National Aeronautics and Space Administration

# Asteroid Redirect Robotic Mission (ARRM): Observation Campaign Study

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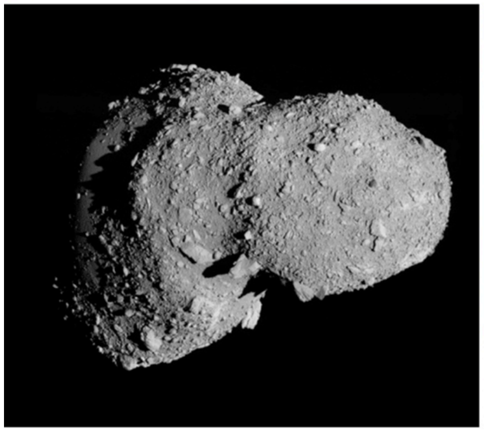
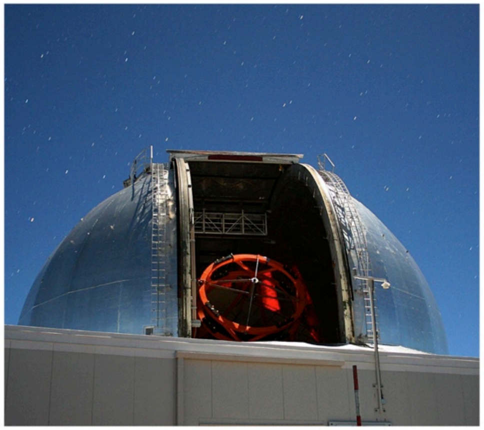




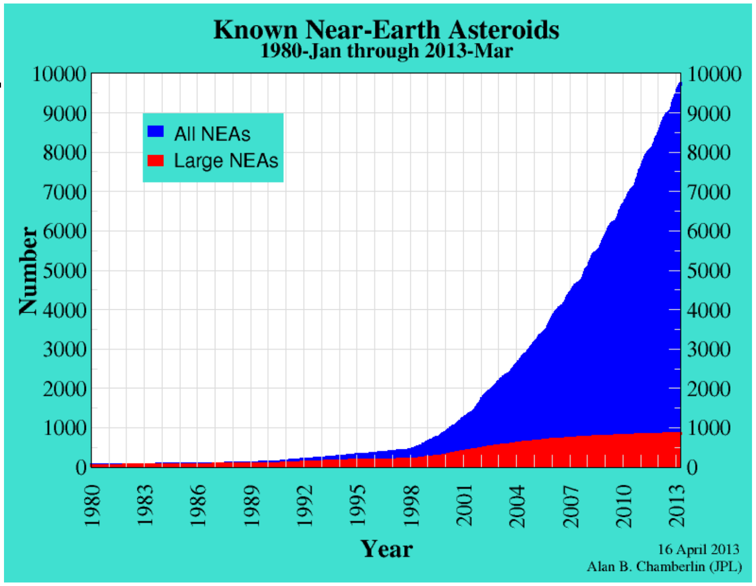
# Executive Summary

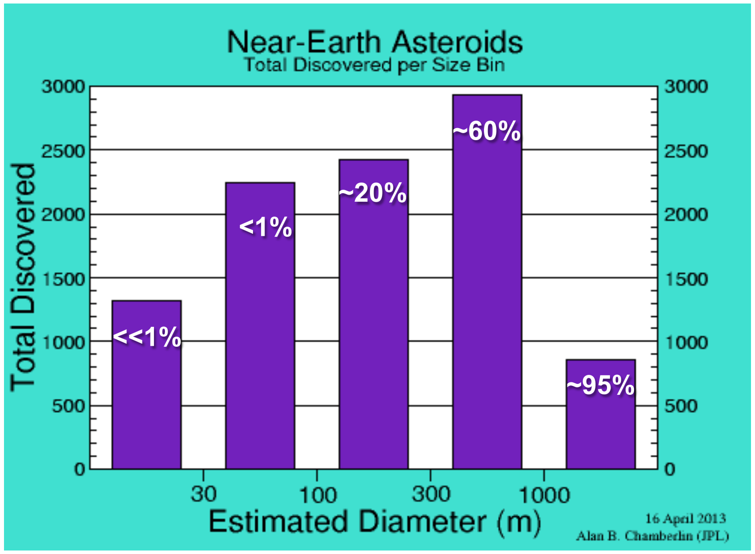
- Current population models suggest that there are a large number of good ARRM candidate targets, but current surveys are finding only 2 to 3 per year, and only 4 of the known candidates can be adequately characterized (2009 BD, 2011 MD, 2013 EC20, 2008 HU4).
- Discovery of good candidates is challenging, but the rate can be increased to at least 5 per year via near-term enhancements to current survey assets, as well as additional assets that can be online by 2015.
- Enhancing surveys to find more ARRM candidates also increases their capabilities for finding potentially hazardous asteroids in general.
- The discovery process alone is not sufficient to identify good candidates: physical characterization is also needed, particularly *re* size and mass.
- Radar is a key characterization asset for ARRM candidates.
- Rapid response is critical for physical characterization of newly discovered ARRM candidates. The process has been successfully exercised for a small candidate asteroid.

