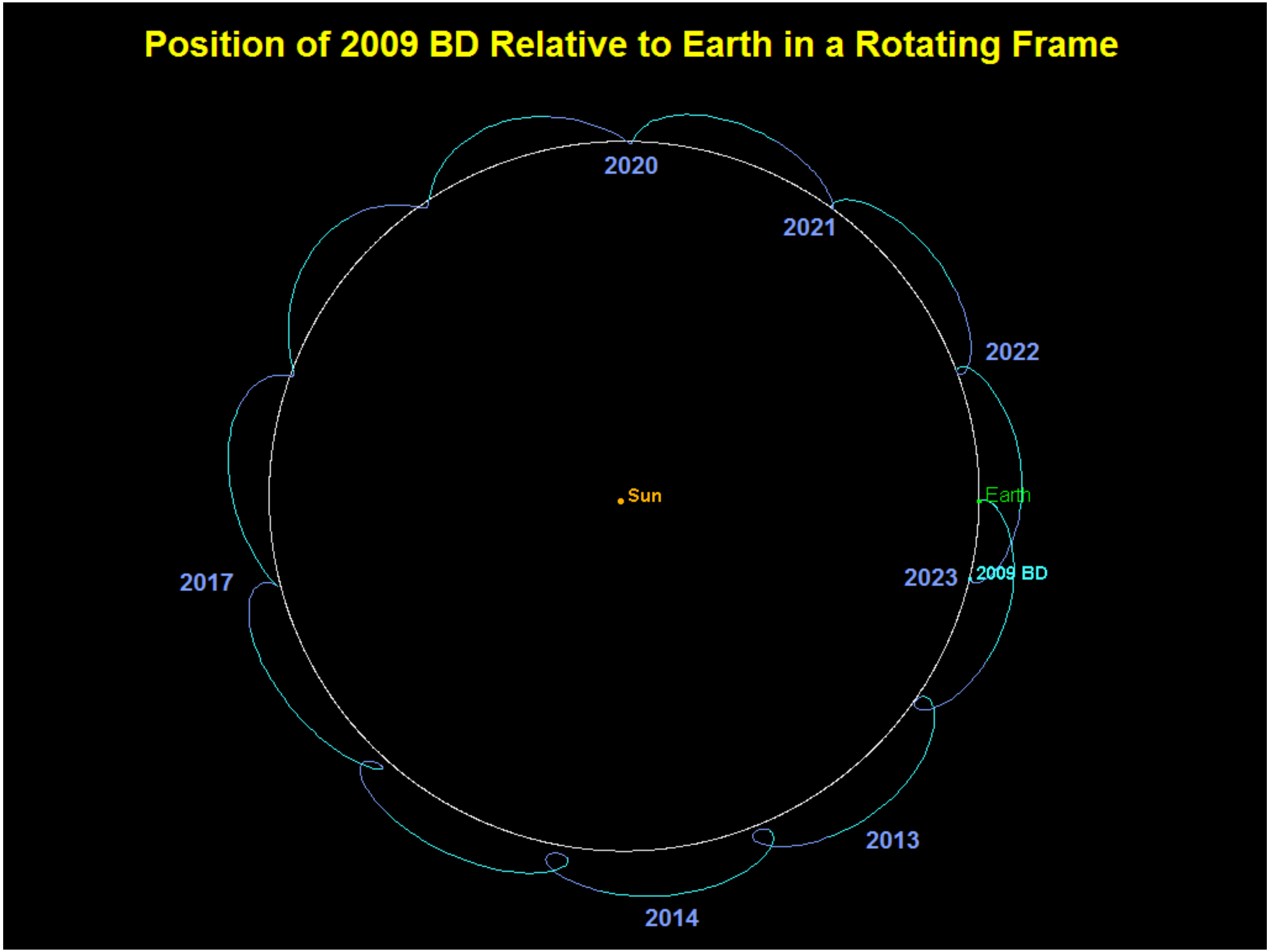
- Spitzer observed 2009 BD in Oct. 2013 but did not detect it because it is smaller than expected: **2.6 to 7 meter** mean size (3σ), and likely smaller than 5 meters.
- If it had been >~8 meters in size, 2009 BD would have been detected.
- The smaller size implies a higher than expected optical albedo, in the range of 25% to 80%.
- The Spitzer observation constrains the mass of 2009 BD to the range ~30 – 85 tons (1σ), with a **3σ upper bound of 145 t**.
- This upper bound on mass is 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 Concept



