RADAR OBSERVATIONS OF NEAR-EARTH ASTEROIDS

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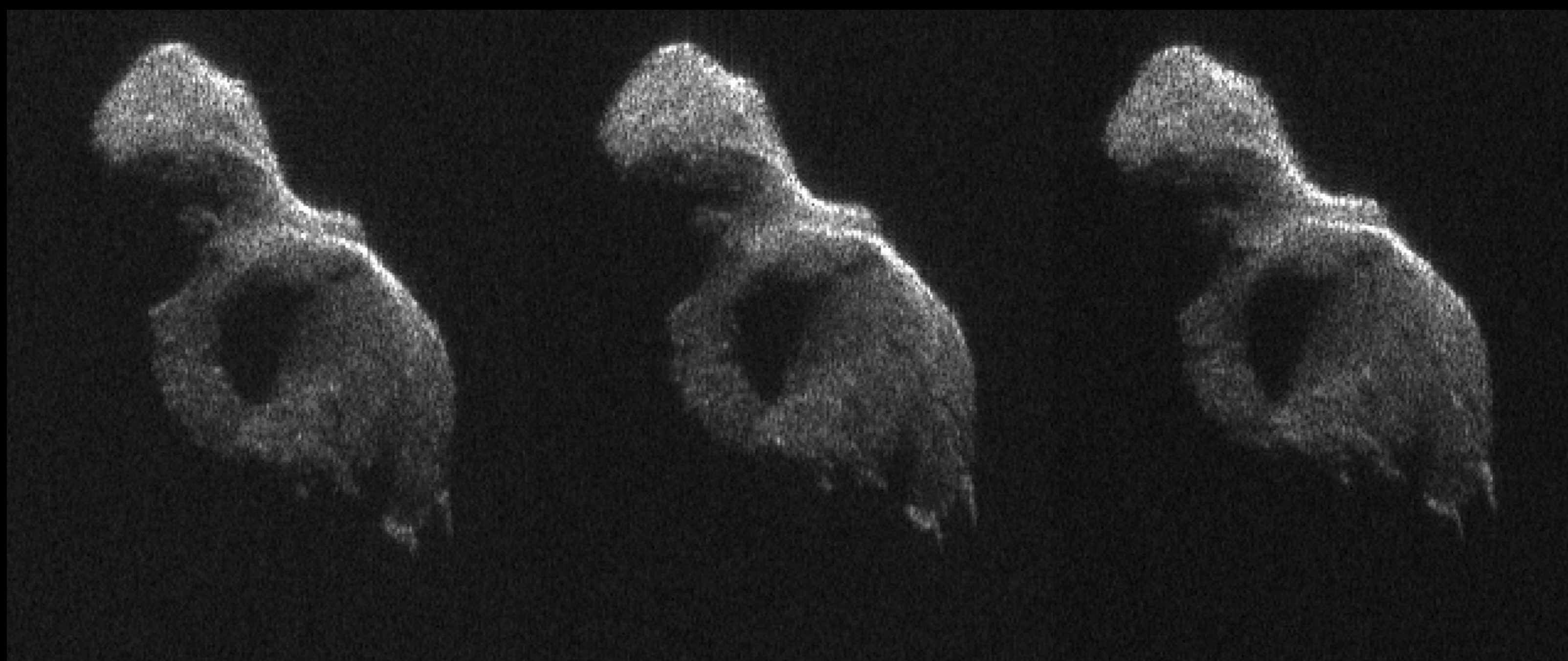
California Institute of Technology



Goldstone/Arecibo Bistatic Radar Images of Asteroid 2014 HQ124

What Can Radar Do?

Study physical properties: Image objects with 4-meter resolution (more detailed than the *Hubble Space Telescope*), 3-D shapes, sizes, surface features, spin states, regolith, constrain composition, and gravitational environments

Identify binary and triple objects: orbital parameters, masses and bulk densities, and orbital dynamics

Improve orbits: Very precise and accurate. Measure distances to tens of meters and velocities to cm/s. Shrink position uncertainties drastically. Predict motion for centuries. Prevent objects from being lost.

→ Radar Imaging is analogous to a spacecraft flyby

Radar Telescopes

Arecibo
Puerto Rico
Diameter = 305 m
S-band

Goldstone
California
Diameter = 70 m
X-band

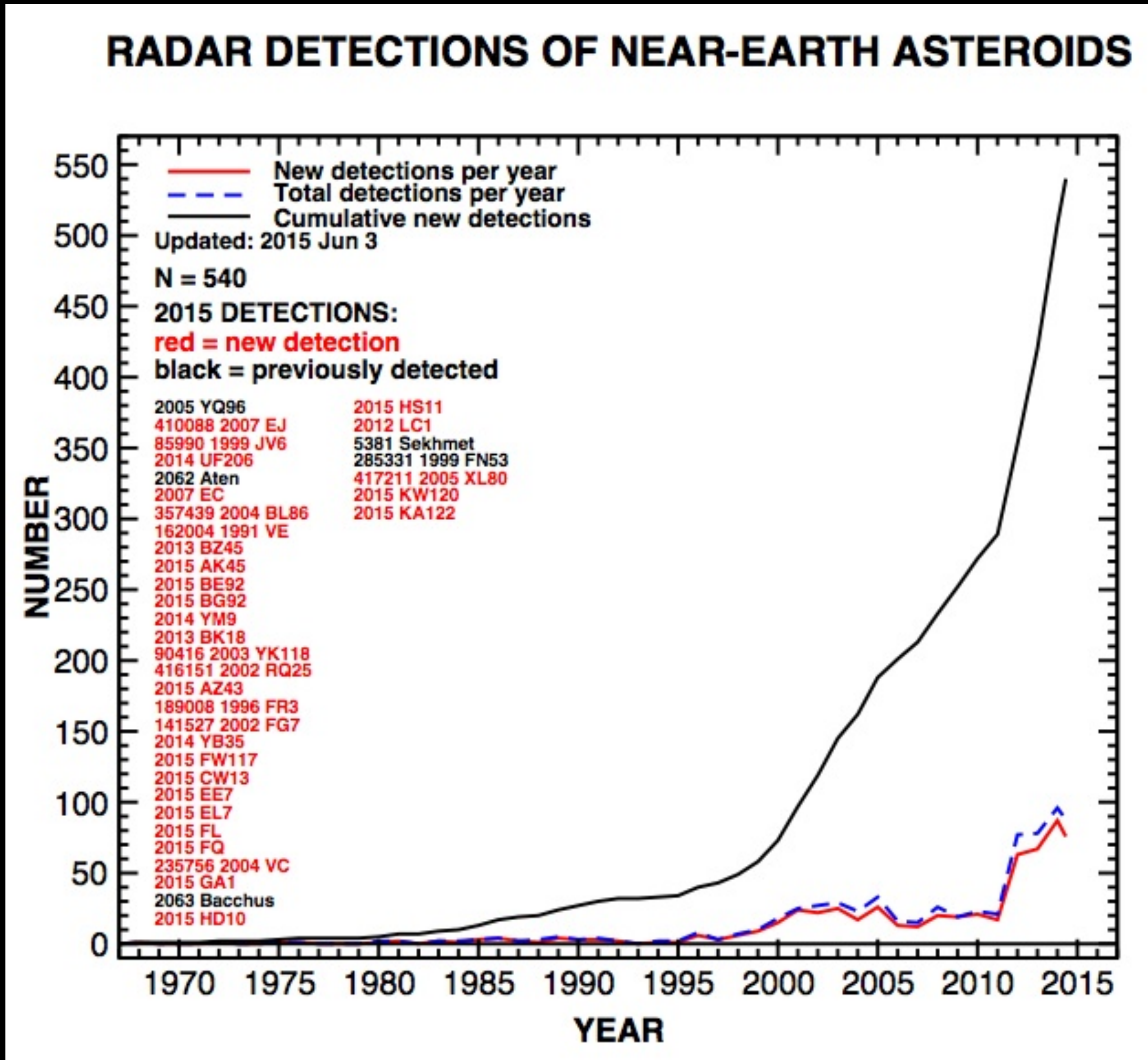
Small-Body Radar Detections

Near-Earth Asteroids (NEAs):	540
Main-Belt Asteroids:	138
Comets:	18

Current totals are updated regularly at:
http://echo.jpl.nasa.gov/asteroids/index.html

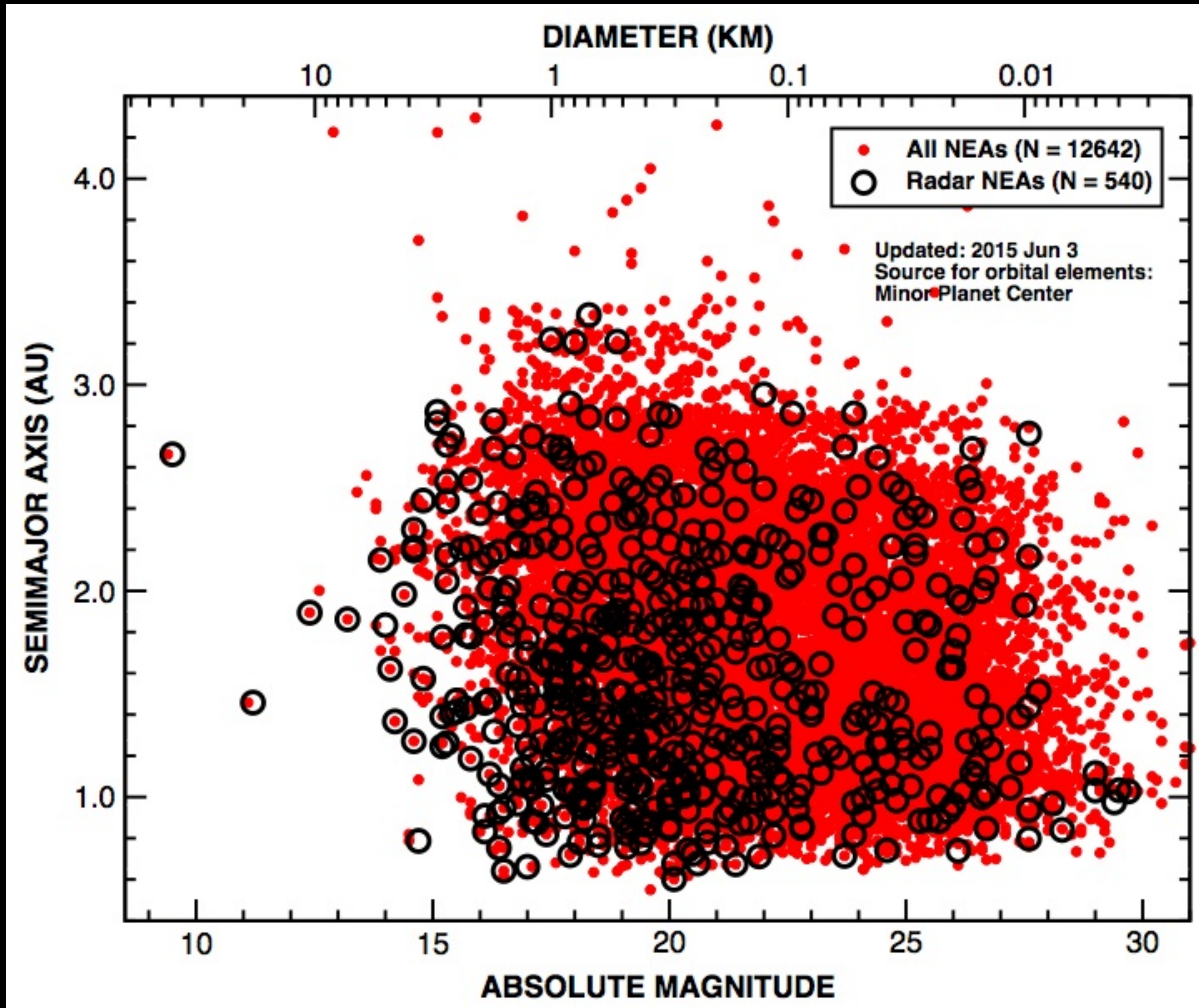
Near-Earth Asteroid Radar Detection History

Big increase started in late 2011



NEA Radar Detections

Year	Arecibo	Goldstone	Number
1999	7	7	10
2000	16	7	18
2001	24	8	25
2002	22	9	27
2003	25	10	29
2004	21	4	23
2005	29	10	33
2006	13	7	16
2007	10	6	15
2008	25	13	26
2009	16	14	19
2010	15	7	22
2011	21	6	22
2012	67	26	77
2013	66	32	78
2014	81	31	96
2015	29	12	36



Number of NEAs known: 12642 (as of June 3)
Observed by radar: 4.3%

Fraction of all potential NEA targets being observed: ~1/3

See the talk by Naidu et al. for more detail.

