# Connecting NEO Origins To Solar System Evolution

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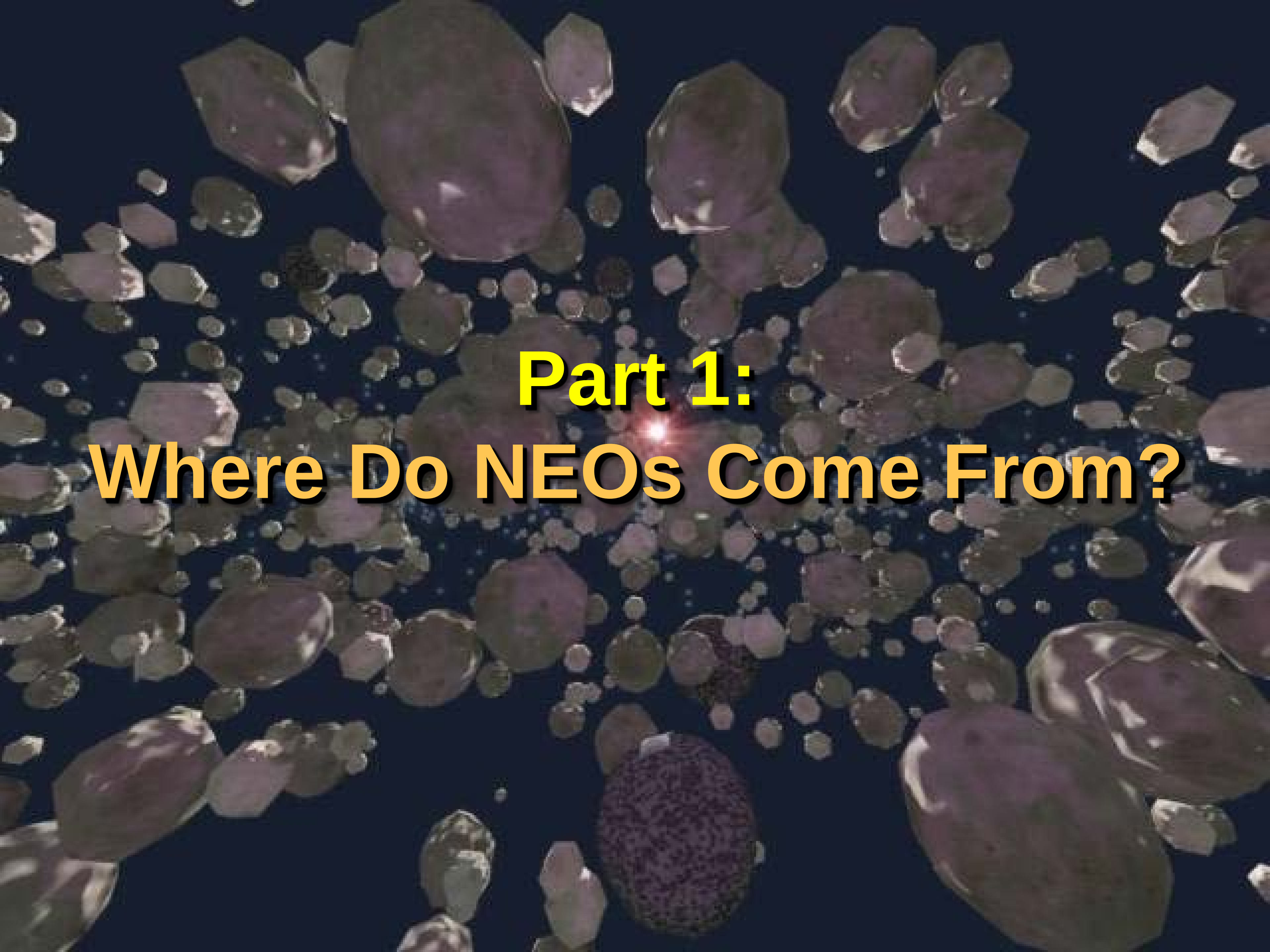
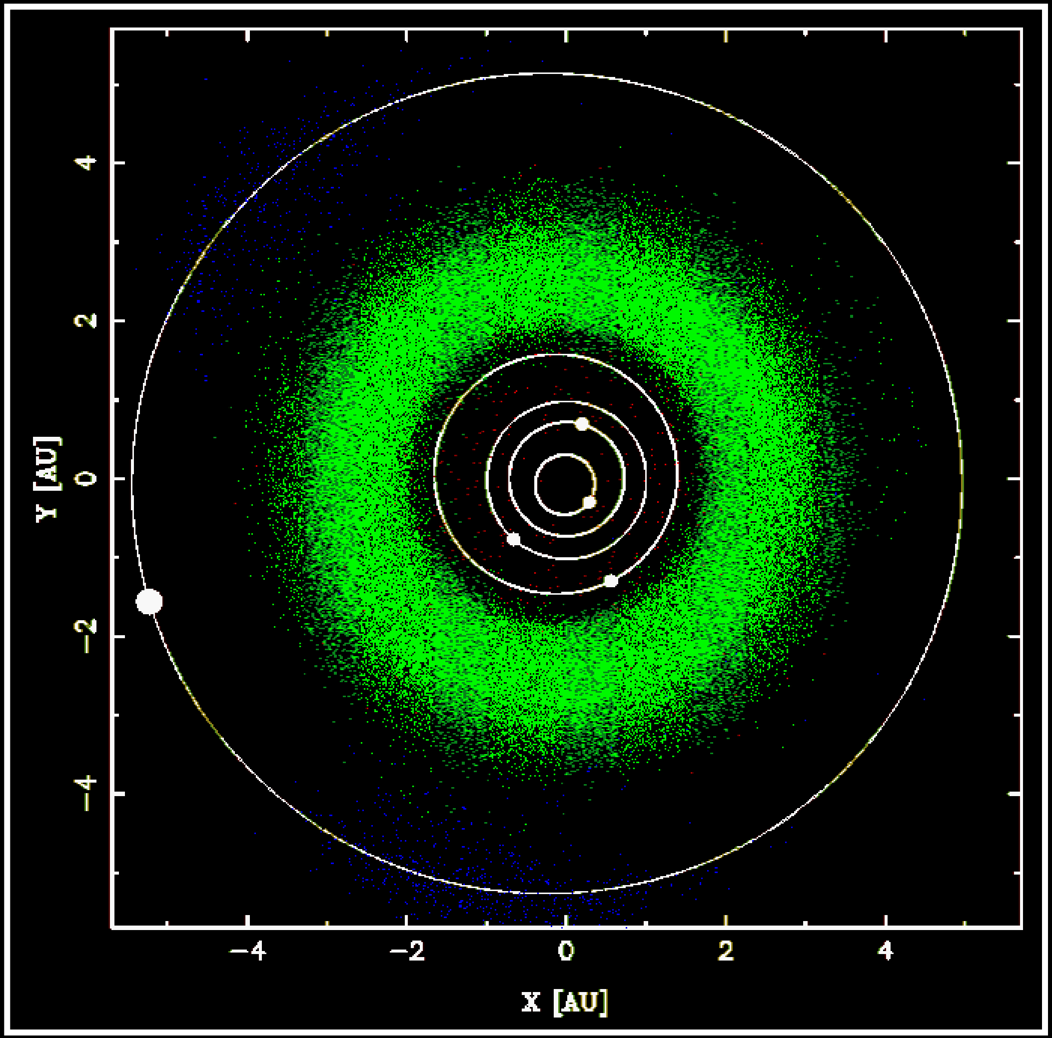
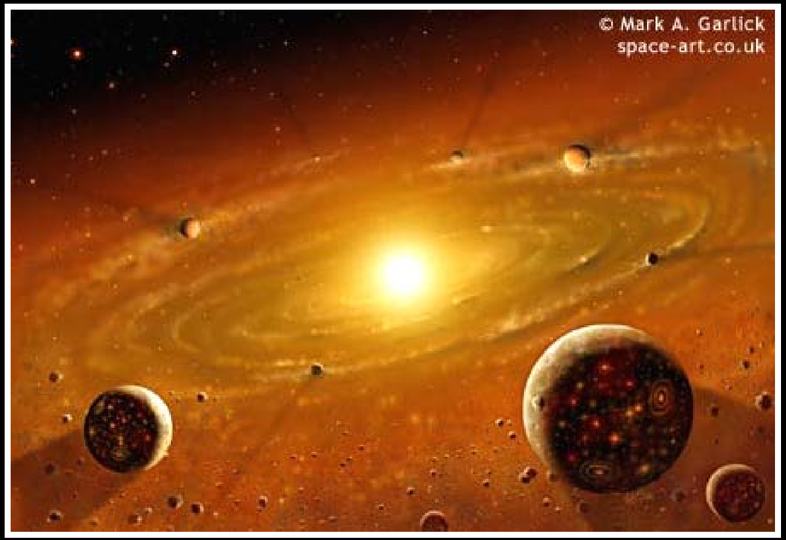
# Part 1:
# Where Do NEOs Come From?