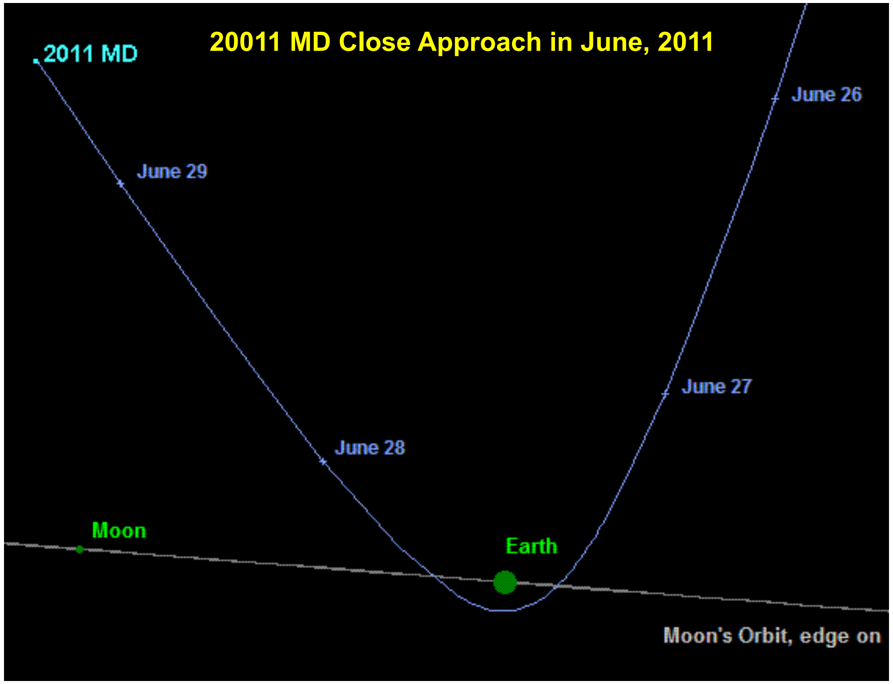
(Asteroid representation notional)

Future Orbit of 2009 BD



Reference Concept Candidate 2011 MD

- Reference Concept candidate 2011 MD, discovered when it passed extremely close to Earth in June 2011, and was observed even more than 2009 BD.
- Slightly brighter than 2009 BD; estimated size range is slightly bigger: 4 – 23m.
- Could have been detected easily by radar, but was not, due to the same mechanical problems as for 2009 BD.
- Observed by Spitzer in Feb. 2014, at a greater distance than for 2009 BD.
- 2011 MD was detected! The observation data is still being reduced.
- Maximum return mass for a mid-2019 launch to 2011 MD is ~620 t, which is more than for 2009 BD.



Current Candidates for Reference Concept
Mid-2019 Launch & 2021-26 Return

- Current list of Potential Candidates for the Reference Concept:

	Name	Was Radar Possible?	Estimated Size (m)	V_∞ (km/s)	Return Date	Maximum Returnable Mass (t)†	Comment
	2007 UN12	Y	3 – 18	1.2	12/2021	90	
	2008 EA9	?	5 – 25	1.9	5/2021	45	
KISS baseline	2008 HU4	Y	4 – 22	0.5	4/2026	800	Characterizable in 2016
Current baseline	2009 BD	Y	2.6 – 7	1.2	6/2023	430	Valid Candidate
	2010 UE51	Y	4 – 22	1.2	12/2022	90	
	2011 MD	Y	4 – 23	1.0	8/2024	620	Being characterized now
	2013 EC20	Y	2 – 3	2.6	4/2025	90	Characterized, too small?
	2013 GH66	Y	4 – 22	2.0	4/2025	100	
	2013 LE7	?	6 – 33	2.5	5/2023	100	
	2013 PZ6	N	5 – 23	n/a	8/2023	100	
	2013 XY20	N	11 – 60	1.8	12/2025	310	
	2014 BA3	Y	4 – 21	1.9	1/2024	500	

