7th IAA Planetary Defense Conference

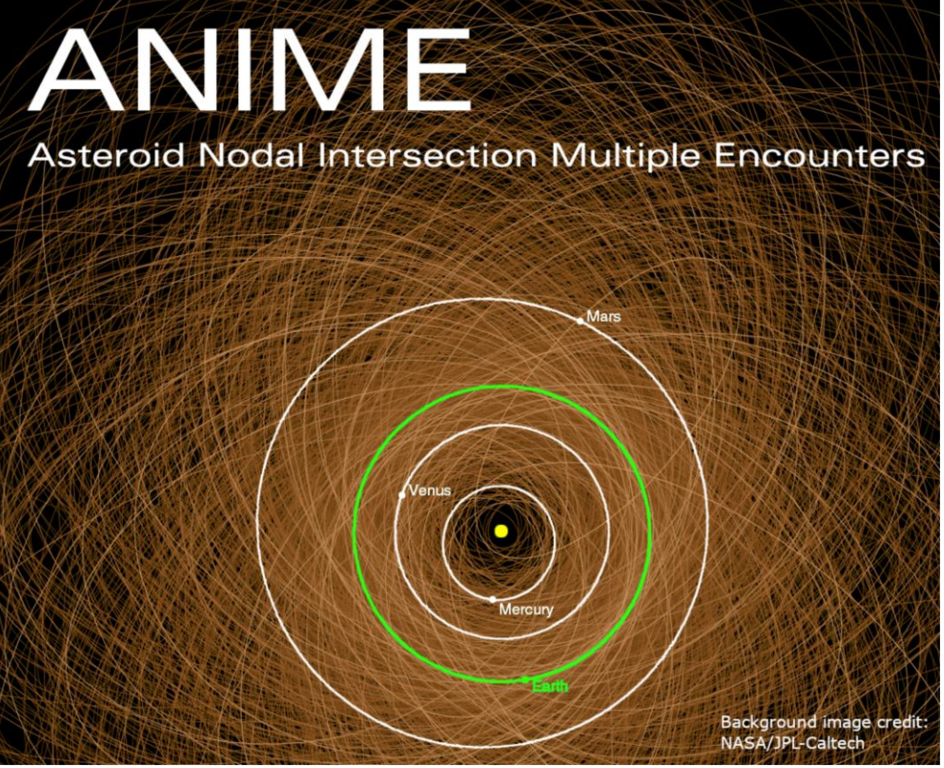
26-30 April 2021, Online Event

Hosted by UNOOSA in collaboration with ESA

Session 8b: Mission & Campaign Design

Chairs: Andy Cheng | Marco Tantardini | George Vardaxis

Presenters: D. Perna | D. Scheeres | S. Sonnett |
B. Barbee | J. Bell



The ANIME CubeSat Mission: Science & Planetary Protection

D. Perna[1], **M. Pajola**[2], **L. Casalino**[3], **S. Ivanovski**[4], **M. Lavagna**[5], **M. Zannoni**[6], **M. Bechini**[5], **A. Capannolo**[5], **A. Colagrossi**[5], **G. Cremonese**[2], **E. Dotto**[1], **A. Lucchetti**[2], **E. Mazzotta Epifani**[1], **J. Prinetto**[5], **E. Simioni**[2], **P. Tortora**[6], **and G. Zanotti**[5]

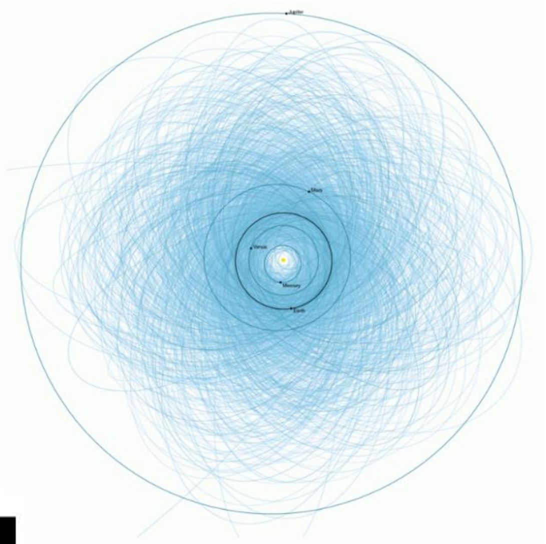
[1]*INAF–OAR* [2]*INAF–OAPd* [3]*Politecnico di Torino*
[4]*INAF–OATs* [5]*Politecnico di Milano* [6]*Università di Bologna*

7th Planetary Defense Conference, 26 – 30 April 2021, Online Event

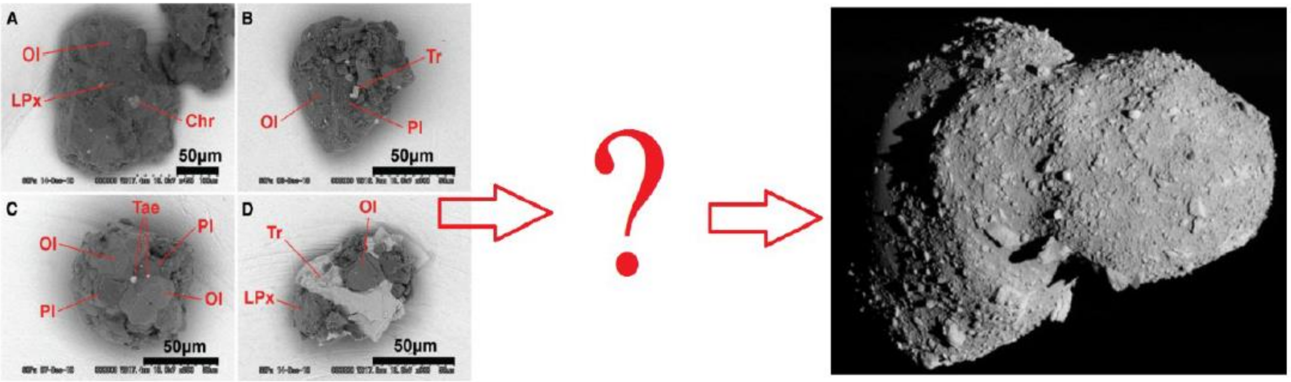
The NEA proximity: a risk…

… & an opportunity

- *Multi-target space missions*
  - ✓ To constrain physical diversity



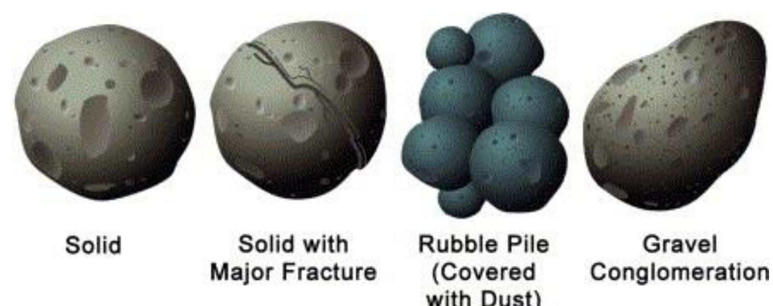
- *Accessibility of ultra-small asteroids*
  - ✓ Unexplored!
  - ✓ To constrain aggregation structure (monolithic vs. cohesive vs. rubble pile)



In a nutshell

- *Concept developed for the 2020 ASI call for “future CubeSat missions”*
  - ✓ ESA GSTP framework
  - ✓ 50-month (phases A-to-D) development plan
  - ✓ 24-month post-launch operations

- *Rendezvous with “high-risk, decametre-size” NEA + 2 PHA fly-bys*
  - ✓ Unexplored physical regimes
  - ✓ Science + Planetary protection



Walkers et al. 2006

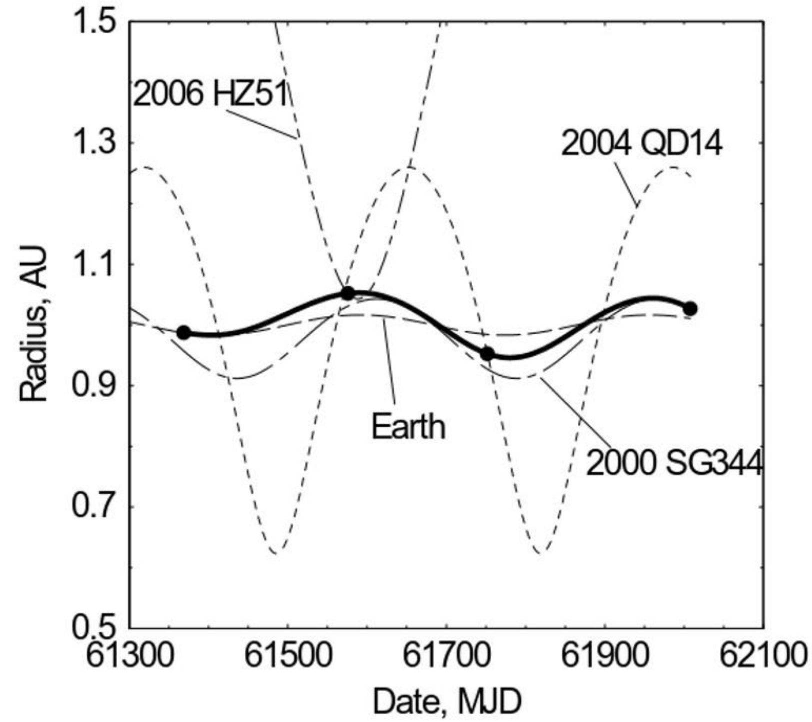
- *COTS, flight-proven components*
  - ✓ Low-cost
  - ✓ Low-risk
  - ✓ High-return!

ANIME
Asteroid Nodal Intersection Multiple Encounters

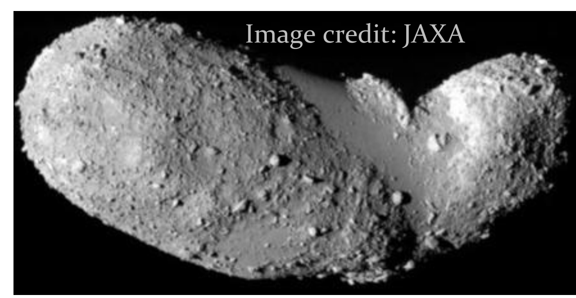
Targets & mission profile

	Earth	2006 HZ51	2004 QD14	2000 SG344
Date	11/2026	6/2027	12/2027	8/2028
V_{rel} (km/s)	0	9.72	10.31	0

- *2000 SG344*
  - ✓ Ø ~ 40 m (H=24.7)
  - ✓ ESA/NASA: Risky & Accessible
- *2004 QD14* *(PHA)*
  - ✓ Ø = 143 (-24/+49) m
  - ✓ p_V = 0.37 (-0.18/+0.20) [Trilling+2016]
- *2006 HZ51* *(PHA)*
  - ✓ Ø = 410 ± 90 m
  - ✓ p_V = 0.42 ± 0.23 [Nugent+2015]



Smallest asteroid visited to date: Itokawa (~350 m)



ANIME
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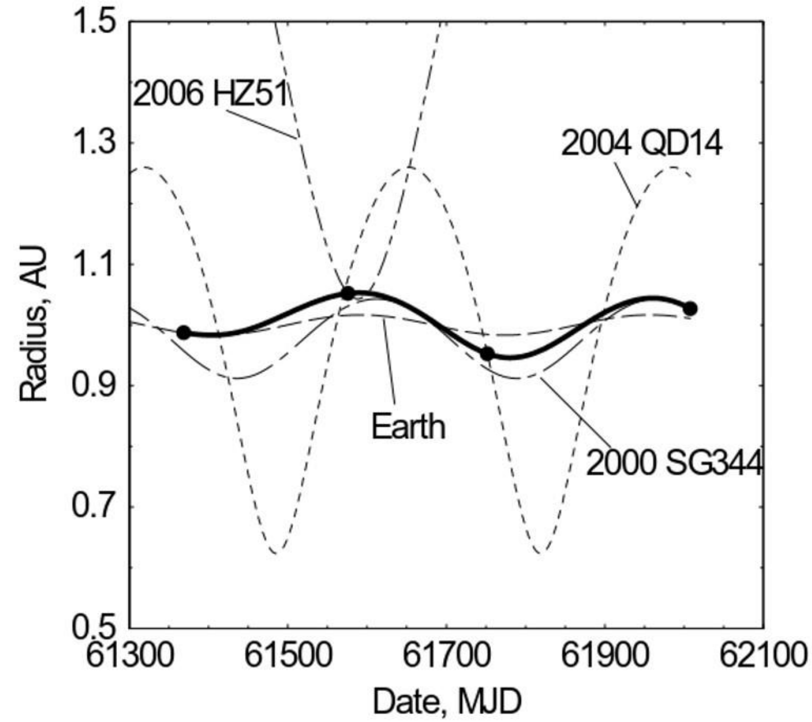
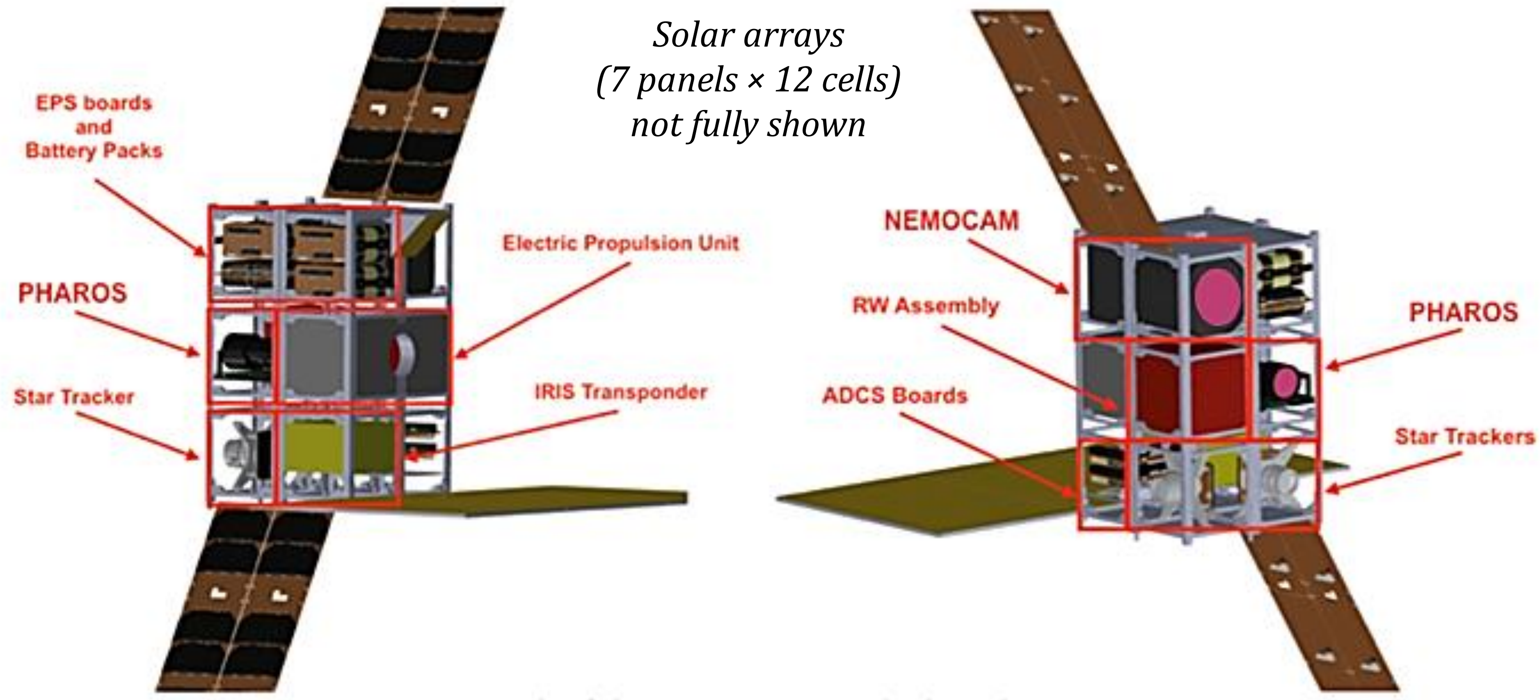


- *Baseline scenario*
  - ✓ Launch window ~ Sep.-Dec. 2026
  - ✓ Total ΔV ~ 1.0 km/s
  - ✓ Ample propellant margin (~30%)

- *Huge flexibility*
  - ✓ Launch dates to 2000 SG344 (late 2025 – early 2028)
  - ✓ Alternative fly-by (PHA) and rendezvous (“small-size”) targets
  - ✓ …

Spacecraft design



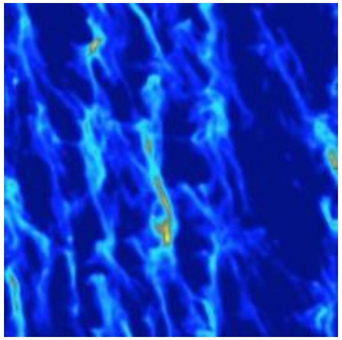
- *12U CubeSat*
- *COTS components, mostly with TRL 9 acquired in LEO*
- *RF ion thruster (thrust ~1 mN, Isp ~2100 s)*
- *Two RGB off-the-shelf cameras (renamed NEMOCAM & PHAROS)*
- *Margined wet mass ~20 kg*

Operations & scientific return

	FoV (across track)	Spatial Resolution (@ 100 km)	Focus
NEMOCAM	2.22°	0.95 m	> 10 km
PHAROS	5.0°	7.8 m	> 400 m

- *Both fly-bys*
  - ✓ V_{rel} ~10 km/s @ ~50 km distance
  - ✓ Decimetre-scale images
- *Rendezvous with 2000 SG344*
  - ✓ 2-month nominal campaign
  - ✓ Cm-scale images
  - ✓ Radio science
  - ✓ Constraints to orbit/Yarkovsky/YORP

input for streaming instability + N-body numerical simulations



Conclusions

- *ASI call for "future CubeSat missions"*
  - ✓ Among proposals that successfully passed the technical and scientific screening (April 2021)
  - ✓ Financial evaluation currently ongoing

- *Flexible, low-risk, high-return mission concept for both planetary science & planetary protection*

- *Opportunity for technological solutions (deep space validation)*

- *For more information:*
  - ✓ See "full manuscript"
  - ✓ davide.perna@inaf.it

Celestial and Spaceflight
Mechanics Laboratory

Janus

A NASA SIMPLEx mission to explore two NEO Binary Asteroids

D.J. Scheeres[1], J.W. McMahon[1], E.B. Bierhaus[2], J. Wood[2], L.A.M. Benner[3], C. Hartzell[4], P. Hayne[5], J. Hopkins[2], R. Jedicke[6], L. LeCorre[7], A. Meyer[1], S. Naidu[3], P. Pravec[8], M. Ravine[9], and K. Sorli[1]

[1]The University of Colorado Boulder, USA; [2]Lockheed Martin Inc, USA; [3]Jet Propulsion Laboratory, USA; [4]University of Maryland, USA; [5]LASP, University of Colorado Boulder, USA; [6]University of Hawaii, USA; [7]Planetary Science Institute, USA; [8]Astronomical Institute of the Academy of Sciences, Czech Republic; [9]Malin Space Science Systems Inc, USA

Janus

A dual spacecraft mission to open a gateway to understand the transitions and lifecycles of rubble pile asteroids

University of Colorado Boulder

NASA SIMPLEx Program

- **SIMPLEx Lead PE:**
  - C. Mercer (HQ)
- **Program Manager:**
  - K. Sykes (MSFC)
- **Program Executive:**
  - W. Knopf (MSFC)
- **Program Scientist:**
  - M. Kelley (MSFC)

- **Class D Mission**
- **Cost cap < $55M**

Institutional Partnerships

University of Colorado Boulder

PI Office
Mission Oversight

LOCKHEED MARTIN

Project Management
Spacecraft
Mission Operations

Malin SSS
Instrument Suite

Science Team

- **PI: Dan Scheeres** (CU) — OREX, NEAR, Hayabusa, Hayabusa2
- **Deputy-PI:** J. McMahon (CU) — OREX, Hayabusa2
- **Project Scientist:** E. Bierhaus (LM) — OREX
- **Instrument Scientist:** M. Ravine (MSSS) — OREX
- **Mission Scientist:** C. Hartzell (UMd) — OREX
- **Visible Imaging:** L. Le Corre (PSI) — OREX, Dawn, Hayabusa2
- **IR Imaging:** P. Hayne (CU-LASP) — DIVINER

- **Radar Astronomers:**
  - L. Benner (JPL)
  - S. Naidu (JPL)
- **Ground-based Observers:**
  - R. Jedicke (UH)
  - P. Pravec (CAS)

- **Graduate Student Researchers (PhD Students):**
  - Alex Meyer (CU)
  - Kya Sorli (CU-LASP)
  - Chloe Long (CU)

Janus Mission Science:
A first close look at binary asteroids

Why Study Binary Asteroids?

- Binary Asteroids are…

… ubiquitous at ~15% of the asteroid population

… thought to form when rubble pile asteroids fission due to high spin rates

… just one of several "pathways" that small rubble pile asteroids travel down

… the key to understanding the mechanical properties of rubble pile asteroids, and by extension the geophysics of microgravity aggregates.

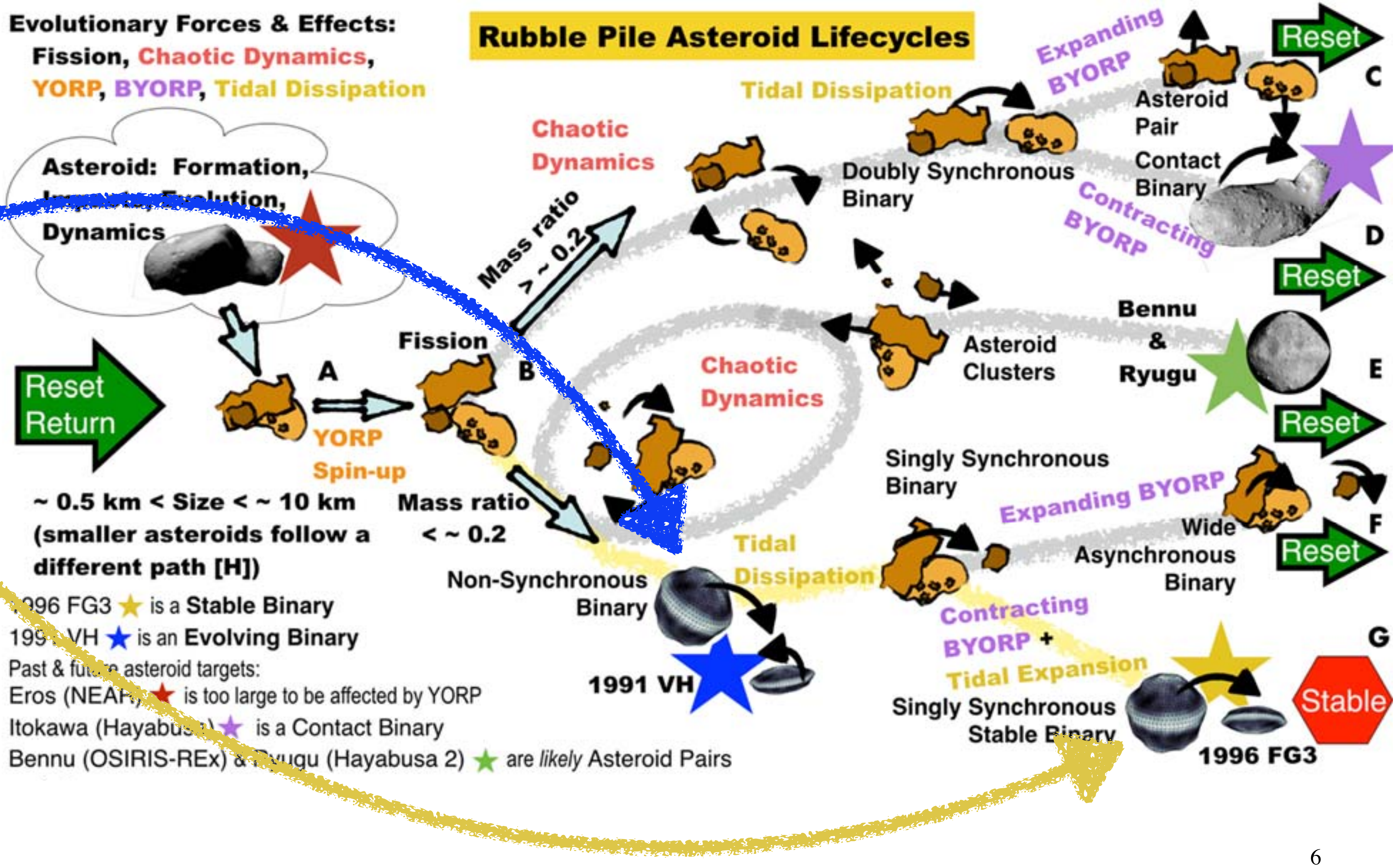
Janus targets are key to understanding the physical evolutionary pathways that drive rubble pile asteroids

Janus targets diverse binaries at key points along their evolutionary pathway:

1991 VH is in its chaotic orbital evolution phase and is an S Type.

1996 FG3 is in a stable end-state and is a C Type.

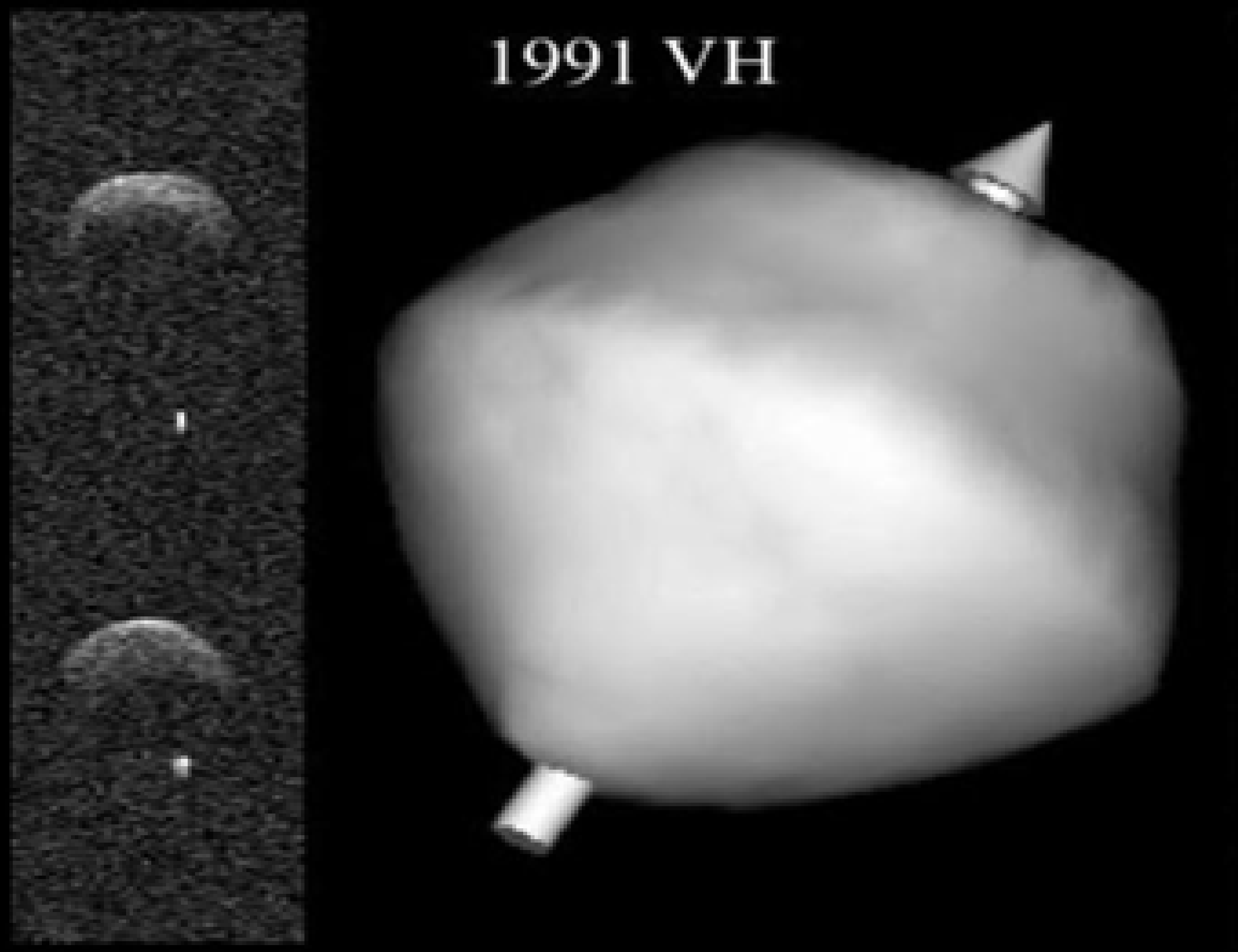
Observing a diversity of binary bodies with one mission will give fundamental insight into rubble pile bodies in the solar system.