# Numbers of Near-Earth Asteroids (NEAs)

- 99% of Near-Earth Objects are asteroids (NEAs).
- Current number of known NEAs: ~10,000, 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: | ~100,000,000 |
| Number currently known: | ~380 |
| Estimated number that meet ARRM orbital criteria: | ~15,000 |
| Number currently known: | 14 |



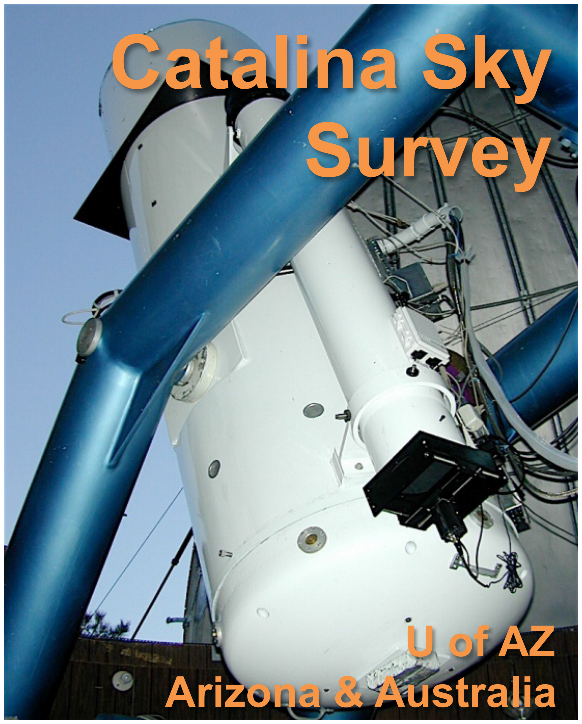



# NEO Observations Program

- US component to International Spaceguard Survey effort has provided 98% of new detections of NEOs since 1998.
- Began with NASA commitment to House Committee on Science in May, 1998 to find at least 90% of 1 km NEOs.
  - Averaged ~$4M/year Research funding 2002-2010
- NASA Authorization Act of 2005 provided additional direction:

  "...plan, develop, and implement a Near-Earth Object Survey program to detect, track, catalogue, and characterize the physical characteristics of near-Earth objects equal to or greater than 140 meters in diameter in order to assess the threat of such near-Earth objects to the Earth. It shall be the goal of the Survey program to achieve 90 percent completion of its near-Earth object catalogue within 15 years [by 2020].
- Current Program Objective: Discover ≥ 90% of NEOs larger than 140 meters in size as soon as possible.
  - Starting with FY2012, has $20.5M/year