H	N	Radar	Fraction
9.5	1	1	1.000
10.5	0	0	0.000
11.5	1	1	1.000
12.5	4	0	0.000
13.5	10	3	0.300
14.5	39	11	0.282
15.5	117	22	0.188
16.5	281	44	0.157
17.5	569	56	0.098
18.5	1129	66	0.058
19.5	1477	74	0.050
20.5	1545	67	0.043
21.5	1321	47	0.036
22.5	1166	32	0.027
23.5	1235	22	0.018
24.5	1307	28	0.021
25.5	1052	22	0.021
26.5	788	26	0.032
27.5	367	9	0.025
28.5	147	2	0.014
29.5	63	5	0.079
30.5	14	0	0.000

Selected NEA Radar Statistics

NEA radar detections	540
Potentially Hazardous:	265/537 = 0.493
NEAs with MOID < 0.05 au:	(265+138)/537 = 0.750
NHATS:	83
Observed twice or more:	67/537 = 0.125
NEAs with H > 22:	141/540 = 0.261
WISE targets	96 NEAs & 1 comet

Near-Earth Asteroid Binaries and Triples

Binaries:	43	(50 are known)
Triples	2	(2 are known)

Binary & triple abundance:	13% (D > 200 m)	
Largest:	Sisyphus:	~8 km
Smallest:	2003 SS84:	~0.15 km

Radar discoveries	37/52 = 0.71
Radar detections	45/52 = 0.87
Radar TOOs	15/45 = 0.33

	Arecibo	Goldstone
Detections	41	20
Discoveries	28	9

Recent Developments

Funding for radar observations at Arecibo much higher than a few years ago. Increased radar staffing. Overall funding remains very tight.

Chirp/digital receiver system at Goldstone: 5x finer range resolution from 18.75 m to 3.75 m. Dramatically more detail visible. Resolve smaller NEAs.

Digital receiver equipment recently installed at Arecibo and Green Bank to receive Goldstone X-band transmissions at up to 3.75 m resolution. Tested at both AO and GBT. Can sample at up to 120 MHz (1.25 m resolution).

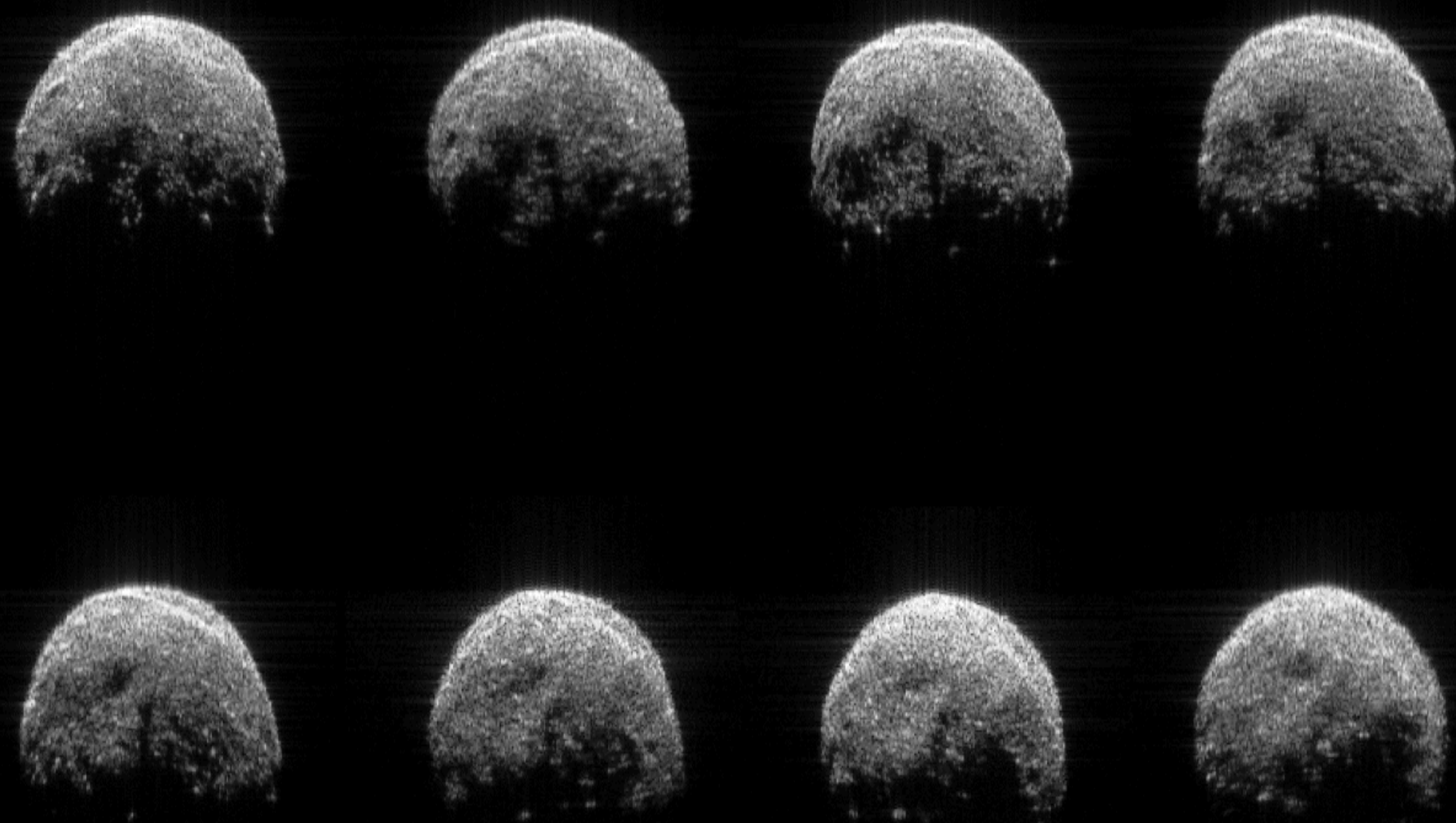
New 80 kW, 80 MHz C-band transmitter at DSS-13. Range resolutions up to 1.875 m. Tested at 15 m resolution with 2004 BL86 in January by receiving at Green Bank.

Recent NEA radar detection of 2012 DA14 with EISCAT, Haystack, Evpatoria/Medicina, Evpatoria/Irbene. Potential for future observations.

DSS-43/Parkes S-band test in November and December. First test of a southern hemisphere planetary radar.

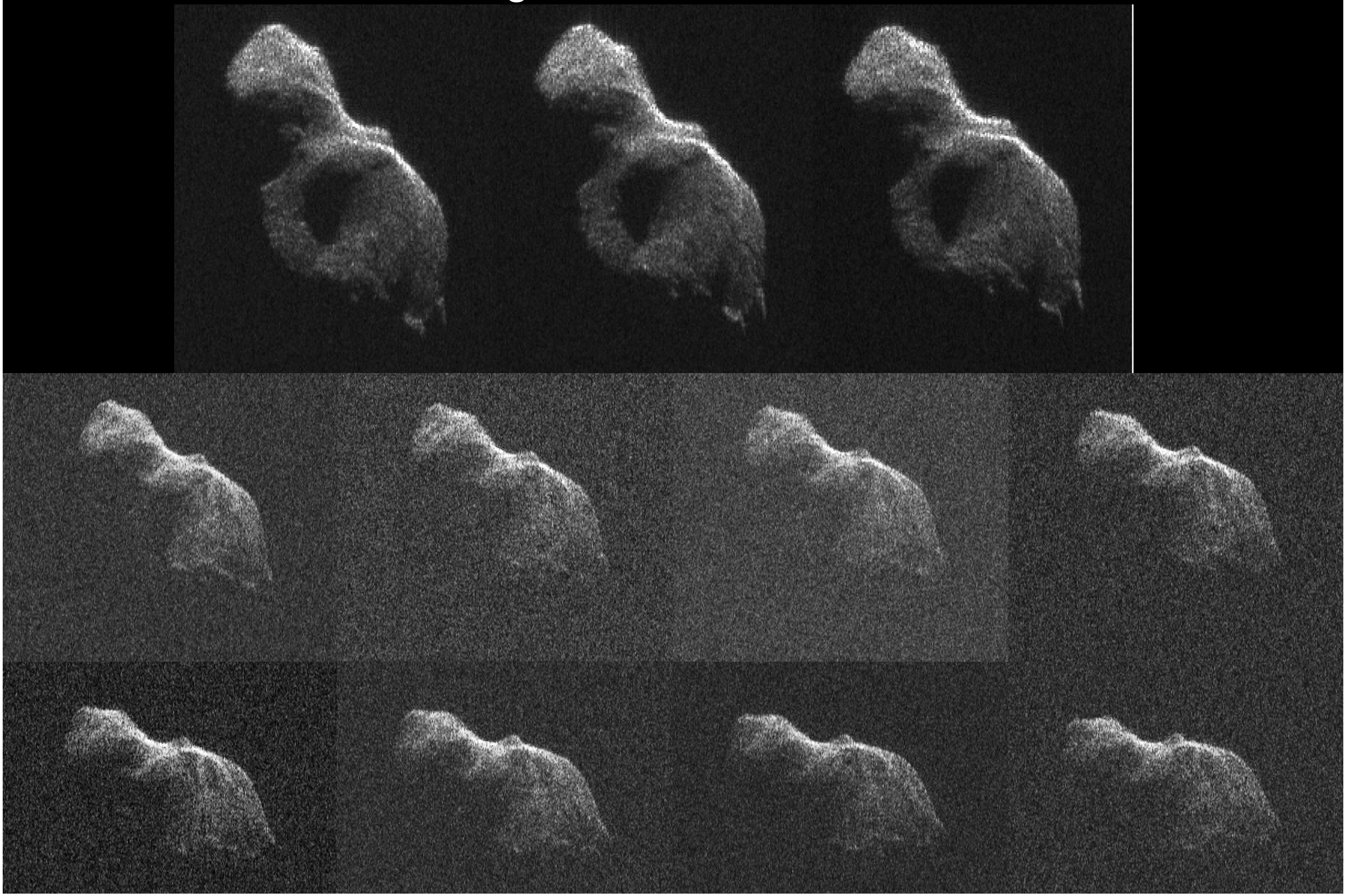
2005 YU55: Goldstone

Evidence for a rounded shape ~360 m in diameter, boulders, an equatorial bulge, and craters. Range res’n = 3.75 m.



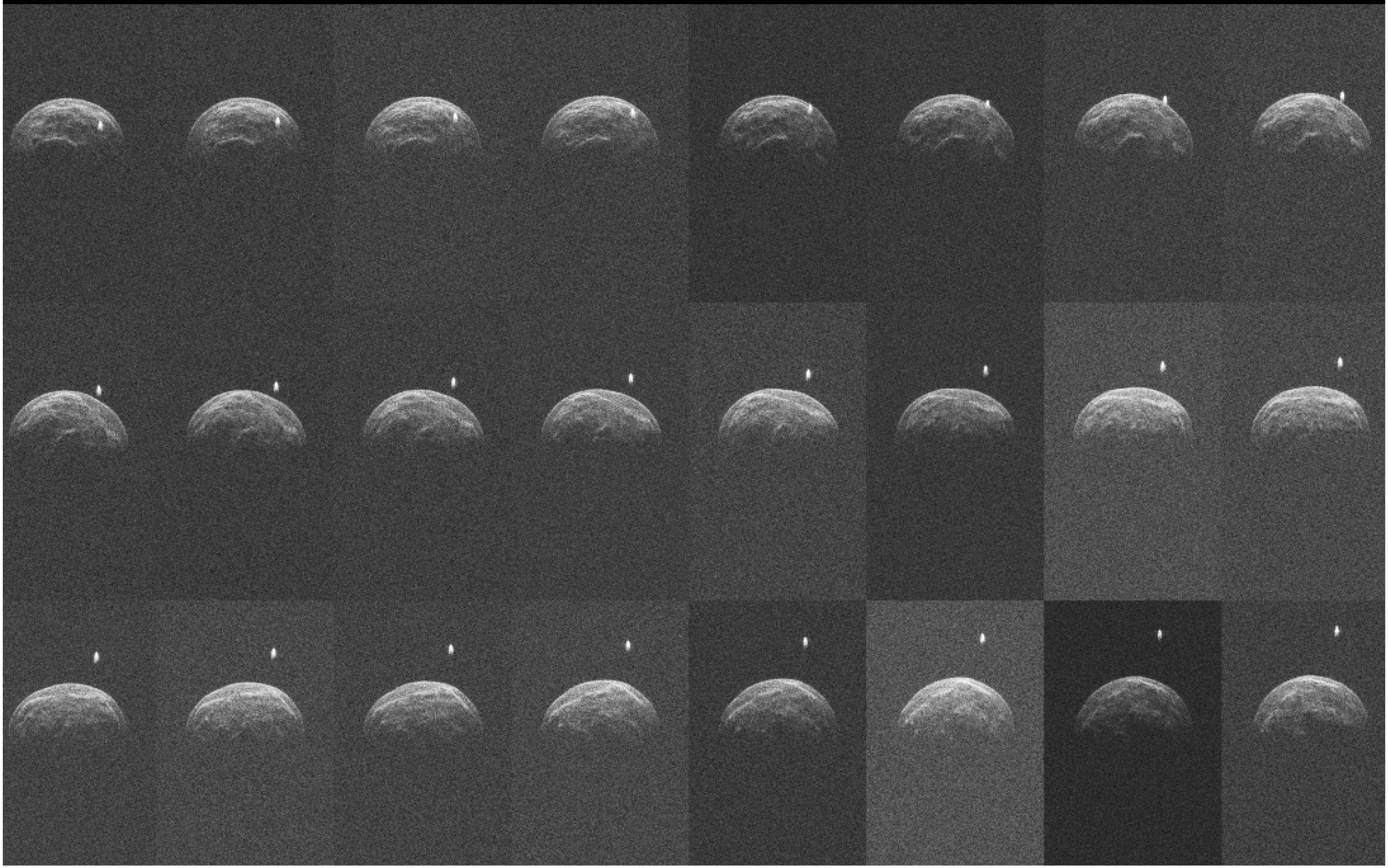
Bistatic Goldstone/Arecibo Images of 2014 HQ124