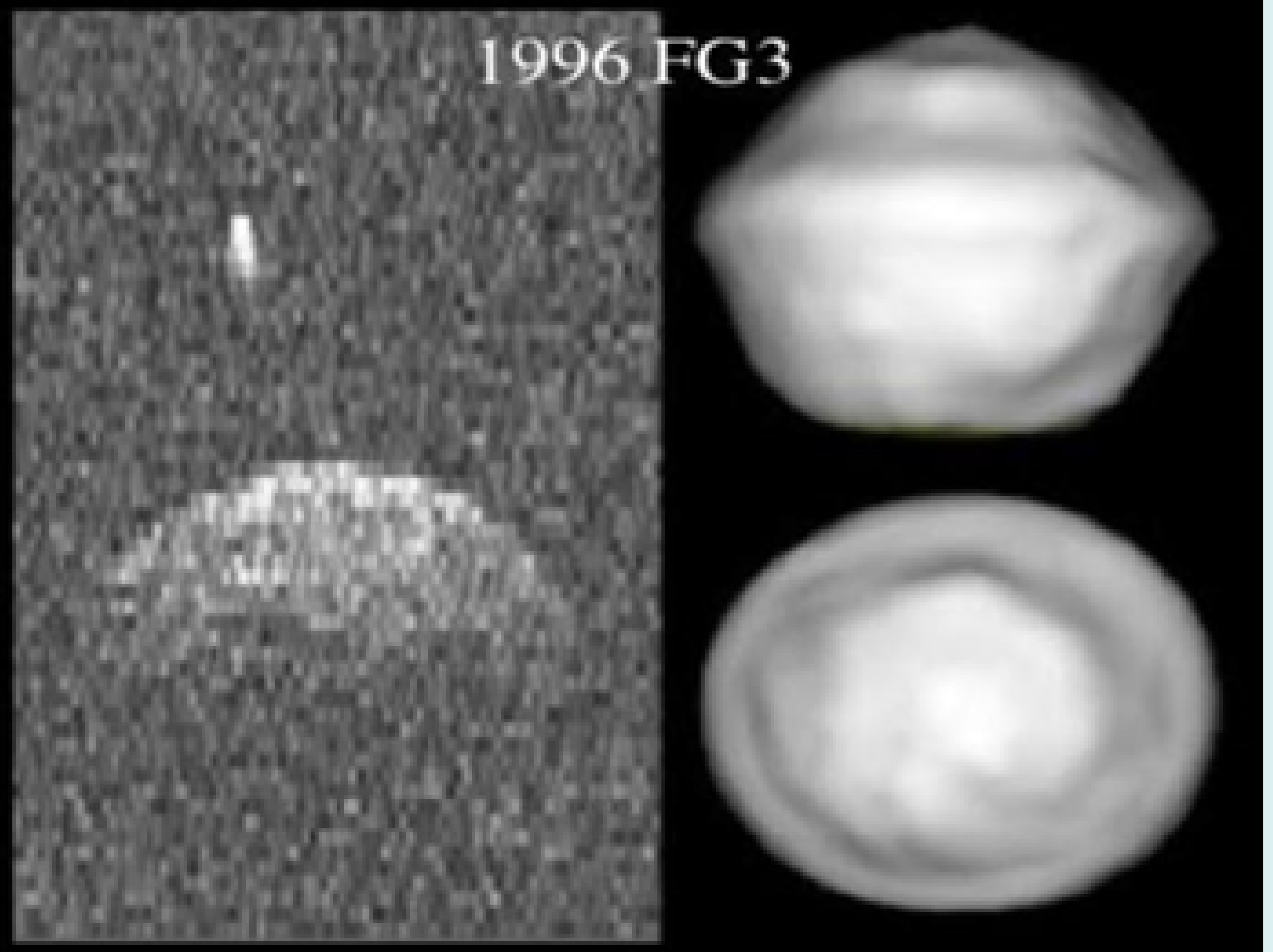
Target Binary Asteroids: (175706) 1996 FG3 and (35107) 1991 VH

Ideal Targets Enable Janus' Science Goals

- *Binary near-Earth asteroids that have been subject to multiple transitions and have similar shapes and morphologies*
- *Distinct systems that lie at different evolutionary stages and which have different compositional properties*
- *Both have been extensively characterized by ground-based observations providing known mass, shape, rotation and orbit*
- *Potentially Hazardous Asteroids*



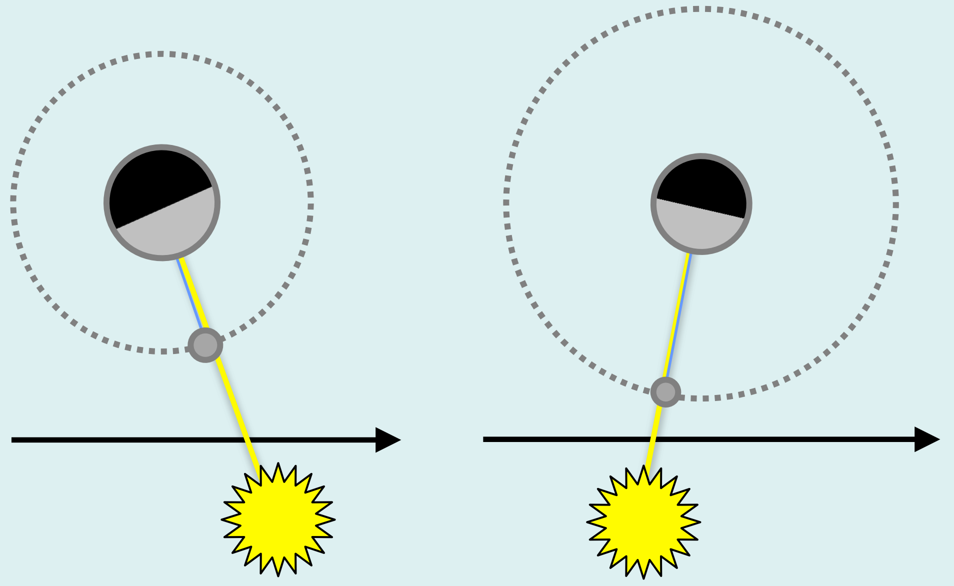
A rocky S-Type in an excited state and a non-synchronous secondary rotation state



A primitive C-Type in a long-term stable state and a synchronous secondary

Binary asteroid system details and spacecraft flyby conditions are similar.

Relative size of systems



System and Encounter Details	**1996 FG3**	**1991 VH**
Diameter of primary	1690 m	1040 m
Diameter of secondary	490 m	420 m
Orbit semimajor axis	2520 m	3295 m
Spacecraft close approach distance	70 ± 10 km	70 ± 10 km
Encounter speed	4-5.5 km/s	2.8-3.7 km/s
Approach phase angle	97°-120°	65°-80°

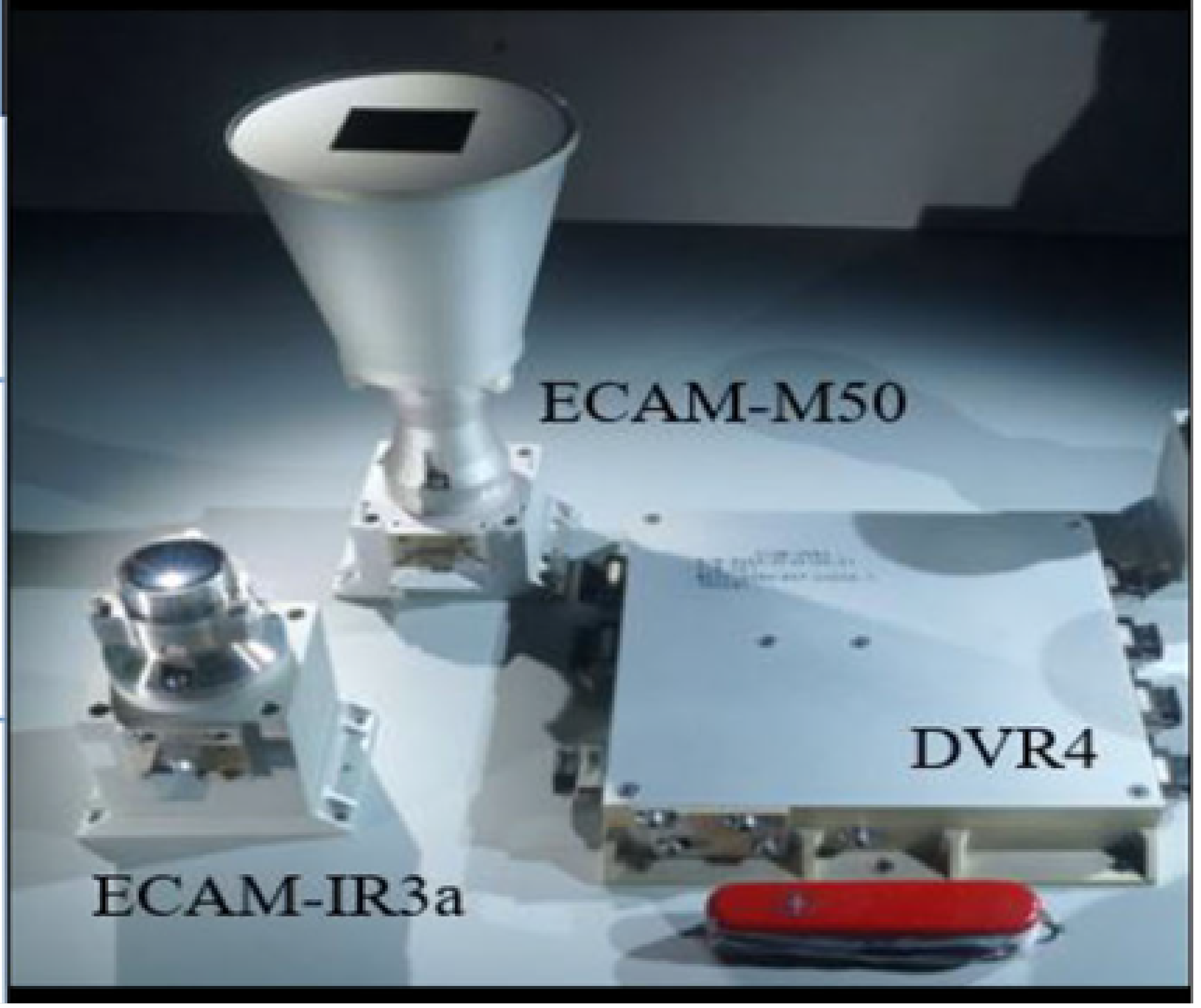
University of Colorado Boulder

The *Janus* instrument suite has high-heritage and proven performance

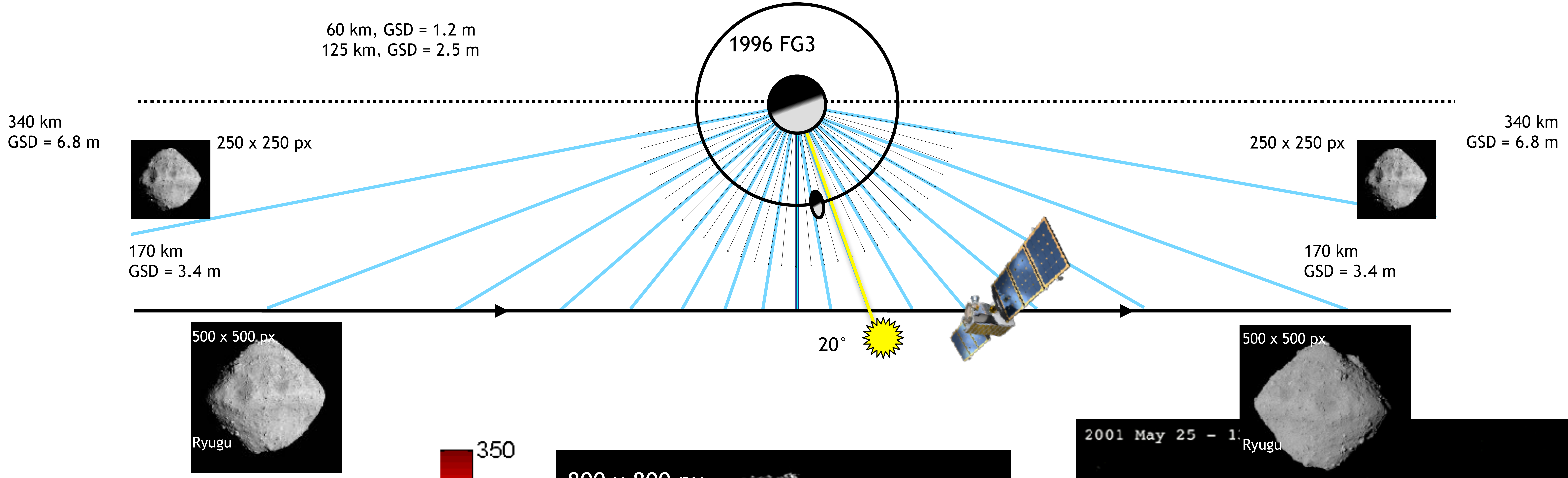
JCam supports visible and near-IR imaging of our target binaries.
JCam is provided by Malin SSS, with detectors and electronics copied from proven instruments.
JCam DVR allows for on-board data compression, windowing and selective downloading of images.

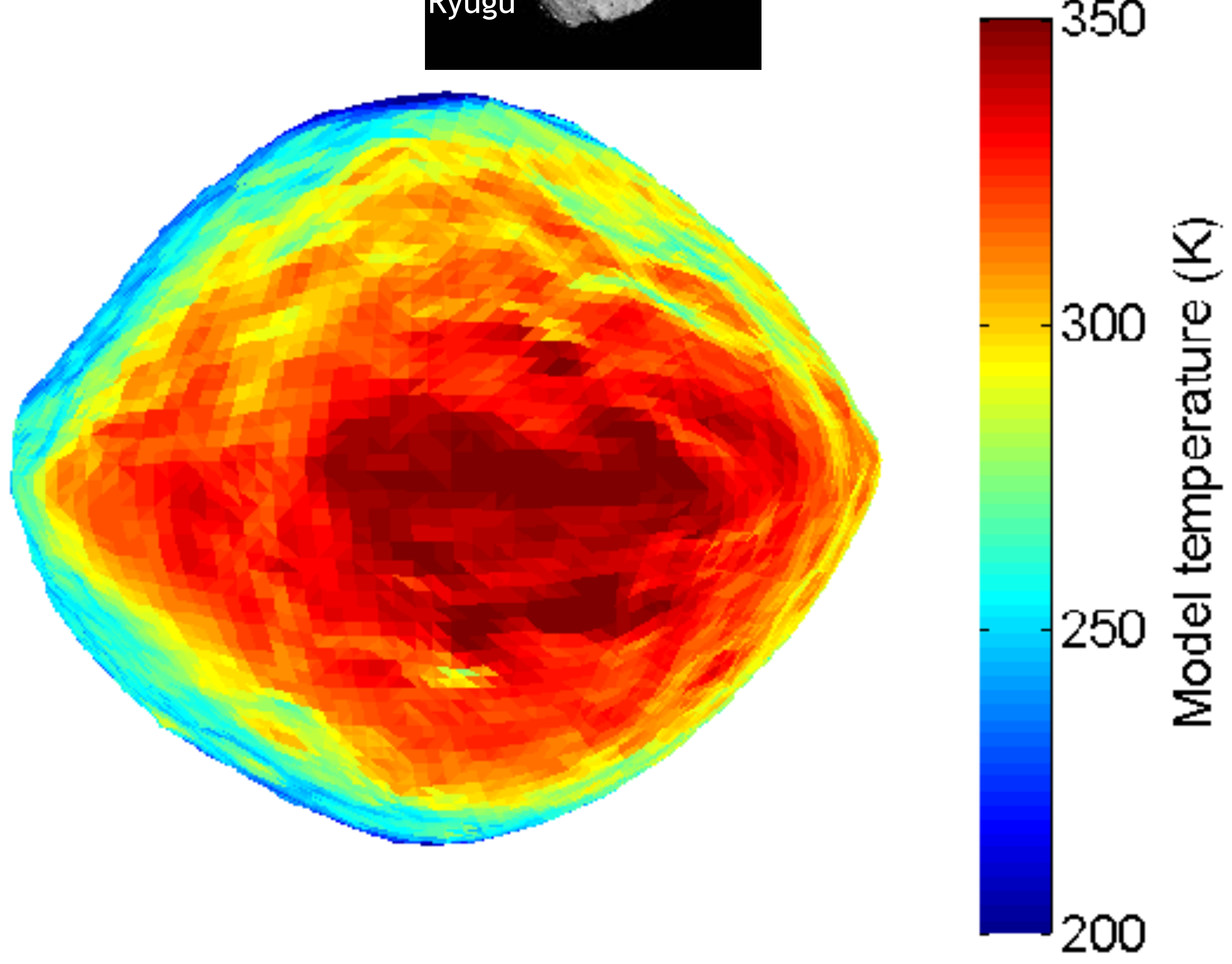
Science Instruments

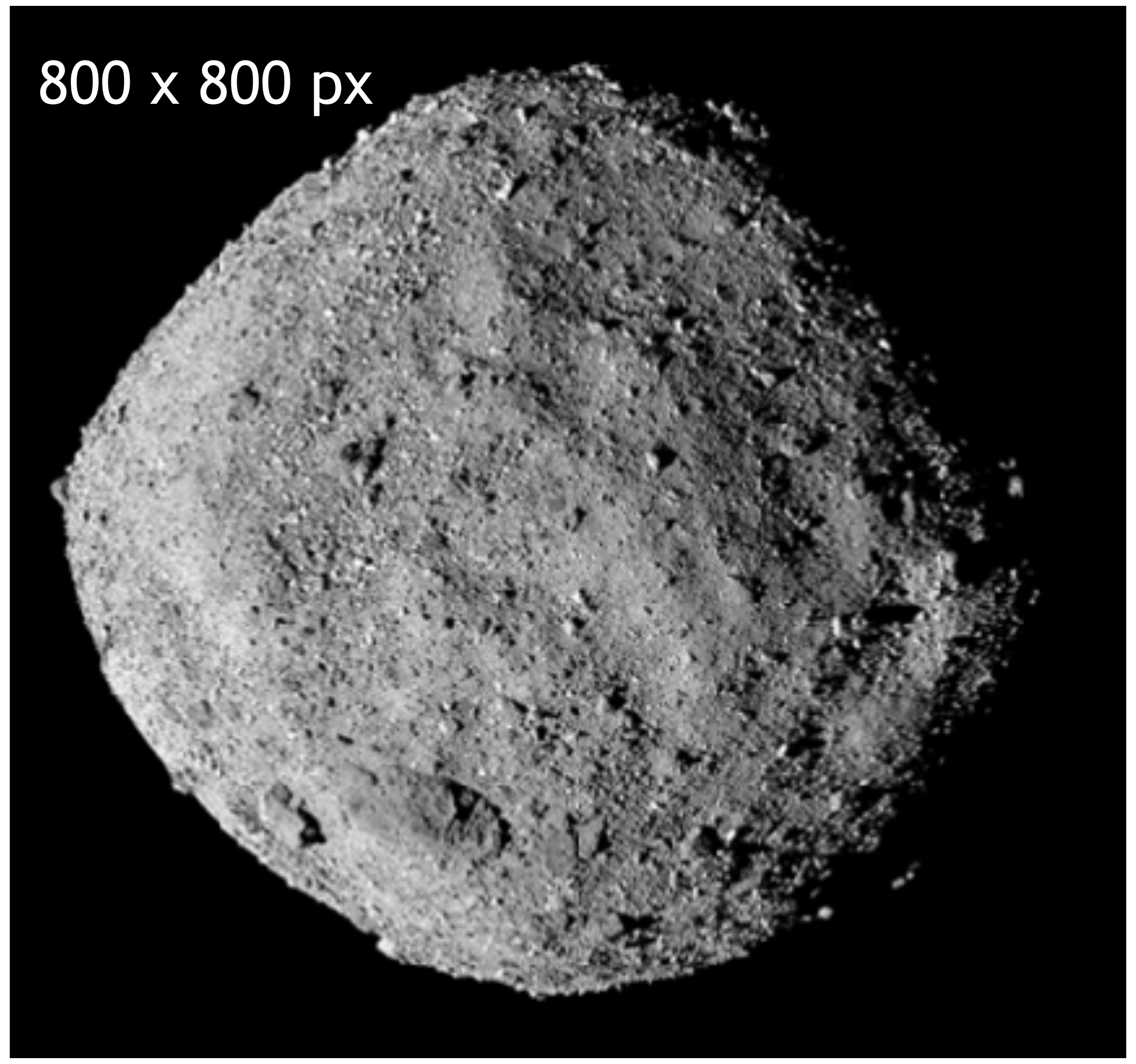
Instrument	Description	Heritage
Visible Imager	ECAM-M50, 2592 x 1944 pixel CMOS sensor with 2.2 μm pixels, 420-680 nm bandpass, and an electronic rolling shutter	OSIRIS-REx, Undisclosed Mission
Infrared Imager	ECAM-IR3a, 640 x 480 pixel uncooled Long-Wave Infrared (LWIR) microbolometer sensor array with 8-12 μm bandpass, integral Read-Out Integrated Circuit (ROIC) and 17μm pixels.	Undisclosed Mission
DVR	ECAM-DVR4, power conditioning, camera control, image processing, compression, subset windowing, and storage.	OSIRIS-REx, Undisclosed Mission



Science Observations During Flyby

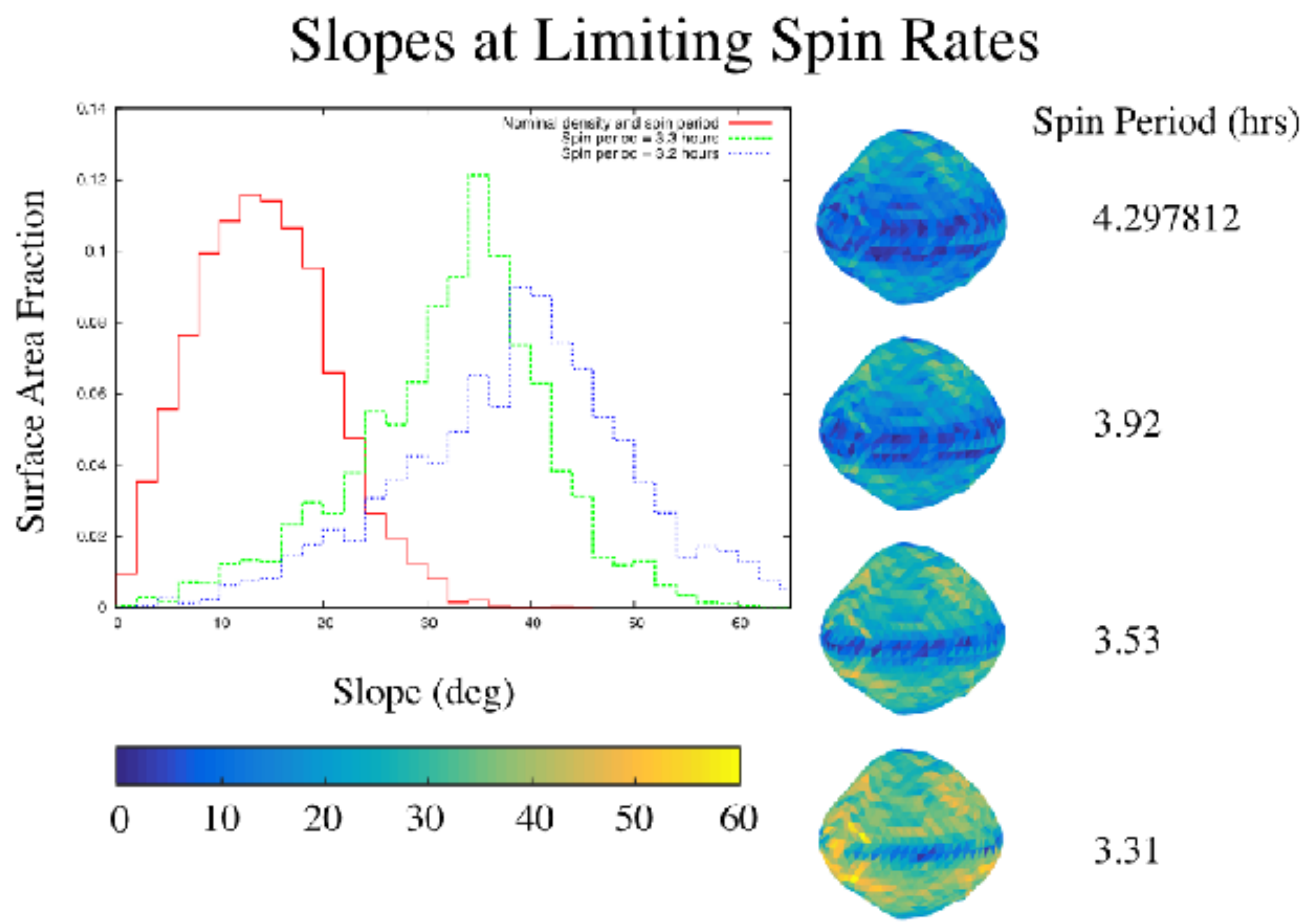






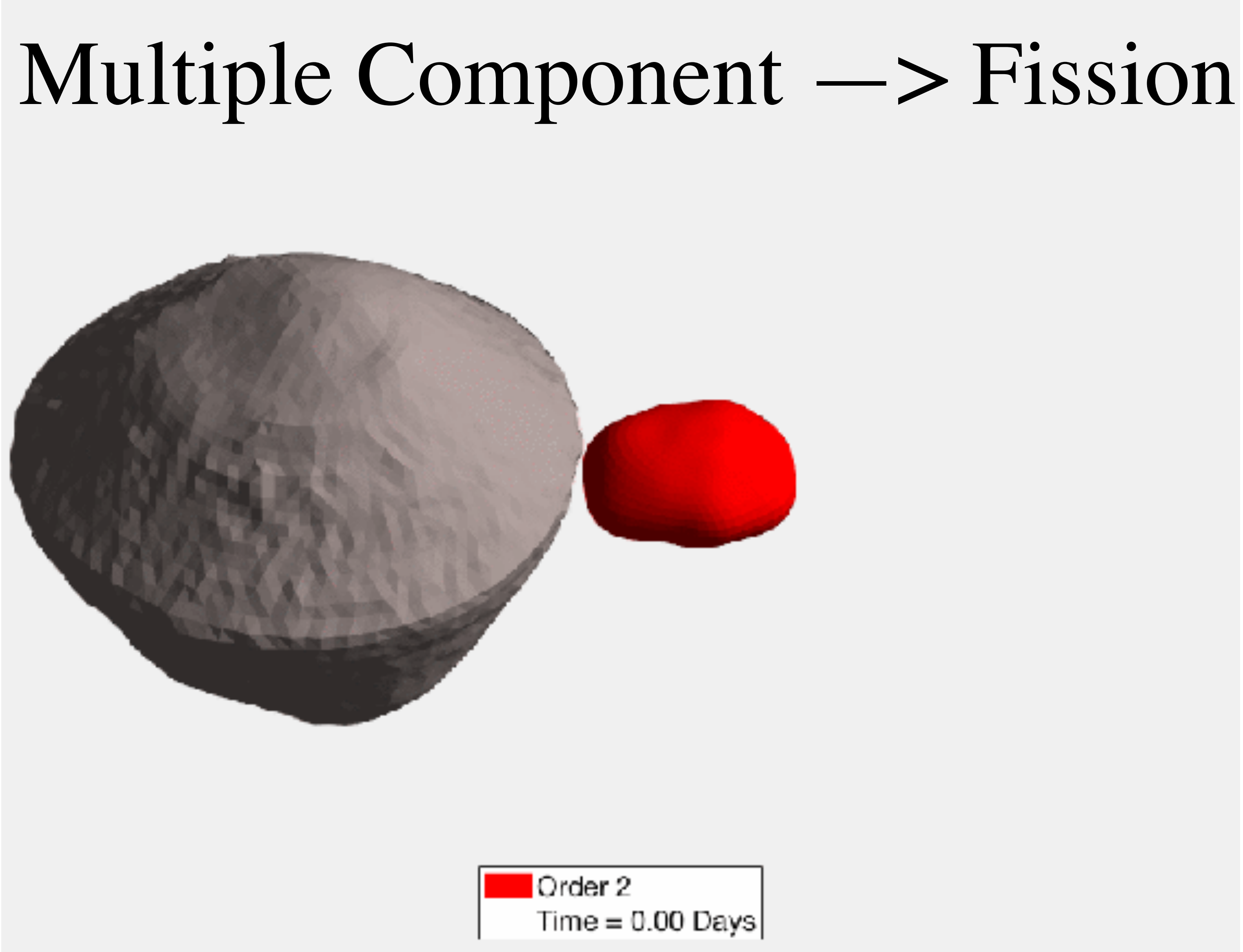
Goal I: How Do Binary Asteroids Form?