# NASA's NEO Search Programs: Current Systems



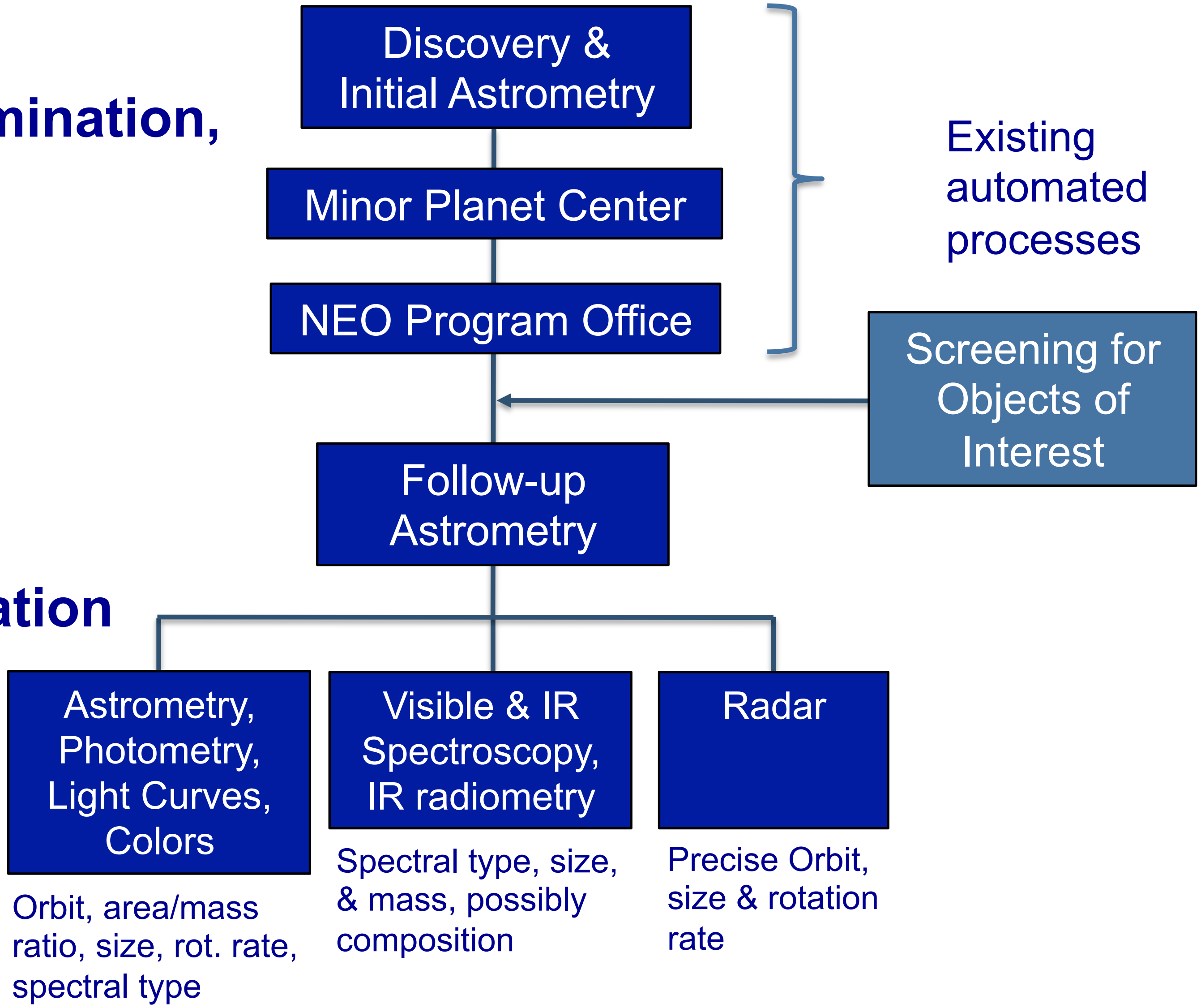



- Currently, most Near-Earth Asteroid discoveries are made by: Catalina Sky Survey (60%), Pan-STARRS-1 (30%), and LINEAR (3%).
- Enhancements and new surveys can come online in the next 2 years. Some will require additional funding.
- These enhancements will increase capabilities to find hazardous asteroids as well as ARRM candidate targets.

# Discovery & Characterization Processes

**Discovery,**
**Orbit Determination,**
**Rough Size**
**Estimation**

**Physical**
**Characterization**



# Characteristics of ARRM Target Candidates

$V_{infinity}$ is the velocity of the asteroid relative to the Earth during an encounter, with the acceleration due to the Earth's gravity removed.

| | Characteristic | Reference Value |
|---|---|---|
| Orbital | Orbit: $V_{infinity}$ relative to Earth | < 2 km/s desired; upper bound ~2.6 km/s |
| Orbital | Orbit: Natural approach to Earth | Orbit-to-orbit distance < ~3 million miles<br>Natural approach to Earth in early 2020s |
| Physical | Size and Aspect Ratio | Estimated mean size: 7 to 10 m<br>Upper limit on maximum dimension: ~14 m<br>Aspect ratio < 2:1 |
| Physical | Mass | <1,000 metric tons<br>(Upper bound decreases as $V_{infinity}$ increases) |
| Physical | Spin Rate | < 2 rpm |
| Physical | Spectral Class | Known Type preferred, but not required<br>(C-type with hydrated minerals desired) |