Range resolution = 3.75 m

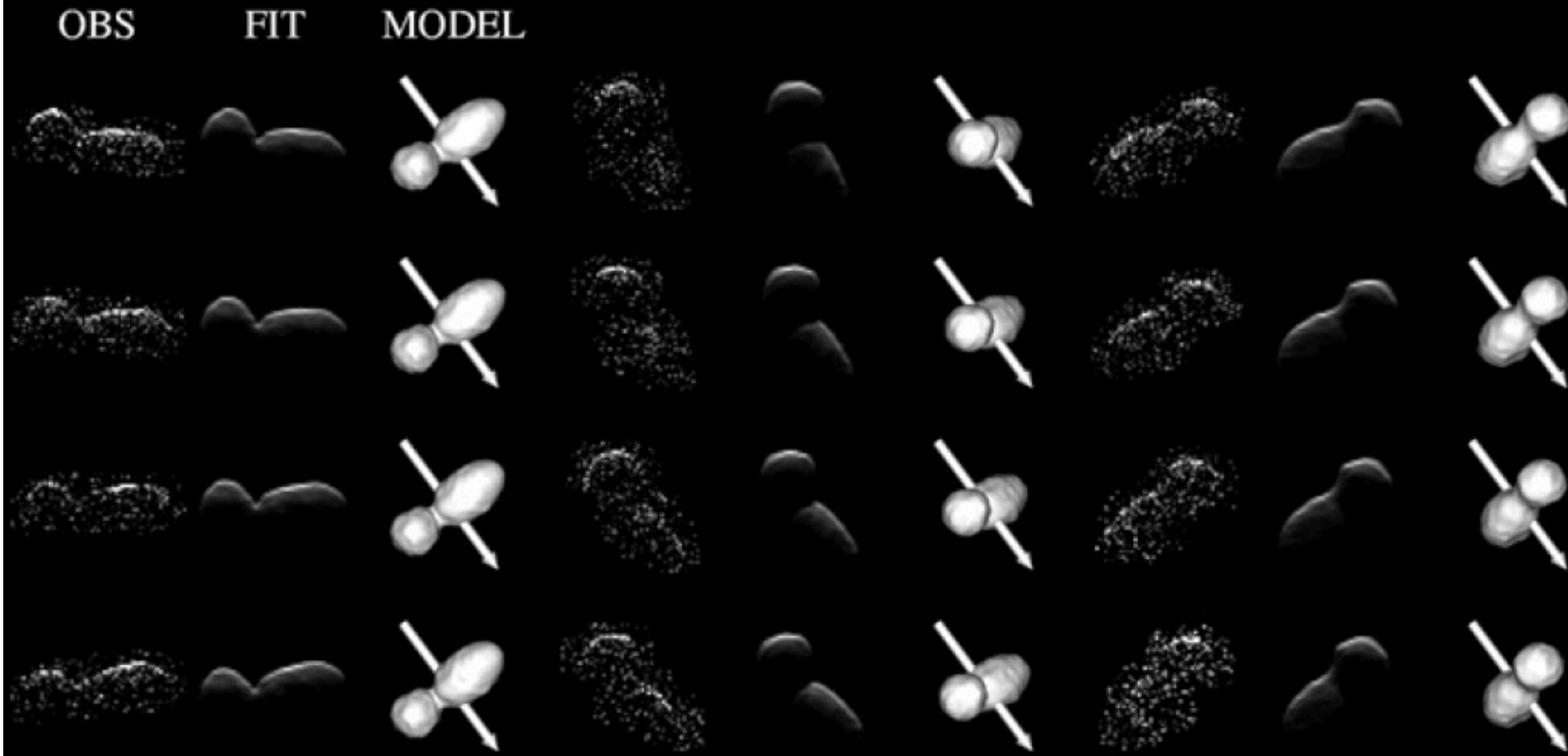


2004 BL86: Goldstone-Green Bank, Jan. 2015

180 sec integrations, resolution = 3.75 m x 0.1 Hz



Observations, Fits, and Shape: 1996 HW1

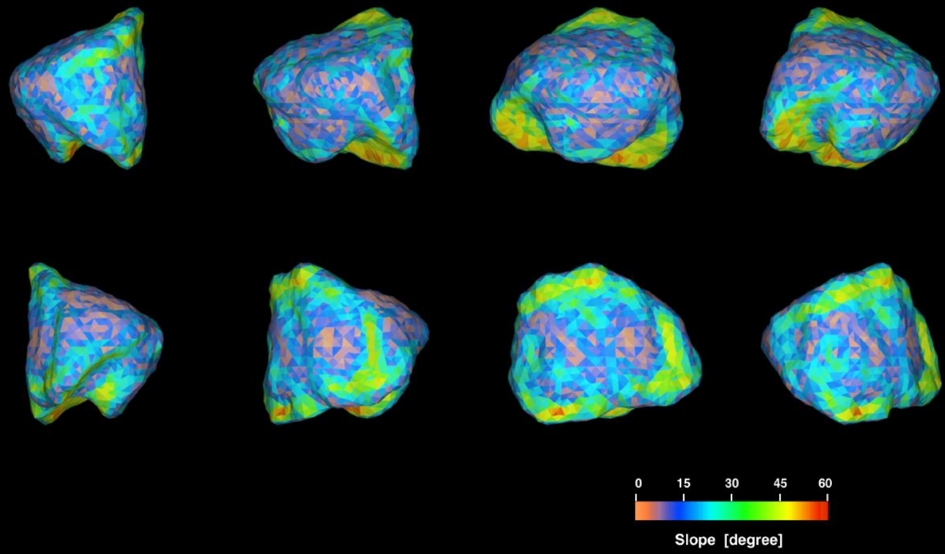


CONTACT BINARIES ARE COMMON

Magri et al. 2011

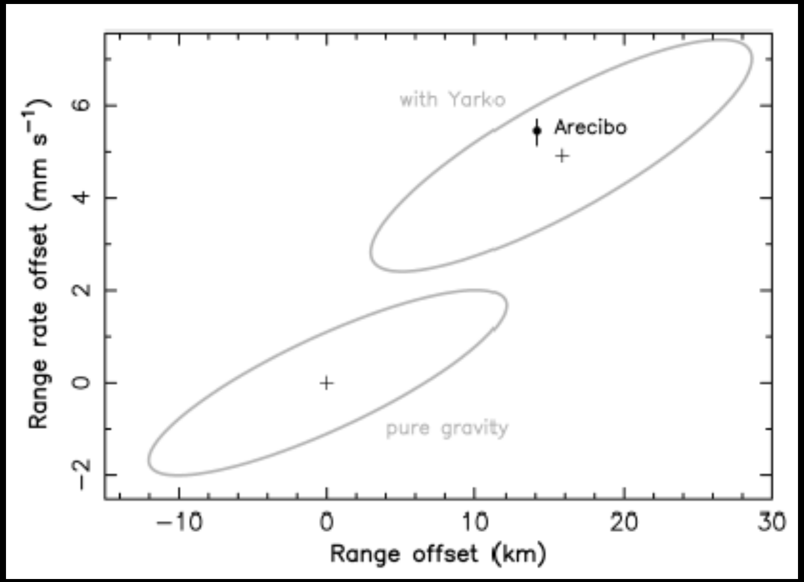
6489 Golevka: First Yarkovsky Effect Detection

3D Model & Gravitational Slopes



Hudson et al. 2000

Yarkovsky Drift



Chesley et al. 2003

Yarkovsky Effect Candidates

Provides coupled contraint on mass and thermal inertia. If TI is available, get mass. If 3D model is available, get density and constraints on interior structure.

Normally need 3+ radar ranging detections, although fewer could suffice for objects with long optical arcs. Objects with larger masses may require more radar ranging observations.

½ of NEAs with the strongest Yarkovsky SNRs (Vokrouhlicky et al. 2015) will be observable with radar in the next decade.

Expect a surge in mass estimates from improved radar astrometry. This highlights the importance of repeated radar ranging.

Calibrate against binary systems where the mass can be estimated from Kepler's 3rd law. First test: 1862 Apollo. Masses are consistent (Ford et al., in prep.)

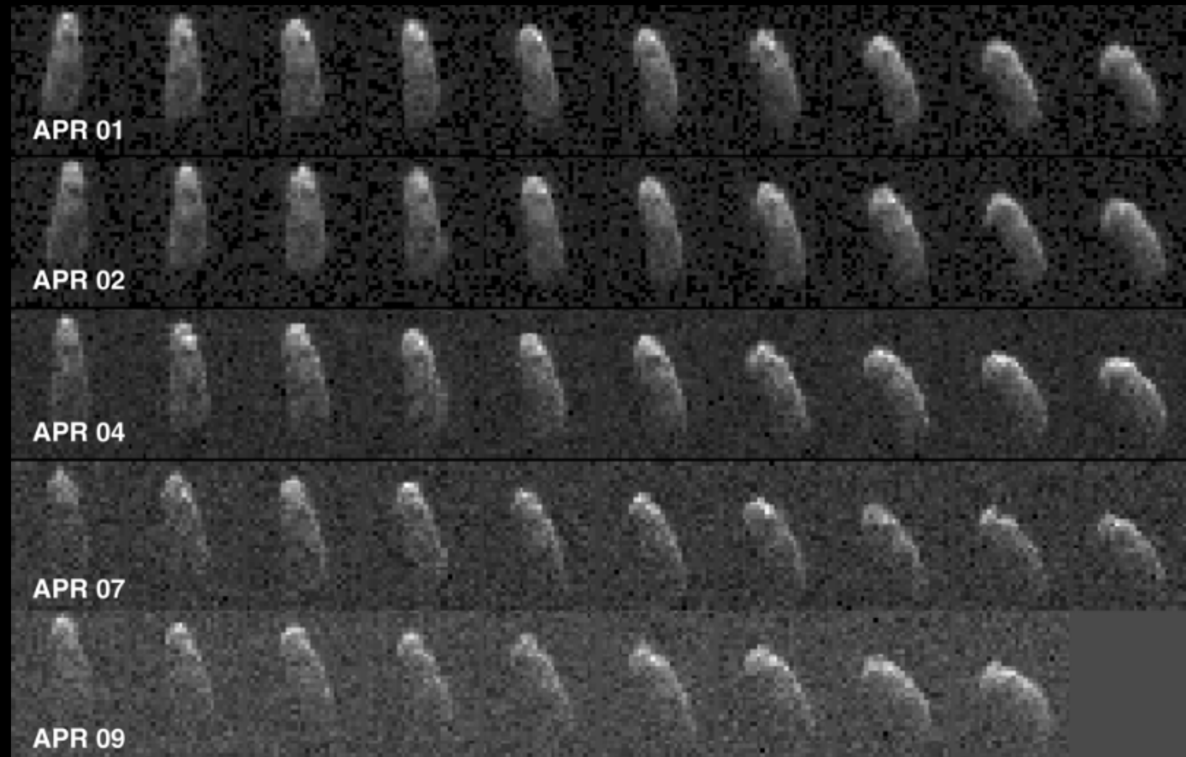
Asteroid and Comet Spacecraft Missions Supported by Radar

NEAR	NASA	Mathilde, Eros
Hayabusa	JAXA	Itokawa
Rosetta	ESA	Lutetia
EPOXI	NASA	Comet Hartley 2
Dawn	NASA	Vesta
Chang'e 2	China	Toutatis
Dawn	NASA	Ceres
OSIRIS-REx	NASA	Bennu (2018-2023)
AIM/DART	ESA/NASA	Didymos (proposed; 2022)
Asteroid Redirect Mission	NASA	Possibly 2008 EV5

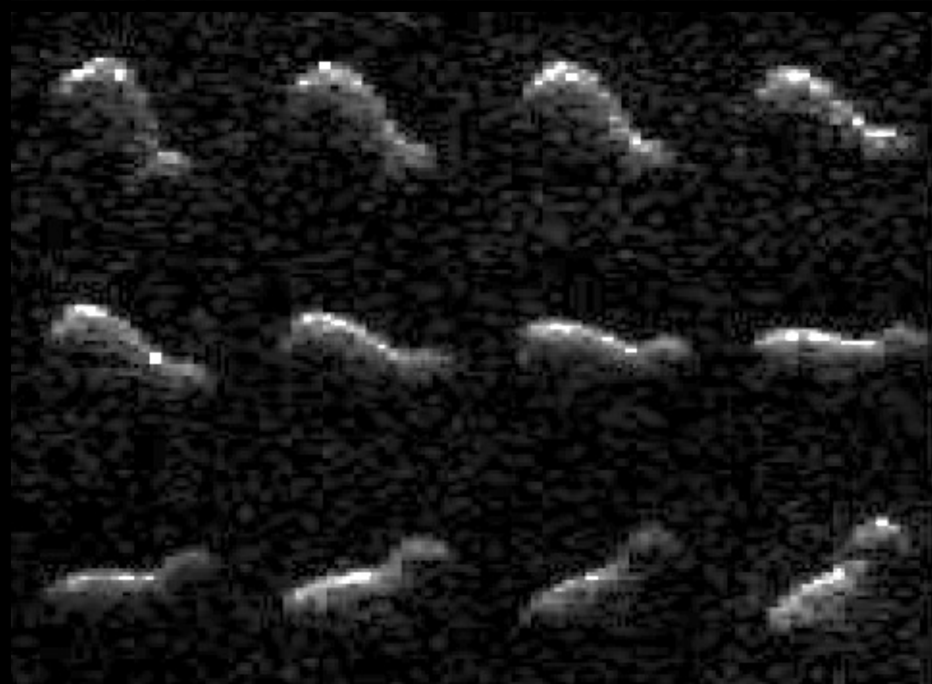
Plus many asteroids observed by NASA's *Spitzer Space Telescope* and *WISE* mission and many others from previous mission proposals.