Strong Interior —> Surface Shedding



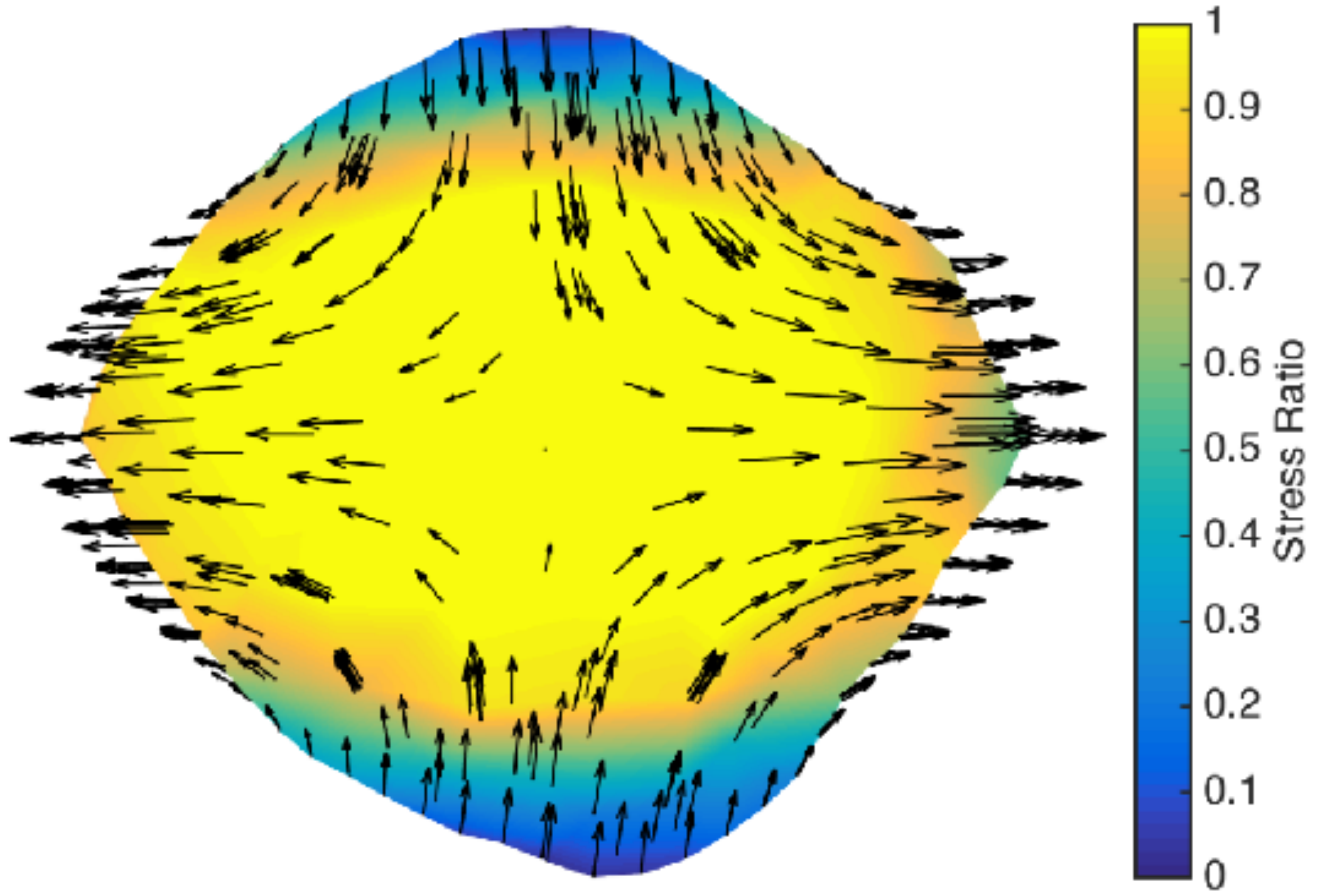
Regolith flows to equator
Secondary accumulated in orbit
Similar secondary and primary surfaces?

Multiple Component —> Fission



Cavity or scar on the surface
Evidence of secondary fission:
- Infall on primary
- Fission evidence on secondary

Weak Interior —> Internal Failure



Outcropping of equator
Secondary accumulated in orbit:
- Potential for a "seed" larger component from equator

Lack of regolith flows

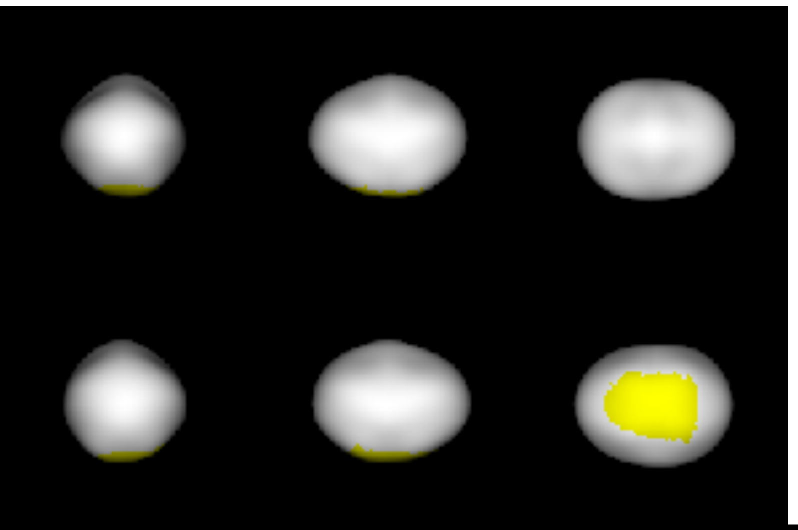
Imaging provides morphology -> insight on formation

Goal II, SO3: Asteroid (175706) 1996 FG3

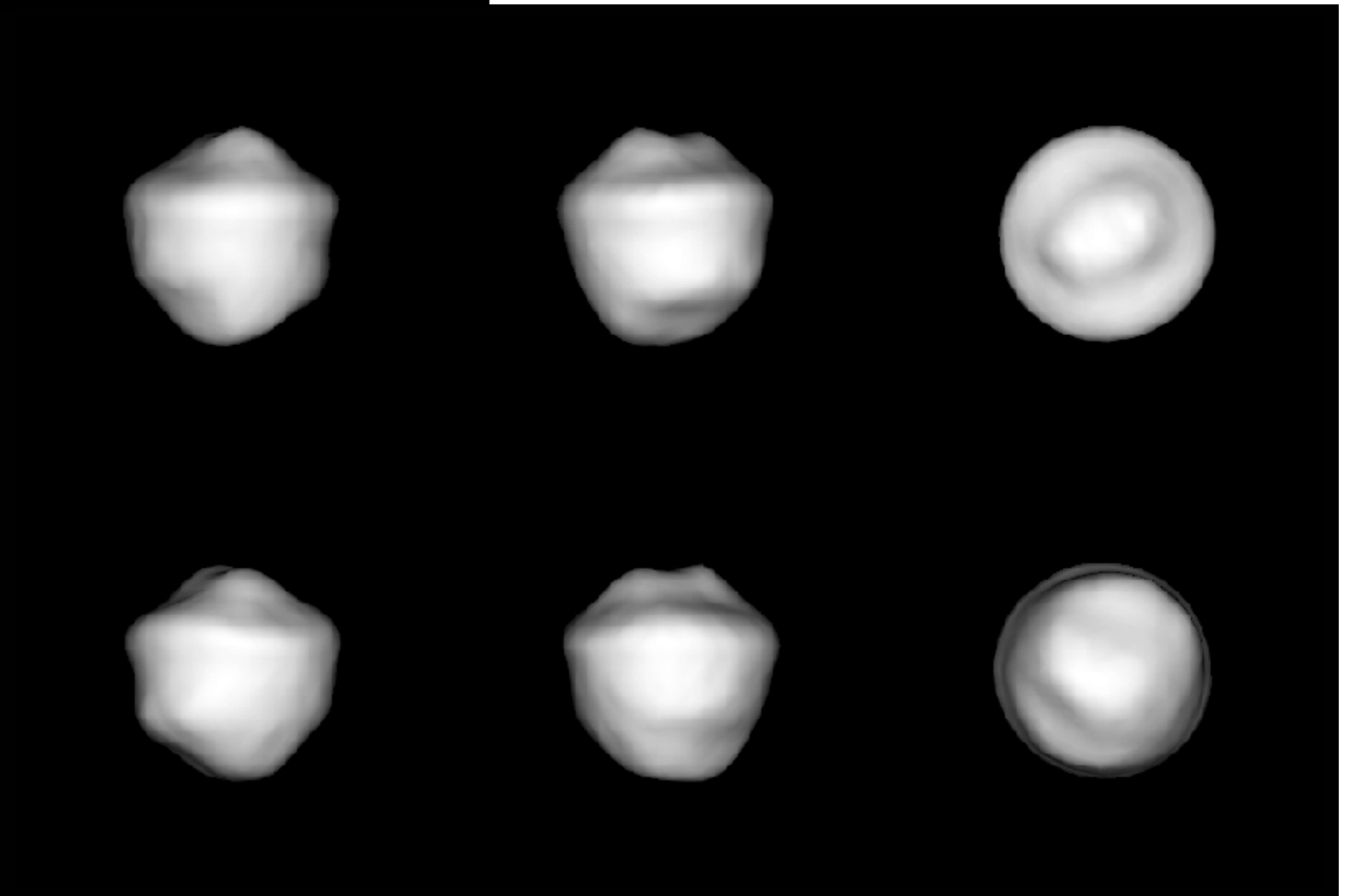
Most precisely measured NEO binary:

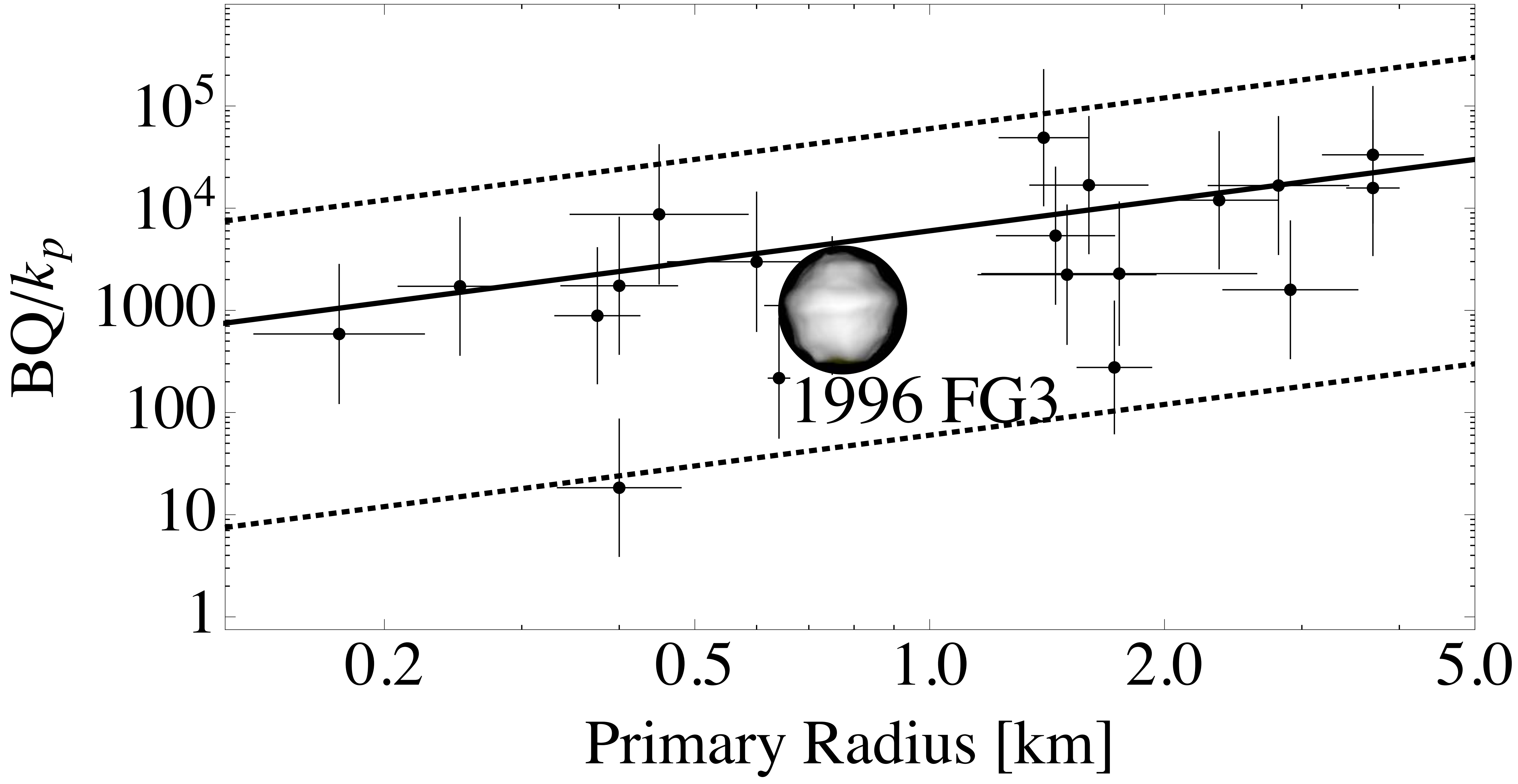
- Primitive C Type: Similar to Ryugu and Bennu in composition and shape
- Lies in a Binary YORP — Tide equilibrium: extremely stable and predictable orbit
- Measurement of BYORP coefficient from thermal modeling and observations will enable constraints on Q/k_p for a rubble pile

Secondary



Primary

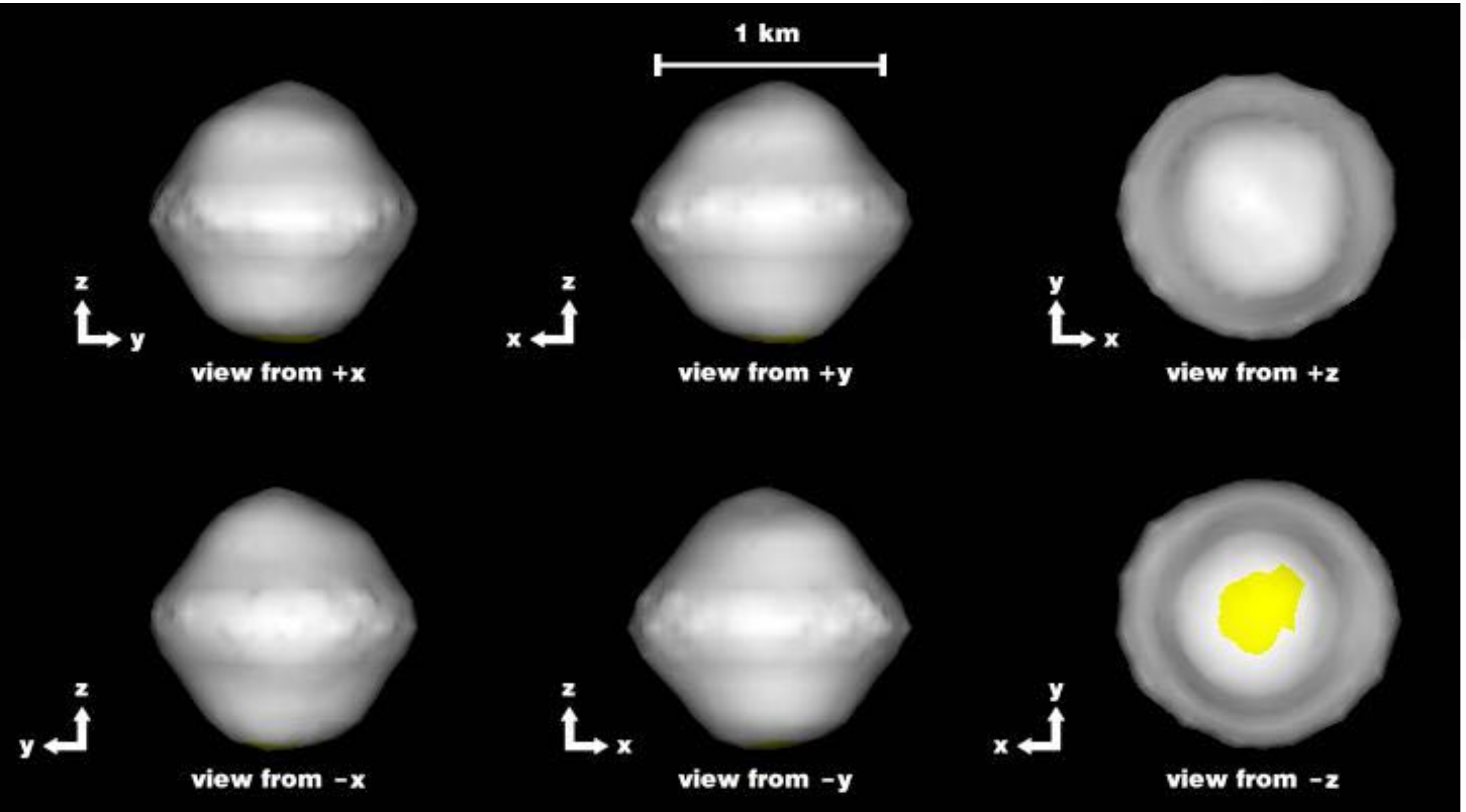


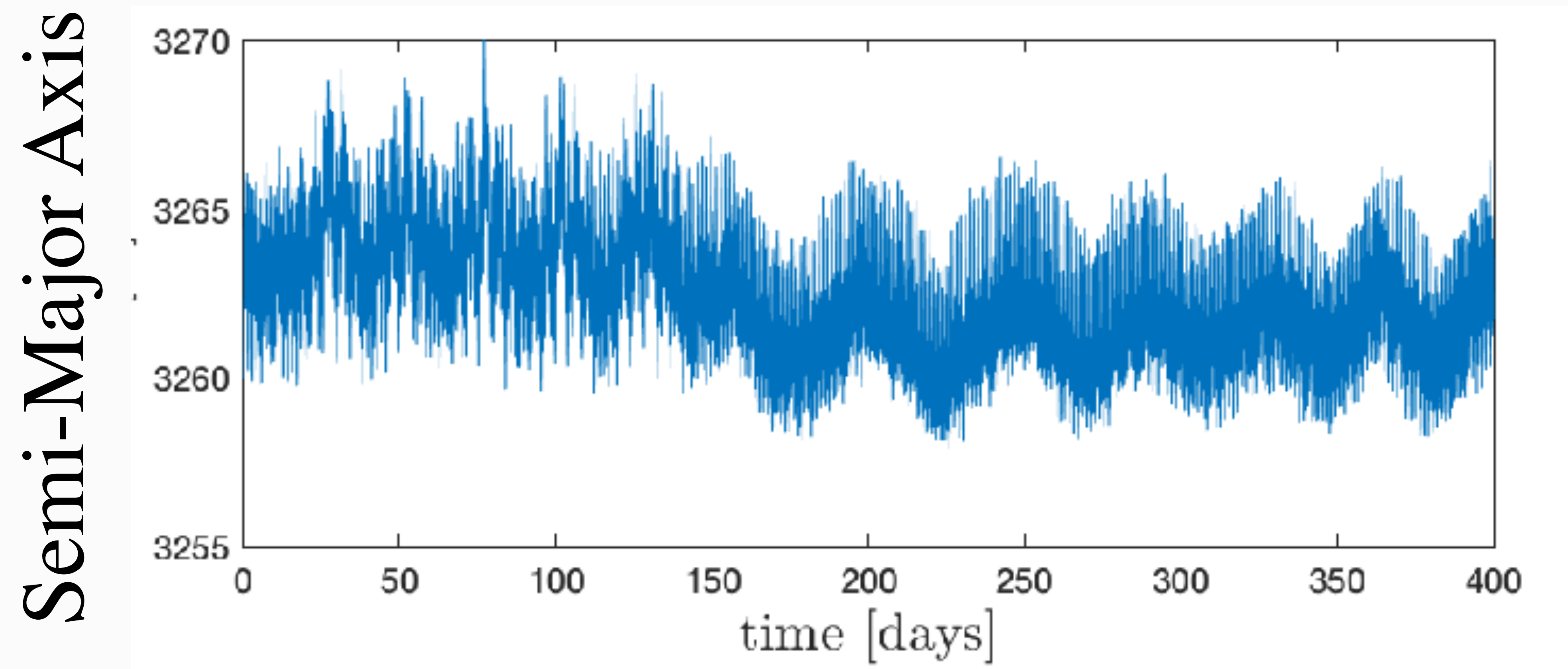


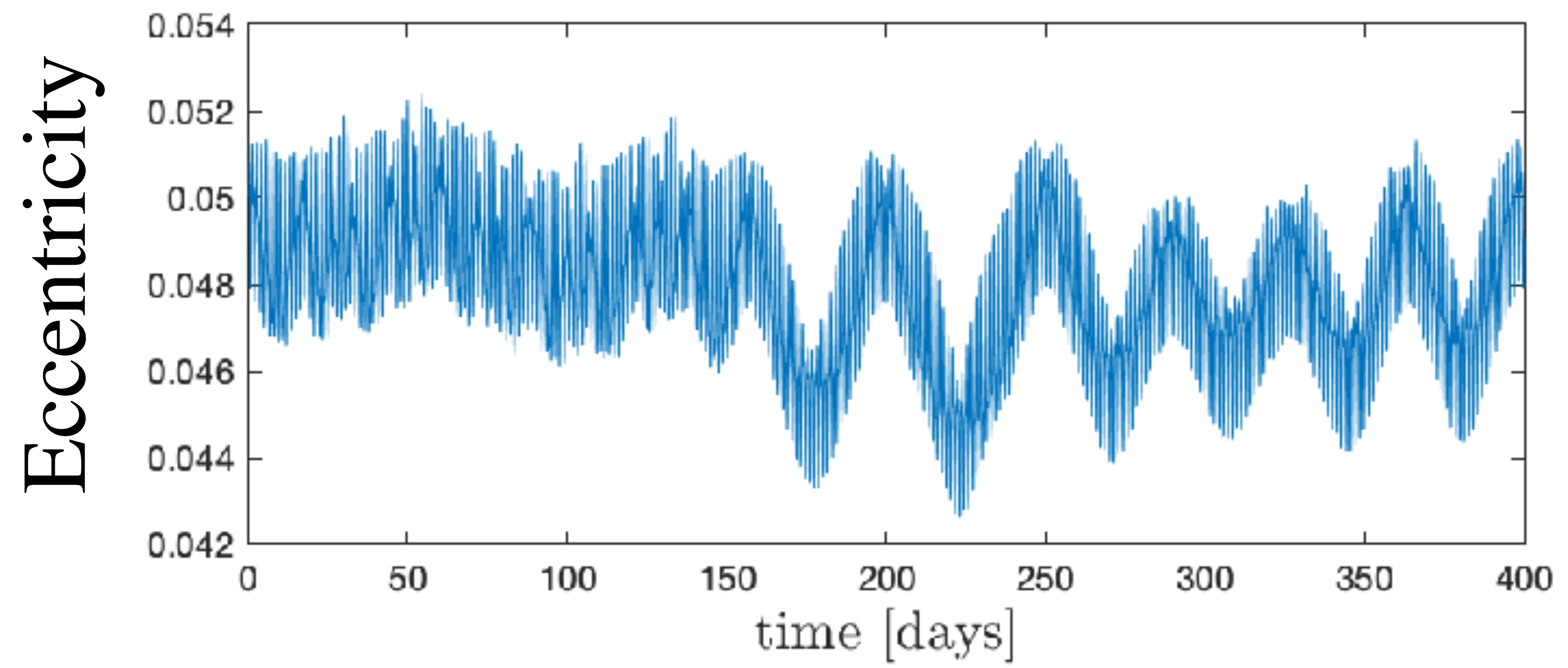
Goal II, SO4: Asteroid (35107) 1991 VH

Asynchronous binary — secondary is in a chaotic spin state
S Type binary asteroid — why do both FG3 and VH look the same?
Complex spin state provides an opportunity to constrain the secondary inertia tensor
Observations can test theories for its excited state.