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

- Potential Candidates:
  - Past discovery rate: **~1-2 per year**; in the last 12 months: **~5**.
  - Estimated discovery rate, with enhanced assets: **~5 per year**.
- Valid Candidates:
  - Currently, one: **2009 BD**.; expected to increase at a rate of **~1-2 per year**.

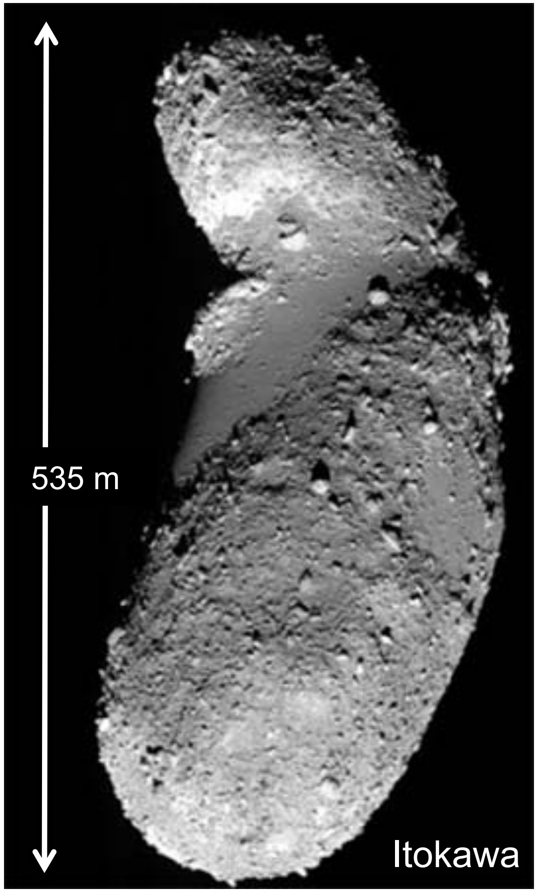
Candidates for the Alternate Concept

- In the 100m size range, the number of known NEAs is an order of magnitude larger than in the 7m size range: larger asteroids are easier to find.
- There are ~200 Potential Candidates for the Alternate Concept with return mass >~10 t and return date before the end of 2024; there are ~700 Potential Candidates with return mass >1 t.
- Current discovery rate of Potential Candidates: **~25 per year**; this rate will increase when observation campaign enhancements come online.
- In order to be a Valid Candidate for the Alternate Concept, the surface of the asteroid must be characterized and the existence of boulders of the size which can be returned must at least be inferred.
- There are two possible means of adequately characterizing the surface:
  1) In situ imaging from a precursor mission, and
  2) Ground-based radar with high enough SNR.
  - Candidates must approach within ~8 lunar distances to have high enough SNR.
- Amount of mass which can be returned from the Alternate Concept candidates which have been characterized, or likely will be characterized before 2019, is <~50 t, corresponding to boulder sizes of <~4 m.