25143 Itokawa

2001
Arecibo



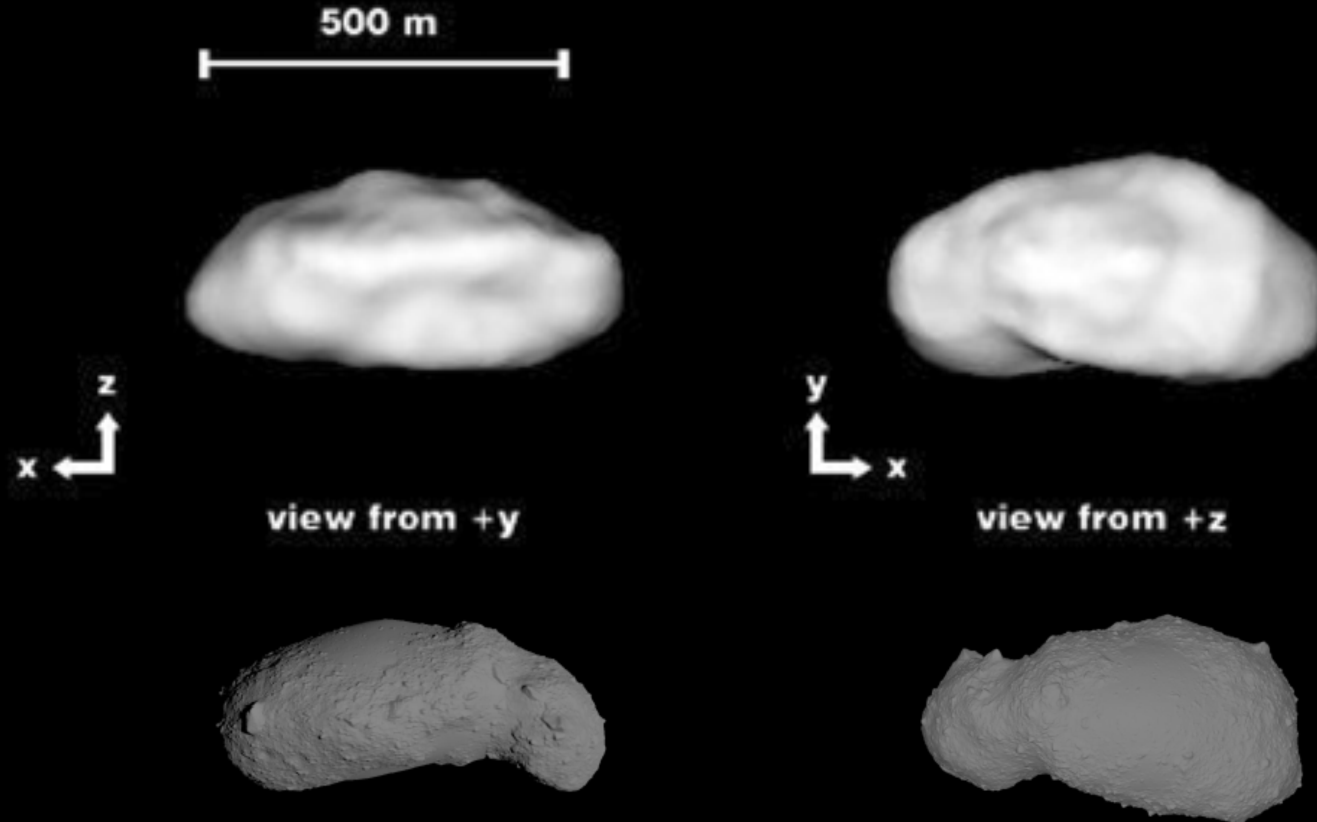
2004
Goldstone



Ground Truth for Radar Models:
25143 Itokawa (2005)

Radar
Model

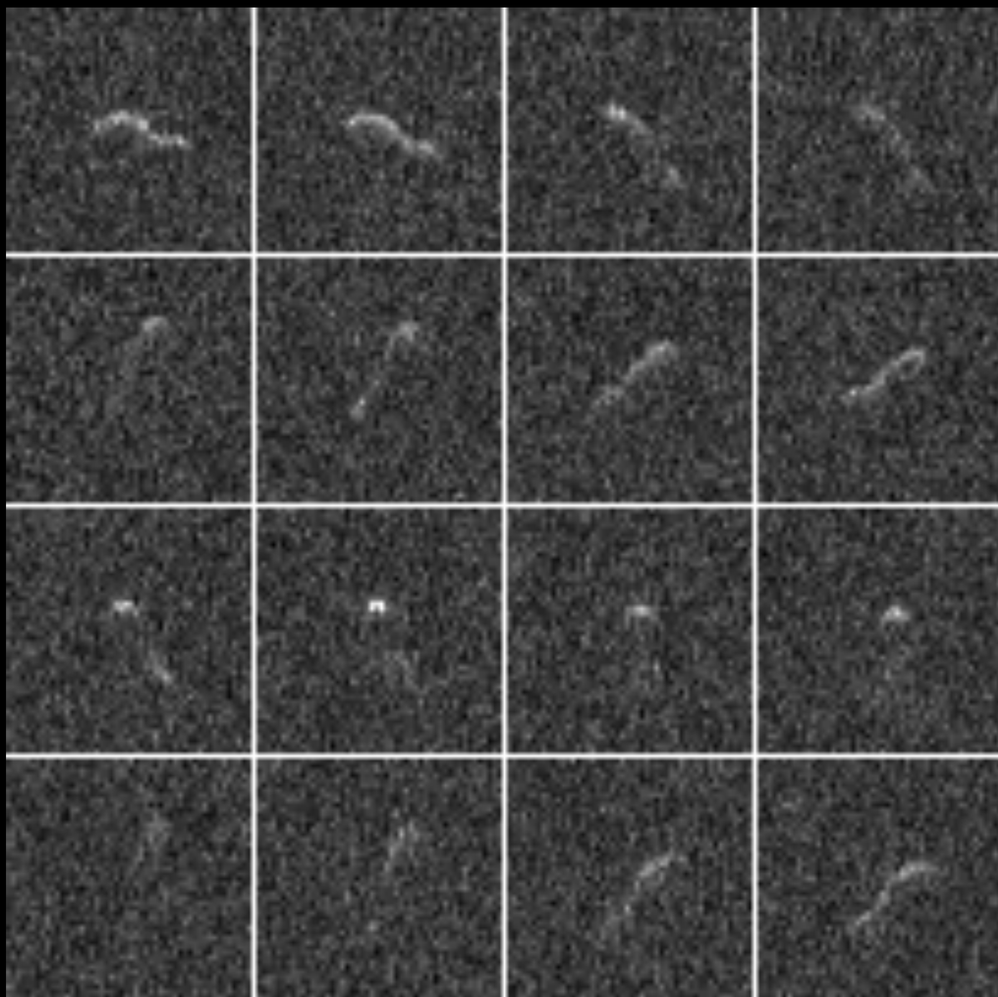
Hayabusa
Model



References: Ostro et al. 2005, Gaskell et al. 2008

EPOXI Spacecraft Target: Comet Hartley 2

Arecibo Radar Images



Harmon et al. 2011

Spacecraft image

Radar images helped spacecraft navigation and provided a preview of the comet's shape

4179 Toutatis

Radar
Model

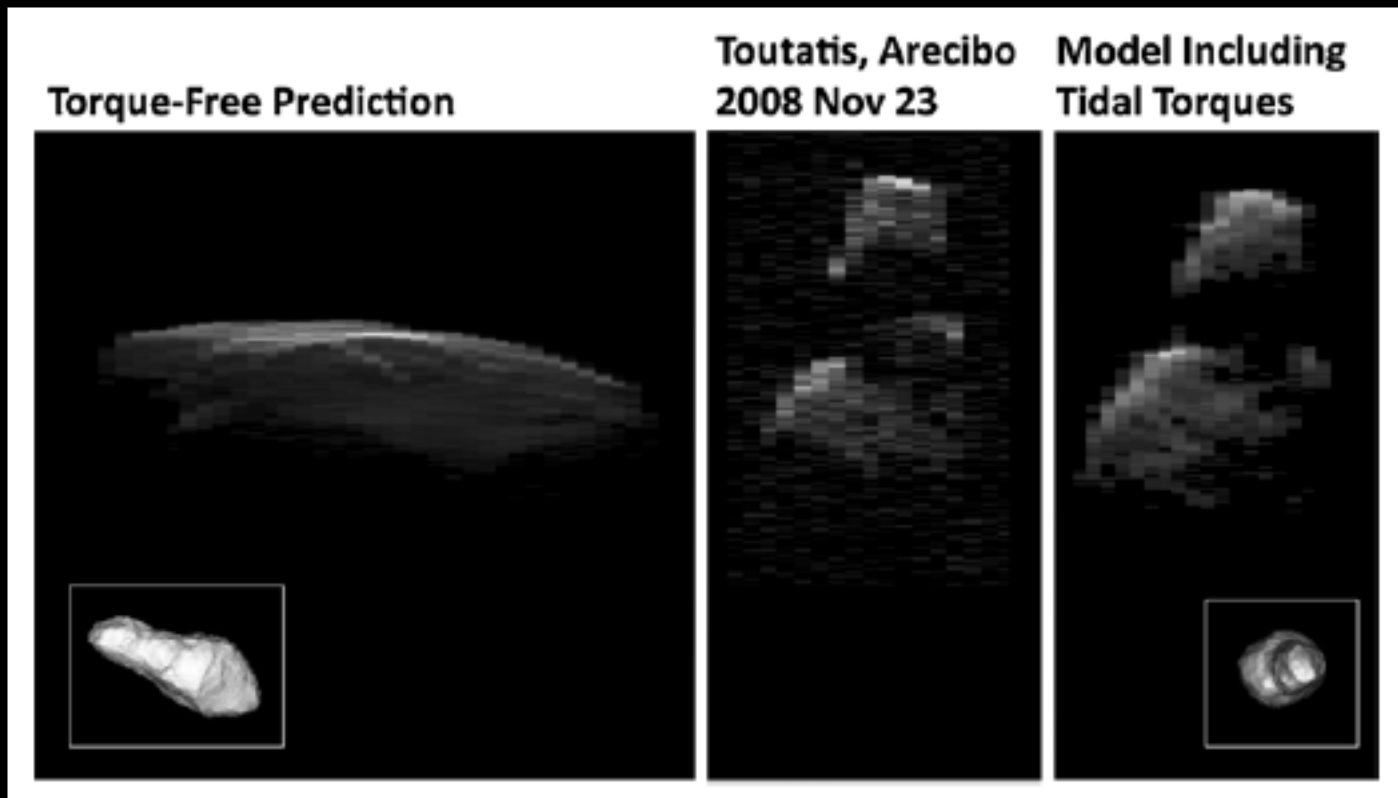
Hudson et al. 2003

Chang'e 2 Spacecraft
image

Huang et al. 2013

Toutatis Spin State Changes

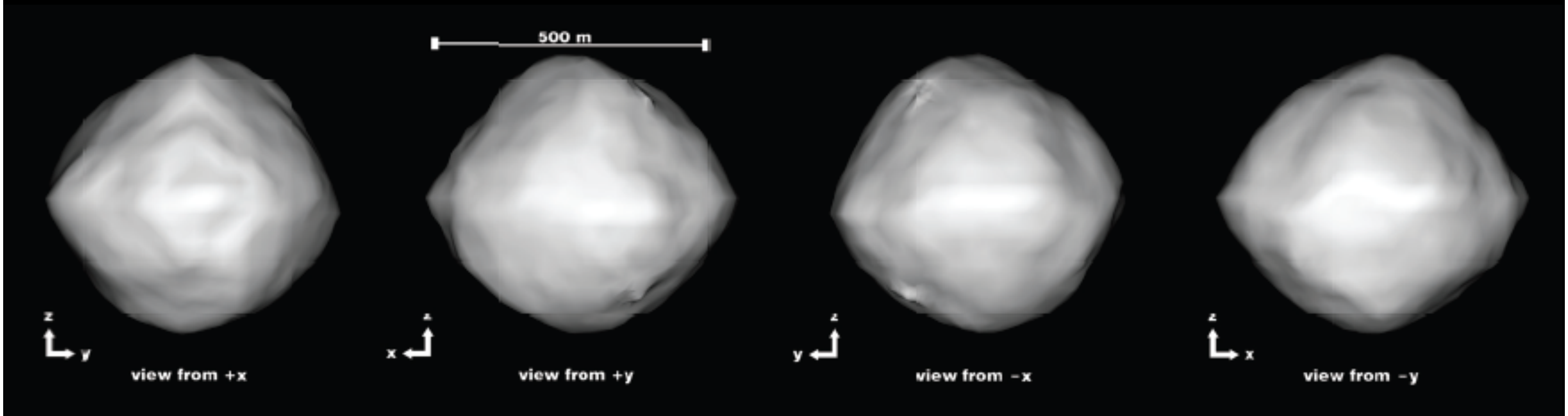
Takahashi, Busch, and Scheeres (2013)