Primary model (still in development)
Secondary model constrained only





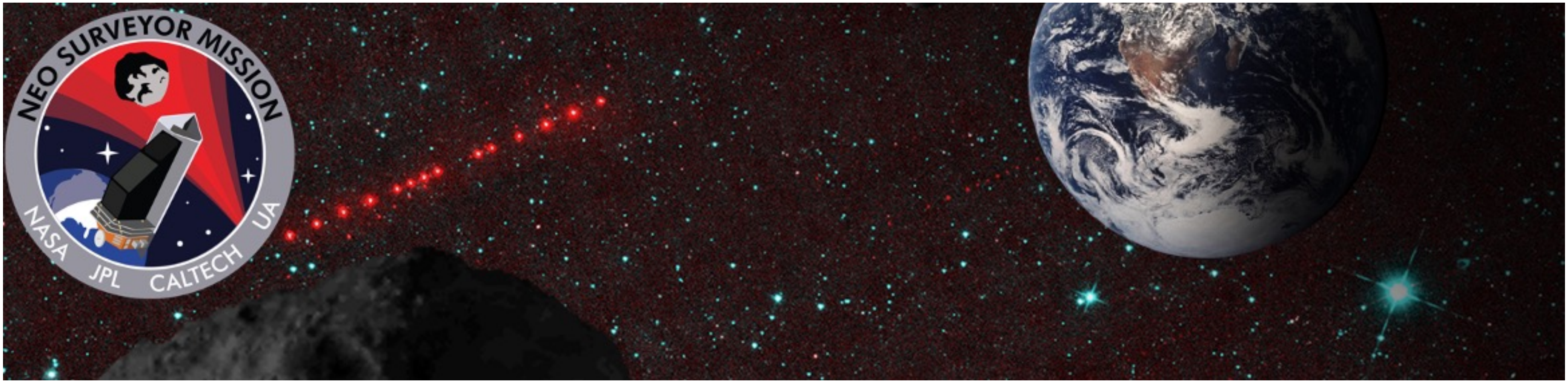


Janus Summary

- ***Janus*** will provide the first high resolution, scientific observations of NEO binary asteroid systems that have significant diversity
- ***Janus*** can provide insight into the mechanics of rubble pile bodies, and into microgravity geophysical processes in general
- ***Janus*** defines a new S/C and mission profile that can provide a responsive scientific and planetary defense capability for NEO characterization
- ***Janus*** has passed PDR and is confirmed by NASA!
- ***Janus*** is ready and able to serve as an inaugural member of NASA's SIMPLEx Program

UNIVERSITY OF COLORADO • NASA • LOCKHEED MARTIN

Janus



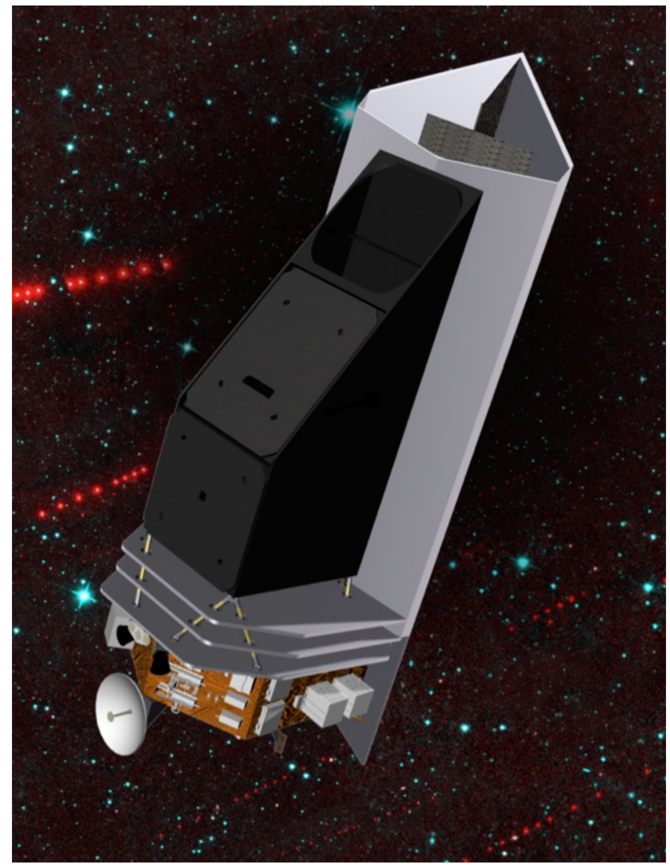
NEO Surveyor Cadence and Simulations

S. Sonnett (Planetary Science Institute)

A. Mainzer (U of Arizona), T. Grav (U of Arizona), E. Lilly (PSI),
T. Spahr (NEO Sciences), J. Masiero (IPAC/Caltech)

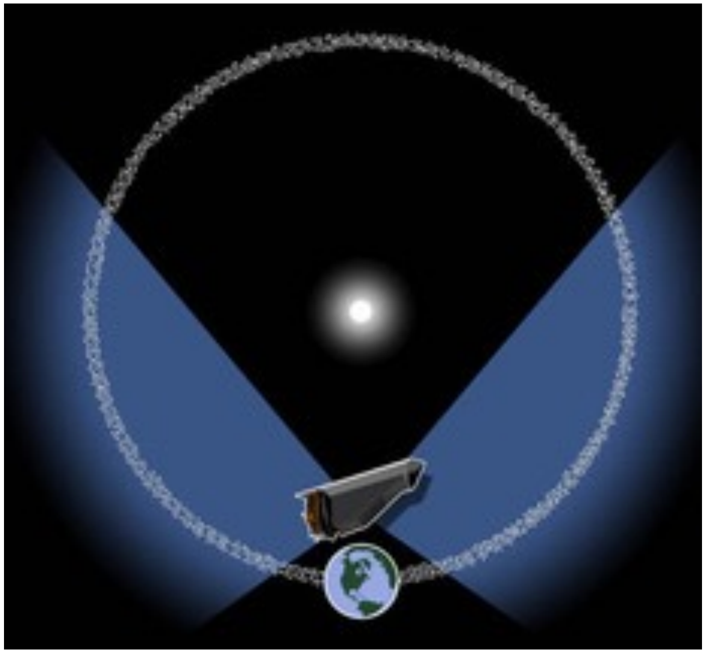
What is NEO Surveyor?

- 50-cm telescope going to L1
- 2 infrared chips imaging simultaneously
  - ~4-5.2 microns & ~6-10 microns
- Nominal launch 2026
- Objectives: discover, track, and characterize hazardous Near-Earth Objects > 140m
- Passively cooled (no cryogen)
- Led by PDCO, A. Mainzer as survey director
- Images & photometry will be publicly available through IRSA every ~6 months



Nominal Survey Region & Pattern

- 5-year survey planned, longer possible
- Nominal scanned field-of-regard:
  - ± 40° ecliptic latitude
  - 45-120° solar elongation
- ~11 days to complete scan cycle
- ~4 asteroid detections within ~8 hours, then another "quad" ~11 days later
- All discoveries will receive self-follow up
- Interruptions possible for particularly challenging targets of opportunity



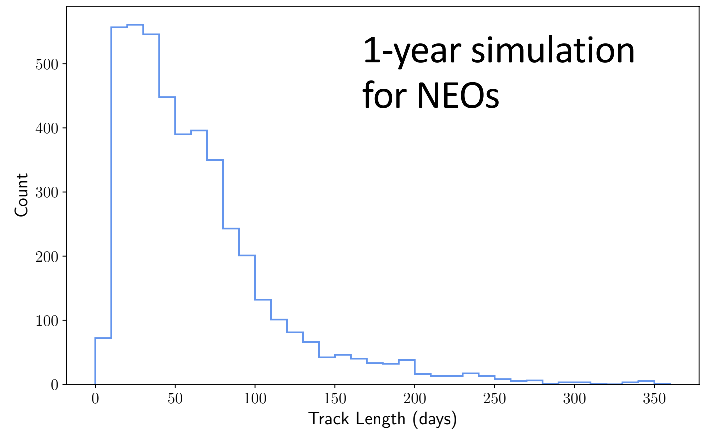
When do we consider an object recovered?

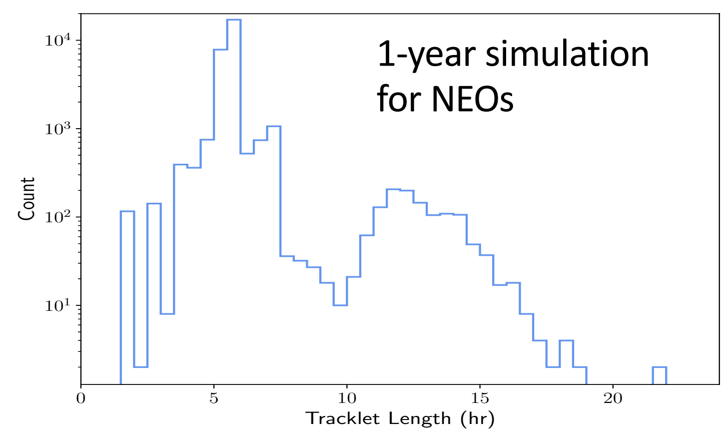
At least 4 viable detections +
<= 12 hours between pairs =
tracklet

At least 2 tracklets +
>= 12 hours apart in time +
no more than a 30-day gap between tracklets =
track, at which point an object is considered "recovered"

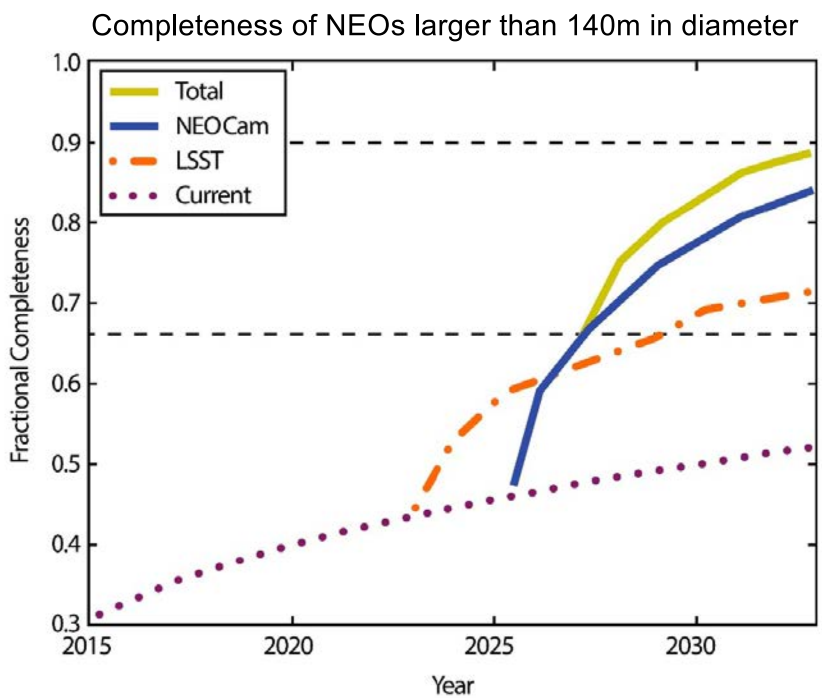
Simulating the survey for NEOs

- Simulator purpose:
  - Evaluate survey efficiency
  - Optimize survey design
  - Help debias
- User defines field of regard, hardware properties, sensitivity, overheads, etc.
- Transferrability: spacecraft, survey, and telescope properties defined external to pipeline.

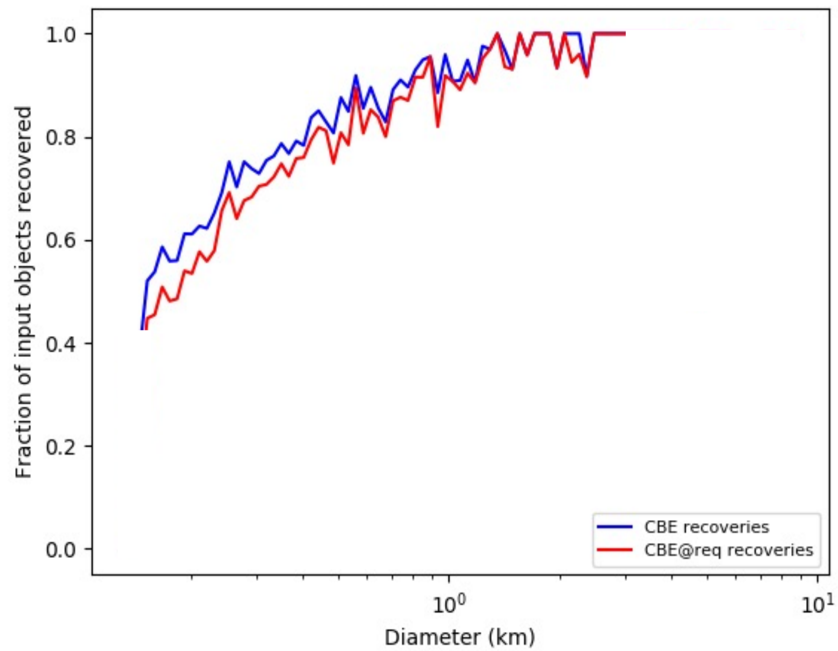




Completeness for the NEO & PHA populations



We will recover 2/3 of PHAs ~2 years into the survey; more if efforts are combined with the Vera Rubin Observatory



Smaller & more distant (colder) objects are harder to detect

Preliminary Results from the Simulator

- ~300,000 NEOs (currently ~25,000 known)
- ~10,000 comets (currently ~7,000 known)
- Millions of MBAs (currently ~900,000 known)
- ~75% of NEOs ≥ 140m in diameter in first 5 years, ~85% in 10 years
- ~80% of PHAs in first 5 years, ~92% in 10 years
- Likely better orbital, physical, and rotational characterization of previous discoveries in an extended mission
- Completeness is higher if combined with another sensitive ground-based survey like Vera Rubin

Risk-Informed Spacecraft Mission Design for the 2021 PDC Hypothetical Asteroid Impact Scenario

Presented to the 7th IAA Planetary Defense Conference

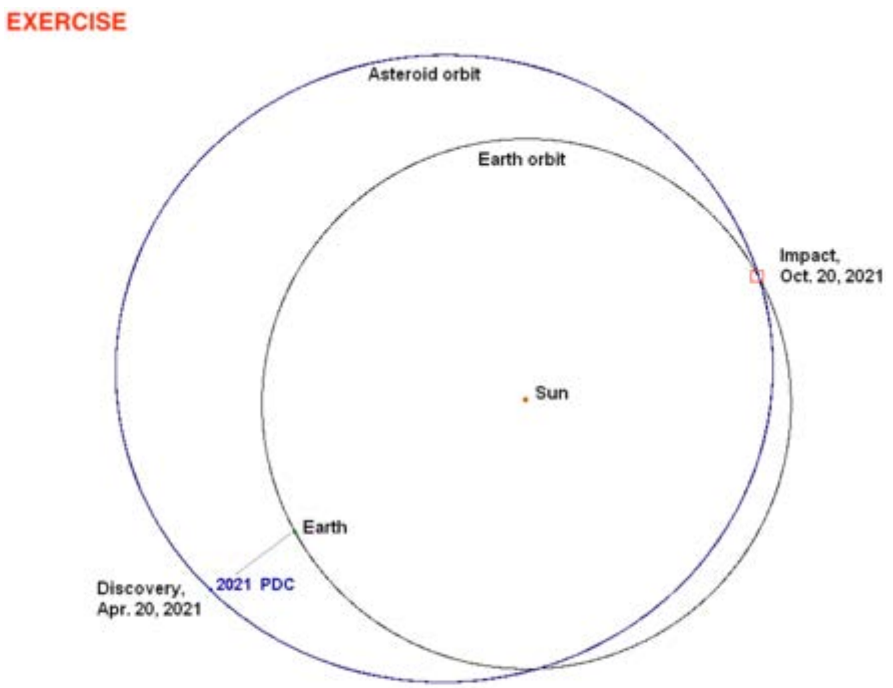
April 28, 2021

Brent Barbee (NASA/GSFC)
Bill Benson (NASA/KSC)
Paul Chodas (CNEOS/JPL/CalTech)
Jessie Dotson (NASA/ARC)
Joshua Lyzhoft (NASA/GSFC)
Miguel Benayas Penas (NASA/GSFC)
Javier Roa (CNEOS/JPL/CalTech)
Bruno Sarli (NASA/GSFC)
Lorien Wheeler (NASA/ARC)

2021 PDC Hypothetical Asteroid Overview

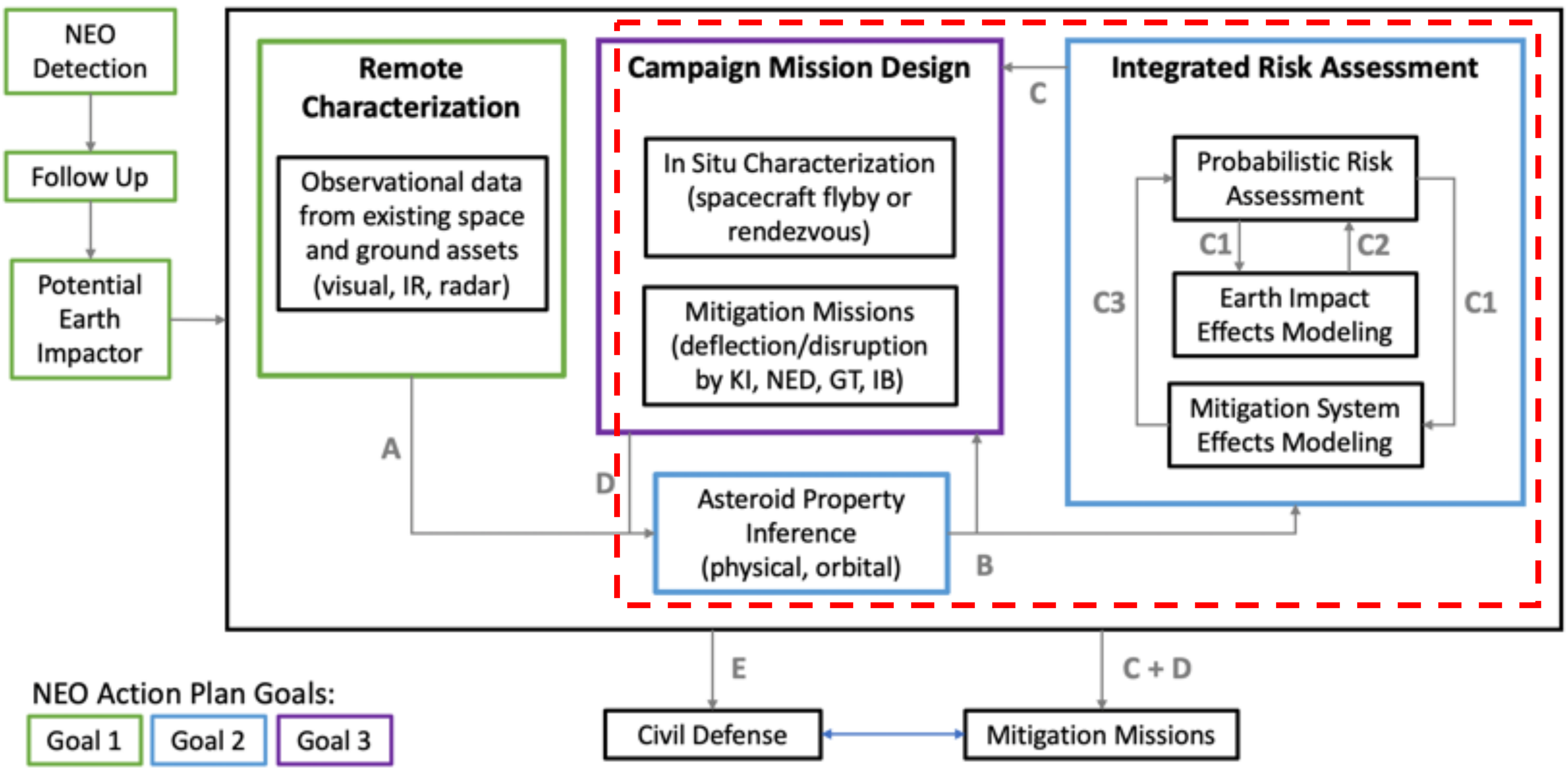
https://cneos.jpl.nasa.gov/pd/cs/pdc21/

- Scenario developed by CNEOS/JPL/CalTech: Paul Chodas.
- Discovery: 2021-04-19.
- Potential Earth impact: 2021-10-20.
  - Only 6 months after discovery.
- 2021 PDC's physical properties are unknown:
  - Absolute (intrinsic) magnitude estimate: H = 22.4 ± 0.3 (1σ).
  - The asteroid's size could range from ~35 meters to ~700 meters – significant size uncertainty.
  - If the asteroid's albedo (reflectivity) is 13%, a typical mean value, then its size would be 120 meters.
- 2021 PDC's orbit has eccentricity of 0.27 and an inclination of 16°. Its orbit semi-major axis is 1.26 au, giving it an orbit period of 1.41 years.
- **Deflection is not practical in this scenario because it would require too much ΔV be imparted to the asteroid, and too far in advance of Earth encounter. Therefore, nuclear disruption approach must be taken.**



Risk-Informed Mission Design Process Summary

We are exercising portions of our planned risk-informed mission design process:
- **NEO properties uncertainties drive mitigation mission effectiveness uncertainties.**
- **Mitigation mission performance included in damage risk model outputs.**



Mission Design Parameters and Constraints

- NEO diameter and density distributions are used to compute statistics for NED yield required for robust disruption of the NEO.
- We use an approximate model for DV imparted to an NEO by a standoff NED, along with the heuristic of robust disruption being achieved if the imparted DV is at least 10x the NEO's surface escape velocity.
  - However, in practice a detailed analysis is required for the specific scenario at hand.
- We consider NEO properties distributions for NED yield requirements and impact damage risk assessments before & after the inclusion of NEOWISE observations, which are modeled to occur partway through the scenario.
- Missions could not actually be launched on such short notice using current infrastructure/capabilities, but here we will examine what could be done **if** rapid spacecraft launch were possible.
- We use a launch performance model for a re-purposed commercial intermediate class launch vehicle with a STAR-48BV kickstage, able to handle declination of launch asymptote (DLA) >28.5° for Cape Canaveral Air Force Station (CCAFS) launches.
- The earliest launch date considered is 2021-05-01 (11 days post-discovery) and the latest arrival date considered is 2021-09-20 (30 days pre-Earth encounter).
- Ballistic and solar electric low-thrust propulsion (NEXT-C and XIPS25) are considered, both with the objective function of maximizing delivered spacecraft mass.

NED Yields & Masses Required for NEO Disruption

NEOWISE observations significantly reduce the spread of NED requirements for NEO disruption, but not enough to make confident predictions of disruption effectiveness.

NED Yields & Masses Required for Disruption - Before NEOWISE Observations

	1σ NEOs	2σ NEOs	3σ NEOs	Outlier NEOs
Minimum	3.3 KT, 1.8 kg	0.3 KT, 0.17 kg	18.6 KT, 10.3 kg	0.116 MT, 65 kg
Median	0.61 MT, 340 kg	27 MT, 15000 kg	848 MT, 470000 kg	31 MT, 17000 kg
Mean	3.2 MT, 1800 kg	100 MT, 55000 kg	2000 MT, 1060000 kg	7000 MT, 3600000 kg
Maximum	52 MT, 29000 kg	1800 MT, 1000000 kg	35000 MT, 19000000 kg	226000 MT), 126000000 kg

NED Yields & Masses Required for Disruption - After NEOWISE Observations

	1σ NEOs	2σ NEOs	3σ NEOs	Outlier NEOs
Minimum	13.3 KT, 7.4 kg	0.3 KT, 0.17 kg	18.6 KT, 10.3 kg	0.116 MT, 65 kg
Median	0.52 MT, 300 kg	22 MT, 12000 kg	134 MT, 75000 kg	22 MT, 12000 kg
Mean	1.8 MT, 1000 kg	42 MT, 23000 kg	263 MT, 146000 kg	320 MT, 178000 kg
Maximum	24 MT, 13000 kg	400 MT, 221000 kg	5000 MT, 2700000 kg	12000 MT, 6500000 kg

Summary of Mission Options

- Rendezvous missions are impractical.
- The flight times are too short for low-thrust propulsion to make a significant difference in delivered NED performance.
- Flyby recon missions delivering ~800-900 kg recon spacecraft are available with earlier launch & arrival dates.
- The deliverable NED yield is ~4.3 to ~4.5 MT.
- The largest size asteroid that can be disrupted ranges from ~100 m to ~210 m, for asteroid densities ranging from 5 g/cm^3 down to 1 g/cm^3.