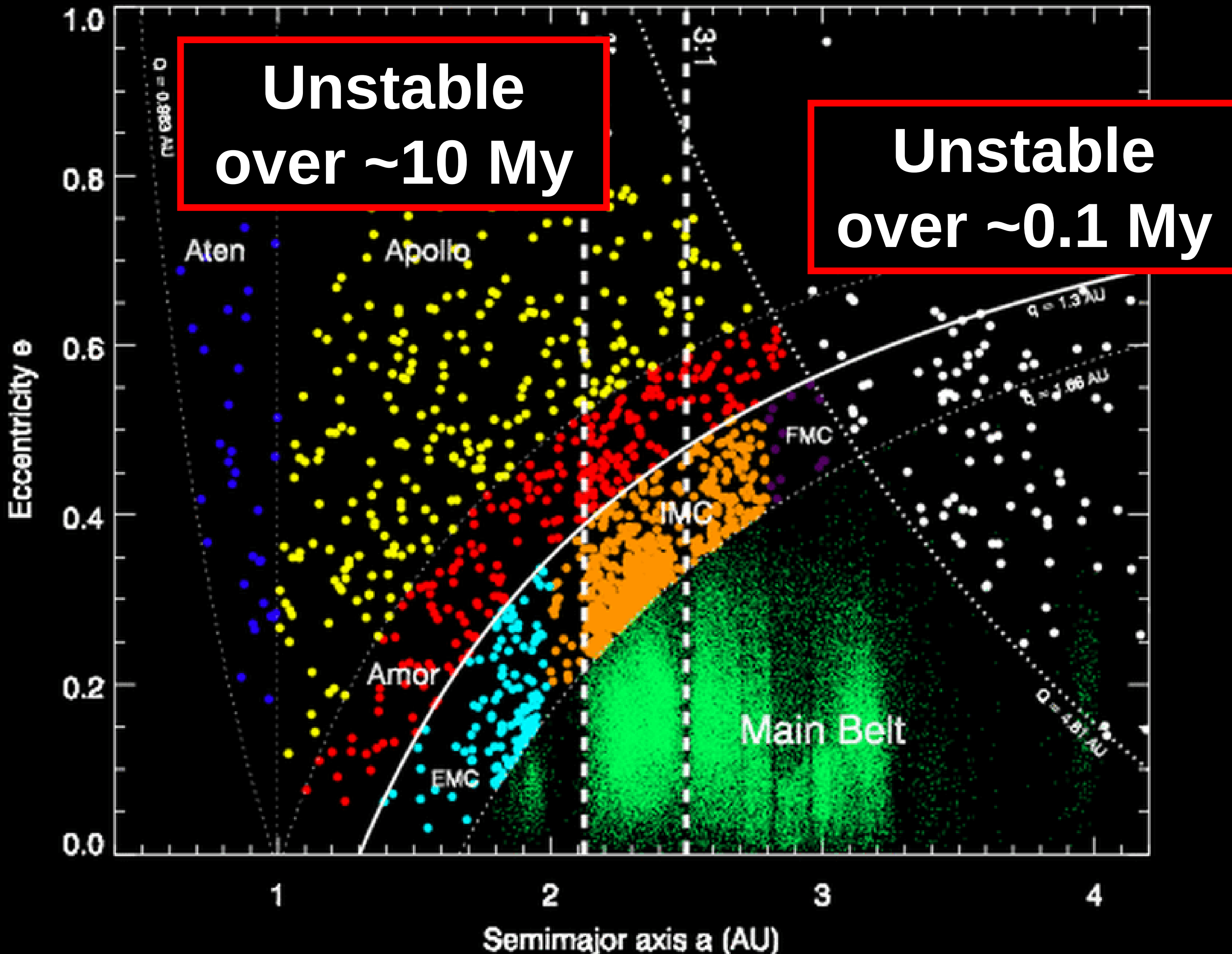
# Fossils of Formation

**~$10^6$ objects with diameters *D* > 1 km between Mars and Jupiter**

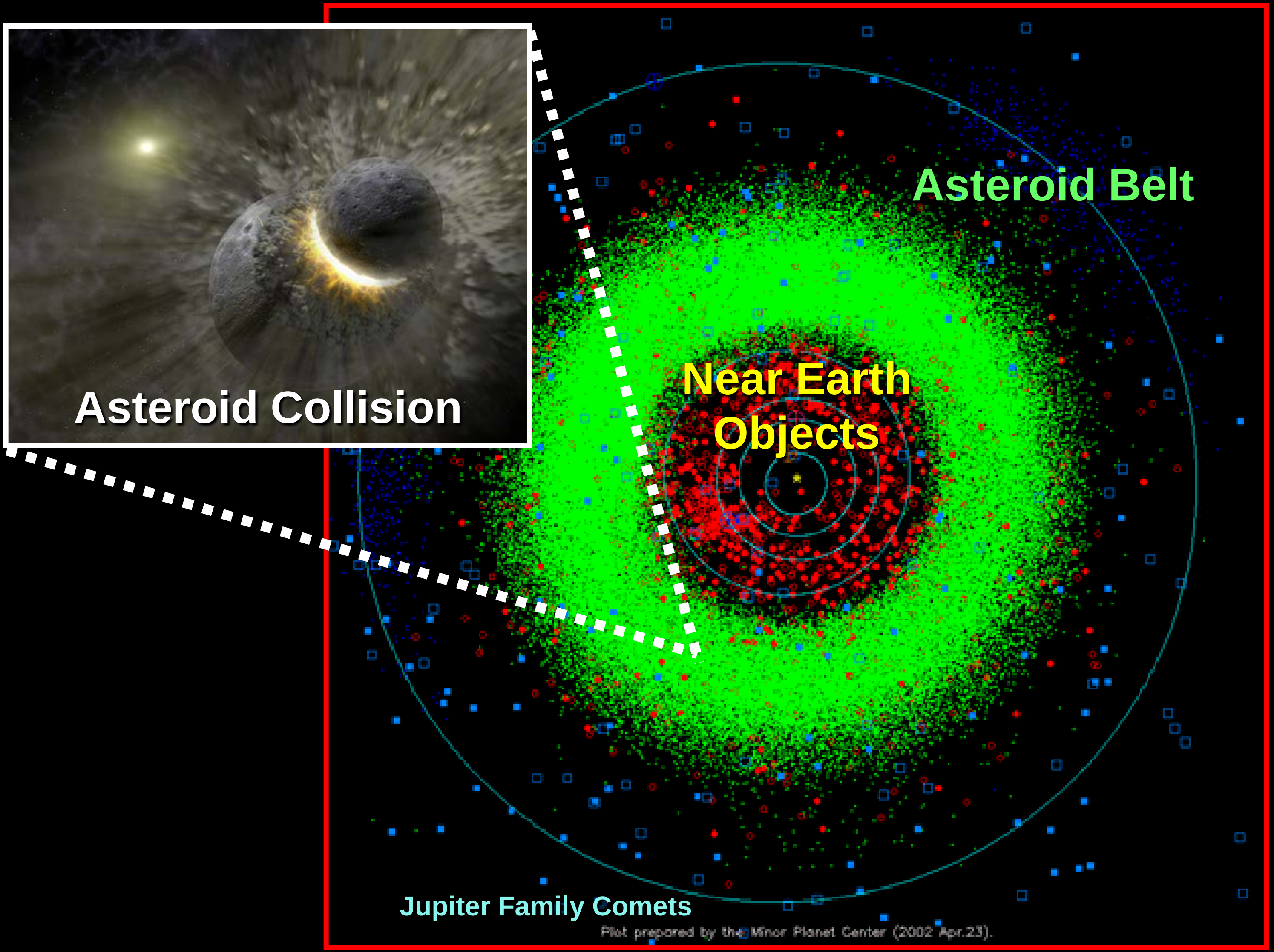


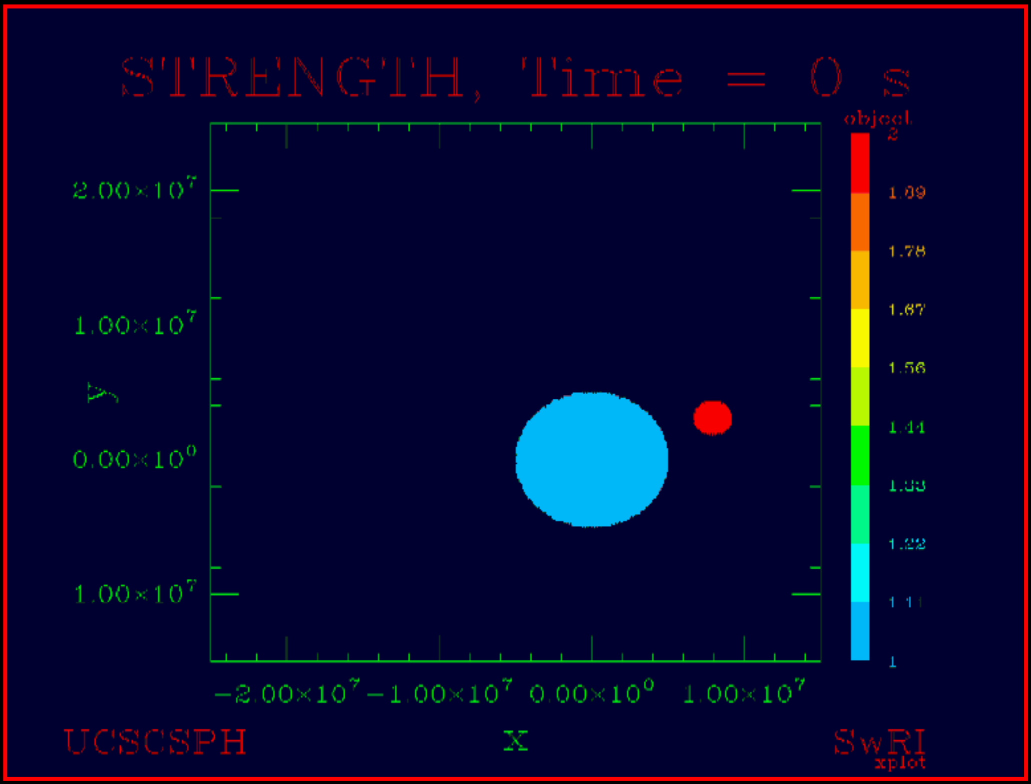

# Inner Solar System Objects

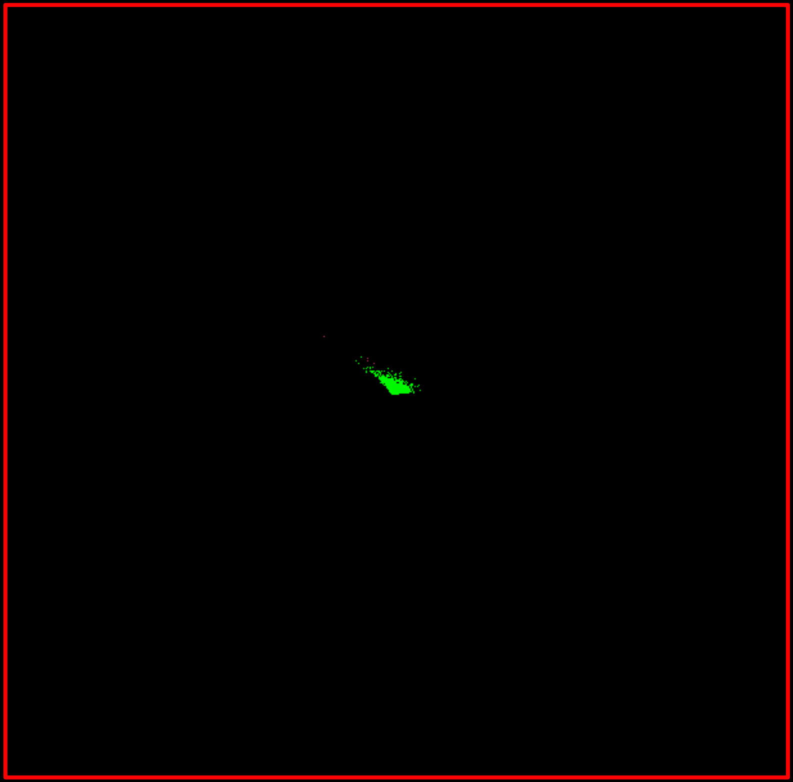