Spin state changed at each apparition but most signifciantly in 2004 during passage within 0.01 au

OSIRIS-REx Mission Target: Bennu

(Nolan et al. 2013)



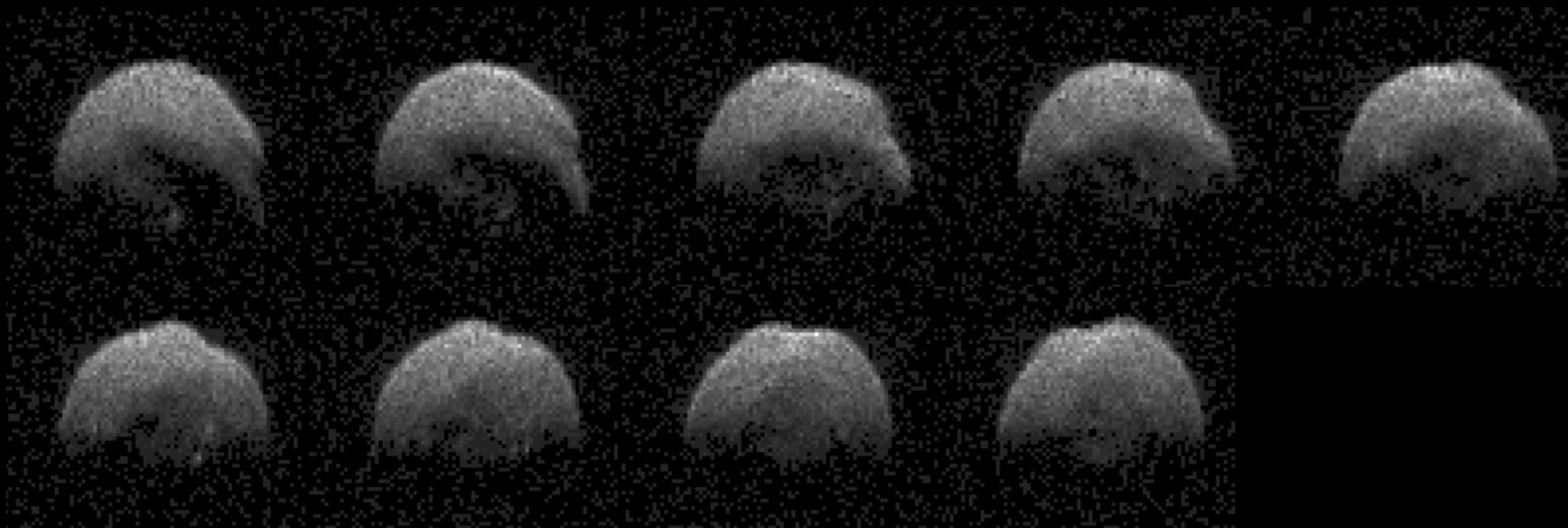
Mass estimated by detection of the non-gravitational "Yarkovsky" effect largely due to radar ranging.

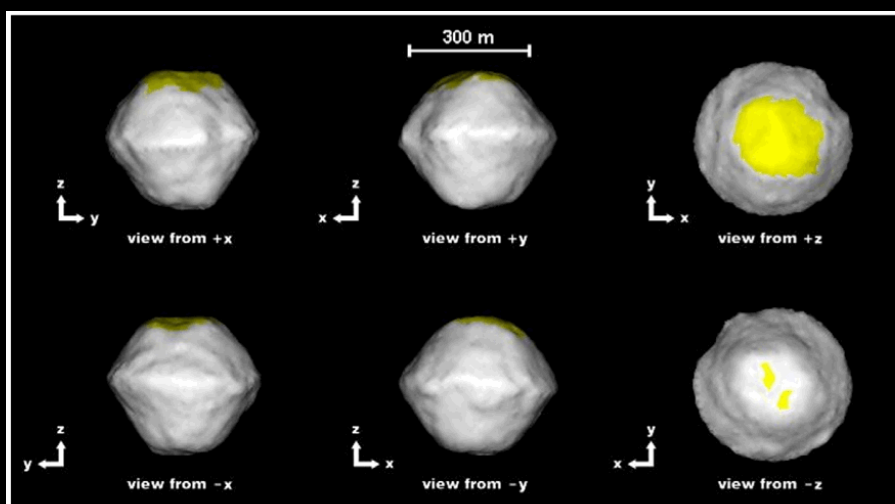
Bulk density = 1.3 g/cm^3 (Chesley et al. 2014)

OSIRIS-REx mission timeline:

2016	Launch
2018-2020	Rendezvous with the asteroid
2023	Samples return to Earth

Asteroid Redirect Mission Candidate: 2008 EV5

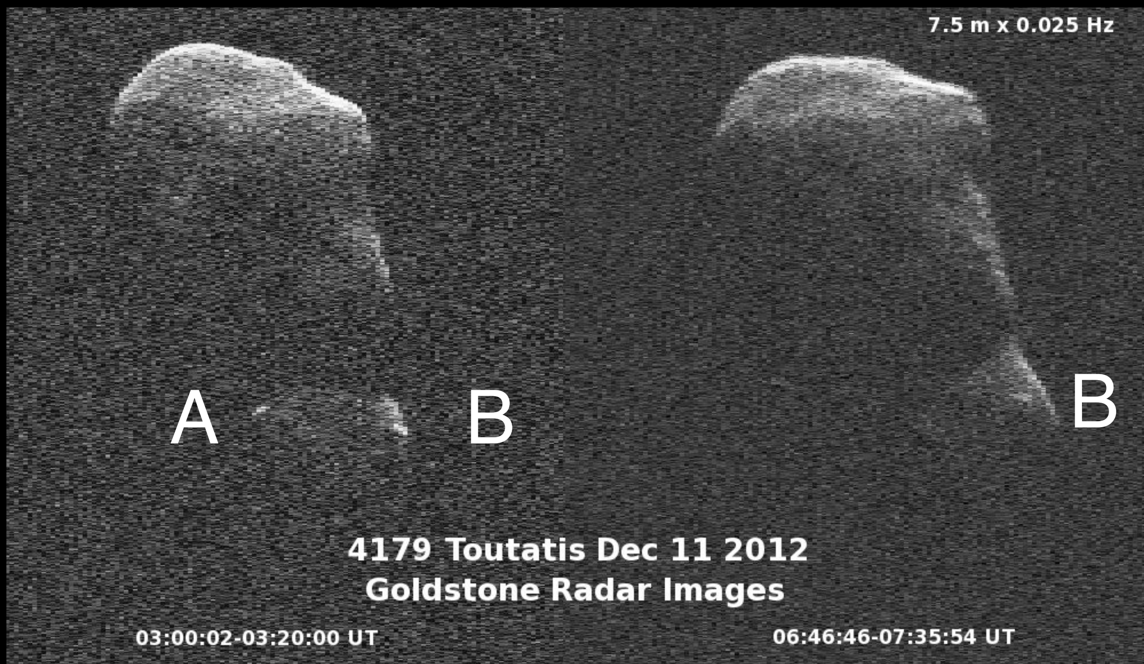


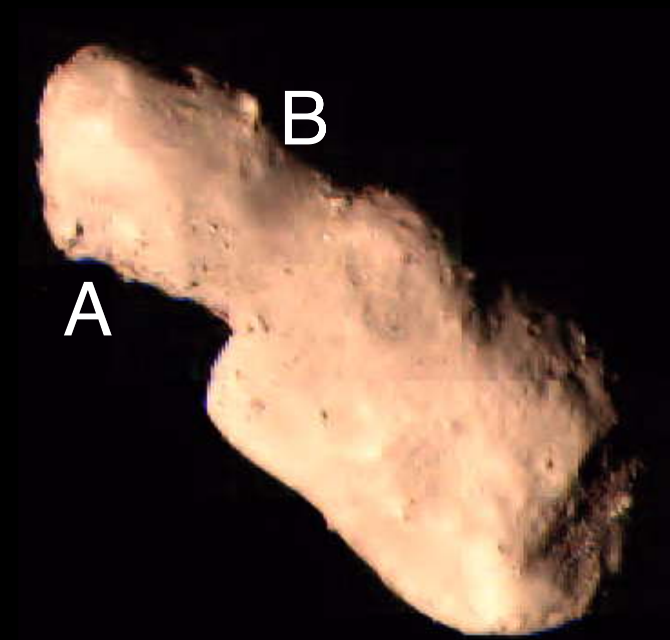


Busch et al. 2011

Evidence for Boulders on 4179 Toutatis

Goldstone, 2012 Dec.11

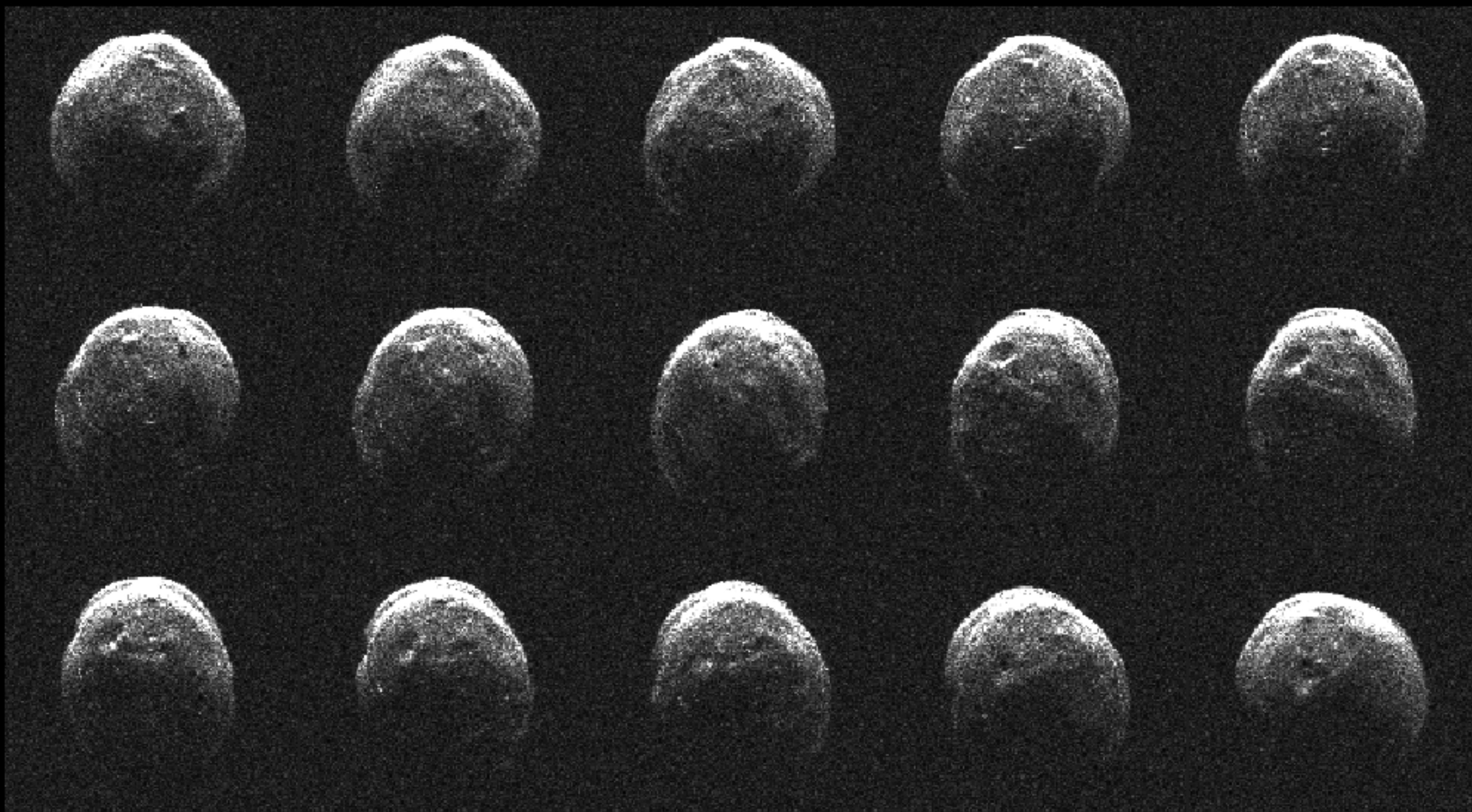




Chang'e 2 image
(Huang et al. 2013)