# Current List of Potential ARRM Candidates

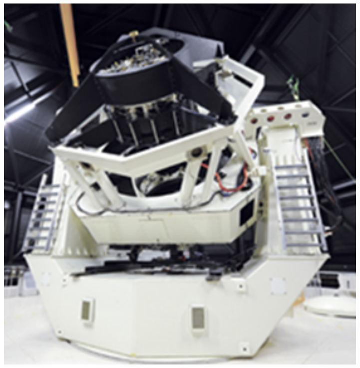
| | Name | Apparent Magnitude at First Detection | Estimated Size (m) | $V_\infty$ (km/s) | Earth Approach Date | Distance at Approach (AU)* | Maximum Returnable Mass (t)† |
|---|---|---|---|---|---|---|---|
| | **Good retrieval trajectories found** | | | | | | |
| | 2007 UN12 | 17.7 | 3 - 14 | 1.2 | 9/15/2020 | 0.043 | 490 |
| | 2008 EA9 | 21.0 | 5 - 22 | 1.9 | 11/15/2020 | 0.073 | 130 |
| | 2013 EC20 | 17.7 | 2 - 4 | 2.6 | 3/15/2021 | 0.067 | 120 |
| | 2010 UE51 | 19.2 | 4 - 17 | 1.2 | 10/15/2022 | 0.023 | 130 |
| Current baseline | 2009 BD | 18.4 | 4 - 8 | 0.7 | 6/26/2023 | 0.199 | 590 |
| | 2011 MD | 19.2 | 5 - 18 | 0.9 | 8/10/2024 | 0.150 | 690 |
| KISS baseline | 2008 HU4 | 17.9 | 4 - 18 | 0.5 | 3/27/2026 | 0.149 | 1600 |
| | **Good retrieval trajectories may be possible** | | | | | | |
| | 2010 XU10 | 20.0 | 6 - 25 | 2.5 | 10/22/2021 | 0.167 | TBD |
| | 2012 WR10 | 19.0 | 4 - 15 | 2.6 | 12/6/2021 | 0.292 | TBD |
| | 2011 BQ50 | 22.8 | 4 - 17 | 2.6 | 11/4/2022 | 0.078 | TBD |
| | 2011 PN1 | 22.0 | 6 - 24 | n/a | 6/30/2023 | 0.300 | TBD |
| | 2005 QP87 | 18.2 | 5 - 22 | 1.5 | 3/1/2024 | 0.457 | TBD |
| | 2010 AN61 | 19.4 | 7 - 30 | 2.6 | 6/10/2025 | 0.251 | TBD |
| | 2013 GH66 | 20.3 | 5 - 18 | 2.0 | 4/15/2025 | 0.894 | TBD |

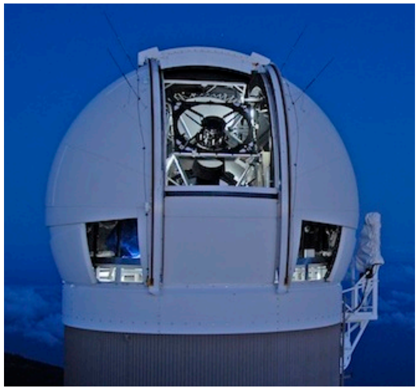
*1 AU = 93,000,000 miles; †Assumes Falcon Heavy launch vehicle and launch dates no earlier than 2017.

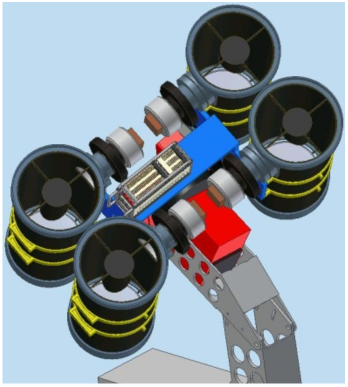
- 14 known asteroids meet the rough size and orbit criteria for ARRM.
- But, most were not physically characterized after discovery due to small size.
- These potential candidates are being discovered at a rate of **2-3 per year**.
- Enhancements to capabilities can increase this discovery rate.
- 4 candidates on this list can be at least partially characterized:
  2009 BD, 2011 MD, 2013 EC20 and 2008 HU4.

# Primary Enhancements for ARRM Candidate Discovery

- **NEO Time on DARPA Space Surveillance Telescope**
  - Large 3.6m telescope, first light: Feb 2011, now in testing.
  - Eventual operations by AFSPC for DoD Space Situational Awareness.
  - Testing of NEO detection capability: Sep 2013.
- **Enhancing Pan-STARRS 1, Completing Pan-STARRS 2**
  - Increase NEO search time to 100% on PS1: Early 2014.
  - Complete PS2 (improved copy of PS1): Late 2014.
  - Simulations suggest the ARRM candidate discovery rate for PS2 alone at 100% will be ~5 per year.
- **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 selection soon.  Completion: Early 2015.
  - Simulations suggest the ARRM candidate discovery rate for ATLAS will be ~10 per year.







# Options for Increasing the ARRM Candidate Discovery Rate

| | Facility | $V_{lim}$ | FOV (deg²) | In Work or Potential Improvements | Ops Date | Notional ARRM discoveries per year* |
|---|---|---|---|---|---|---|
| Current Surveys | Catalina Sky Survey: | | | Increase ML field of view 4x | Late 2013 | 2-3 |
| | Mt. Bigelow | 19.5 | 8 | Increase MB FOV 2.5x | Late 2014 | 1-2 |
| | Mt. Lemmon | 21.5 | 1.2 | Retune observation cadence | Mid 2014 | 3-5 |
| | Pan-STARRS 1 | 21.5 | 7 | Increase NEO time to 50% | Late 2013 | 2-4 |
| | | | | Increase NEO time to 100% | Early 2014 | 4-8 |
| Future Surveys | DARPA SST | 22+ | 6 | Schedule some NEO time | Sep. 2013 | 2-5 |
| | Palomar Transient Facility (PTF) | 21 | 7 | Improve software to detect streaked objects | Late 2013 | 1-2 |
| | Pan-STARRS 2 | 22 | 7 | Request 100% NEO time | Late 2014 | 5-10 |
| | ATLAS (North) | 20 | 40 | Entire night sky every night x2 | Early 2015 | 8-16 |

*Discoveries per year that meet ARRM's rough size and orbit criteria for retrieval. $V_{lim}$ = limiting magnitude
N.B. Predictions for future discovery rates are based on extrapolated coverage and cadence.