# How Do Near-Earth Asteroids Get Here? (Part 1)



# Collisions in the Asteroid Belt

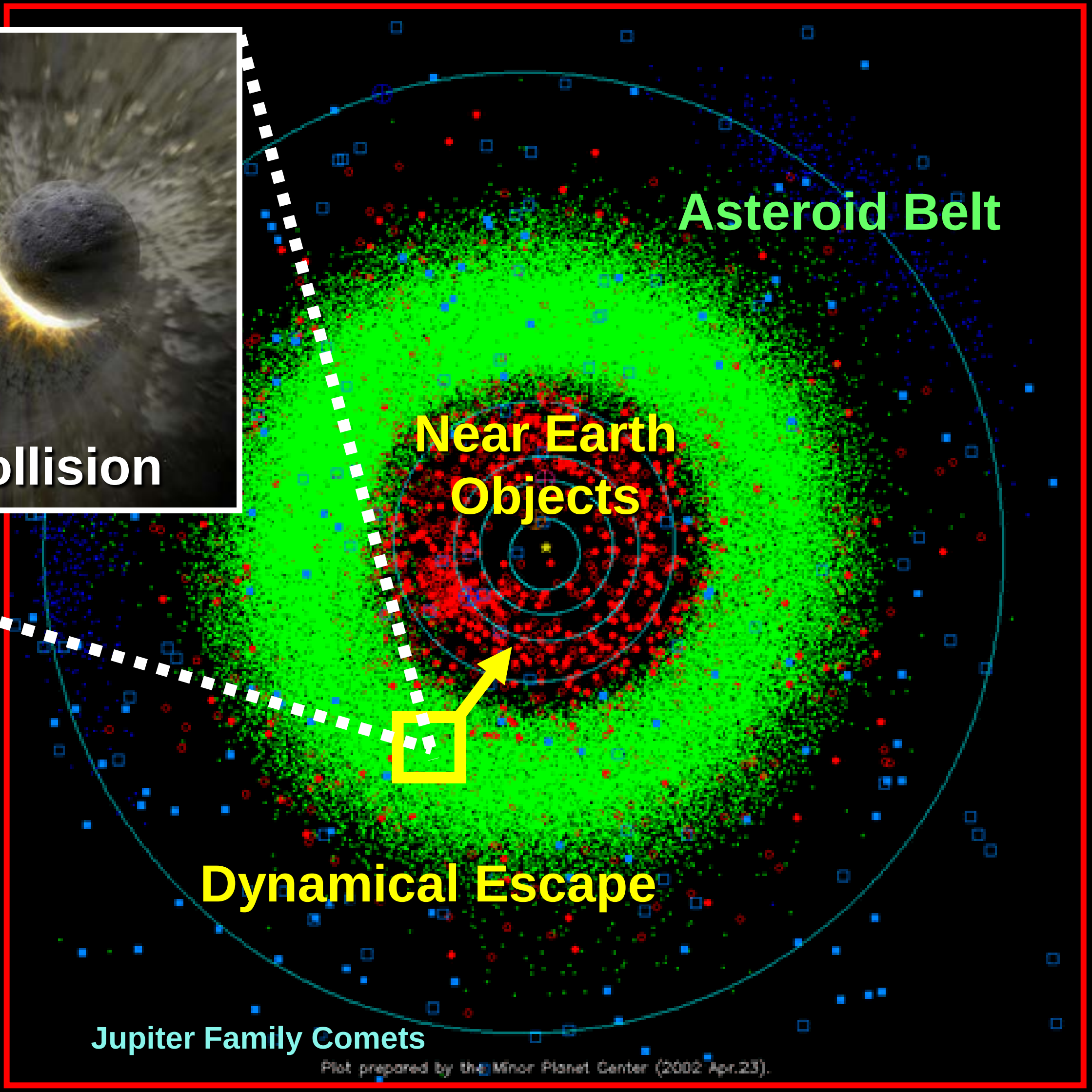


- Asteroids strike one another and create ejecta.
- Most fragments ejected at low velocities (V < 100 m/s).