1998 CS1

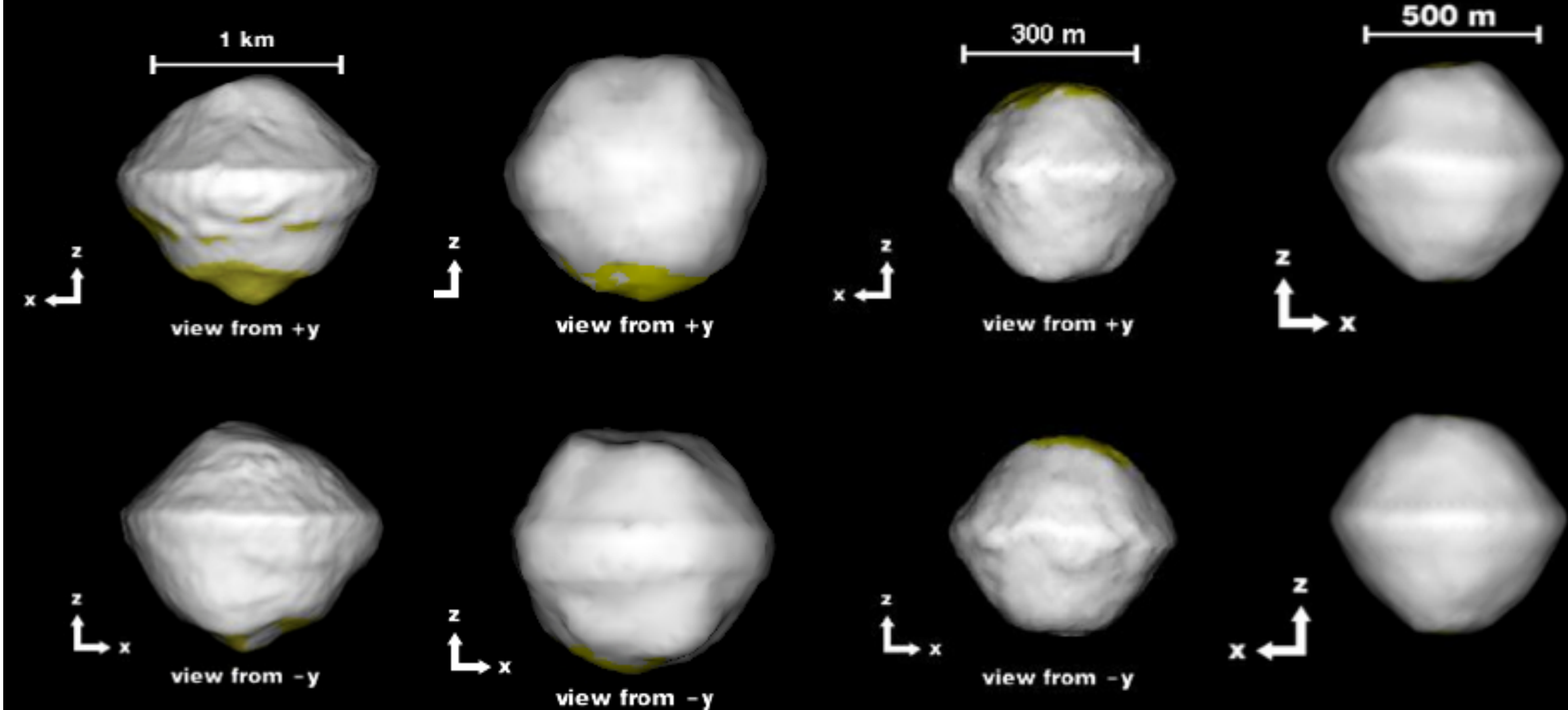
Arecibo, January 2009



T. Ford et al., in prep.

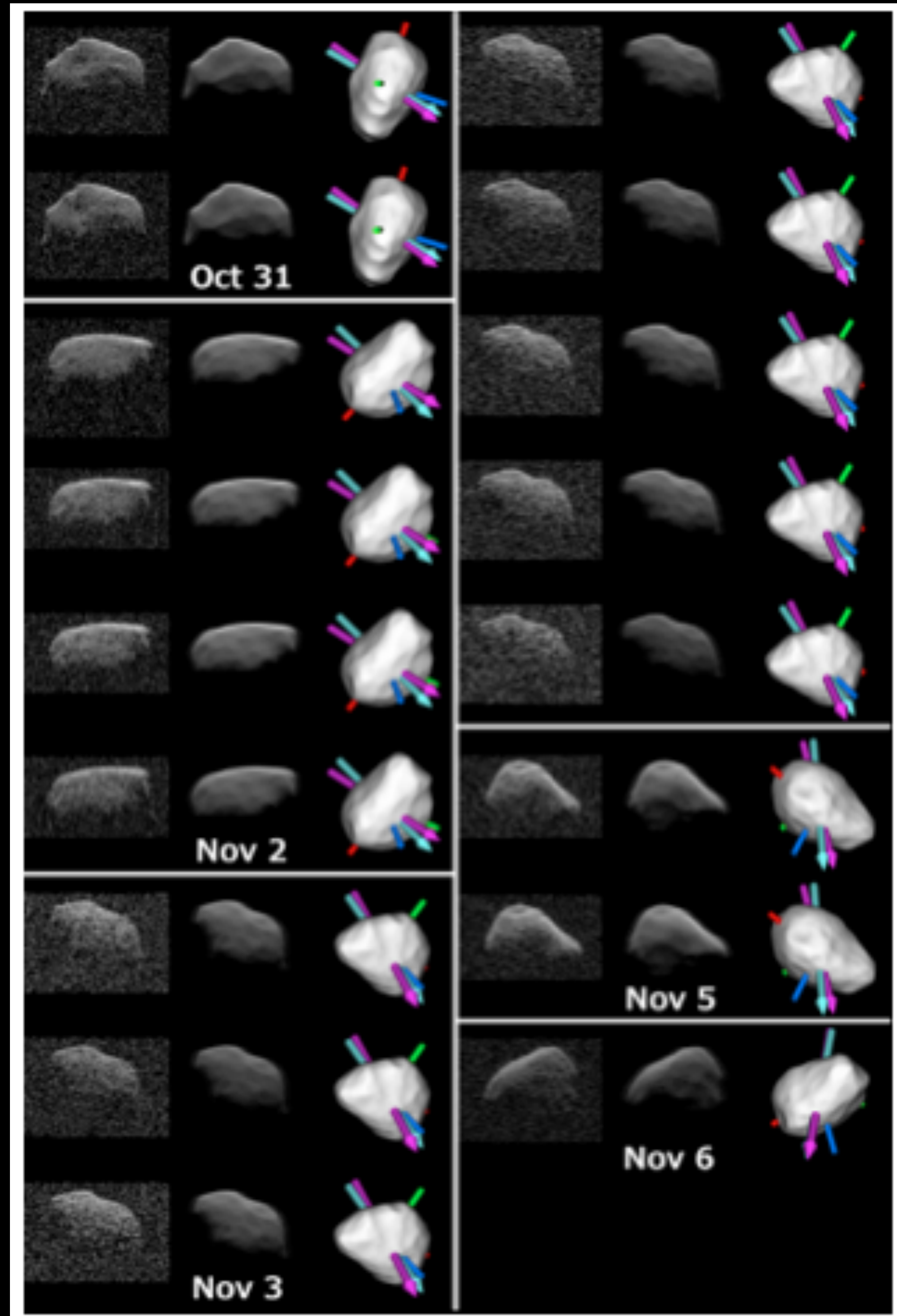
Oblate Shapes Are Common

1999 KW4 | 2004 DC | 2008 EV5 | 1994 CC



Ostro et al. 2006 | Taylor 2009 | Busch et al. 2011 | Brozovic et al. 2011

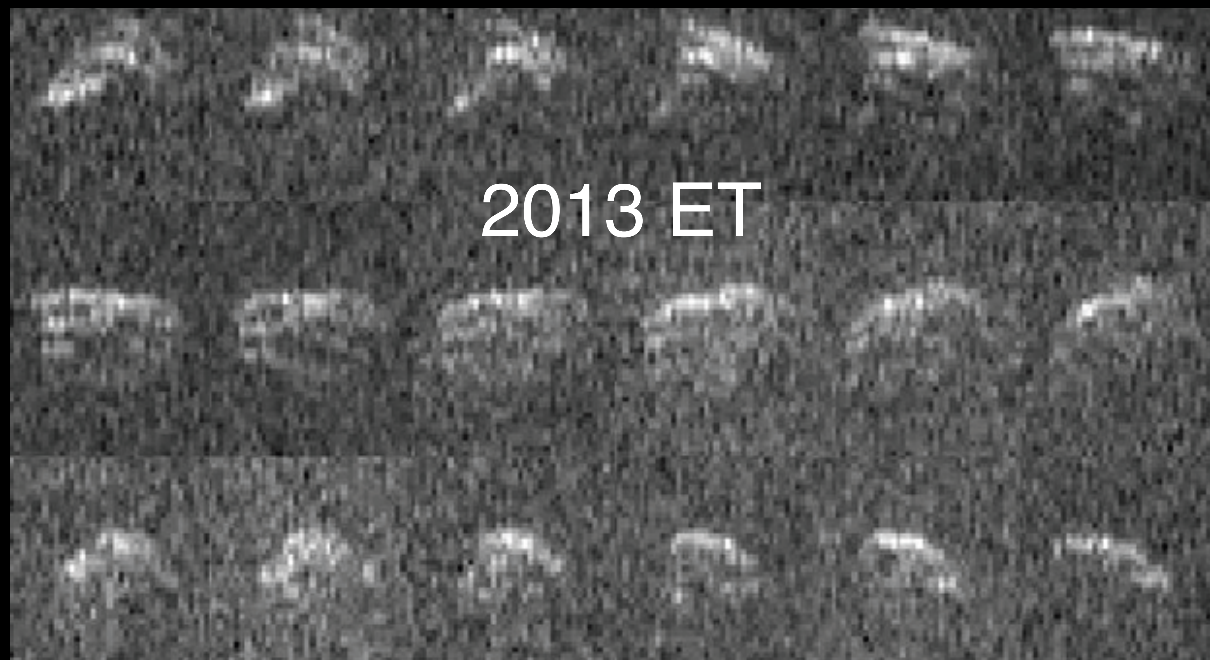
Short-Axis Mode Non-Principal Axis Rotation: 2007 PA8



Brozovic et al.

Images of Tiny NEAs: 2013 ET and 2014 BR57

Goldstone; range resolution = 3.75 m



The Future

Number of NEAs is growing steadily. Expect many more radar targets in general and especially for objects with $H > 25$

Easiest way to detect more NEAs with radar is to use Arecibo (see Naidu et al.). Need more reliability and greater access to time on short notice. Need new generators with lower emissions due to pollution laws.

Can do more at Goldstone but short-notice requests remain problematic. More TOO detections but often only one or two tracks. We are observing more weak targets and obtaining more time for targets identified months in advance.

DSS-13 could be a niche facility for very strong and close targets. Most will be $<$ 50 m in diameter.

Haystack could contribute on very short notice but no regiular observing program there.

We anticipate using GBT regularly to receive Goldstone transmissions.

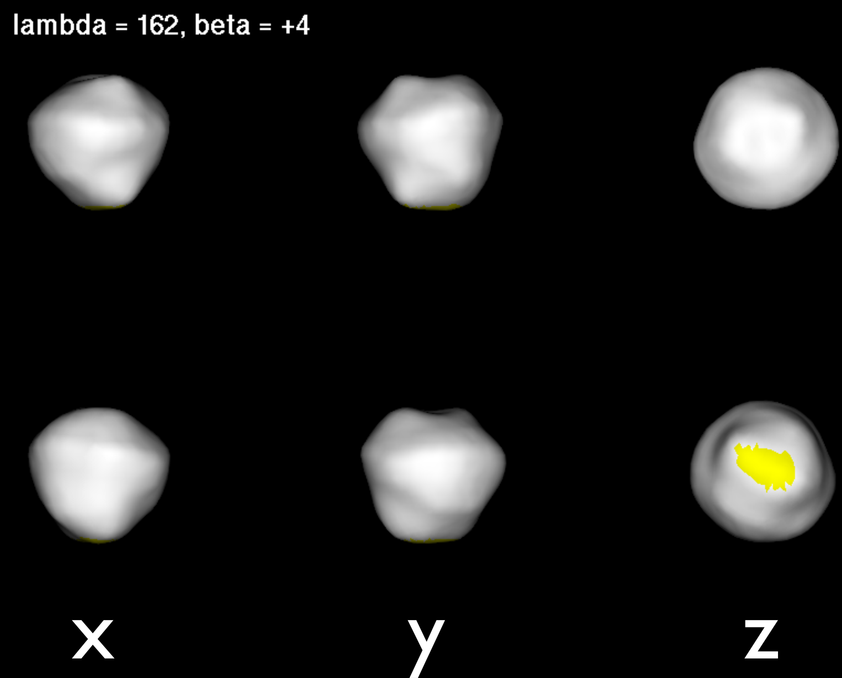
Upcoming NEA Radar Observations: 2015

Jun	Icarus	16.9
Jun	2010 NY65	21.4
Jun	2004 MW2	19.2
Jun	2010 LN14	21.1
Jun	1998 KU2	16.6
Jul	2015 HM10	23.8
Jul	2011 UW158	19.4
Jul	1994 AW1	17.5
Jul	2003 NZ6	19.0
Jul	2010 PR66	19.3
Jul	1999 JD6	17.1
Aug	2005 GO22	18.6
Aug	2011 AK5	21.5
Aug	2005 JF21	17.1
Aug	2003 RB	18.7
Aug	2004 BO41	17.8
Sep	1998 CS1	17.6
Sep	2001 UZ16	19.4
Oct	2000 FL10	16.8
Oct	2015 FS332	18.3
Oct	2014 UR	26.6
Oct	1998 XN2	19.5
Oct	2006 UY64	19.5
Oct	2009 FD	22.1
Nov	2005 UL5	20.2
Nov	2011 YS62	19.7
Nov	Daedalus	14.8
Nov	2007 BG29	18.0
Dec	2011 WN15	19.6
Dec	2003 EB50	16.4
Dec	1998 WT24	17.9
Dec	2003 SD220	16.9
Dec	1995 YR1	20.2
Dec	2002 AC5	19.9
Dec	2008 CM	17.3
Dec	2010 BB	20.4
Dec	2004 MQ1	18.0