**Discovery rates are not additive. There will be duplications of detections, particularly in the optimistic scenarios.**

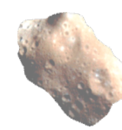
# Summary on Future Discovery Rate of ARRM Candidates

- The ARRM candidate discovery rate will almost certainly **increase** due to enhancements to existing surveys and new surveys coming online.
- Several asteroid survey enhancements are already in process and funded by the NEOO Program.  Some could be accelerated with additional funding.
- A conservative projection, based on study of enhancements, is that the discovery rate will increase to **at least 5 per year**.
- Search for ARRM candidates will continue until final selection.
- With at least another 3-4 years to accumulate discoveries, at least **15 more candidates are expected**.
- With rapid post-discovery characterization capabilities in place, there will be better opportunities to physically characterize future ARRM discoveries.
- Enhancing surveys to find more ARRM candidates also increases their capabilities for finding potentially hazardous asteroids in general.

# Physical Characterization of ARRM 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 should 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 ARRM 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.

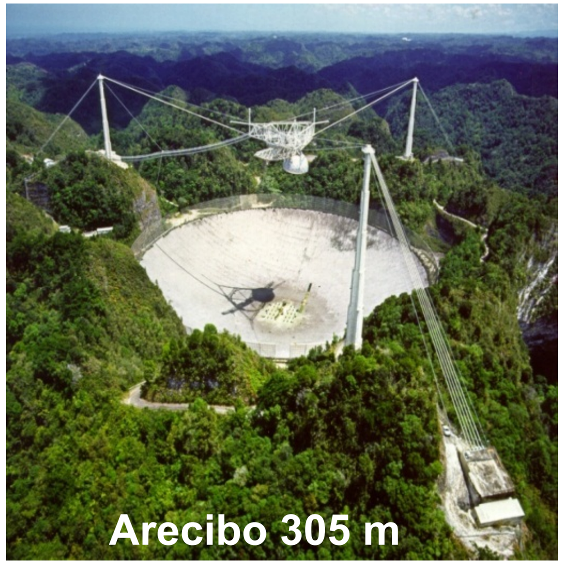
Assumed albedo
$\rho$ = 0.04



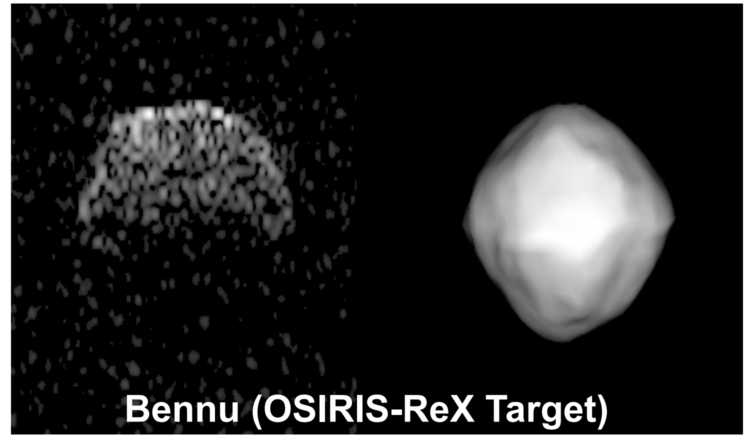
Assumed albedo
$\rho$ = 0.34

# Radar Observations of NEOs

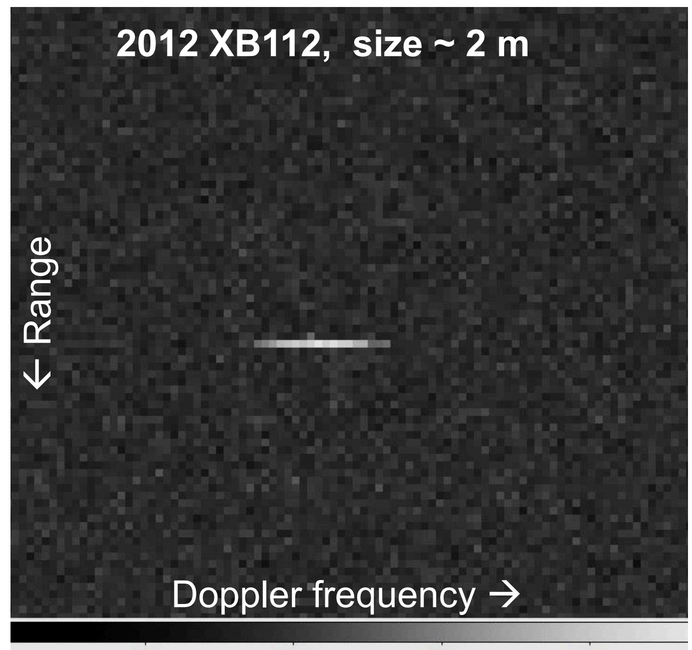
Goldstone 70 m



Arecibo 305 m



Bennu (OSIRIS-ReX Target)