	Flyby			Rendezvous		
	NEXT-C	XIPS-25	Ballistic	NEXT-C	XIPS-25	Ballistic/Chemical
Launch Date (Days After Discovery)	2021-06-15 (X)	2021-06-10 (X)	2021-06-14 (X)	2021-05-01 (12)	2021-05-01 (12)	2021-05-01 (12)
Flight Time (Days)	97	101	98	142	142	142
Arrival Date (Days Before Earth Encounter)	2021-09-20 (30)	2021-09-20 (30)	2021-09-20 (30)	2021-09-20 (30)	2021-09-20 (30)	2021-09-20 (30)
C3 (km^2/s^2)	25.5	22.5	27.8	100	100	43.5
DLA (degrees)	38	38		38	38	56.5
Asteroid-Relative Intercept Speed (km/s)	11	10.9	10.7	-	-	-
Sun Phase Angle (degrees)	125.2	125.3	125.9	-	-	-
Launch Mass (kg)	2945	3143	2787	210	450	1870
Total Delivered Mass (kg)	2912	3073	2787	158	344	179
Delivered NED Mass (kg)	2402	2493	2384	-	-	-
Delivered NED Yield (MT)	4.3	4.5	4.3	-	-	-
Max. Disruptable Asteroid Size (m) w/ density 1 g/cm^3	211	212	211	-	-	-
Max. Disruptable Asteroid Size (m) w/ density 1.5 g/cm^3	174	175	173	-	-	-
Max. Disruptable Asteroid Size (m) w/ density 2.5 g/cm^3	136	137	135	-	-	-
Max. Disruptable Asteroid Size (m) w/ density 5 g/cm^3	97	98	97	-	-	-

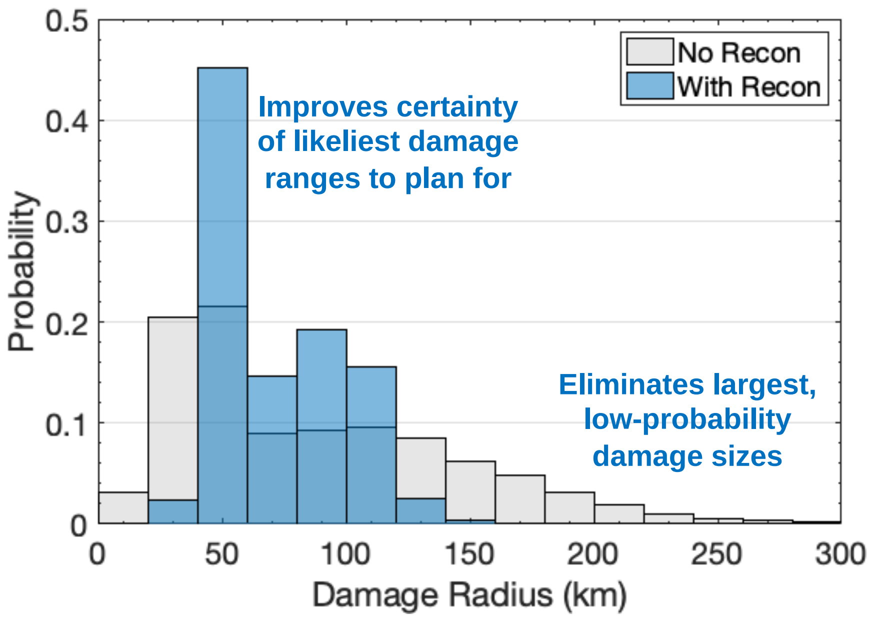
Recon Mission Benefits for Disaster Planning

How much could a hypothetical recon mission refine damage area estimates?

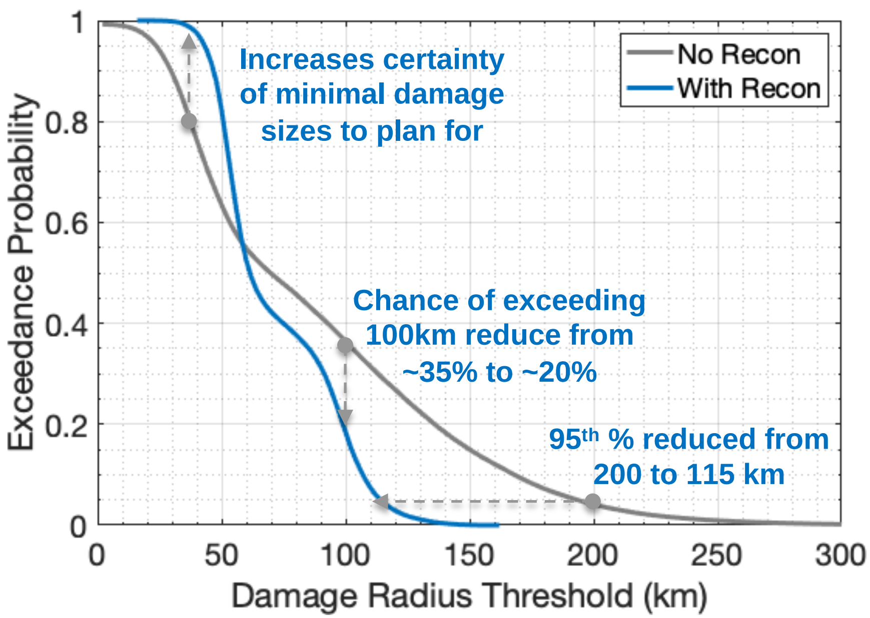
Assuming recon could determine diameter to within 10% for a median-sized 118 m object:

- Asteroid diameter range reduced to 118±12 m (~106–130 m vs 30–700 m without recon)
- Substantially narrows range of potential damage areas for disaster response and improves confidence in likeliest damage areas to plan for
- Reduces maximum potential radius from ~470 km to ~160 km

Damage radius risk histogram: Probabilities of damage radii within each range



Damage radius exceedance risk: Probability of damage radii being *at least* the given size *or larger*



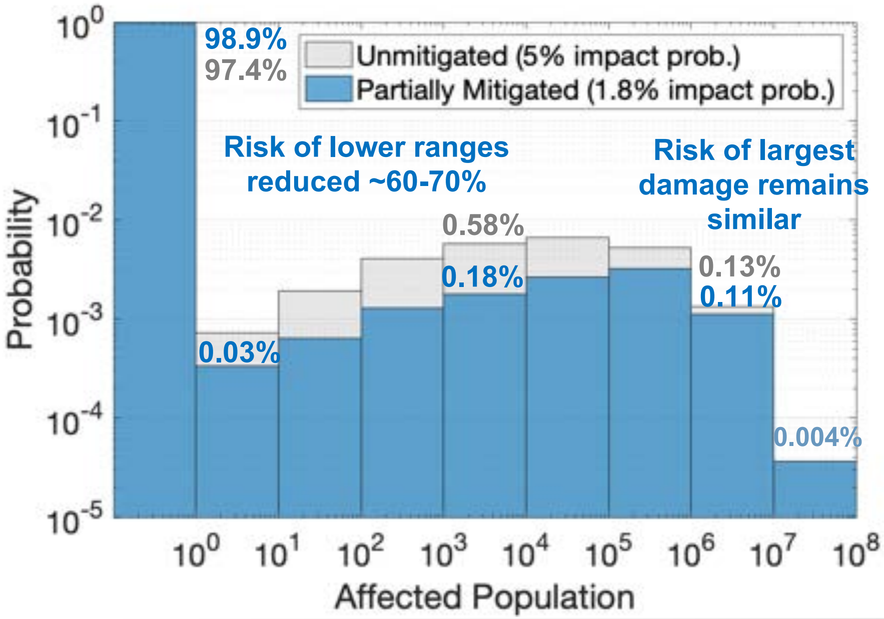
Hypothetical Risk Mitigation

How much could a hypothetical NED mission reduce risk of impact damage?

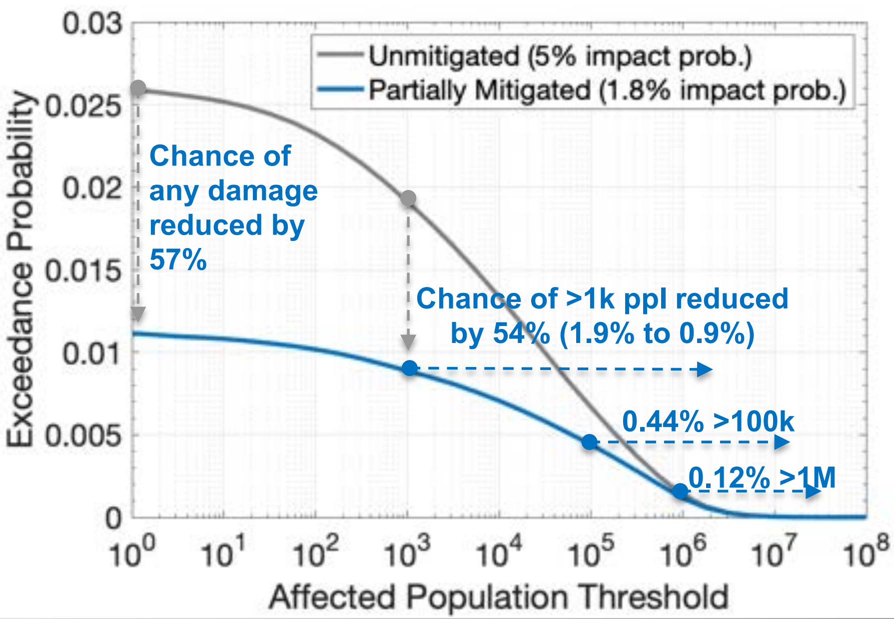
Assuming successful mitigation of all objects under mass/density disruption criteria:

- ~64% of cases successfully mitigated, reducing impact probability from 5% to ~1.8%
- Average affected population reduced by ~20%, from ~5,900 to ~ 4,700
- Chance of damage affecting any population reduced by 57% (from 2.6% to 1.1%).
- Chance of affecting lower population ranges reduced by ~60-70%
- Risk of largest population ranges (>1M or >10M) remains low but similar due to unmitigated largest objects

Population risk histogram: Probabilities of affecting the number of people within each range



Population exceedance risk: Probability of affecting *at least* the given number of people *or more*



Hypothetical Risk Mitigation

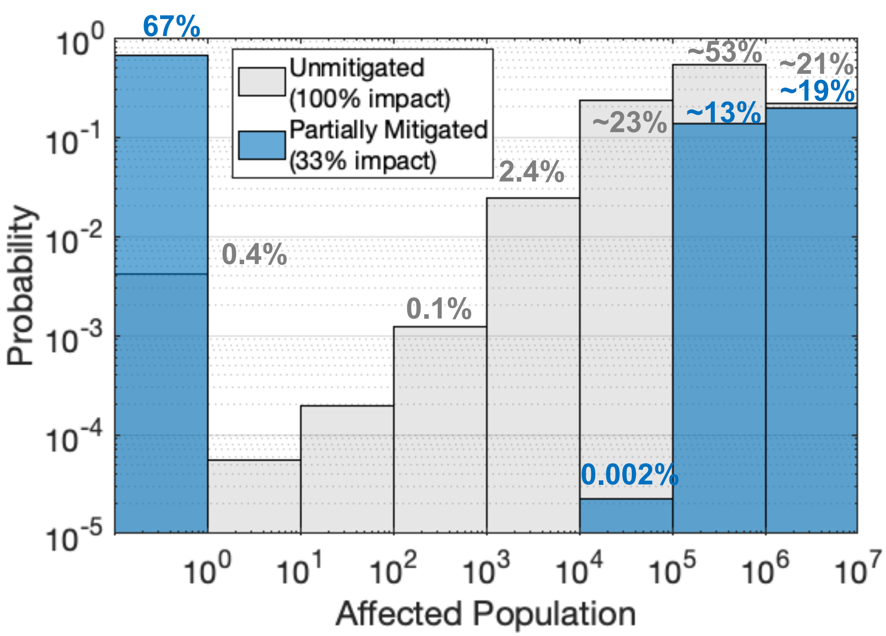
*** After NEOWISE Observations Are Included ***

How much could a hypothetical NED mission reduce risk of impact damage?

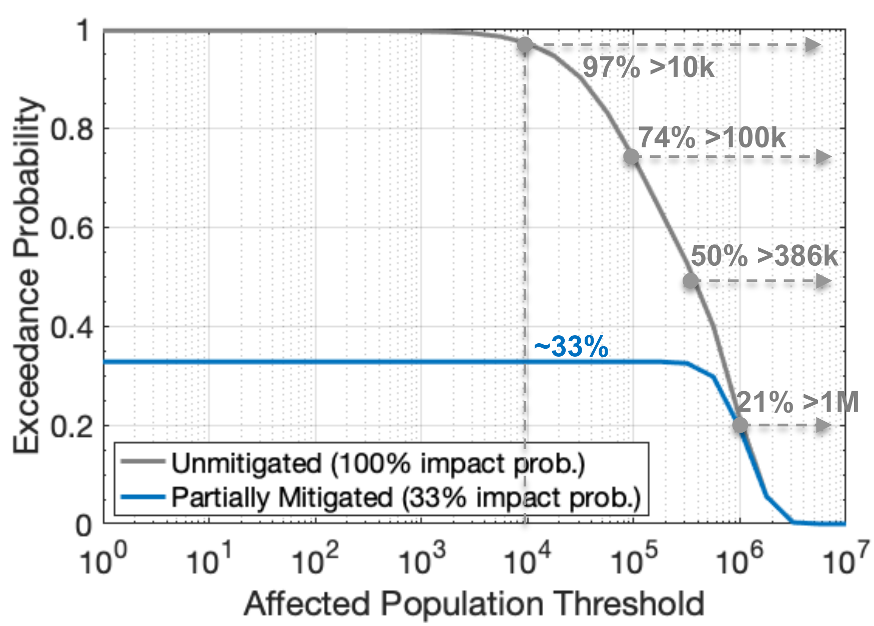
Assuming successful mitigation of all objects under mass/density disruption criteria:

- ~67% of cases successfully mitigated, reducing impact probability from 100% to ~33%
- Average affected population reduced by ~31%, from ~580k to ~400k
- Chance of damage affecting any population reduced from almost 100% to 33%.
- Chance of affecting lower population ranges eliminated
- Risk of largest population damage (>1M) remains ~20% due to unmitigated largest objects

Population risk histogram: Probabilities of affecting the number of people within each range



Population exceedance risk: Probability of affecting *at least* the given number of people *or more*



Outcome of a Disruption Mission

The ~4.5 MT NED carried by the spacecraft is more than enough to robustly disrupt the actual NEO, by a factor of 5.

- Actual NEO physical properties:
  - Diameter: 105 m
  - Density: 2.4 g/cm^3
  - H = 22.2
  - Albedo = 0.21
- The actual NEO should be robustly disrupt-able by a ~0.92 MT NED.

Summary of Findings and Recommendations

- The significant uncertainties in 2021 PDC's physical properties, especially size and mass, make it very difficult to define mitigation mission requirements or assess the likelihood of mitigation mission success.
- Current real-world infrastructure for spacecraft development and launch would not enable us to deploy either reconnaissance or mitigation spacecraft in such a short warning scenario if this were a real situation.
  - Rapid spacecraft launch is a critical element of any rapid reconnaissance or NED disruption mission. Therefore, we recommend that this capability be developed.
- However, **if** rapid launch were possible then the only practically viable mitigation approach would be robust disruption of 2021 PDC via nuclear explosive device (NED).
  - Deflection is not practical in this scenario because it would require too much ΔV be imparted to the NEO, and too far in advance of Earth encounter.
- While rendezvous is generally preferred, the rapid response timeline and inclination of the asteroid's orbit make rendezvous impractical, necessitating flyby missions that encounter the asteroid at high relative speeds and high Sun phase angles.
  - This makes spacecraft guidance, navigation, and control especially challenging.
- **Deploying a nuclear disruption mission appears to be the only realistic mitigation possibility (if launch were possible). It can significantly reduce the risk of impact damage even in the face of substantial uncertainty in the asteroid's properties.**
- **Should a nuclear disruption attempt be foregone, we recommend at least deploying a flyby reconnaissance spacecraft because the data it would provide about the asteroid's properties would significantly reduce the uncertainties faced by disaster response planners.**

HYPOTHETICAL EXERCISE ONLY – INTERNAL DRAFT

Appendices

Remarks on Forward Work

- The lack of rapid response launch systems for planetary defense is a severe capability gap.
  - Recommendation: Rapid response capabilities for planetary defense should be developed and demonstrated.
- The combination of high arrival speeds and high Sun phase angles make terminal GNC challenging and prone to error, especially for smaller NEOs (i.e., below ~300 m size).
  - Recommendation: Study the benefits of thermal infrared (IR) terminal guidance sensors for NEO intercept missions. IR sensors are also better able to ascertain the size and shape of the NEO. Uncooled microbolometers with reasonable pixel pitches are becoming more practical, and Forward Looking IR (FLIR) technology offers some lightweight options that could be assessed for performance in space.
- NEO disruption via NED is the only viable mitigation option in very short warning scenarios. However, the ability of typical NEDs to robustly disrupt NEOs may not be adequate for larger NEOs.
  - Recommendation: NED requirements for NEO disruption should be assessed in more detail, including various types of NEDs as appropriate.

Risk-Informed Mission Design Data Flow

Label Code	Source	Recipients	Data Products
A	Remote Characterization	Asteroid Property Inference	• Astrometry (RA, DEC, time) • Photometry (H, colors, light-curves) • Spectroscopy (taxonomy) • IR (size, albedo) • Radar astrometry (range, Doppler) and radar imaging
B	Asteroid Property Inference	Campaign Mission Design Integrated Risk Assessment	• Orbital Solution (impact probability, impact risk corridor, B-plane coordinates, B-plane deflection partials, covariance matrix, SPK file) • Physical Property Distributions and States (diameter, density, mass, porosity, aerodynamic strength, albedo, taxonomic type, structure, shape, rotation state)
C	Integrated Risk Assessment	Campaign Mission Design Mitigation Mission Response Decisions	• Affected population and damage probabilities • Hazard types and severities • Damage corridor (at-risk regions) • Infrastructure at-risk* • Economic effects* • Risk sensitivities
C1	Probabilistic Risk Assessment	Earth Impact Effects Modeling Mitigation Effects Modeling	• Asteroid properties of high-priority impact cases (prioritized by likelihood, uncertainty, and/or consequence)
C2	Earth Impact Effects Modeling	Probabilistic Risk Assessment	• Specific damage regions for prioritized cases (from C1) • Reduced-order models* for damage regions from each hazard as a function of impactor properties
C3	Mitigation System Effects Modeling	Probabilistic Risk Assessment	• Reduced-order models* for ΔV and/or disruption as a function of (B) • Specific ΔV and/or disruption models for prioritized cases (C1)
D	Campaign Mission Design	Asteroid Property Inference (orbital) Integrated Risk Assessment Mitigation Mission Response Decisions	• Available or needed launch assets (vehicles, sites) • Spacecraft and mitigation system properties • Mission timelines (launch dates, flight times, intercept dates, recon timeframes) • Mitigation requirements (ΔV requirements, disruption requirements)
E	Integrated Risk Assessment	Civil Defense	• Damage region plots for risk percentiles

* Ongoing development

Deflection Is Not Practical

- Deflection ΔV requirements (assuming ideally oriented ΔV vector and a geocentric impact):
  - Computed via the CNEOS NEO Deflection App: https://cneos.jpl.nasa.gov/nda/.
  - 6 months before Earth impact – 25.5 cm/s deflection ΔV required.
  - 5 months before Earth impact – 28.2 cm/s deflection ΔV required.
  - 4 months before Earth impact – 39.6 cm/s deflection ΔV required.
  - 3 months before Earth impact – 65.9 cm/s deflection ΔV required.
- The above values are shown for reference, but intercepting the asteroid earlier than ~3 months before Earth impact is not possible because the asteroid is discovered only 6 months before Earth impact.
- Imparting such large ΔV to the asteroid would be very difficult:
  - If the asteroid were ~130 meter in size with a bulk density of ~1.5 g/cm^3, deflecting it via kinetic impactors would be impractical, requiring launch ~2 weeks after discovery and sending ~294,000 kg worth of kinetic impactors to the asteroid (~37 notional NASA SLS 2B rocket launches); assumes β=1.
  - A ~1 MT NED could impart 65.9 cm/s of ΔV to a ~130 meter size asteroid with a bulk density of ~1.5 g/cm^3, but if the asteroid is larger and/or denser, then a much larger NED yield (and/or different type of NED) would be required.
- Regardless of the foregoing, imparting such large ΔV to the asteroid would almost certainly accidentally fragment it, which is undesirable because that could leave sizeable fragments on Earth collision trajectories.
  - For the range of possible asteroid sizes and bulk densities, the asteroid surface escape velocity could be 1.3 to 45 cm/s.
  - The required deflection ΔV would be ~57% to ~500% of the asteroid's surface escape velocity, depending on the asteroid's size and density, but he threshold for weak disruption is only >10% of asteroid surface escape velocity.

Rapid Launch Capabilities are Not Yet Available

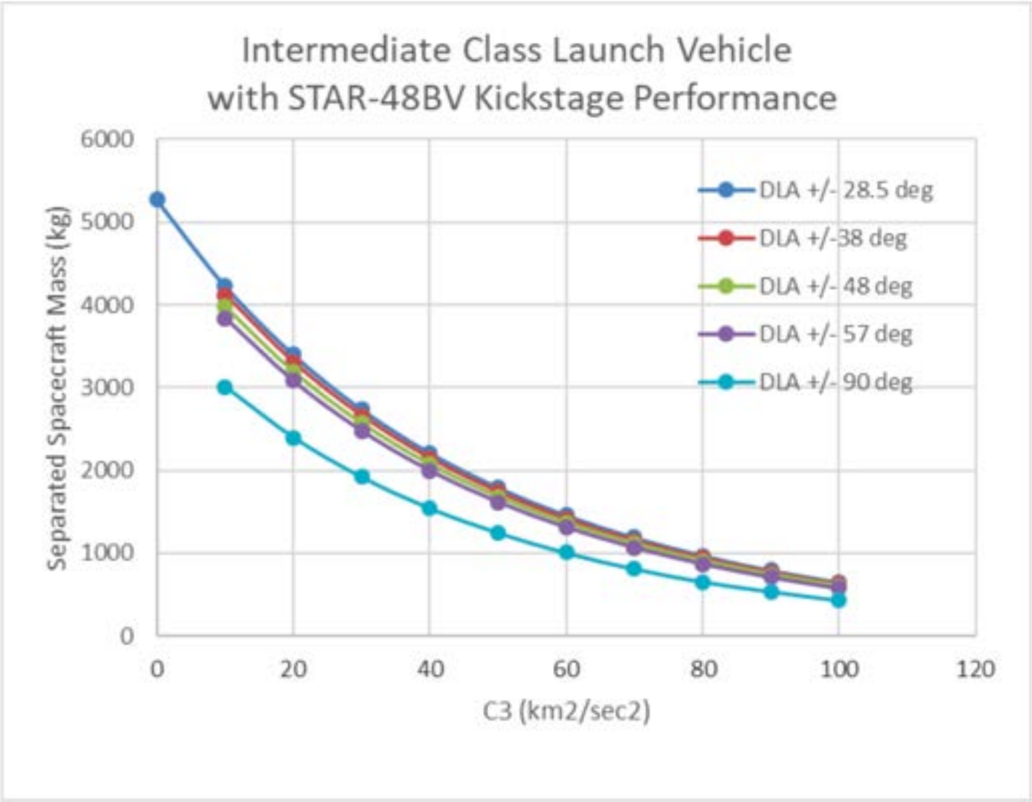
- **Current infrastructure for spacecraft development and launch would not enable us to deploy either reconnaissance or mitigation spacecraft in such a short warning scenario if this were a real situation.**

- Nevertheless, for the sake of discussion only, we will describe space mission options that ***could*** hypothetically be available to decision makers **if** our planetary defense space mission infrastructure were upgraded to enable mission deployment within ~2 to 6 weeks of Authority to Proceed (ATP). **Again, we currently do not have such rapid launch capability.**

- *Our current inability to rapidly deploy reliable and effective planetary defense space missions is a significant capability gap that must be closed in order to become prepared to handle short warning Earth impact threats from asteroids or comets.*

Launch Vehicle Performance

- Launch vehicle is an intermediate class launch vehicle with a STAR-48BV kickstage, able to handle declination of launch asymptote (DLA) >28.5° for Cape Canaveral Air Force Station (CCAFS) launches.
  - Launch vehicle performance data provided by NASA/KSC: Bill Benson.
  - The amount of time required to prepare such a vehicle for launch during a rapid response planetary defense scenario is currently unknown but is being analyzed.



Please direct any questions regarding this performance assessment to:

William Benson
NASA Launch Services Program
Phone: 321-867-9455
Email: William.W.Benson@nasa.gov

Intermediate Launch Vehicle w/Kickstage High Energy Performance to various DLAs

C3	DLA = 28.5	DLA = 38	DLA = 48	DLA = 57	DLA = 90
10	4230	4115	3975	3840	3010
20	3400	3305	3190	3080	2395
30	2735	2660	2570	2475	1920
40	2210	2150	2075	2000	1540
50	1790	1740	1680	1620	1245
60	1455	1415	1365	1315	1005
70	1190	1150	1110	1070	815
80	970	940	905	870	655
90	790	765	735	710	540
100	645	625	600	575	430

*Due to range safety considerations, assume DLA = 90 performance for all DLA's higher than 57 deg

Please direct any questions regarding this performance assessment to:

William Benson
NASA Launch Services Program
Phone: 321-867-9455
Email: William.W.Benson@nasa.gov

Launch Vehicle Ground Rules / Assumptions

- 3-sigma guidance reserves.
- Instantaneous launch attempt. Finite window accommodations may significantly reduce performance for missions with inertially fixed targets.
- STAR-48BV-based kickstage is assumed. All masses required to make this a complete stage such as separation systems, vehicle adapters, avionics, attitude control systems, etc. have been accounted for in this performance quote. Note that this is a non-standard service that will incur additional cost and risk.
- 2 payload fairing doors.
- Payload mass greater than 700 kg may require heavier 3rd stage structural masses than that assumed in this performance quote, resulting in performance impacts.
- 160 km (86 nmi) park orbit perigee altitude.
- This performance does not include the effects of orbital debris compliance, which must be evaluated on a mission-specific basis. This could result in a significant performance impact for missions in which launch vehicle hardware remains in Earth orbit.
- Trajectories for DLA's higher than 57 degrees may require modification to be compliant with range safety requirements, resulting in performance impacts.
- Launch from SLC-40 at CCAFS (Cape Canaveral Air Force Station).