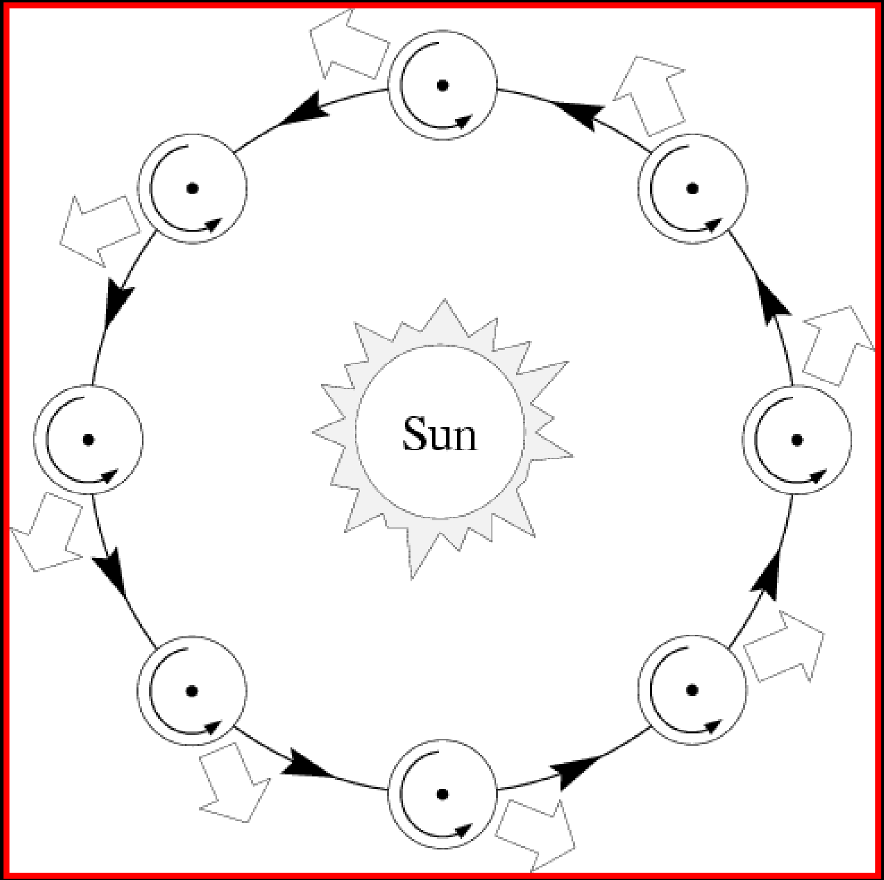
Sample references: Benz and Asphaug (1999); Michel et al. (2001); Durda et al. (2004)

# How Do Near-Earth Asteroids Get Here? (Part 2)

# The Yarkovsky Effect

**The "Diurnal" Effect**




- **Asteroids absorb sunlight and heat up.**
- **The energy is reradiated away after a short delay, causing asteroid to recoil.**
- **This "kick" causes the asteroid to spiral inward or outward.**

**Sample references: Rubincam (1995; 1998); Farinella et al. (1998); Bottke et al. (2006)**

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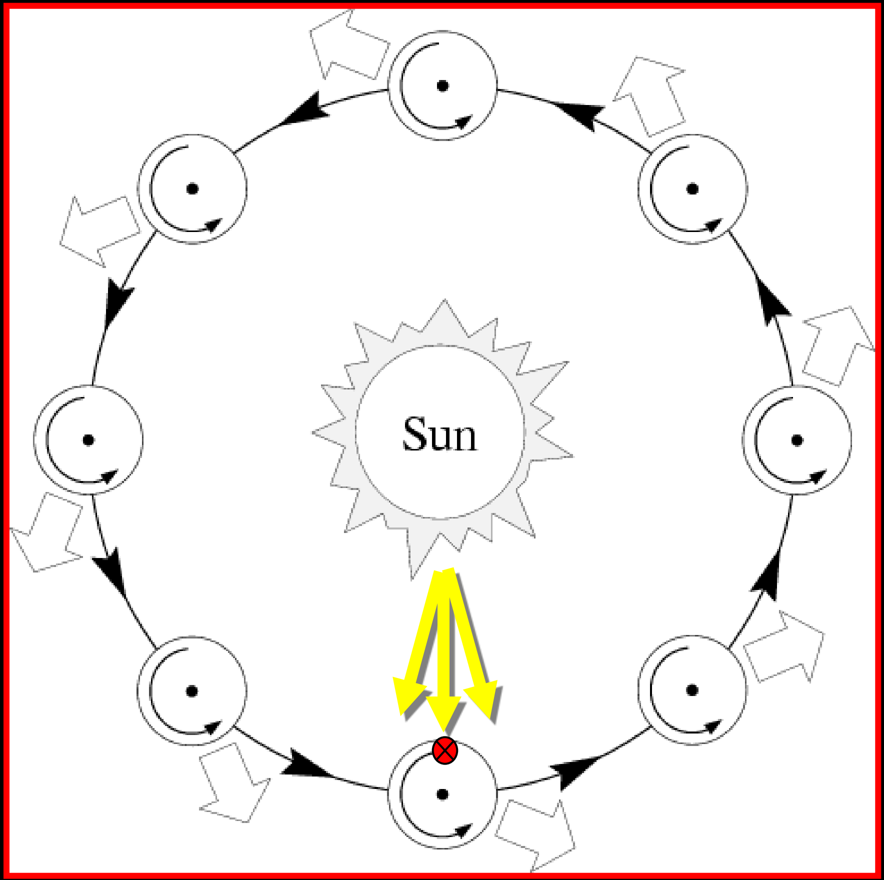
**The "Diurnal" Effect**

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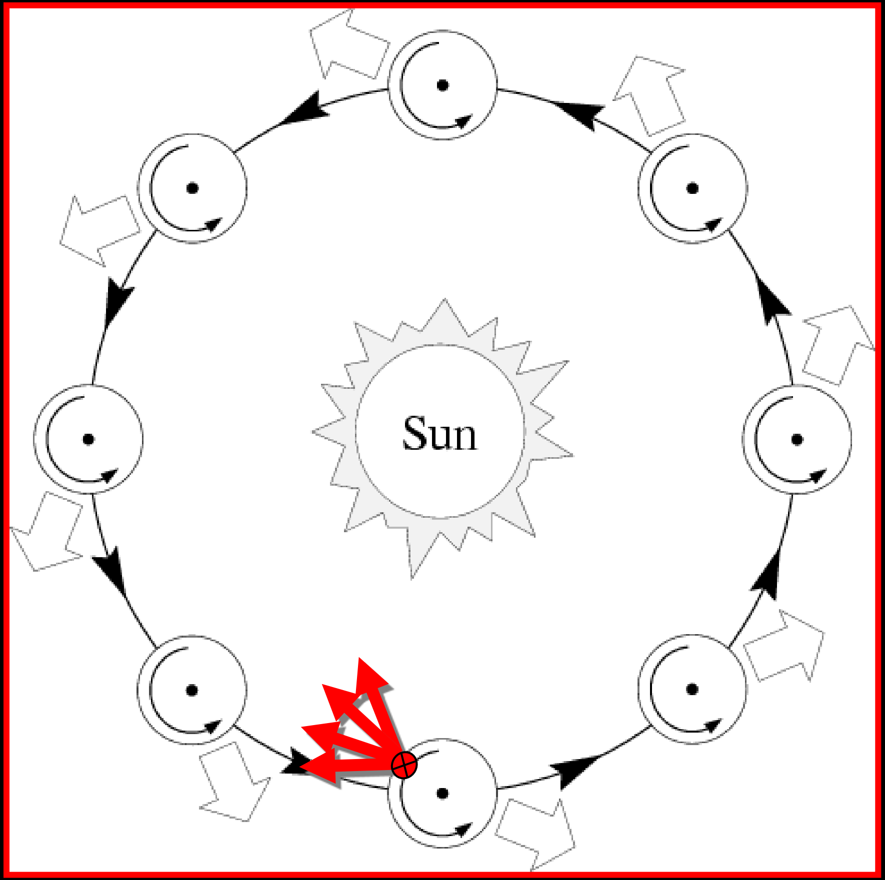