2012 XB112, size ~ 2 m

- These are complementary capabilities.
- Currently, 70-80 NEOs are observed every year.
- A 10-m-class ARRM candidate must pass within ~5 lunar distances to be detected; ~80% of the 14 known candidates could have been detected.
- Radar observations can provide:
  - Size and shape to within ~2 meters.
  - High precision range/Doppler orbit data.
  - Spin rate, surface density and roughness.

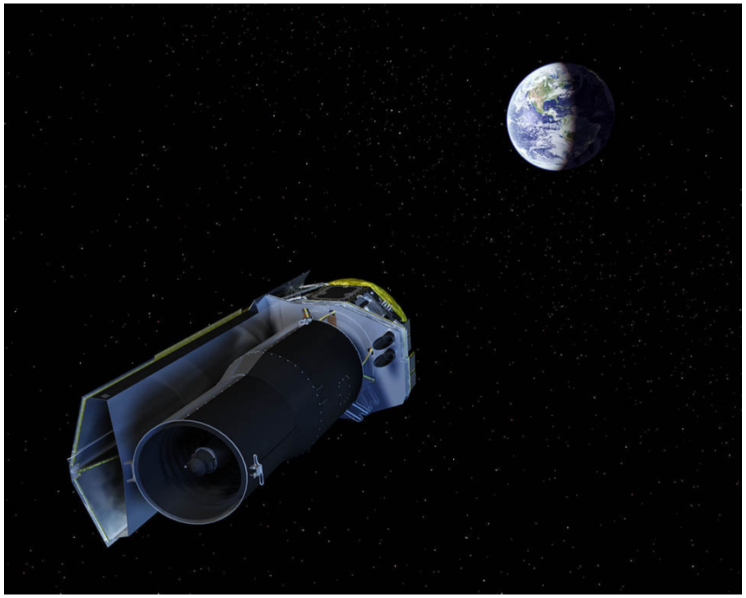
# Infrared Characterization of NEOs

## NASA InfraRed Telescope Facility (IRTF)

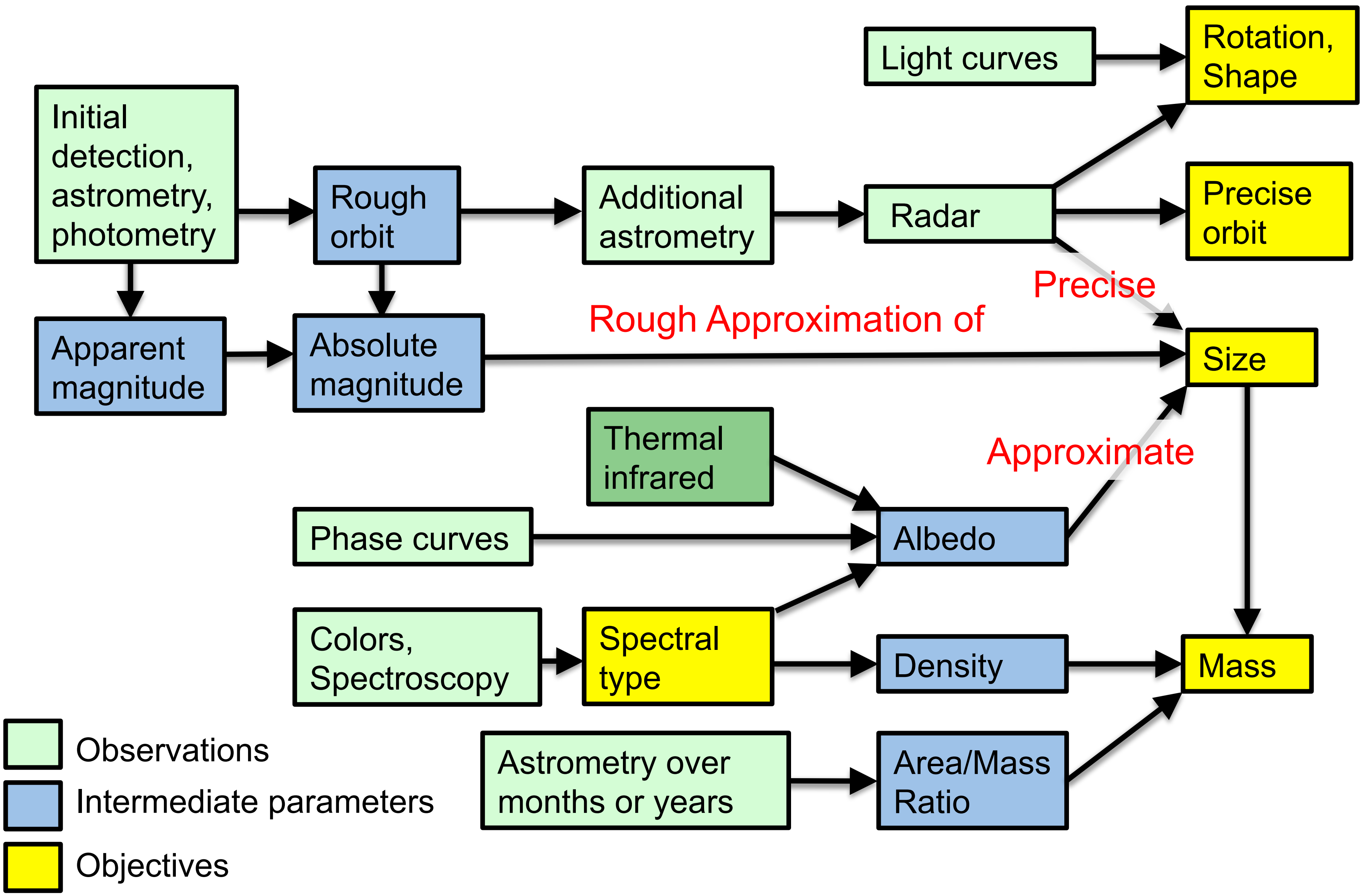
- Dedicated Planetary Science Observatory
- Characterization of Comets and Asteroids
- Spectroscopy and Thermal Signatures
- On-call for Rapid Response on Discoveries