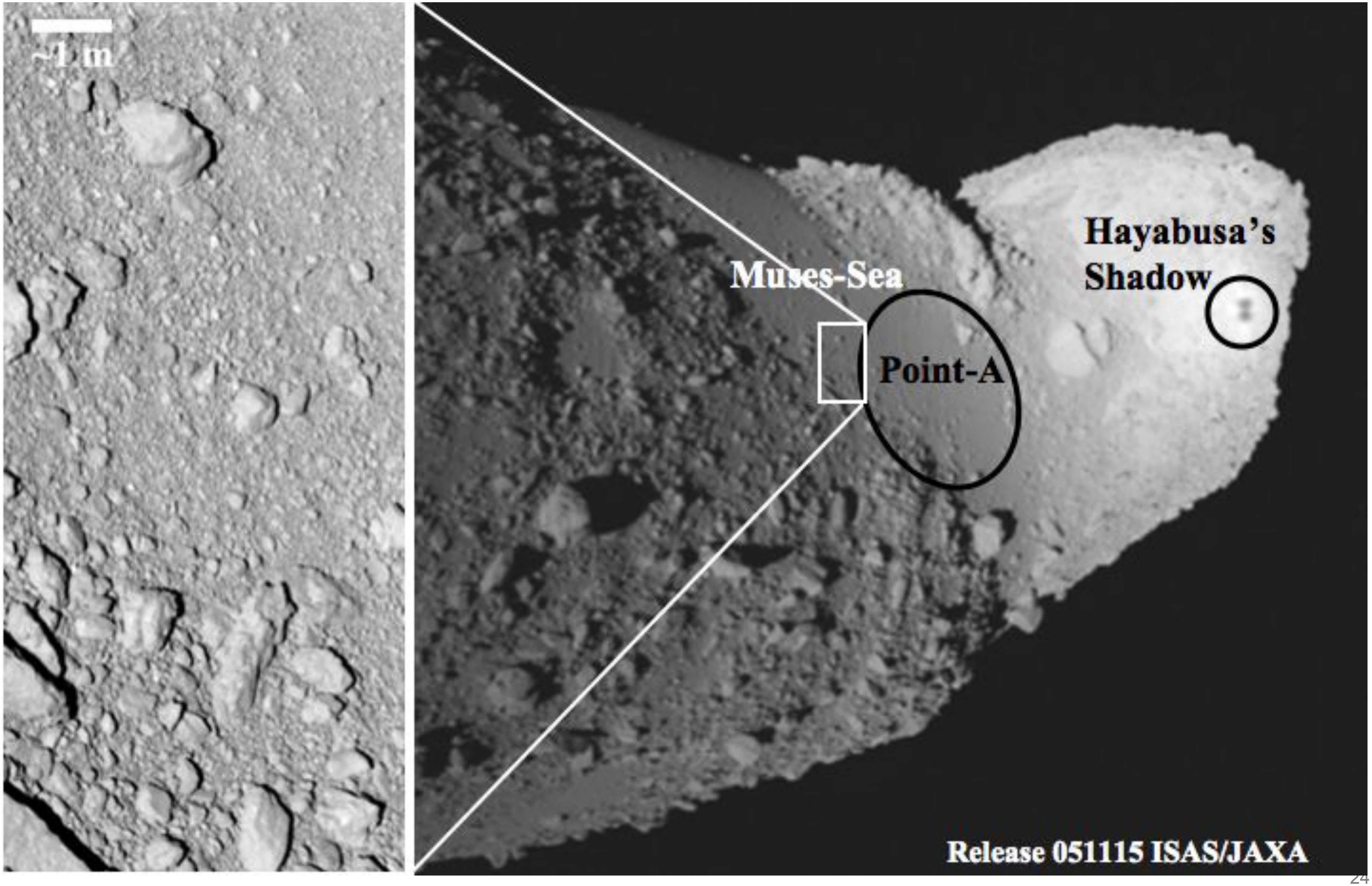
In Situ Characterization for the Alternate Concept

- One Alternate Concept candidate has been visited by a spacecraft and characterized well enough to detect boulders of a size which could be returned:
  - **Itokawa**, visited by Hayabusa in 2005.
- Two Alternate Concept candidates are planned to be similarly characterized by spacecraft in 2018:
  - **Bennu** (OSIRIS-Rex), and
  - **1999 JU3** (Hayabusa 2).