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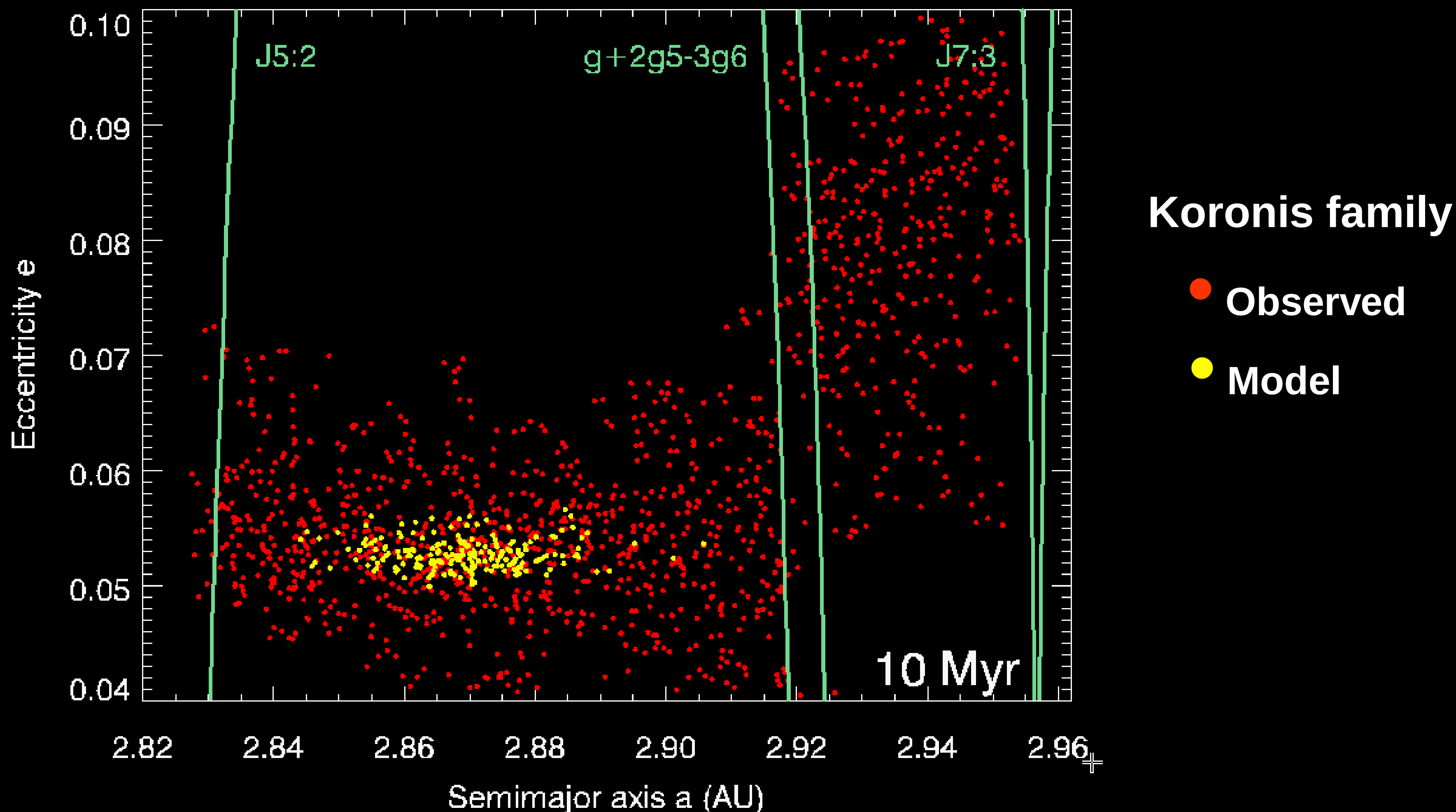
Sample references: Rubincam (1995; 1998); Farinella et al. (1998); Bottke et al. (2006)

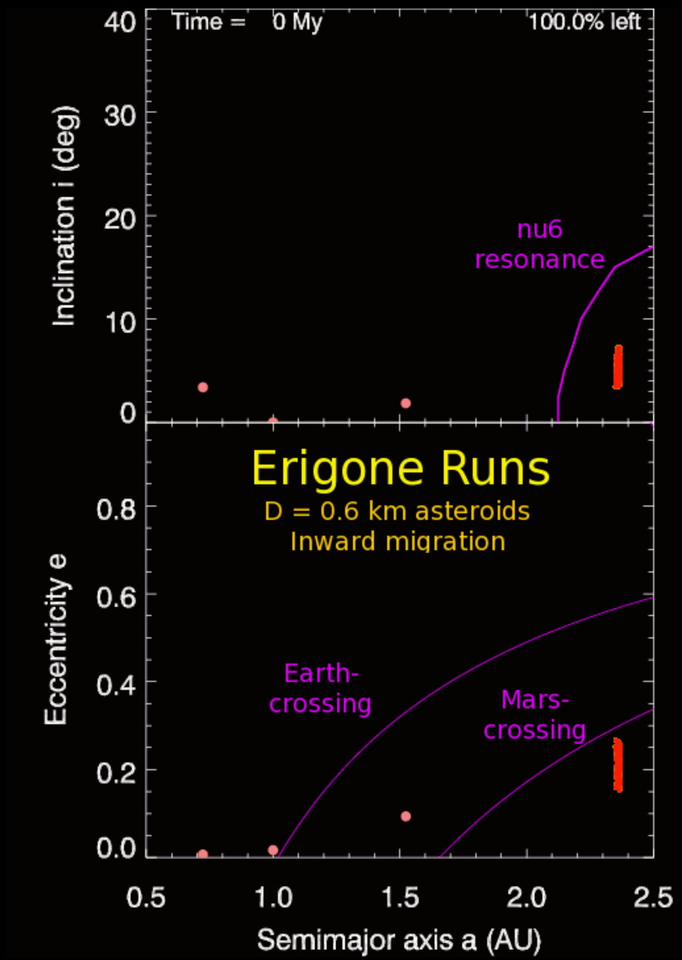
# Yarkovsky Effect Allows Fragments to Reach "Escape Hatches"