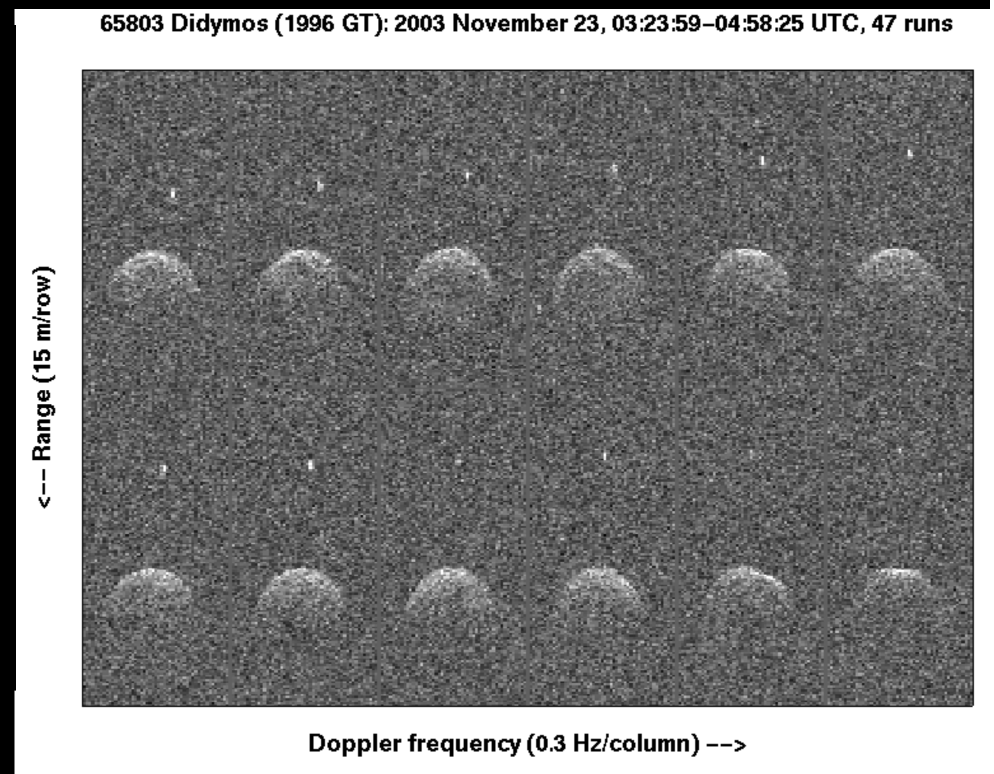
[redacted]

Backup Slides

Target for the proposed *AIM/DART* Mission
Binary 65803 Didymos



Preliminary shape model



AIM: Asteroid Impact Mission (ESA)
DART: Double Asteroid Redirection Test (NASA)

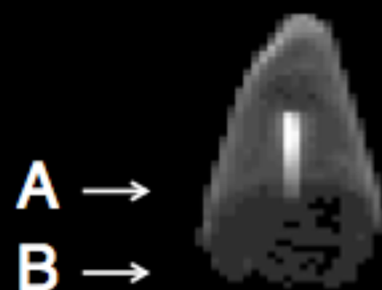
Direct Evidence for Oblate Shapes

2013 WT44

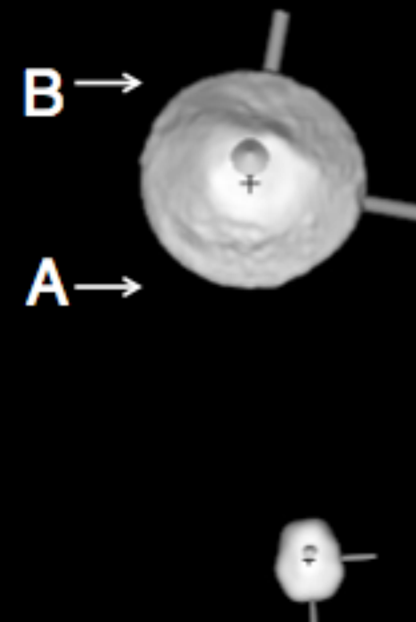
Radar Data

1999 KW4

Synthetic Image

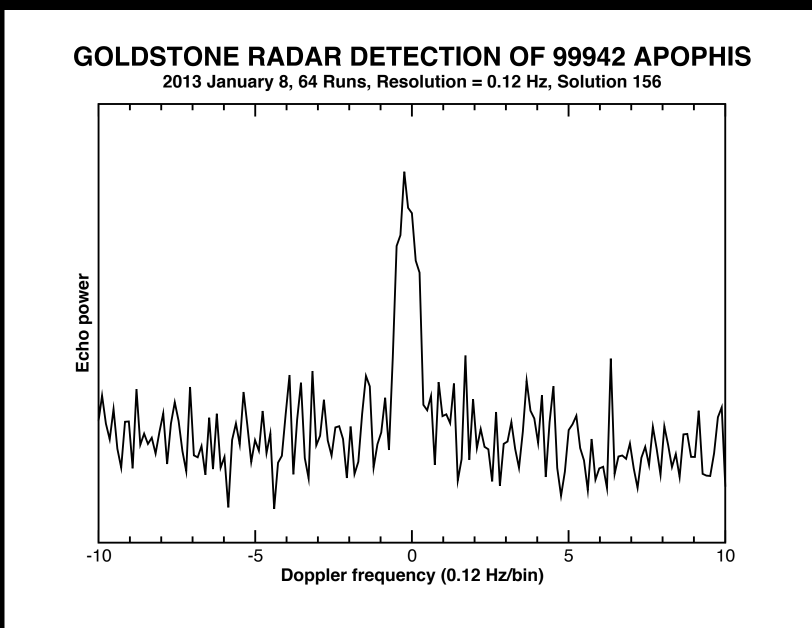


Shape Models



Subradar latitude = 80°

99942 Apophis



Goldstone radar astrometry ruled out any chance of an Earth impact in 2036.

Reliable orbit estimation into the 2060s.

Short-Axis Mode Non-principal axis rotator: Pravec et al. 2014.

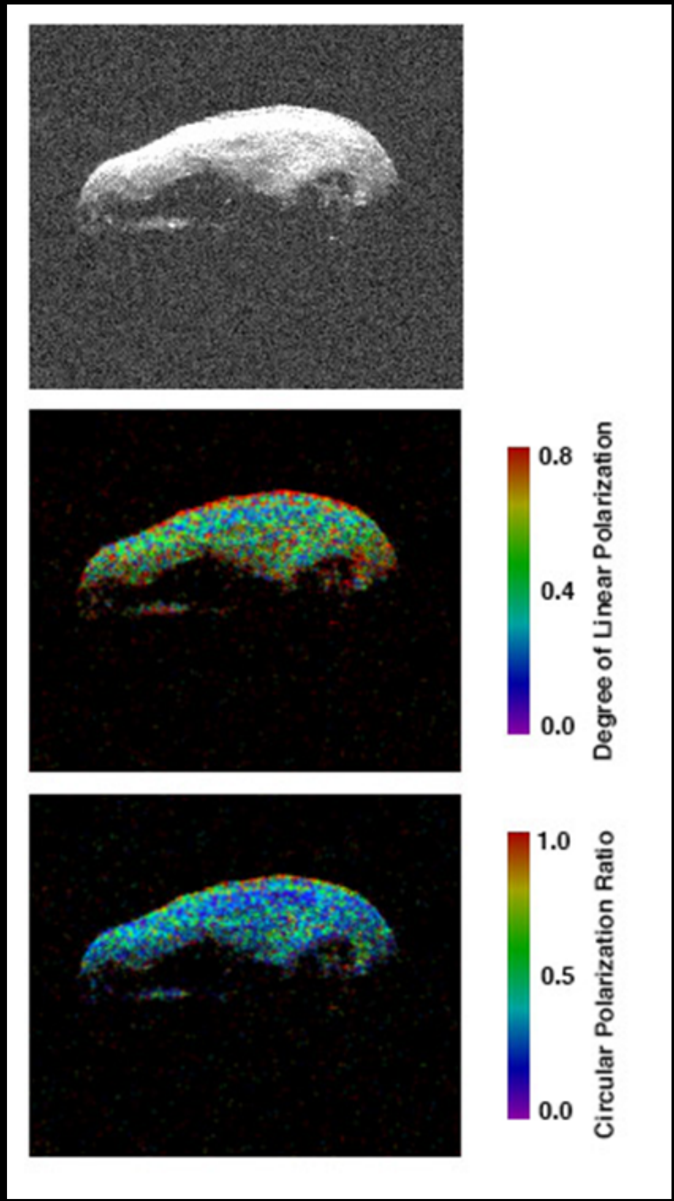
Next radar opportunity: 2021.

Selected Near-Earth Asteroids With Radar Evidence for Boulders

Asteroid		Class	Diameter (km)	
29075	1950 DA	X	1.3	(retrograde model)
33342	1998 WT24	E	0.4	
100085	1992 UY4	P	2	
101955	Bennu	B	0.5	
136849	1998 CS1	S	1	
192642	1999 RD32	dark	~6	(long axis)
285263	1998 QE2	C	3.2	(binary)
308635	2005 YU55	C	0.35	
341843	2008 EV5	C	0.4	
357439	2004 BL86			
374851	2006 VV2	S	1.8	(binary)
	2014 BR57	dark	0.08	
	2014 HQ124	bright	0.4	(long axis)

Regolith Distribution from Polarimetry

2006 VV2 (Arecibo-Green Bank data), range resolution = 15 m



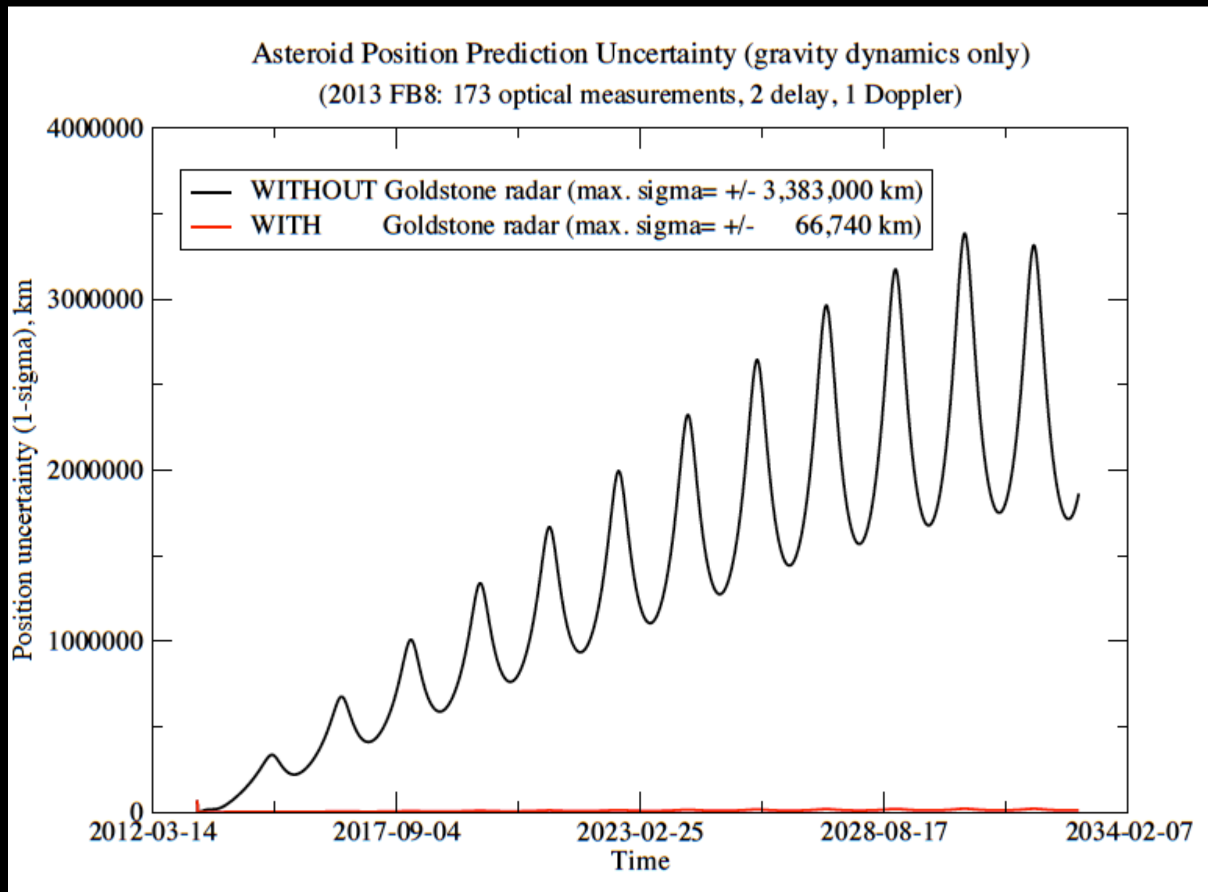
OC Delay-Doppler image

Degree of linear polarization

Circular polarization ratio

(Carter et al., in prep.)