Please direct any questions regarding this performance assessment to:

William Benson
NASA Launch Services Program
Phone: 321-867-9455
Email: William.W.Benson@nasa.gov

Mission Design Constraints and Assumptions

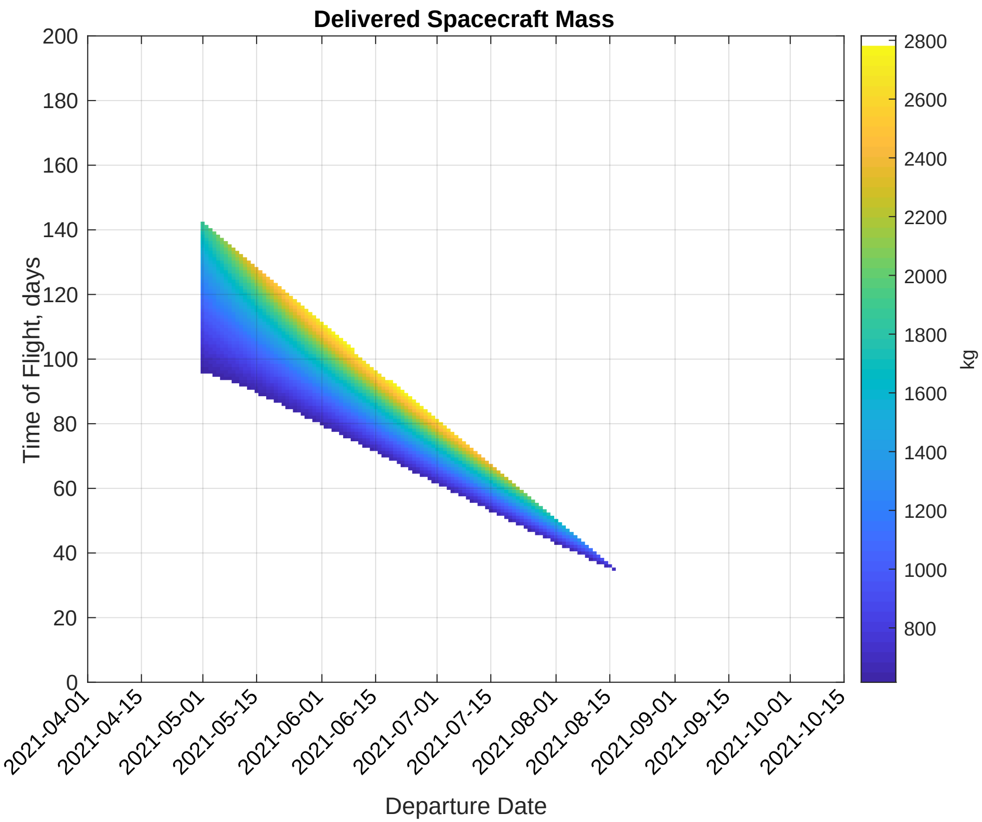
- Launch no earlier than 2021-05-01 (12 days after discovery).
- Reach the 2021 PDC asteroid no later than 2021-09-20 (1 month before Earth encounter).
  - If a mission to disrupt the asteroid is deployed, this provides at least 1 month for the disrupted asteroid material to spread out and avoid interaction with Earth or Earth/Moon-orbiting assets.
    - Further studies are required to better understand the actual timing requirements associated with asteroid disruption.
    - In a real situation, detailed analysis and modeling of the specific scenario at hand would be required (and would be limited by the data available on the NEO).
    - The disruption impulse may be applied along the optimal deflection direction to optimize the dispersion of the disrupted asteroid material.
- No constraint on declination of launch asymptote (DLA).
  - NASA/KSC has provided preliminary performance estimates for launch with DLA up to ±90° from Cape Canaveral Air Force Station (CCAFS).
- No constraint on asteroid-relative speed for flyby missions.
  - However, the higher the flyby speed, the higher the probability of mission failure.
- No constraint on Sun phase angle @ flyby/rendezvous.
  - However, the higher the phase angle, the higher the probability of mission failure.
- Sun-Earth-Spacecraft (SES) angle @ flyby/rendezvous ≥3°.
  - Ensures a viable radio link is available with the Deep Space Network (DSN) antennas.
- Spacecraft trajectory optimization seeks to maximize the amount of spacecraft mass delivered to the asteroid, subject to the above constraints.

Spacecraft Assumptions

- We assume using the components of a DART-like spacecraft for purposes of estimating spacecraft mass and modeling low-thrust solar electric propulsion (SEP) system performance.
- The spacecraft components would have to be arranged around the NED payload, but the mechanical design of the spacecraft is beyond the scope of this study. This should be considered in future work.
- We also consider three spacecraft configurations:
  - DART-like, but flying ballistic trajectories using conventional chemical propulsion. (storable hypergolic bipropellant with a specific impulse (Isp) of 310 seconds for the rendezvous analysis) and not carrying the low-thrust propulsion system hardware.
  - DART-like, using the nominal DART propulsion system (NEXT-C ion engine).
  - DART-like, but using off-the-shelf commercial propulsion (XIPS-25 ion engine) and with more solar array power.
- For nuclear missions (deflection or disruption), we assume the DART-like spacecraft will carry as large a nuclear explosive device (NED) as possible, given the spacecraft mass and the delivered mass capability of the trajectory solution.
  - For computing NED yield / mass, we use the heuristic of 1.8 KT/kg provided by Los Alamos National Laboratory (LANL).

Delivered Spacecraft Mass for Flybys

- The launch date to maximize ballistic flyby delivered mass is 2021-06-14.
  - 2787 kg delivered mass, arrival phase angle 125.9°, arrival speed 10.7 km/s.
- Later launches are possible, but delivered mass performance falls off rapidly and arrival speeds increase
  - Launch 2021-07-01: 2662 kg delivered mass, arrival phase angle 123.4°, arrival speed 12.2 km/s.
  - Launch 2021-07-15: 2372 kg delivered mass, arrival phase angle 121.4°, arrival speed 13.5 km/s.
- Low-thrust propulsion can improve flyby delivered mass only slightly, due to the very short flight times. The trends in launch dates, etc., are very similar to the trends in ballistic mission options.



- Terminal GNC may be challenging if the asteroid's size is much less than ~300 m.

Representative scenario cases for simulations.

Case	V_∞ (km/s)	Phase angle (deg)
1	7.5	30
2	7.5	80
3	12.5	140
4	20	5

Probability of asteroid impact.

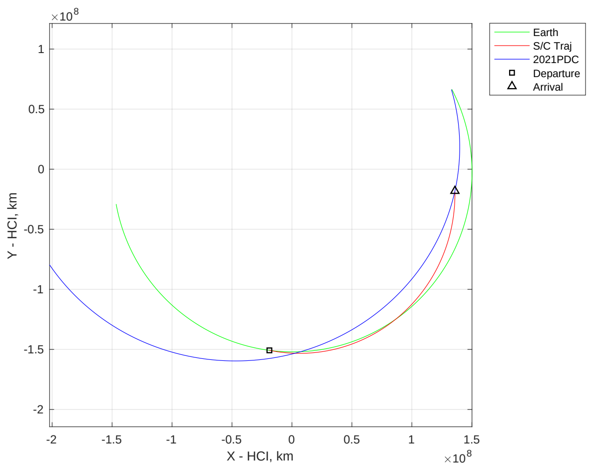
Case	Stellar reference		SSIRU	
	100 m (%)	300 m (%)	100 m (%)	300 m (%)
1	98.8	100.0	85.5	100.0
2	96.5	100.0	73.8	99.2
3	56.6	99.4	53.8	90.6
4	100.0	100.0	75.4	99.6

Tables from: Bhaskaran & Kennedy (2014). Closed loop terminal guidance navigation for a kinetic impactor spacecraft. *Acta Astronautica* 103, 322-332.

Maximum Delivered Spacecraft Mass - Flyby

Ballistic

Chemical propulsion

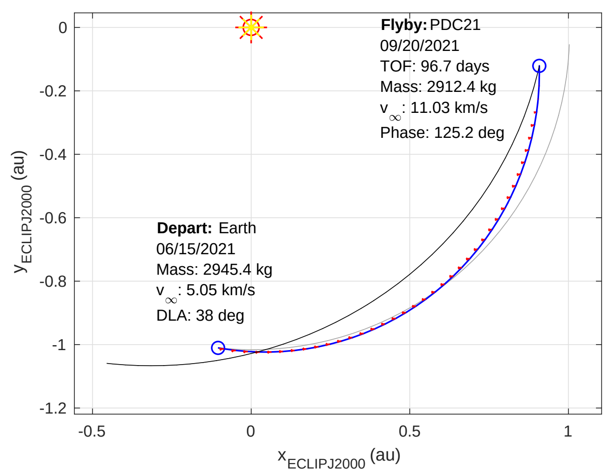


Ballistic analysis by NASA/GSFC:
Brent Barbee

Departure Date	2021-06-14
TOF (days)	98.0
Arrival Date	2021-09-20
Mass Delivered to asteroid (kg)	2787.1
Phase angle @ Intercept	125.9°
Rel. Speed @ Intercept (km/s)	10.73
Departure C3 (km^2/s^2)	27.764
Declination of Launch Asymp., DLA	39.79°

NEXT-C Propulsion (similar to DART)

Low-thrust solar electric propulsion

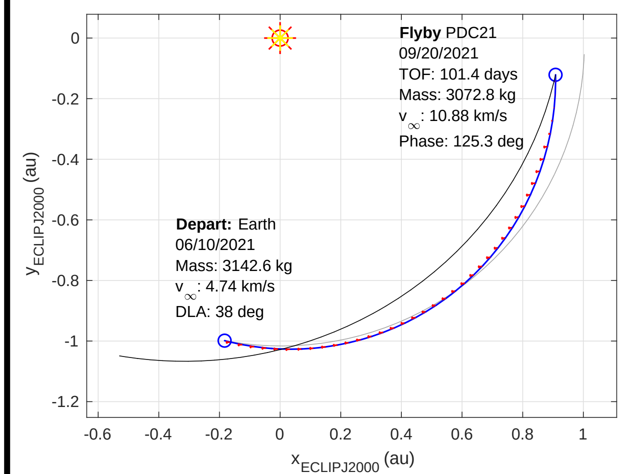


Low-thrust analysis by CNEOS/JPL/CalTech:
Javier Roa

Departure Date	2021-06-15
TOF (days)	96.7
Arrival Date	2021-09-20
Mass Delivered to asteroid (kg)	2912.4 kg
Phase angle @ Intercept	125.2°
Rel. Speed @ Intercept (km/s)	11.03
Departure C3 (km^2/s^2)	25.503
Declination of Launch Asymp., DLA	38.00°

XIPS25 Propulsion

Low-thrust solar electric propulsion



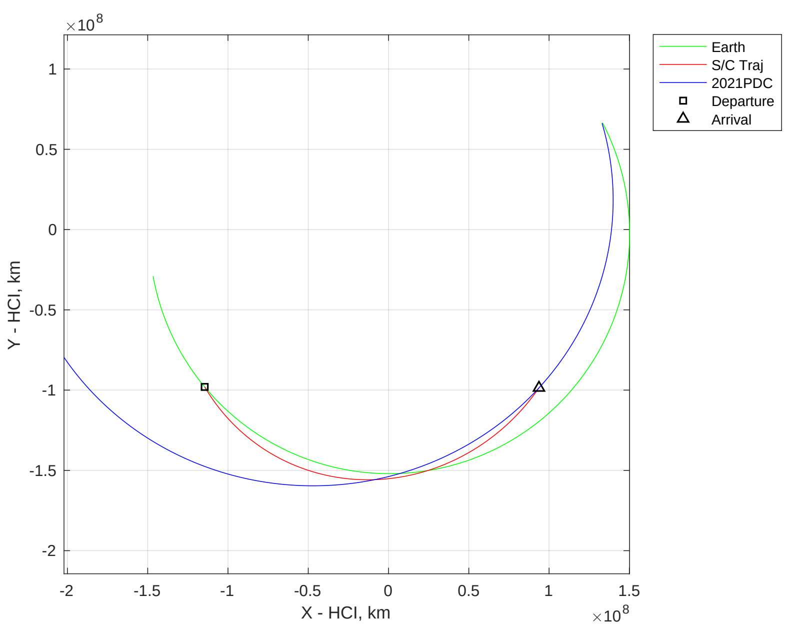
Low-thrust analysis by CNEOS/JPL/CalTech:
Javier Roa

Departure Date	2021-06-10
TOF (days)	101.4
Arrival Date	2021-09-20
Mass Delivered to asteroid (kg)	3072.8
Phase angle @ Intercept	125.3°
Rel. Speed @ Intercept (km/s)	10.88
Departure C3 (km^2/s^2)	22.468
Declination of Launch Asymp., DLA	38.00°

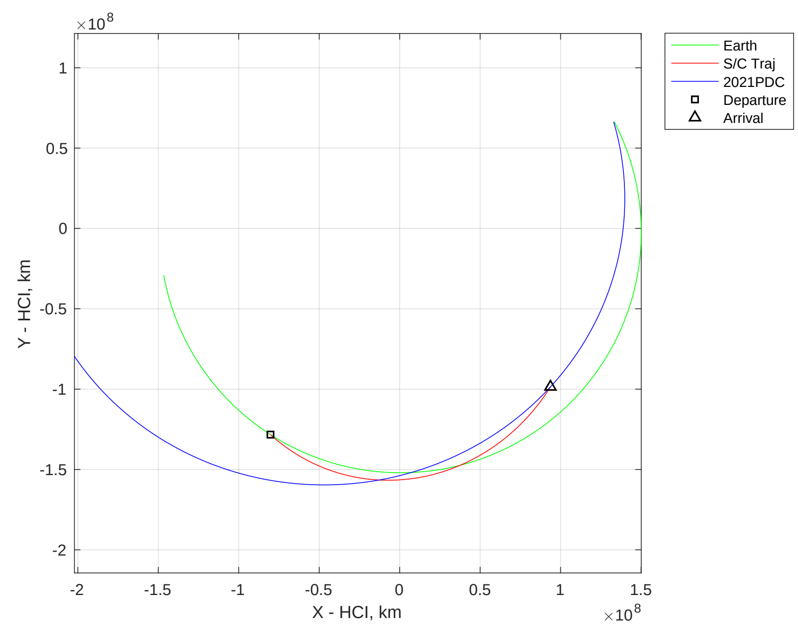
Flyby Reconnaissance Options

- Earlier launch dates / earlier arrival dates are possible, with reduced delivered spacecraft mass that should be sufficient for reconnaissance but not enough for nuclear disruption.
- Examples:

Launch 2021-05-01
Arrive 2021-08-20
919 kg delivered spacecraft mass
6.72 km/s flyby speed
118.6° flyby phase angle

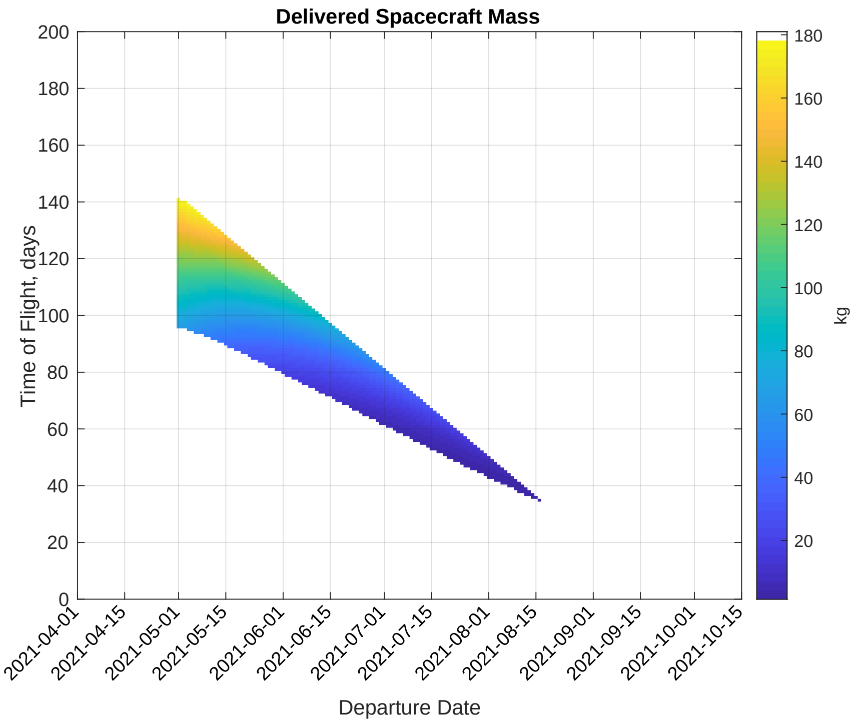


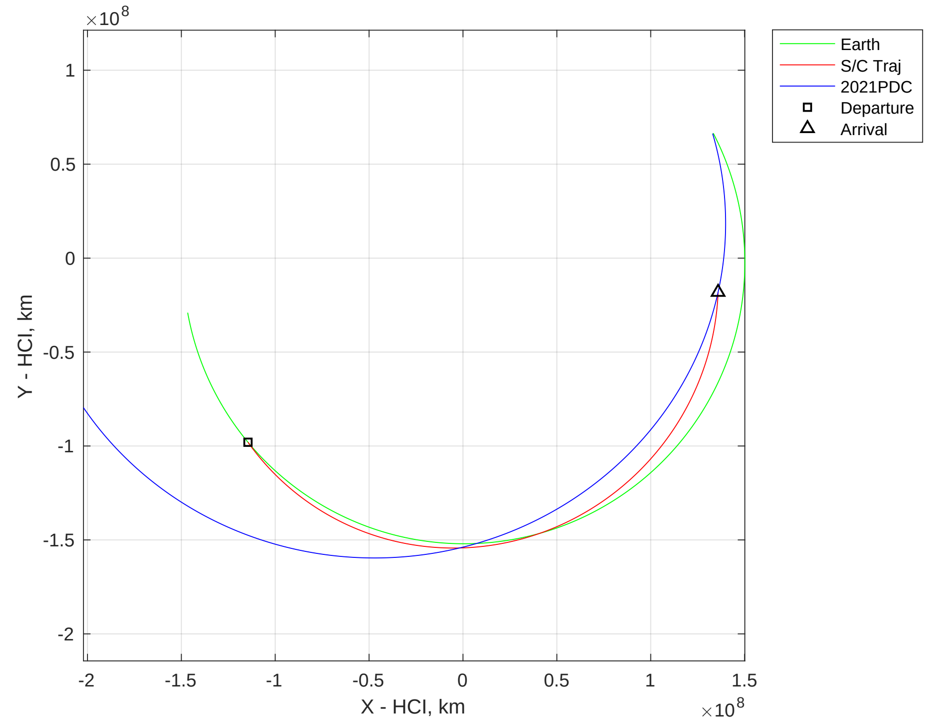
Launch 2021-05-19
Arrive 2021-08-20
823 kg delivered spacecraft mass
8.73 km/s flyby speed
115.8° flyby phase angle



Delivered Spacecraft Mass for Rendezvous Missions

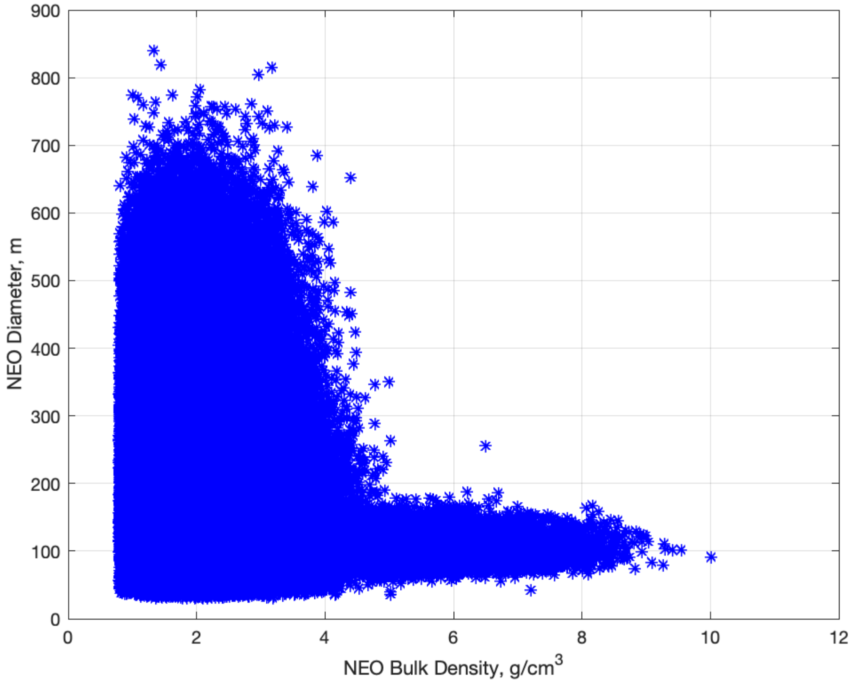
- The maximum delivered mass for a ballistic rendezvous spacecraft is 179 kg, which is insufficient.
- Low-thrust propulsion improves delivered mass somewhat for rendezvous, but not enough to make a rendezvous mission practical. This is due to the very short flight times.



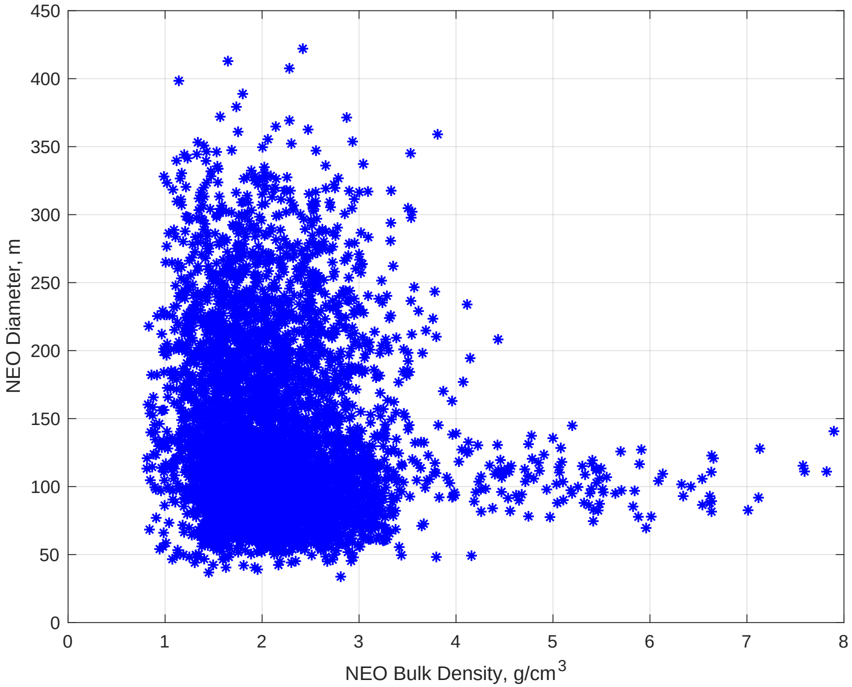


Asteroid Bulk Density vs. Diameter

Before NEOWISE Observations

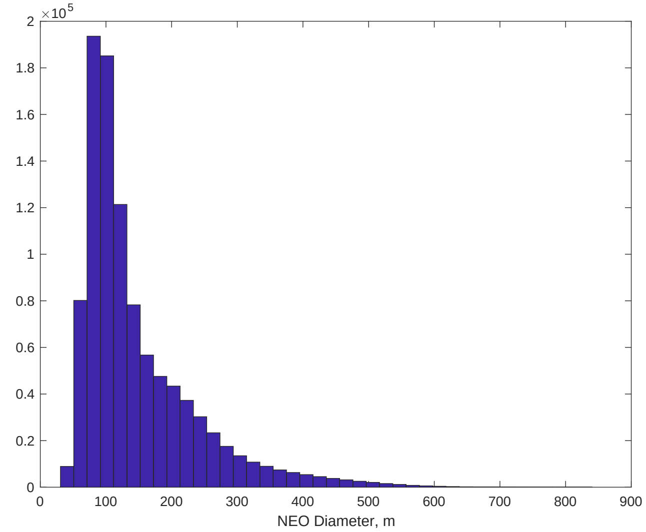


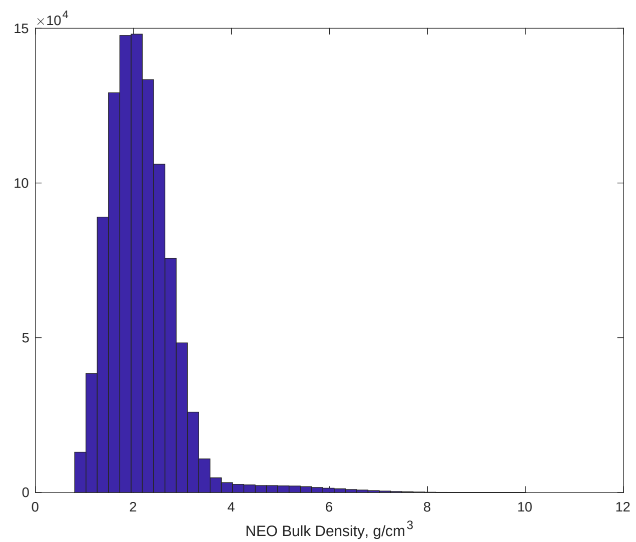
After NEOWISE Observations



NEOWISE Effects on Diameter & Density Distributions

Before NEOWISE Observations





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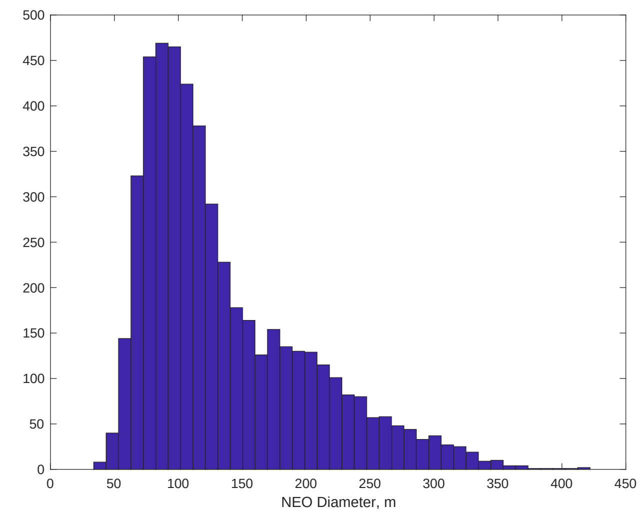
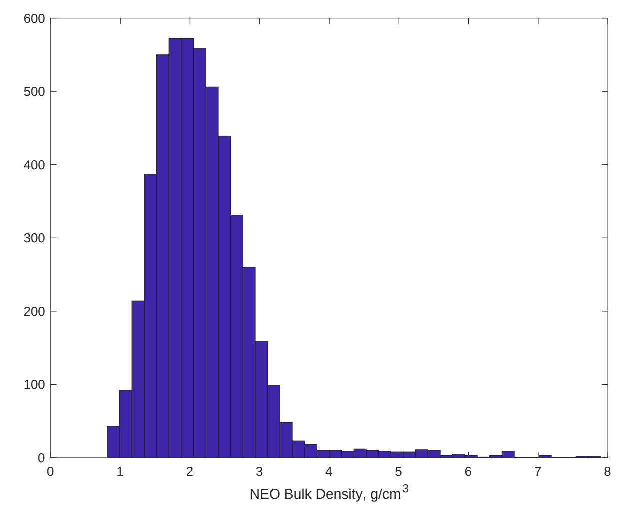
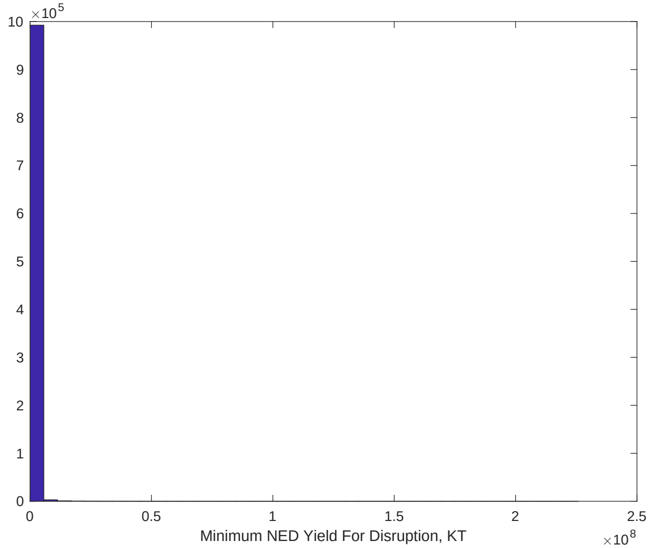
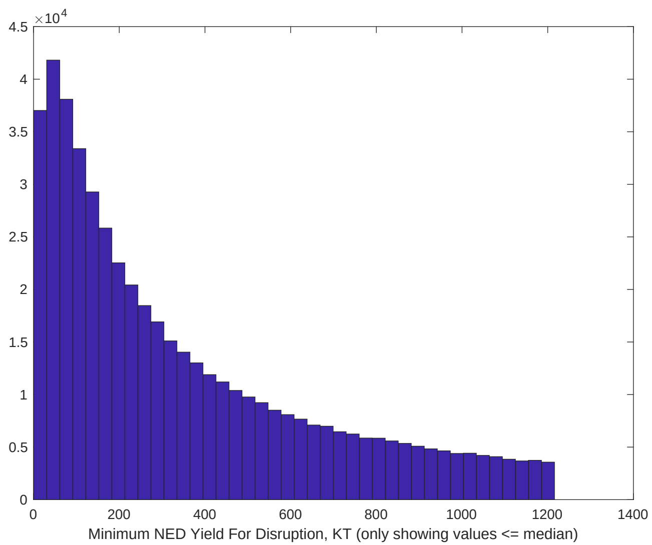