Itokawa is considered a Valid Candidate for the Alternate Concept, while Bennu and 1999 JU3 are expected to become Valid Candidates

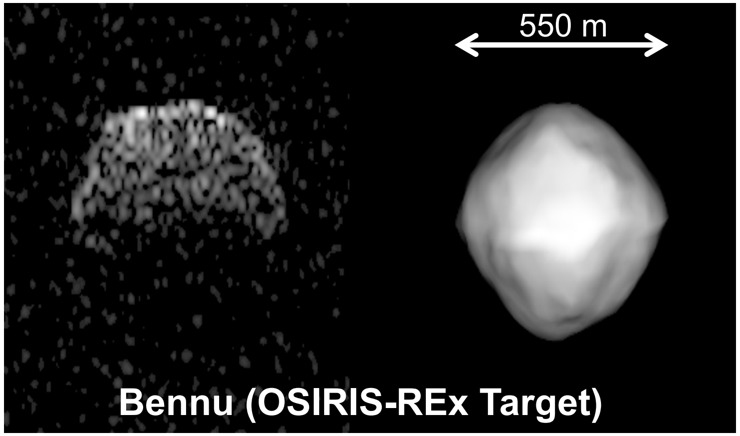


In Situ Characterization of Boulders on Itokawa



Radar Characterization of Boulders on Asteroids

- Current ground-based radar range resolution: 8 m (Arecibo), 4 m (Goldstone).
- Currently, radar cannot definitively detect boulders <4m, regardless of the SNR, but the presence of boulders might be inferred from radar observations.
- If the radar SNR exceeds ~5000, radar could detect ~4m-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 <4m-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.
- 11 potential candidates for the Alternate Concept have been observed by radar with high enough SNR; evidence for 10m-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.



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

- Current list of Valid Candidates and possibly Valid Candidates for the Alternate Concept:

Target	Type	Asteroid V_{∞} (km/s)	Earth Launch or Escape	Earth return	Max Return mass (t)	Boulder max diam (m)[c]	Characterization	
Itokawa[a]	S	5.7	3/2019	10/2023	6	1.6 - 1.8	Visited by Hayabusa in 2005	Valid
Bennu[b]	C	6.4	5/2019	11/2023	12	2.0 - 2.3	OSIRIS-REx, mid-2018	Expected
1999 JU3	C	5.1	6/2019	7/2023	13	2.0 - 2.3	Hayabusa 2, mid-2018	Expected
2008 EV5[a]	C	4.4	1/2020	6/2024	32	2.7 – 3.1	Radar in Dec. 2008, SNR= 240,000	Valid
2011 UW158	?	5.3	7/2018	7/2024	10	1.8 - 2.1	Radar in Jul. 2015, SNR = 280,000	Possible
2009 DL46[a]	?	5.7	11/2019	8/2024	11	1.9 - 2.2	Radar in May 2016, SNR= 48,000	Possible

[a]Earth gravity assist ~1yr prior to capture

[c]Assuming densities in the range 2.0 to 3.0 g/cm^3

NB: Max Return masses and Boulder max diameters vary significantly with launch date and return date.

- Assumes a Falcon Heavy L/V, Earth departure in mid-2019, 400-day stay, and return in 2023, unless otherwise noted.
- Green rows: in situ characterization by imaging from a precursor mission.
  Grey rows: characterization by radar and inference of appropriate-sized boulders.
- Potential Candidates are characterized by radar at an average rate of ~1 per year.

Current and Possible Future Validated Candidates

- **Small Asteroid Capture (Reference) Concept:**
  - Currently, 7 potential candidates
  - 1 validated candidate: **2009 BD**
  - 1 possibly Valid Candidate pending Spitzer final analysis: **2011 MD**
  - Possibly another Valid Candidate in 2016: **2008 HU4**
  - Potentially future Valid Candidates, at a rate of a few per year

- **Large Asteroid Boulder Capture (Alternate) Concept:**
  - Currently, 6 potential candidates
  - Currently, 1 validated 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