Orbit Improvement Example: 2013 FB8

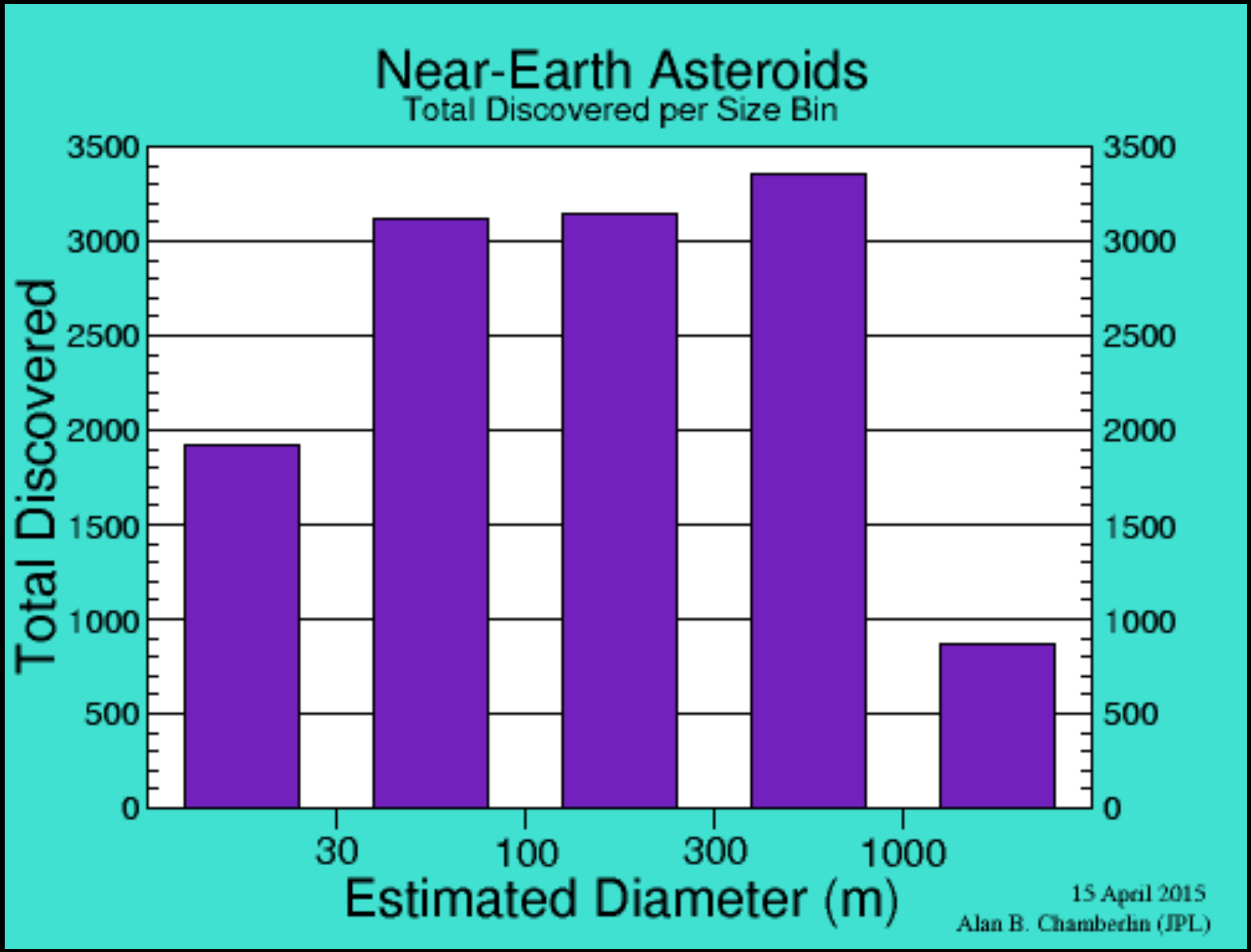


For newly-discovered asteroids, radar can enable computation of trajectories for centuries farther into the future than is possible otherwise

Figure credit: Jon Giorgini, JPL

12619 Near-Earth Asteroids Have Been Discovered

(as of May 26, 2015)

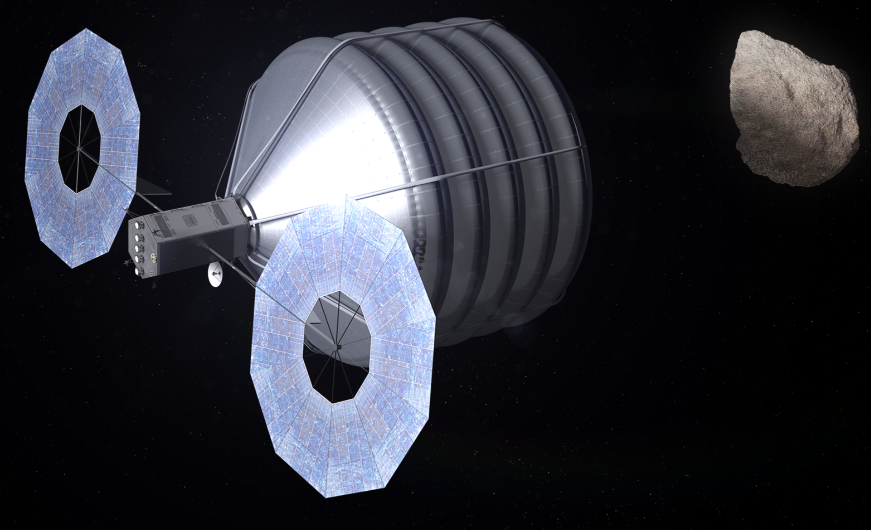


How Many Near-Earth Asteroids Exist?

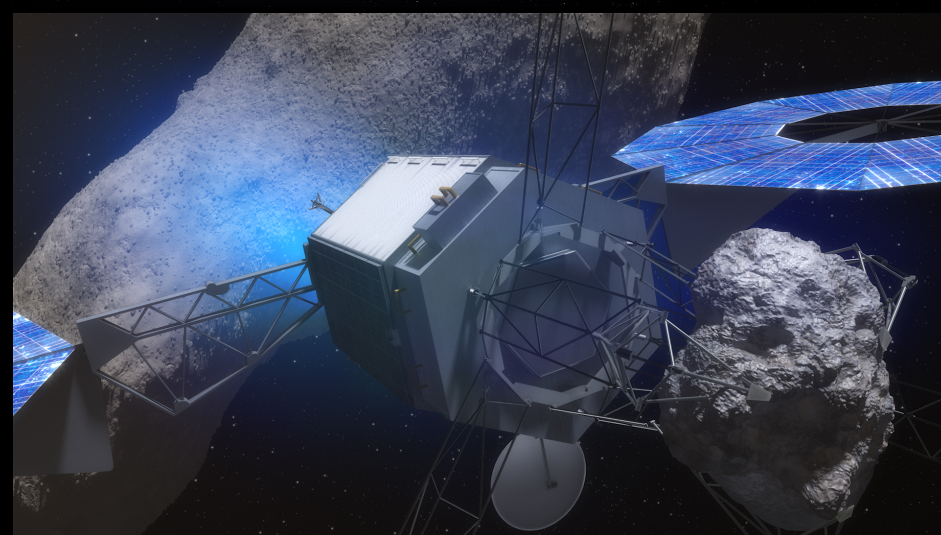
Diameter	Number	Impact Frequency
1 km	940	1 million years
100 m	20,000	10,000 years
10 m	30 million	10 years

NASA'S PROPOSED
ASTEROID REDIRECT MISSION (ARM)

Option A:
Capture a small NEA



Option B:
Pull a boulder off
a larger NEA



The Future, Cont'd

To really increase sensitivity, resolution, range, and sample size, need a major upgrade by an order of magnitude. Not likely with existing facilities.

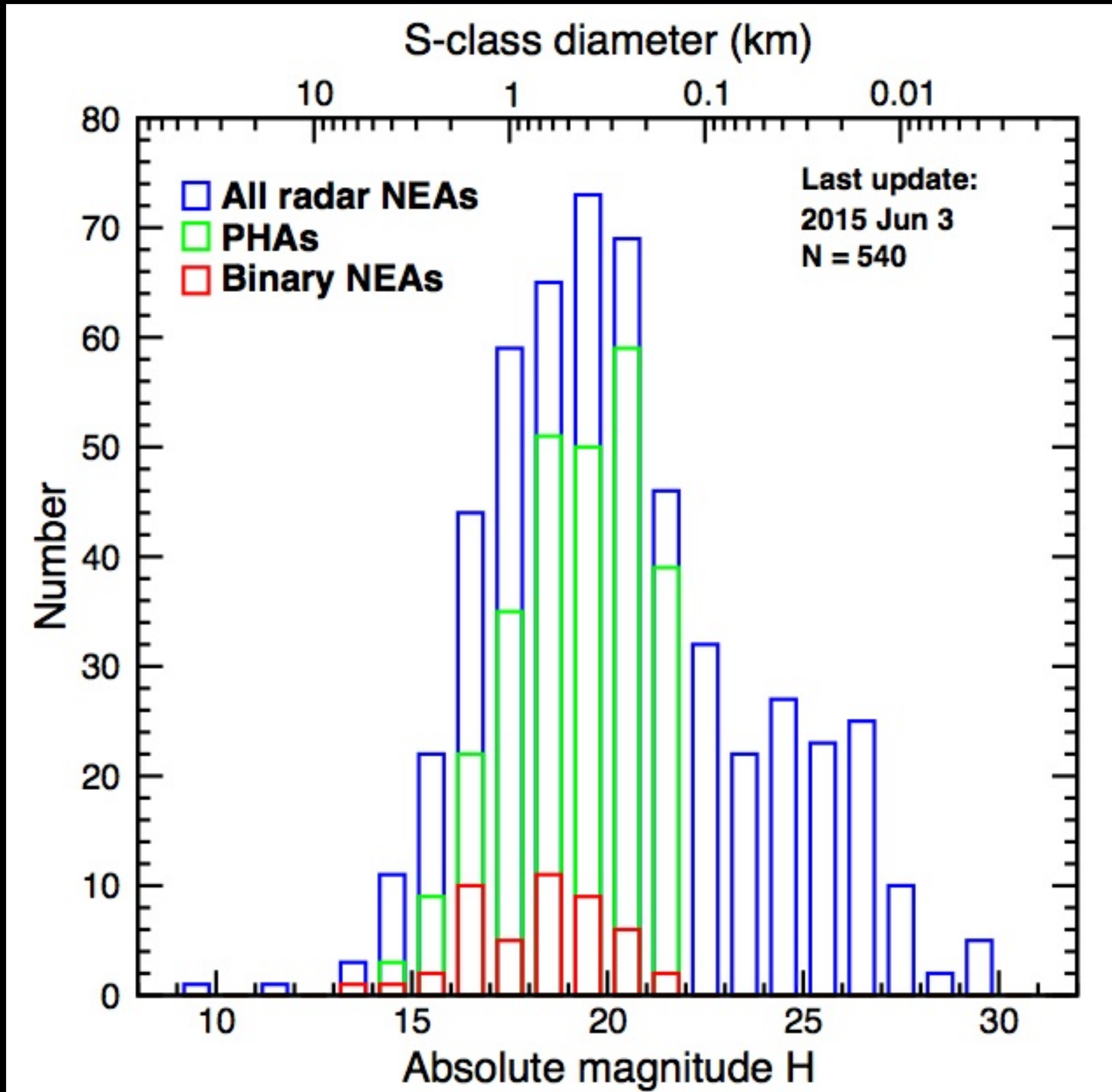
Goldstone: double SNRs with new klystrons. Increase range by 19%. Could also increase resolution to 1.25 m.

Arecibo: Could achive higher resolution with new klystrons. Switch to X or C band could boost SNRs but water vapor will become an issue.

Green Bank might offer the best chance for a big improvement if a high-power Ka-band transmitter could be implemented.

Efficacy of Ka-Band should be studied in more detail to see if Ostro's (1997) idea of a bistatic GBT clones with 1 megawatt transmitters is feasible.

Phased arrays may be an option; Ka-BOOM testbed in development at KSC. Not yet known if this will work.



S-class diameter (km)
10
1
0.1
0.01
All radar NEAs
PHAs
Binary NEAs
Last update:
2015 Jun 3
N = 540
Number
0
10
20
30
40
50
60
70
80
10
15
20
25
30
Absolute magnitude H