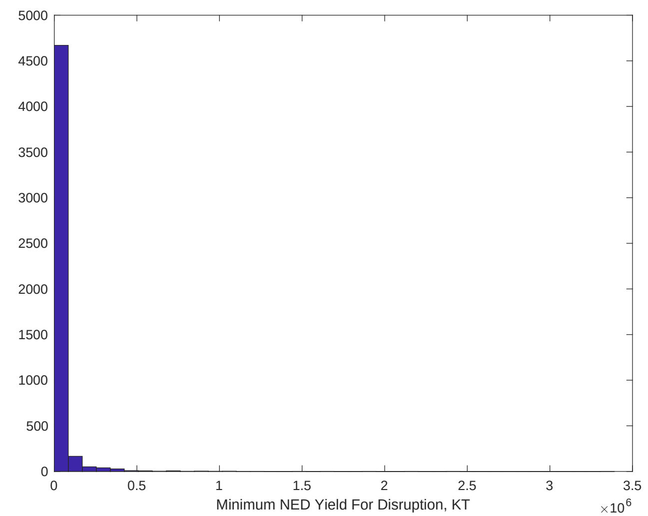
NEOWISE Effects on Required NED Yield Distributions

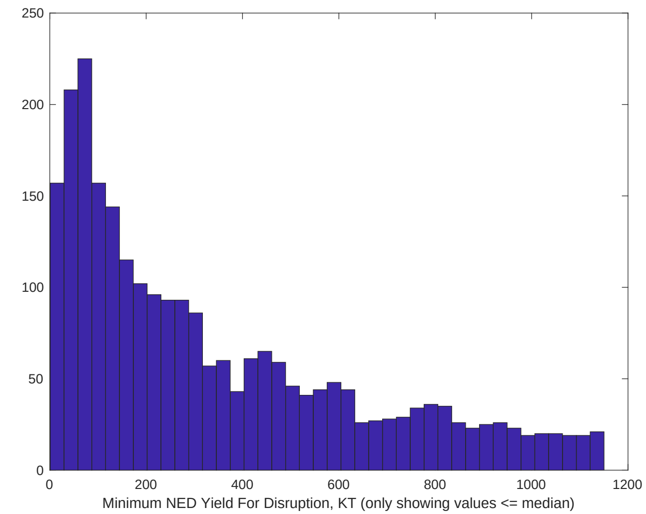
Before NEOWISE Observations





After NEOWISE Observations

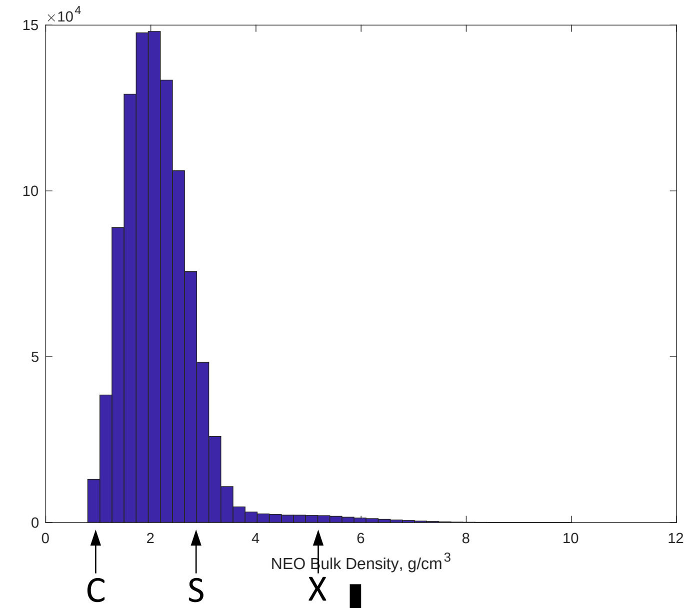


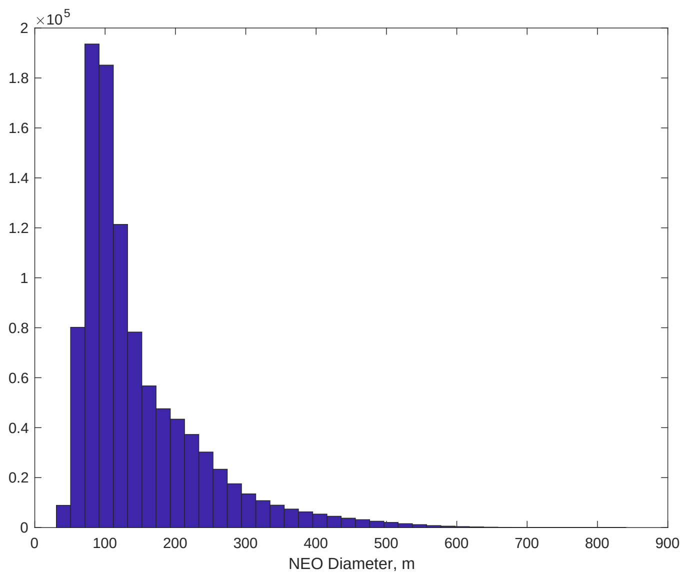


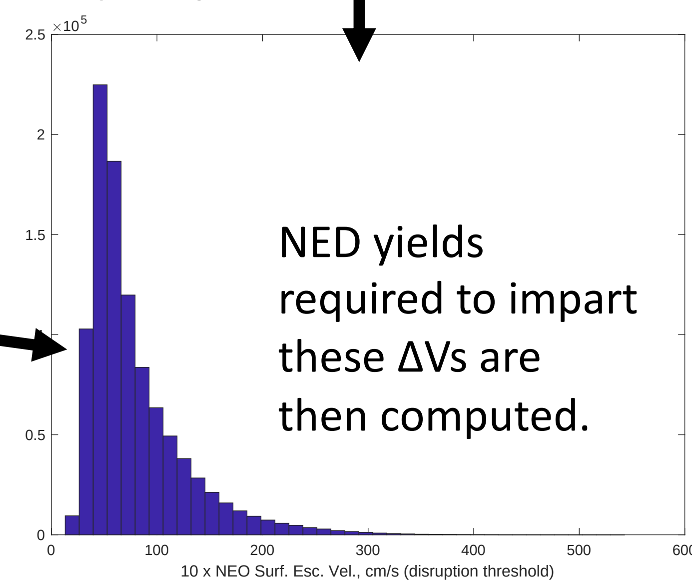
HYPOTHETICAL EXERCISE ONLY – INTERNAL DRAFT

Asteroid Diameter & Bulk Density Set Disruption Requirements

- 2021 PDC physical property distributions from NASA/ARC: Jessie Dotson & Lorien Wheeler
- Note the significant uncertainties in asteroid diameter and density.
- The diameter and density are used to compute the asteroid surface escape velocity.
- **<u>The requirement for robust disruption is to impart ΔV of at least 10✕ surface escape velocity to the asteroid.</u>**
- Robust disruption means that the NEO is disrupted with sufficient energy to break it into fragments that are small enough and scattered widely enough to not pose a significant threat to the Earth-Moon system.
- This is only a heuristic, and detailed analysis is required in practice to assess disruption requirements, etc.
- For computing NED yield / mass, we use the heuristic of 1.8 KT/kg provided by Los Alamos National Laboratory (LANL).







Statistics for NED Yields Required for Asteroid Disruption

Before NEOWISE Observations

Minimum required NED yield: 0.307 KT
- NEO diameter: 38.2 m
- NEO bulk density: 0.832 g/cm^3
- ΔV imparted: 13 cm/s

Mean required NED yield: 137763.527 KT
Std. Dev. of reqd. NED yield: 1201202.657 KT

Median required NED yield: 1215.711 KT

Maximum required NED yield: 225808655.824 KT
- NEO diameter: 815.5 m
- NEO bulk density: 3.172 g/cm^3
- ΔV imparted: 543 cm/s

After NEOWISE Observations

Minimum required NED yield: 0.911 KT
- NEO diameter: 36.8 m
- NEO bulk density: 1.451 g/cm^3
- ΔV imparted: 17 cm/s

Mean required NED yield: 25411.278 KT
Std. Dev. of reqd. NED yield: 111856.763 KT

Median required NED yield: 1151.056 KT

Maximum required NED yield: 3390551.975 KT
- NEO diameter: 359 m
- NEO bulk density: 3.810 g/cm^3
- ΔV imparted: 262 cm/s

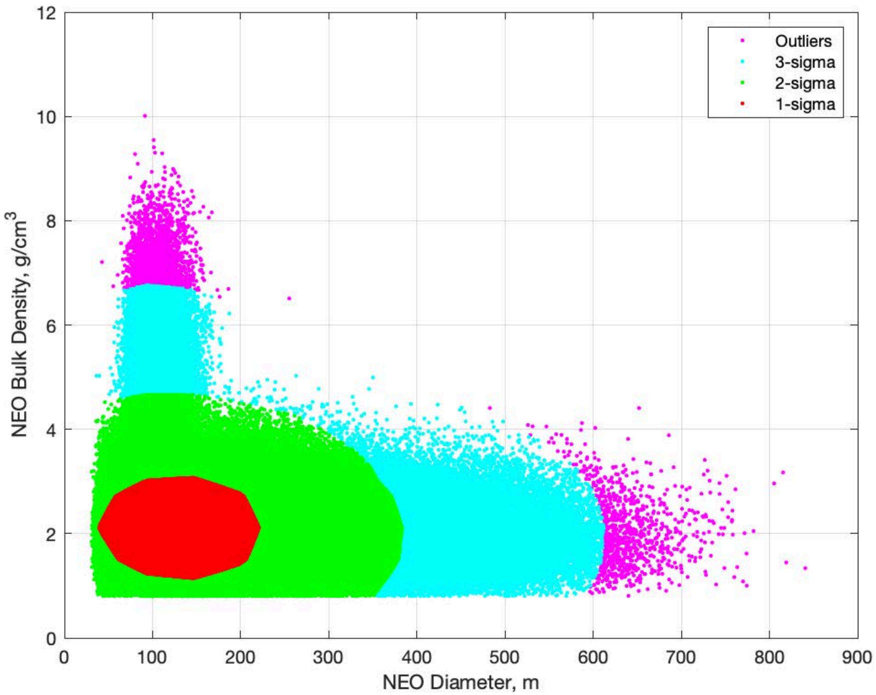
- **Remarks:**
  - For computing NED yield / mass, we use the heuristic of 1.8 KT/kg provided by Los Alamos National Laboratory (LANL)
  - Both the mean and maximum required NED yield values are completely impractical.
  - This distribution is quite skewed, with a very long tail, and is, therefore, difficult to deal with.
  - The median required NED yield value is reasonable (in terms of availability of such a NED).
  - **In practice, if the need ever arose to disrupt a large NEO, then a different type of NED may be required.**

Effects of NEOWISE Observations on NEO Properties Distributions

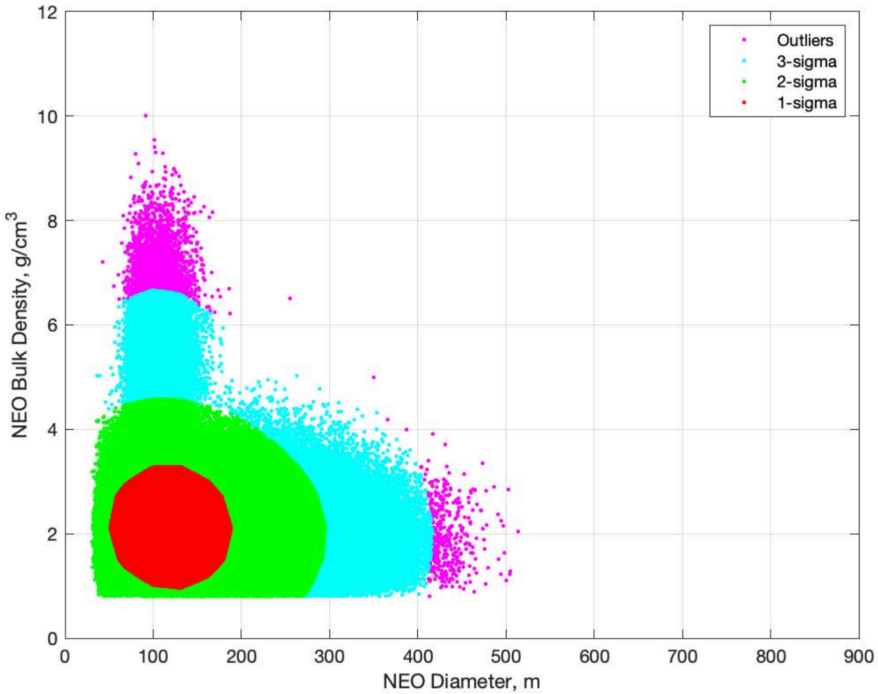
NEOWISE observations reduce the uncertainty in NEO diameter and eliminate the possibility of larger diameters, but significant diameter and density uncertainty remain.

- NEOWISE observations are processed and incorporated into NEO properties modeling after 2021-06-30 in the scenario.
- A mission would have to launch without the NEOWISE-provided knowledge improvements, but mission performance predictions would be updated well before the spacecraft reaches the NEO.

Before NEOWISE Observations



After NEOWISE Observations



Statistical Analysis of NED Yield Requirements

Before NEOWISE Observations

Statistics For NED Yields Required For Asteroid Disruption

	1σ Asteroids	2σ Asteroids	3σ Asteroids	Outlier Asteroids
Minimum	3.3 KT, 1.8 kg	0.3 KT, 0.17 kg	18.6 KT, 10.3 kg	116 KT (0.116 MT), 65 kg
Median	607 KT (0.61 MT), 337 kg	26648 KT (27 MT), 14805 kg	848086 KT (848 MT), 471160 kg	31095 KT (31 MT), 17275 kg
Mean	3209 KT (3.2 MT), 1783 kg	99386 (100 MT), 55215 kg	1903380 KT (1904 MT), 1057434 kg	6428347 KT (6429 MT), 3571304 kg
Maximum	52008 KT (52 MT), 28894 kg	1824810 KT (1825 MT), 1013784 kg	34539670 KT (34540 MT), 19188706 kg	225808656 KT (225809 MT), 125449254 kg

Remarks:

- For computing NED yield / mass, we use the heuristic of 1.8 KT/kg provided by Los Alamos National Laboratory (LANL)
- The large uncertainties in NEO physical properties drive large spreads of possible asteroid diameters and densities.
- Additionally, the ways in which asteroid diameter and bulk density are correlated in the properties model results in long tails in the distribution of NED yields required for disruption.
- Median values of required NED yield for disruption are significantly smaller than mean values.
- The required NED yield to disrupt the worst case 1σ asteroid is probably impractically large: 52 MT.
- **Thus, no practical NED yield can be recommended for confidence of asteroid disruption at the 1σ, 2σ, or 3σ level.**
- **In practice, if the need ever arose to disrupt a large asteroid then a different type of NED might be required.**

Standoff NED Model (from J.Wasem/LLNL) (1/2)

$$A_1 = \sqrt{yrd^2/(r+d)}$$

$$A_2 = \sqrt{1 - \sqrt{(1+d/r)(1+d/r) - 1}/(1+d/r)}$$

$$A_3 = \sqrt{(2r/d)\left(1 + ln\left(y/((3.16\times10^{-4})d^2)\right)\right) - ((1+(2r/d))(ln(1+(2r/d))))}$$

$$\Delta v = \frac{2}{\varrho}\frac{5750}{r^3}A_1A_2A_3$$

where

Δv is the magnitude of the change-in-velocity imparted to the asteroid via the standoff nuclear detonation. Note that the *direction* of the Δv must be selected independently of these equations in order to specify the full Δv vector. (i.e., $\Delta\bar{v}$), which is needed for propagating the motion of the deflected asteroid and computing by how much it is deflected from Earth (i.e., its perigee altitude when it encounters Earth around the date when the undeflected asteroid would originally have hit Earth). The units of Δv given by this equation are cm/s.

y is the yield of the nuclear device in units of kT

r is the radius of the (assumed spherical) asteroid in units of meters

d is the distance between the nuclear device and the asteroid's surface in units of meters at the time of detonation

ϱ is the bulk density of the asteroid in units of g/cm^3

Standoff NED Model (from J.Wasem/LLNL) (2/2)

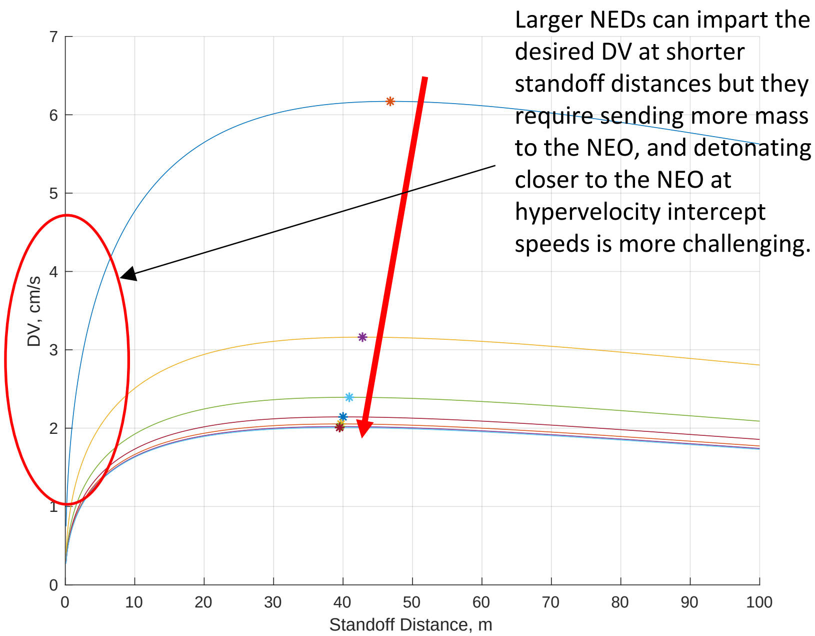
The ranges of values for y, r, and d for which this model is valid are:

- Yield can be set very low (e.g., a few kT), or very high (e.g., >100 MT), without loss of model accuracy. When yield is set too low for the given scenario, the model will give imaginary results.
- d can range from 0 (i.e., on the asteroid's surface) to larger values; the results of the model become imaginary when d is too large for the specified scenario.
- r can be set very low (e.g., a few meters). r can also be set to large values, and it is likely that the achieved deflection change-in-velocity on the asteroid will become too small to be worthwhile well before a large value of r exceeds the mathematical limits of the model.

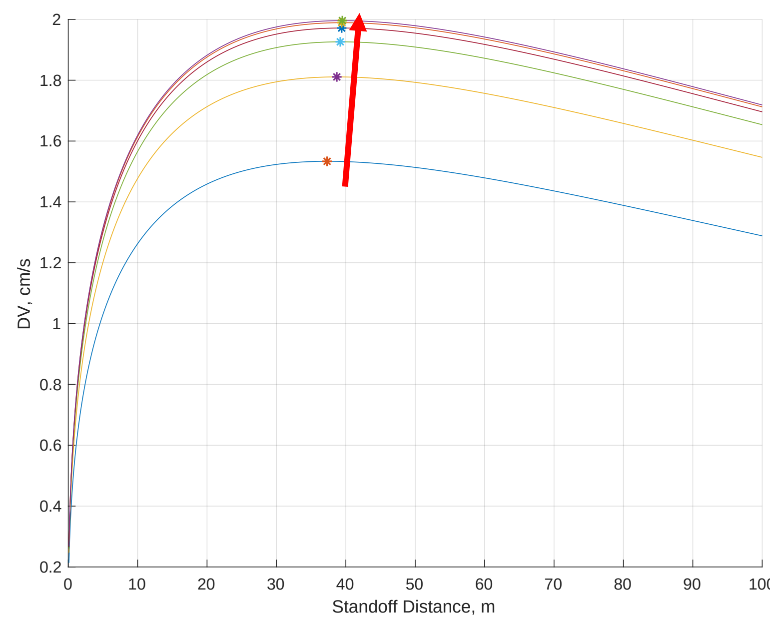
Solving For Minimum Required NED Yield

- The minimum required NED yield for imparting a given ΔV should achieve that value of ΔV at its peak (at the standoff detonation distance that maximizes ΔV imparted to the given NEO).
- The minimum NED yield with peak ΔV at the desired value can readily be solved for iteratively.
- The examples below are for an NEO with diameter and bulk density of 340 m and 2 g/cm³, respectively. The desired imparted ΔV is 2 cm/s.

Converging from above:



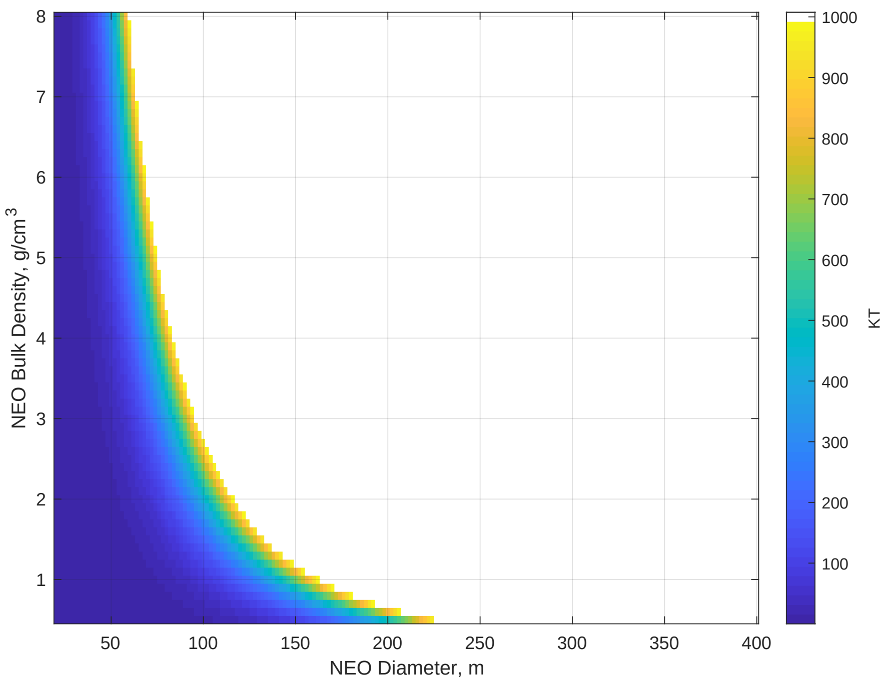
Converging from below:



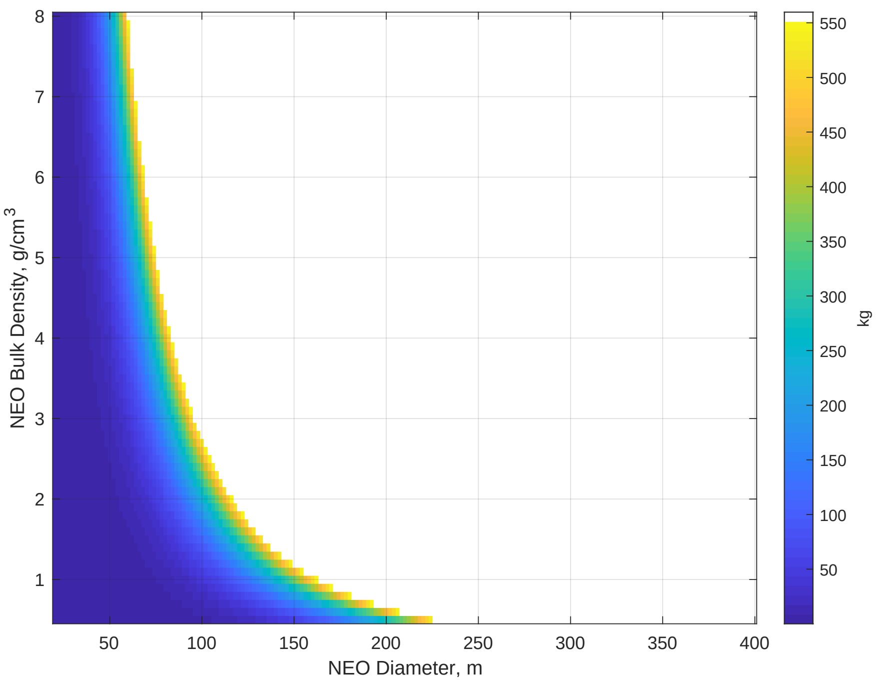
Parametric Analysis of Disrupt-able NEOs

- Several representative NED yields were studied parametrically, to ascertain the span of NEO diameters and bulk densities for which each particular NED yield can impart at least 10× NEO surface escape velocity, for robust disruption.
- NED yields of 1000, 2000, 3000, 4000 KT.
- NEO diameter spanning 20 to 400 m.
- NEO bulk density spanning 0.5 to 8 g/cm^3.

NEOs Disrupt-able with a 1000 KT NED

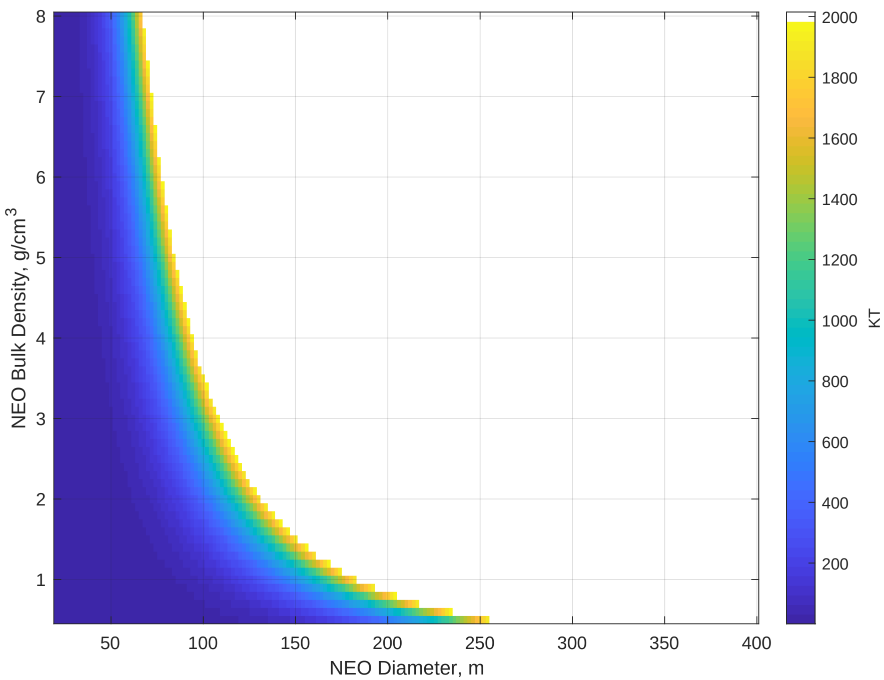


NED yield (up to 1000 KT) required for disruption NEOs of given diameter & density.