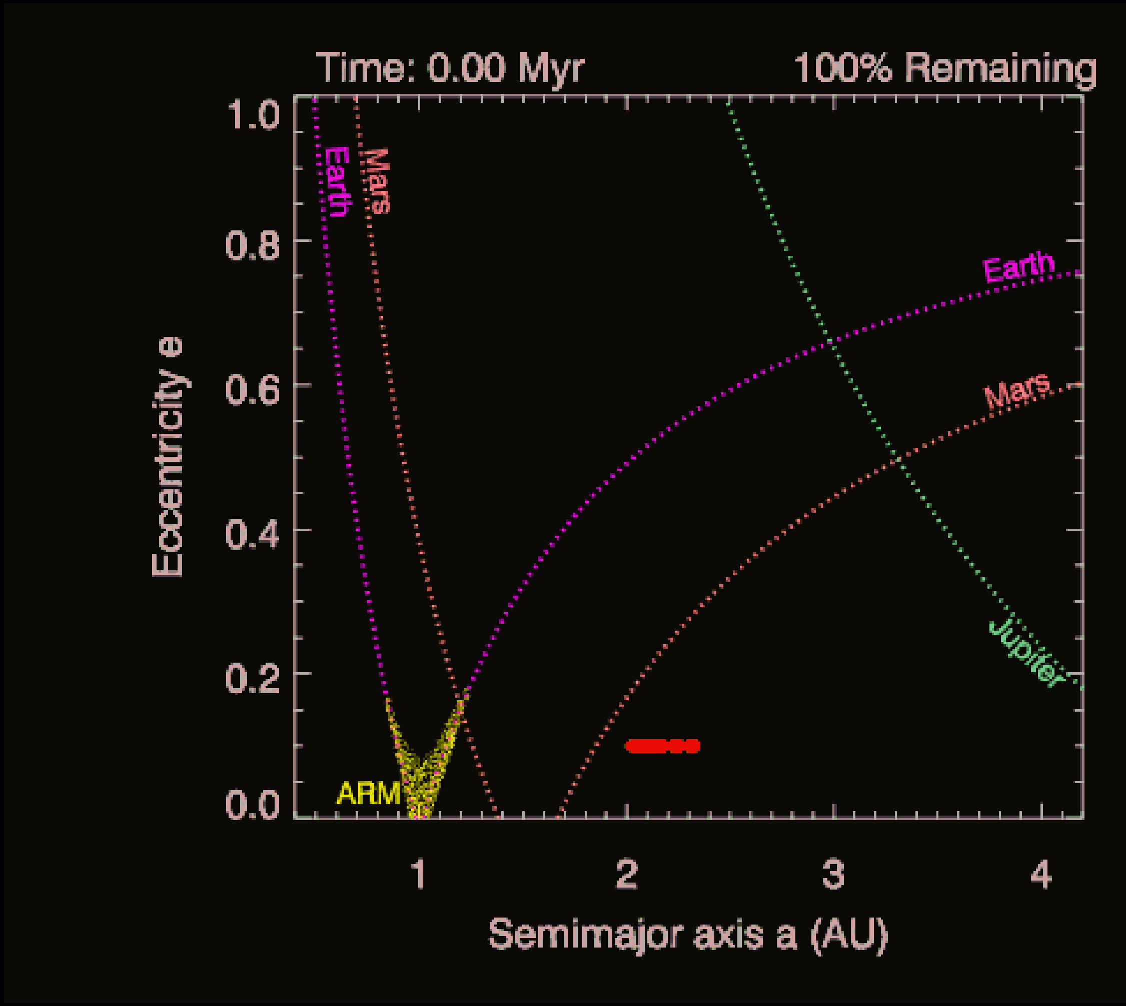

*Bottke et al. (2001)*

# Escaping the Main Belt

**Objects evolving into $\upsilon_6$ resonance**



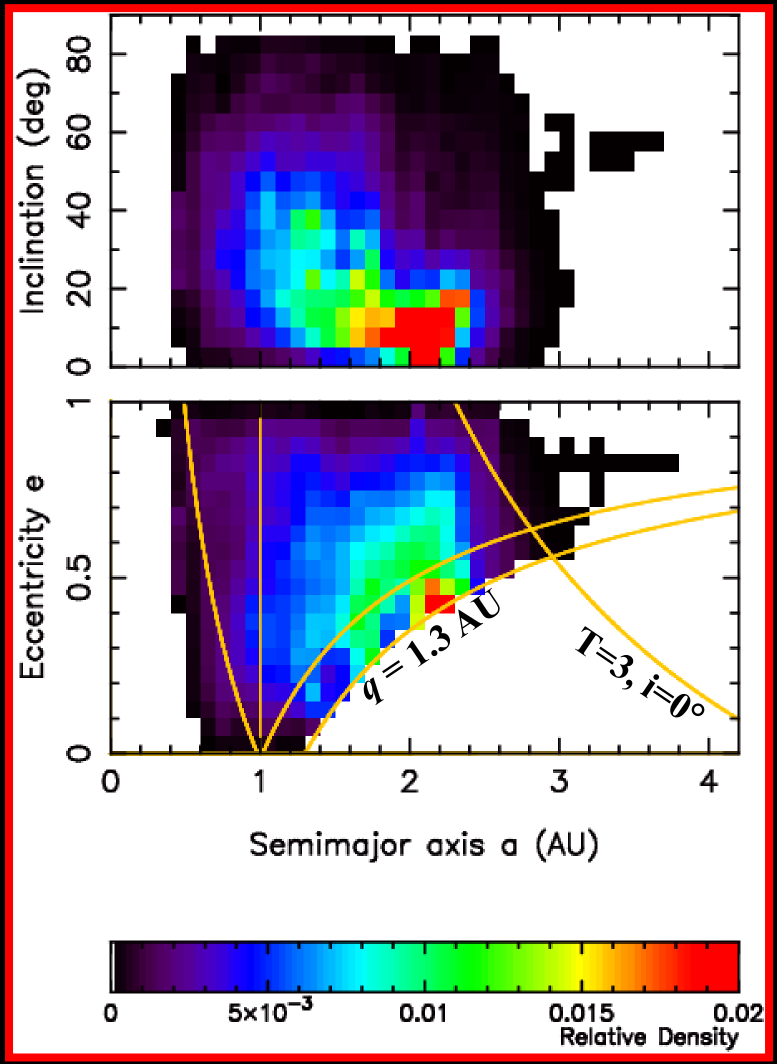

**NEOs started in $\upsilon_6$ resonance**




- **Asteroids reach NEO orbits by combo of Yarkovsky drift, resonances, and planet encounters.**