## Spitzer Infrared Space Telescope

- Orbit about Sun, ~176 million km from Earth
- In extended Warm-phase mission
- Characterization of Comets and Asteroids
- Thermal Signatures, Albedo/Sizes of NEOs
- Longer time needed for scheduling

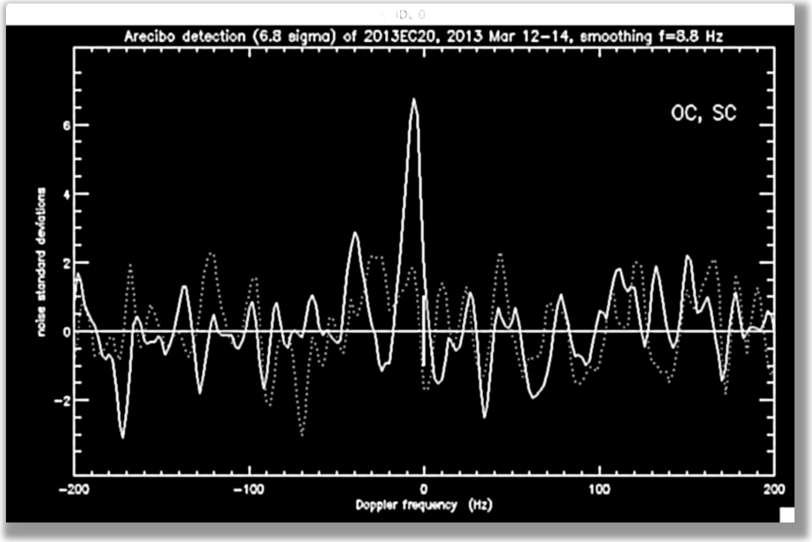


# NEA Characterization Process



# ARM Candidate Characterization Process Exercised for 2013 EC20

- Discovered 7 March 2013 (during ARM study), by Catalina Sky Survey.
  - Initial size estimate: ~6m, Close approach 8 March at 0.5 lunar distance.
- Manually recognized as potential ARRM target (process now automated).
- Request follow-up astrometry ⇨ orbit update to enable IRTF observation.
- IRTF Interrupt: Spectra and thermal IR [Moskovitz & Binzel]:
  - L- or Xe-type, inferred albedo range of 0.1-0.4, density range of 2.0-3.0 g/cc
  - Diameter = 2.6 - 8.4 m, mass = 20 - 930 t
  - Spin rate ~0.5 rpm
- Arecibo radar @~3 lunar dist. [Borozovic]:
  - Diameter = 1.5 - 3 m ⇨ albedo > ~0.4
  - Constrains mass to < 50 t
  - Spin rate: 0.5 – 2 rpm
- Preliminary mission design indicates a feasible retrieval trajectory for 2021.



# ARM Candidate Characterization Process

- **Rapid response** after discovery is essential while the asteroid is within range of characterization assets, since the asteroid will not likely be any closer for many years.
- Need rapid response for **radar** observation at Goldstone and/or Arecibo. The Goldstone interrupt response process especially needs to be streamlined.
- **Follow-up astrometry** from the observing community is essential for characterization.
- Request interrupt observations from **IRTF** and other large-aperture assets that can provide thermal IR data for faint objects. (This may require additional interagency agreements for target-of-opportunity observing time.)
- Obtain high precision astrometry, photometry and light curve measurements from geographically dispersed observatories (e.g. Palomar, Keck, European Southern Observatory in Chile).
- Solicit support from smaller telescopes, including amateurs, to provide quick follow-up astrometry and photometry.