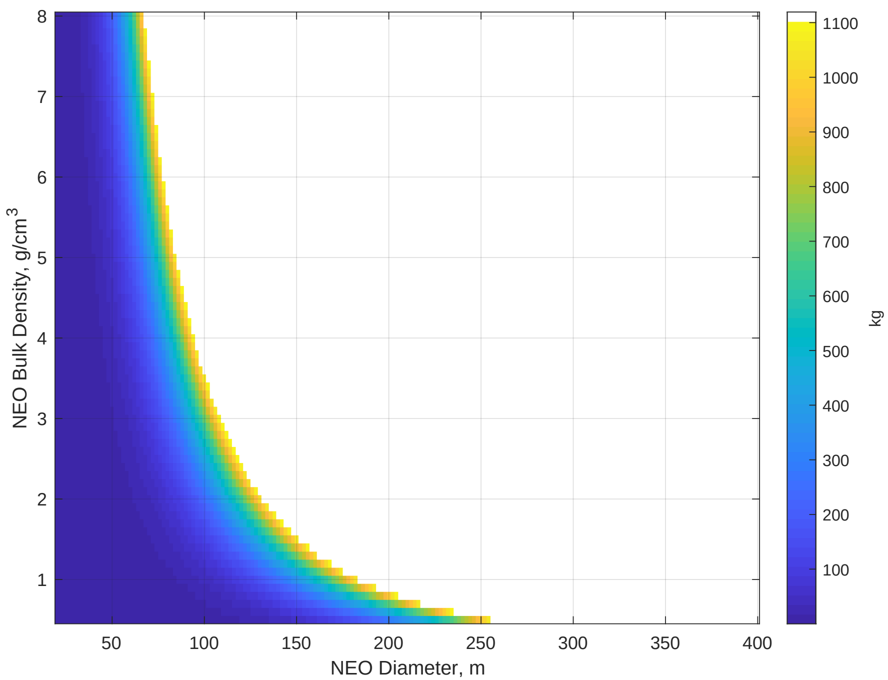


NED mass (for up to 1000 KT) required for disruption NEOs of given diameter & density.

NEOs Disrupt-able with a 2000 KT NED

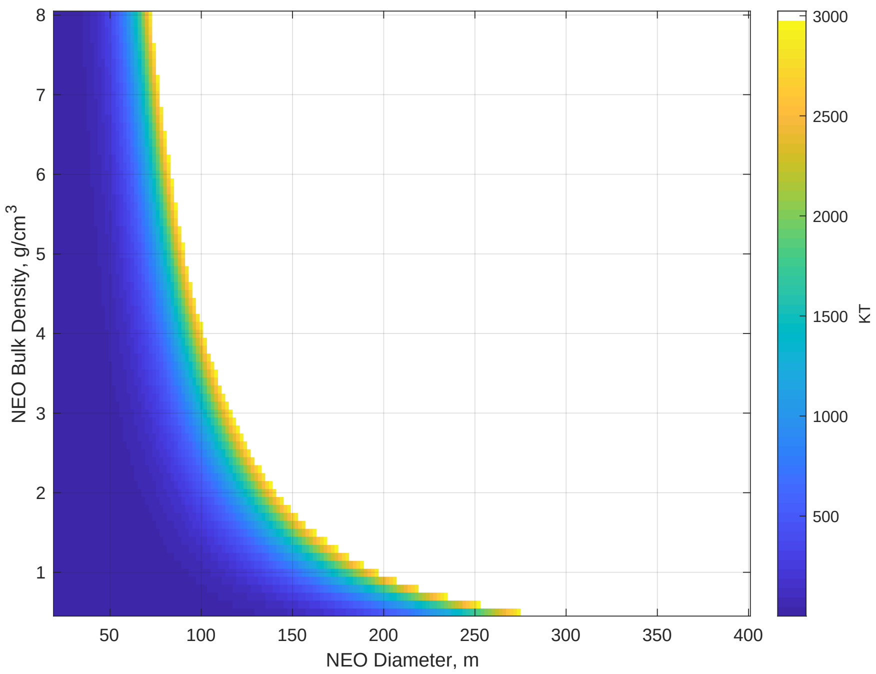


NED yield (up to 2000 KT) required for disruption NEOs of given diameter & density.

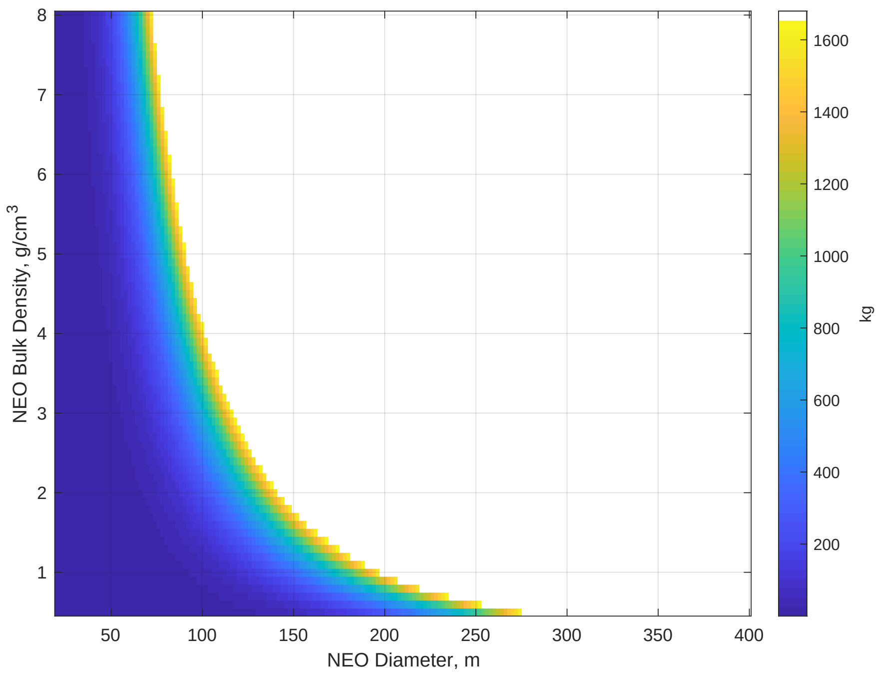


NED mass (for up to 2000 KT) required for disruption NEOs of given diameter & density.

NEOs Disrupt-able with a 3000 KT NED

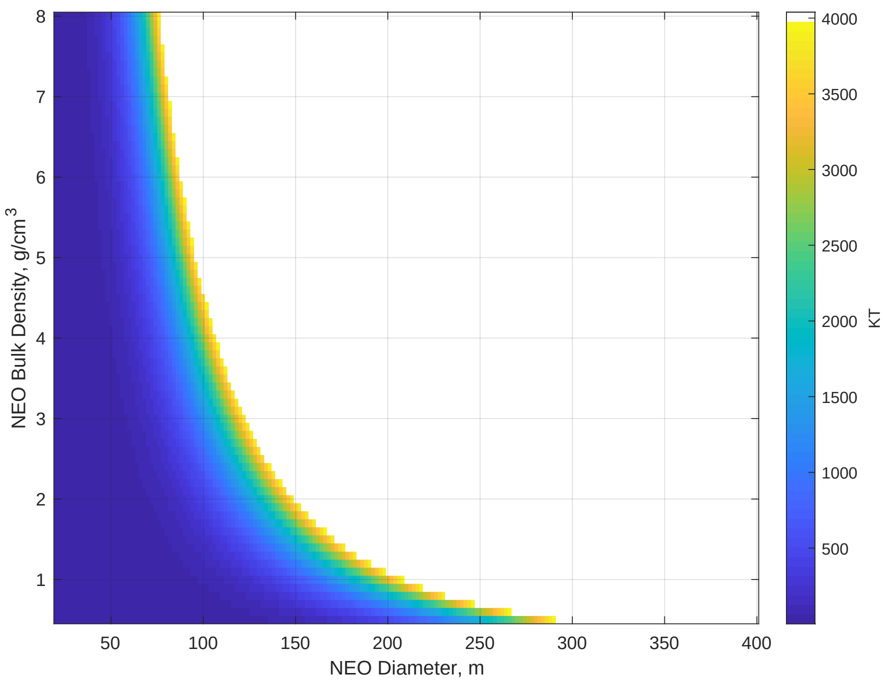


NED yield (up to 3000 KT) required for disruption NEOs of given diameter & density.

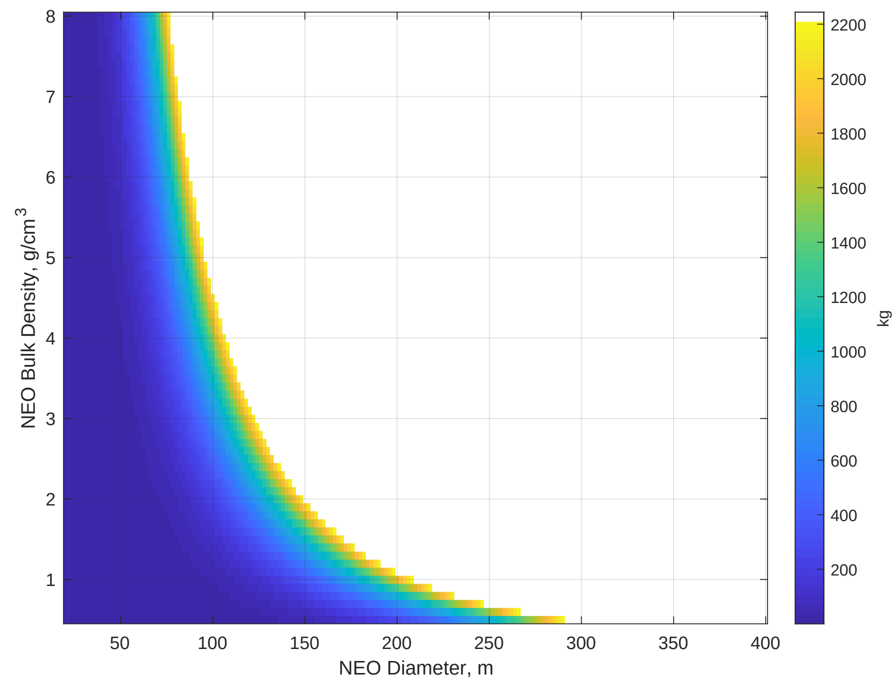


NED mass (for up to 3000 KT) required for disruption NEOs of given diameter & density.

NEOs Disrupt-able with a 4000 KT NED



NED yield (up to 4000 KT) required for disruption NEOs of given diameter & density.



NED mass (for up to 4000 KT) required for disruption NEOs of given diameter & density.

Remarks on Disrupt-able NEO Analysis

- At anticipated common/average NEO bulk densities (e.g., around ~2 g/cm^3), robust disruption of an NEO via a NED with yield up to ~several MT appears to only be feasible for NEO diameters up to ~100-150 m.
- An NEO with lower bulk density closer to ~1 g/cm^3 may be disrupt-able via a ~several MT NED, up to NEO diameters of up to ~150-200 m.
  - Note that carbonaceous NEOs Bennu (B-type) and Ryugu (C-type) both have a bulk density of about 1.19 g/cm^3.
- Even very dense (e.g., iron) NEOs may be robustly disrupted up to ~70-100 m NEO diameter.
- This is all because NEO mass scales cubically with diameter but only linearly with bulk density.

The MILO Space Science Institute: Enabling New, Science-Focused Deep Space Smallsat Missions to Near Earth Objects

Jim Bell[1], Lindsay Papsidero[2],
& the MILO Space Science Institute

[1]Arizona State University (Jim.Bell@asu.edu); [2]Lockeed Martin

http://miloinstitute.org

The MILO Space Science Institute

The MILO Institute is a non-profit research collaborative led by **Arizona State University**, with support from **Lockheed Martin**

Collaboration
MILO missions will be conducted by a consortium of domestic and international universities and space agencies.

Affordable Access
Brings members together to fund an entire mission, each paying a fraction of the total cost, leveraging lower cost mission concepts and resource sharing.

Hands on Experience
The Institute is helping to train the next generation of scientists and engineers by offering workforce development through hands-on projects, technology demonstrations, and advancement of scientific discoveries.

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To enable world class scientific discovery, the MILO institute has developed a suite of mission opportunities for members

Compelling Science
The goal of all MILO missions is to enable Decadal Survey-quality science, exploration, and discovery that would otherwise not be easily accessible

"In the Neighborhood"
To ensure relatively quick scientific return (5 years or less), MILO mission targets are close to Earth, such as Venus, Mars, the Moon, and **Near Earth Asteroids**

Low Cost Architectures
MILO architectures leverage high heritage commercial products, ridesharing, **smallsats, and cubesats**

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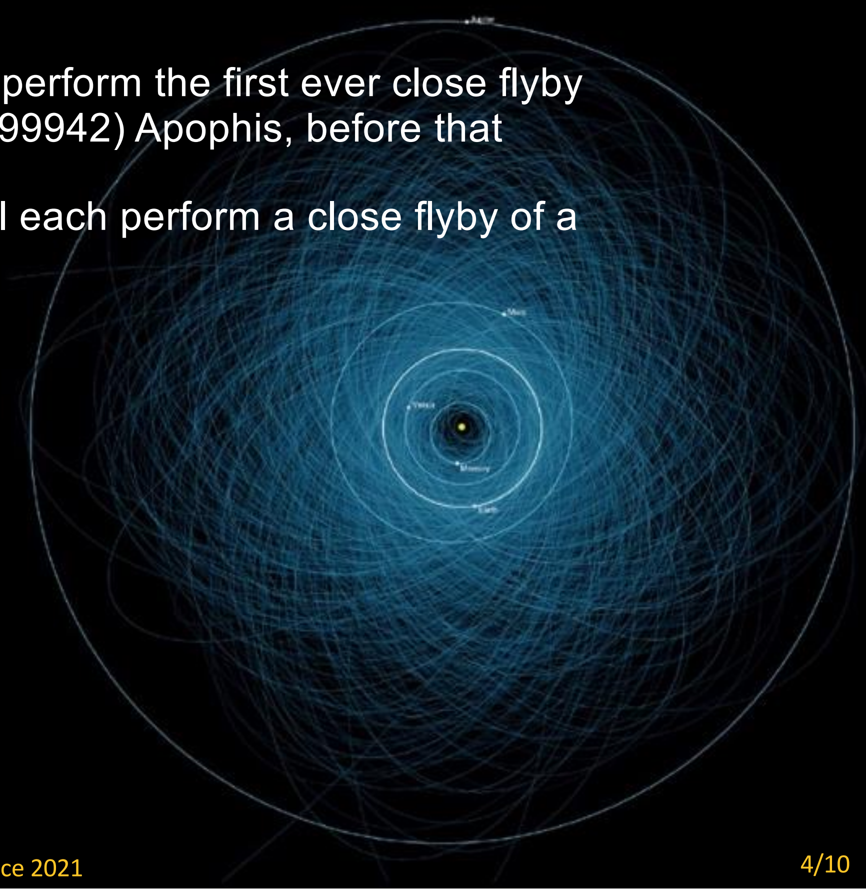
NEO Smallsat Mission Concepts

Mission Opportunities

- **Apophis Pathfinder**, uses a pair of small spacecraft to perform the first ever close flyby of the 370-meter diameter Potentially Hazardous NEO (99942) Apophis, before that small body's extremely close flyby of Earth in 2029
- **NEOShare**, will launch a cluster of six smallsats that will each perform a close flyby of a different NEO close to Earth



Target Partners

- Emerging space agencies
- University space science institutes and departments
- New space companies
- Philanthropic organizations

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Apophis Pathfinder

MILO is seeking members interested in compelling asteroid science and planetary defense

Science Goals

- Surface geology and shape/topography
- Crater size-frequency distribution and NEO bombardment history
- Surface composition/mineralogy and relationship to meteorites
- Thermophysical/regolith properties and relationship to Yarkovsky (etc.)
- Assess geophysical parameters (the "before" measurements prior to 2029)

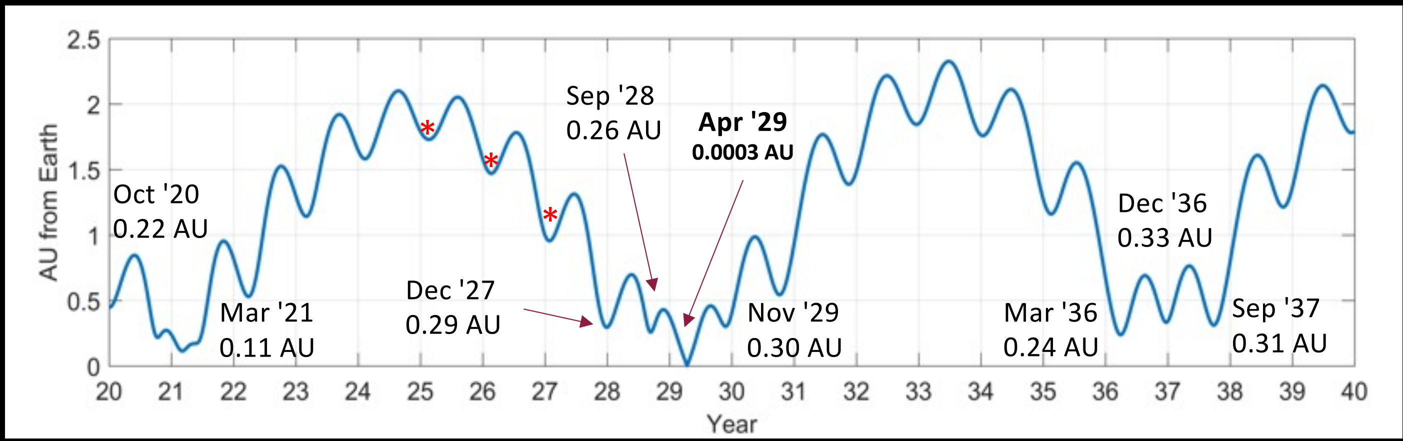
Planetary Defense and Future Mission Support Goals

- Assess physical properties/parameters for "threat assessment" and mitigation
  - Mass (for future orbiters, etc.)
  - Shape and Topography (for future landers, probes, etc.)
  - Regolith properties (for future landers, probes, etc.)

Apophis Pathfinder Opportunities

http://miloinstitute.org

(99942) Apophis



Bell *et al.* (2019) PDC

- MILO's Apophis Pathfinder mission would conduct a precursor flyby of (99942) Apophis several years or more in advance of its 2029 Earth flyby
- Many opportunities for Apophis encounters (roughly annual), some better than others
- Initial launch window analysis provides options:
  - Earliest launch opp: 2024 with encounter ~6 months later
  - Launch opportunities in 2026 with encounter in ‘27-’28

Apophis Pathfinder

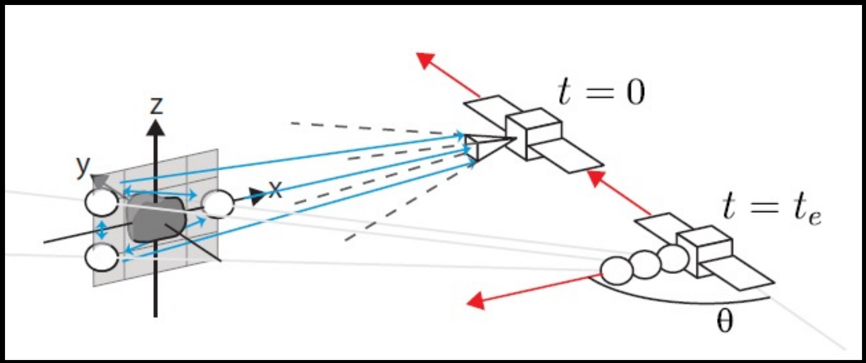
http://miloinstitute.org

Simple Payload

- Imaging system with RGB color and capable of resolution down to ~1-2 m/pix
- Near-IR point spectrometer for detection of silicates, hydrates, organics
- Thermal-IR imager, multi-band
- Can accommodate additional member payloads

Simple Spacecraft & Mission Design

- We will test and validate an innovative dual small spacecraft approach to mass determination
  - Christensen, Park, & Bell (2021) Estimating Asteroid Mass from Optically Tracked Radio Beacons, AIAA *Journal of Spacecraft and Rockets*, doi:10.2514/1.A34830
- Measure disturbances caused by asteroid's gravity
- Heritage spacecraft based on deep space experience



Christensen, Park, & Bell (2021)

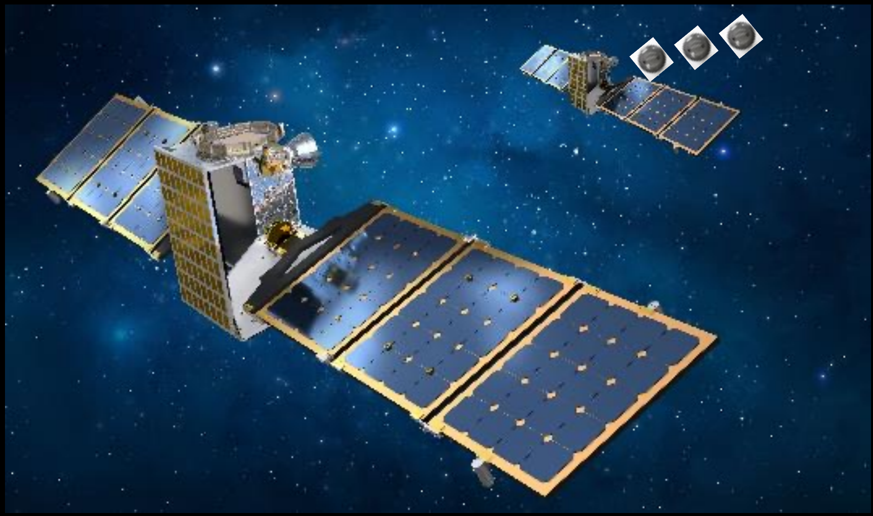


Image credit: Lockheed Martin

NEOShare

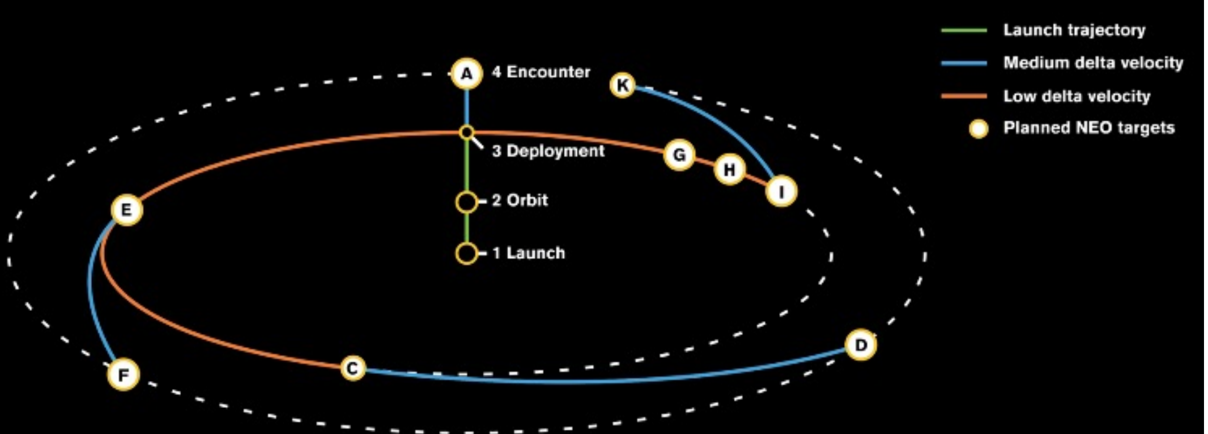
MILO is seeking members interested in detailed scientific studies of diverse NEOs

Mission Overview

- Send a cluster of propulsive small spacecraft into heliocentric orbit to perform close flyby characterization of a diverse set of Near Earth Objects (NEOs)
- Six spacecraft will individually fly by one or more different target bodies, encountering 8 or more different asteroid targets in total, in a single mission

Mission Objectives

- Perform full asteroid characterization
- Increase knowledge of asteroid orbit, geology, composition, and estimate mass and density
- Assess physical and regolith properties for science and threat assessment and mitigation
- Perform observations across a wide sample set of diverse objects (size, color, composition, binarity, orbit, etc.)



NEOShare

Member participation in the form of instrumentation and spacecraft development

Mission Requirements

- Low delta-V of 100 m/s to reach closer target objects
- High delta-V of 500+ m/s to reach farther objects, or encounter two objects
- For any given launch window, up to ~100 different NEO targets can be reached

Spacecraft Concepts

- Six small spacecraft attached to deployer ring
- Individually deploy from dispenser onto individual trajectories
- Equipped with cameras, spectrometers, and other high heritage instrumentation
- Equipped with individual communications systems for direct to Earth comms
- Platforms of 12U or larger
  - To meet difficult packaging requirements of propulsion and communications systems

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Please contact us to get involved!

The MILO Space Science Institute

Testing a New Model to Enable Deep Space Science

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Arizona State University

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Participation

To support members at all stages of development and resources, the MILO Institute offers a range of ways to participate

Training Programs ($)
We offer various training and education programs around space science, engineering, and entrepreneurship

Workforce Development Programs ($$)
We customize programs to develop your local technology and a space ecosystem

Mission Contributions and Participation ($$$)
The Institute pulls together consortiums of interested members together to conduct deep space science missions, providing architectures, integration, launch, and operations services

Opportunity Cost

$ — Custom-online training courses — Immersive cubesat program — Principal Investigator training — Space Science Innovation Challenge — Mission data analytics and research — Mission hardware contributions — $$$

Membership pricing available to meet member budgets

Steps to Membership

Collaborate: Share your space science plans with the Institute and collaborate on your goals

Outline: Draft a framework memorandum to clarify collaboration plans (non-binding)

Proposal: Develop a proposal specific to your desires

Contract: Draft Statement of Work and sign the contract

Membership confirmed!

Membership Benefits

- Affordable participation in deep space science missions
- Spacecraft or instrument development guidance
- Involvement in design reviews and mission development
- Flight opportunities for your instrument/spacecraft
- Propose/iterate on your mission ideas with the Institute
- Design, build, test, and qualify hardware

7th IAA Planetary Defense Conference

26-30 April 2021, Online Event

Hosted by UNOOSA in collaboration with ESA

Q&A

Session 8b: Mission & Campaign Design

7th IAA Planetary Defense Conference

26-30 April 2021, Online Event

Hosted by UNOOSA in collaboration with ESA

End of Day 3

Thank you