# Residence Time Probability Distribution

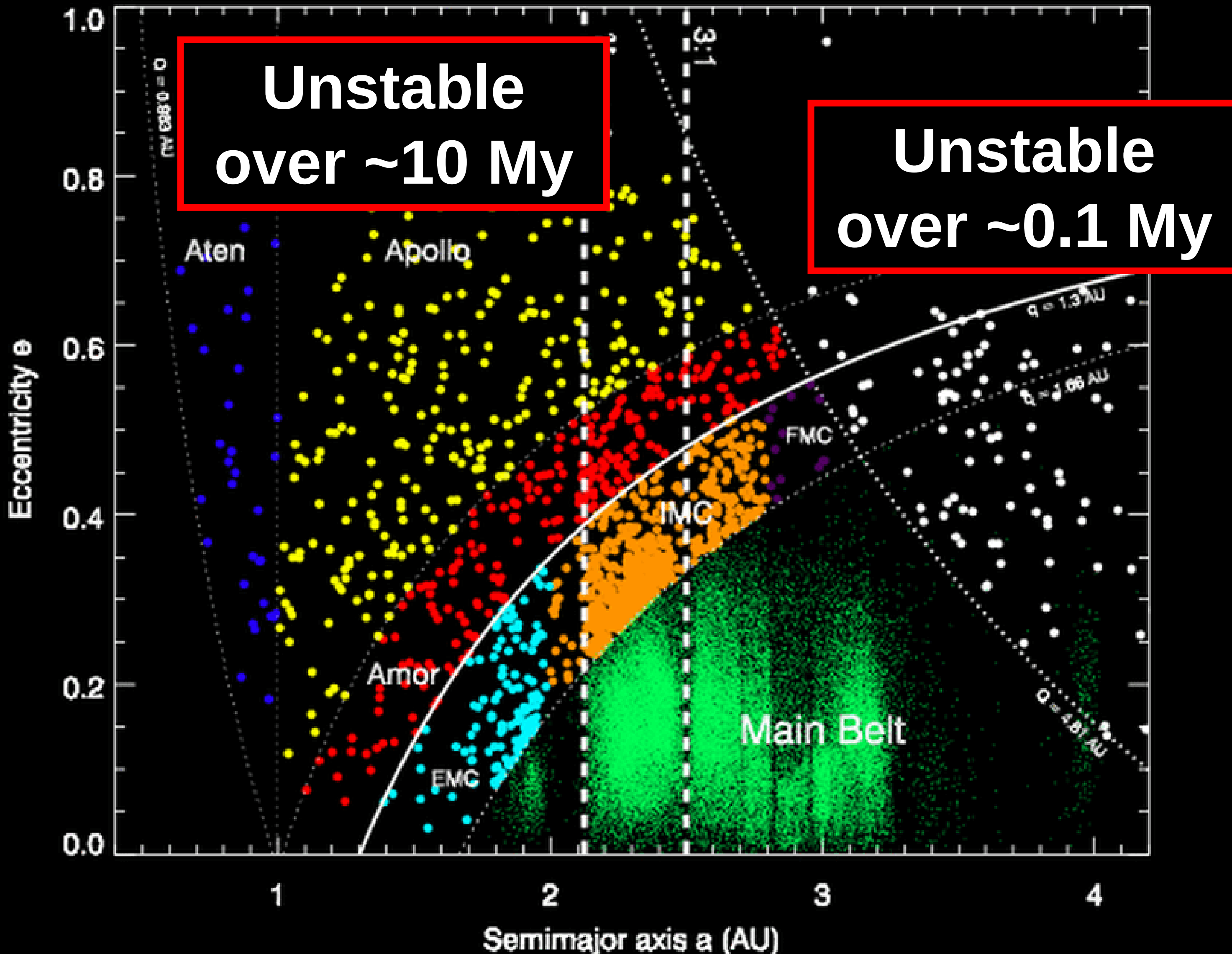
NEOs from $\nu_6$ region



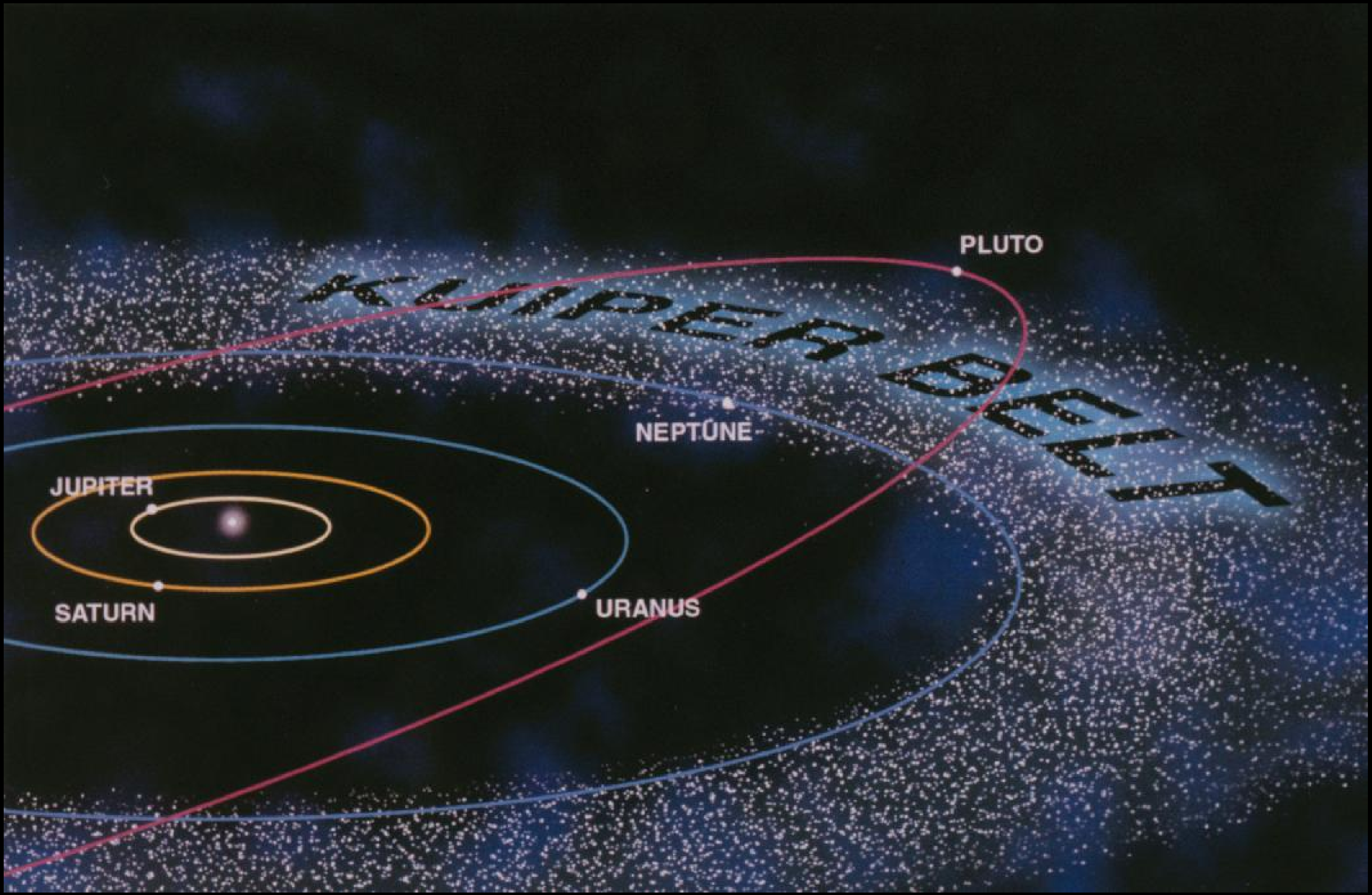

- The plot shows where NEOs are ***statistically*** spend their time in (*a*,*e*,*i*) space.
- This probability distribution is ***equal*** to the steady state orbital distribution from the source.

Bottke et al. (2002)

# What About Comets?

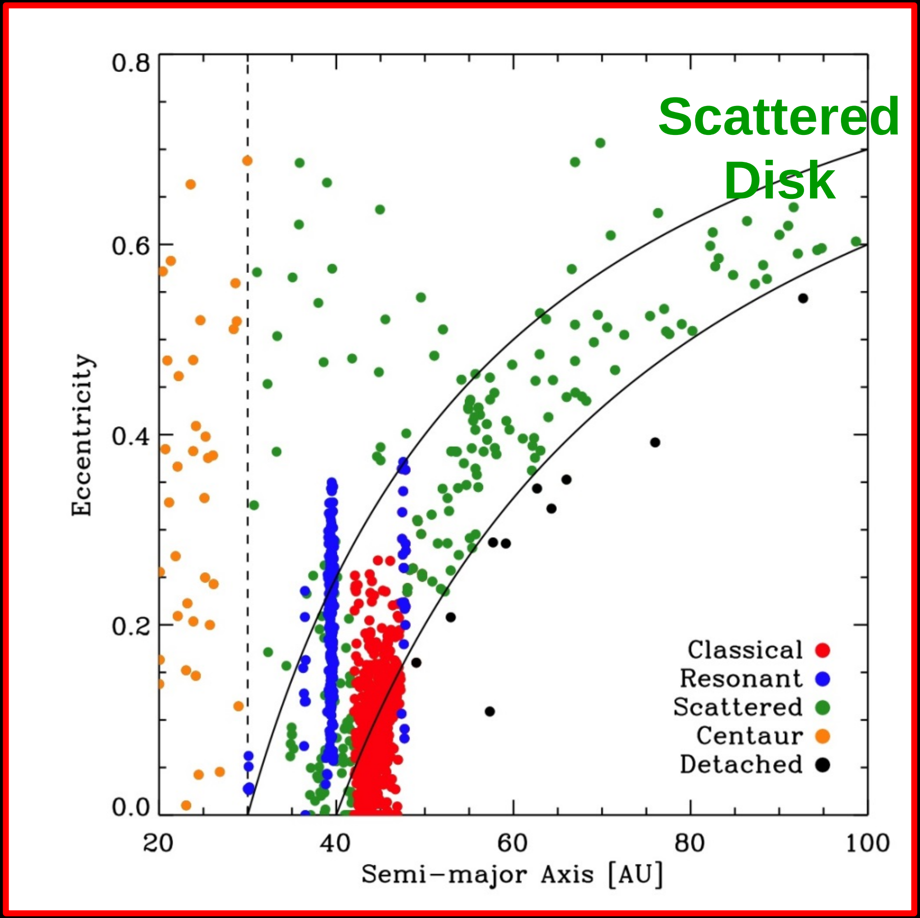


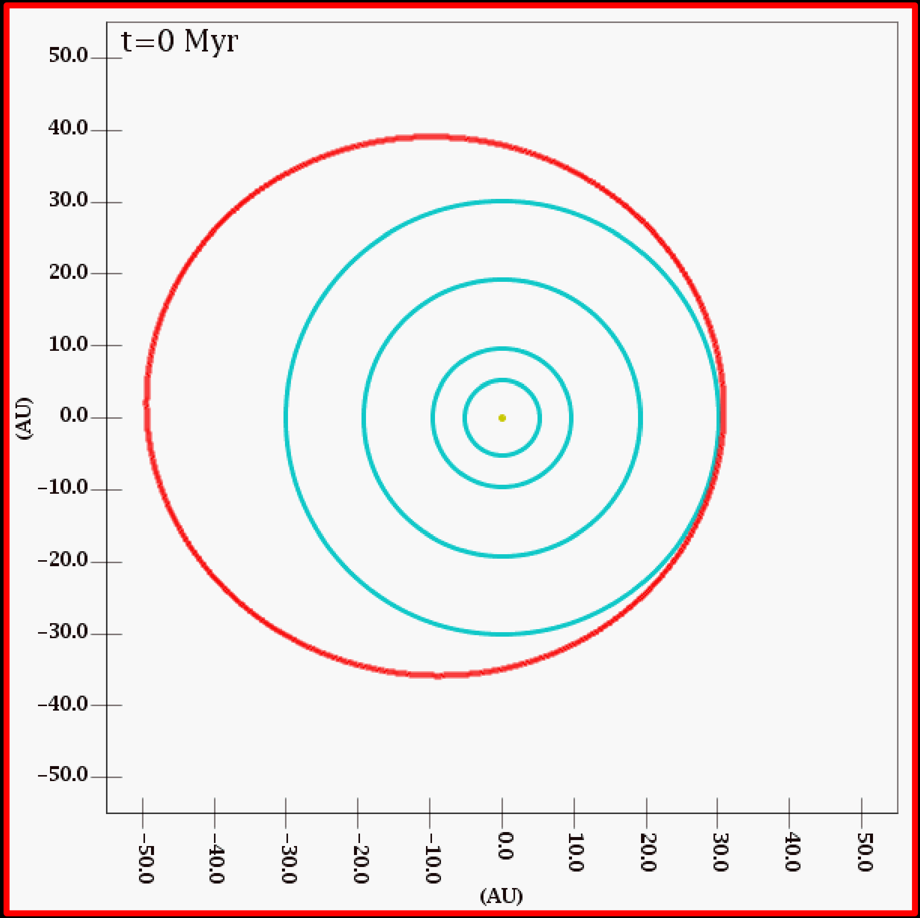
# The Transneptunian Region




- A huge reservoir of comets near or beyond the orbit of Neptune. Many are on long-term unstable orbits.