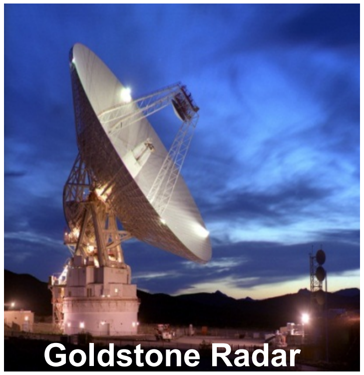
# Currently Known Characteristics of Current Candidates

| Characteristic | Reference Value | 2009 BD | 2011 MD | 2013 EC20 | 2008 HU4 | 2007 UN12 | 2010 UE51 |
|---|---|---|---|---|---|---|---|
| Orbit Confidence | OCC < 4 | Excellent | Good | Recoverable | Recoverable | Recoverable | Good |
| Orbit: Vinfinity (km/s) | < 2<br>(< 2.6 req.) | 0.7 | 0.9 | 2.6 | 0.5 | 1.2 | 1.2 |
| Orbit: Natural return year | Early 2020s<br>(2020-26) | 2023 | 2024 | 2020 | 2026 | 2020 | 2023 |
| Size (m) | < 10 m and<br>> 7 m | 4-8 [1] | < 30 [4] | 2-3 [6] | < 28 [4] | < 22 [4] | < 27 [4] |
| Mass (t) | < 1000 t | < 350 [2] | < 50,000 [5] | < 50 | < 40,000 [5] | < 20,000 [5] | < 36,000 [5] |
| Spin Rate (rpm) | < 2 | < 0.01 [3] | 0.1 [3] | < 2 [6] | Unknown | Unknown | Unknown |
| Spectral Class | Known<br>(C preferred) | Unknown | Unknown | L or Xe | Unknown | Unknown | Unknown |
| Next Observation Opportunity | A=Astrometric<br>O=Optical<br>IR=Infrared<br>R=Radar | 2013-Oct: IR | 2014: IR? | 2013-Aug: A? | 2016-Apr: A, O?, R | None | 2014: IR?? |

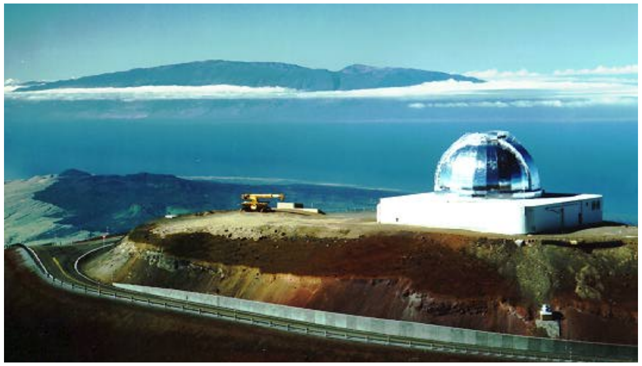
**Notes:** [1] Upper bound from NEOWISE stacked non-detection, lower bound assumes upper bound albedo of 50%; [2] Lower bound Area/Mass Ratio: 1.55 x $10^{-4}$ $m^2/kg$ from Farnocchia et al.; [3] Magdalena Ridge lightcurve; [4] Lower bound on abs. mag. and lower bound albedo of 3%; [5] Upper bound density of 3.5 g/cc; [6] Arecibo radar.

# NEO Characterization Enhancements

**Radar (Goldstone and Arecibo)**
- Increase time for NEO observations.
- Streamline Rapid Response capabilities.







**NASA InfraRed Telescope Facility (IRTF)**
- Increase On-call for Rapid Response.
- Improve Instrumentation for Spectroscopy and Thermal Signatures.

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

# Summary

- Simulations suggest there are thousands of suitable ARRM candidate targets; the challenge is to find them.
- Candidates are currently being discovered at the rate of 2-3 per year.
- With several survey enhancements in process, and new surveys coming online within the next 2 years, the ARRM candidate discovery rate should increase to at least 5 per year.
- Discovery enhancements will add capability to find hazardous asteroids as well as ARRM candidate targets.
- Rapid response after discovery is critical for physical characterization of ARRM candidates. The process has already been successfully exercised for a difficult-to-characterize candidate.
- Goldstone and Arecibo radars are key characterization assets for ARRM candidates because they provide accurate estimates of size and rotation state.
- Other major assets for characterization are available. Interagency agreements for target-of-opportunity observing time from important non-NASA facilities (eg. Subaru) can be negotiated.