# Jupiter Family Comets from Scattered Disk



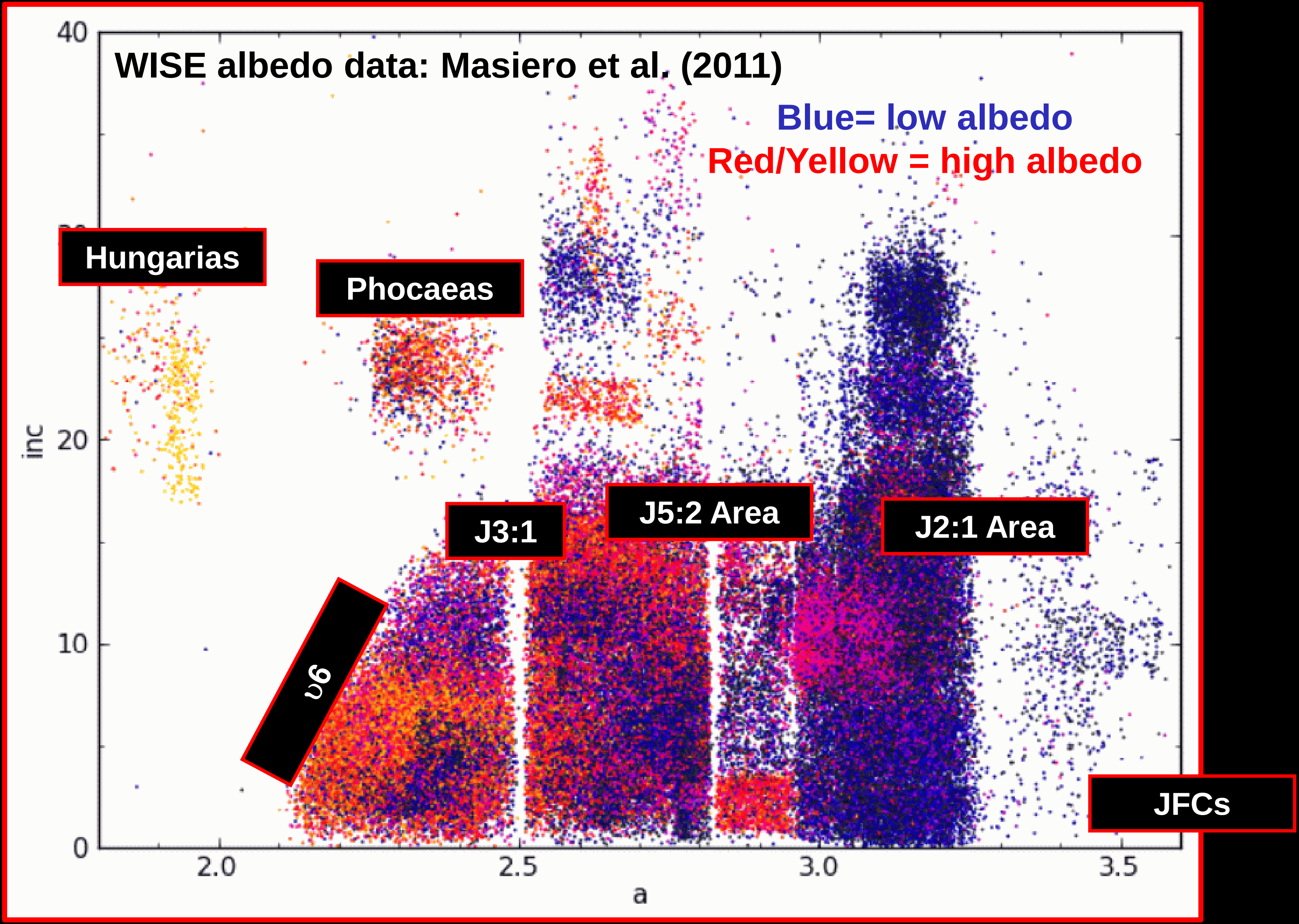




- Many scattered disk objects unstable, and evolve into inner solar system via encounters with the giant planets.

Sample Reference: Duncan and Levison (1997); Jewitt et al. (1998)

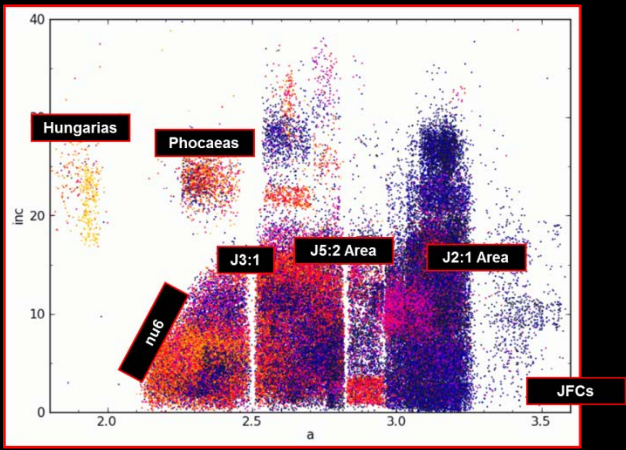
# Part 2:
# Modeling the NEO Population
## *Old: Bottke et al. 2002*
## *New: Granvik et al. 2014*

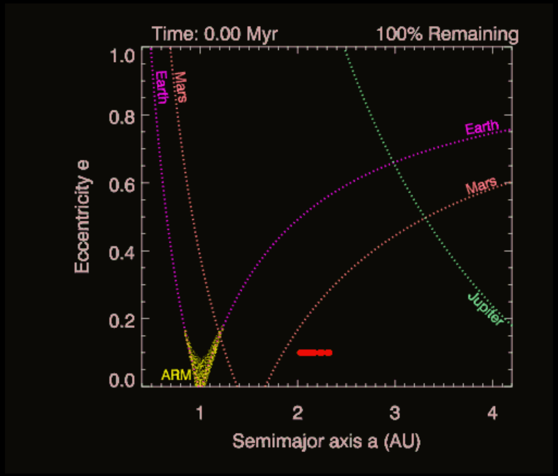
# NEO Source Regions




- Years of study allow us to identify main NEO sources. Each source produces distinctive orbital histories.

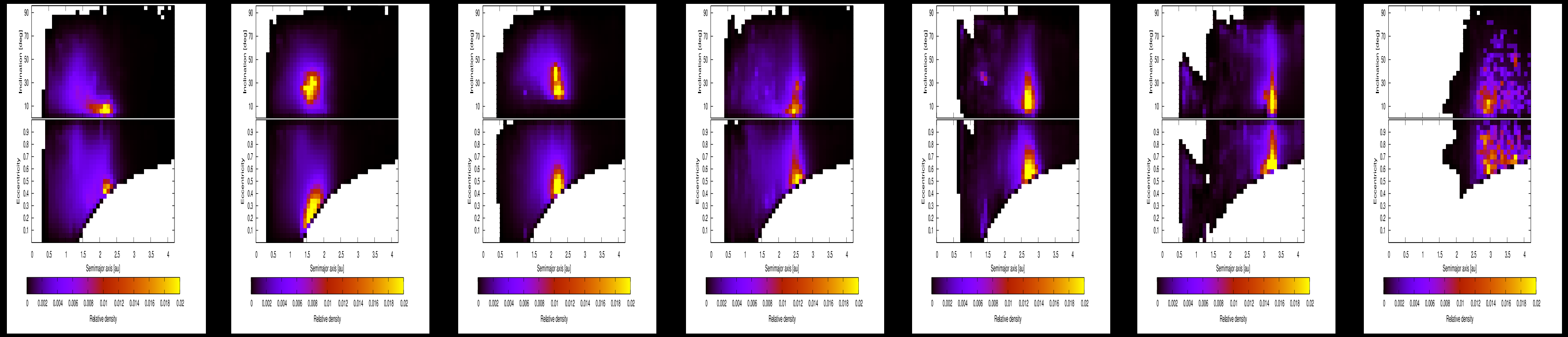
# Components of the NEO Population




**Combine NEO Sources**
R *(a,e,i)*

| nu6 | Hungarias | Phocaeas | J3:1 | J5:2 Area | J2:1 Area | JFCs |
|---|---|---|---|---|---|---|

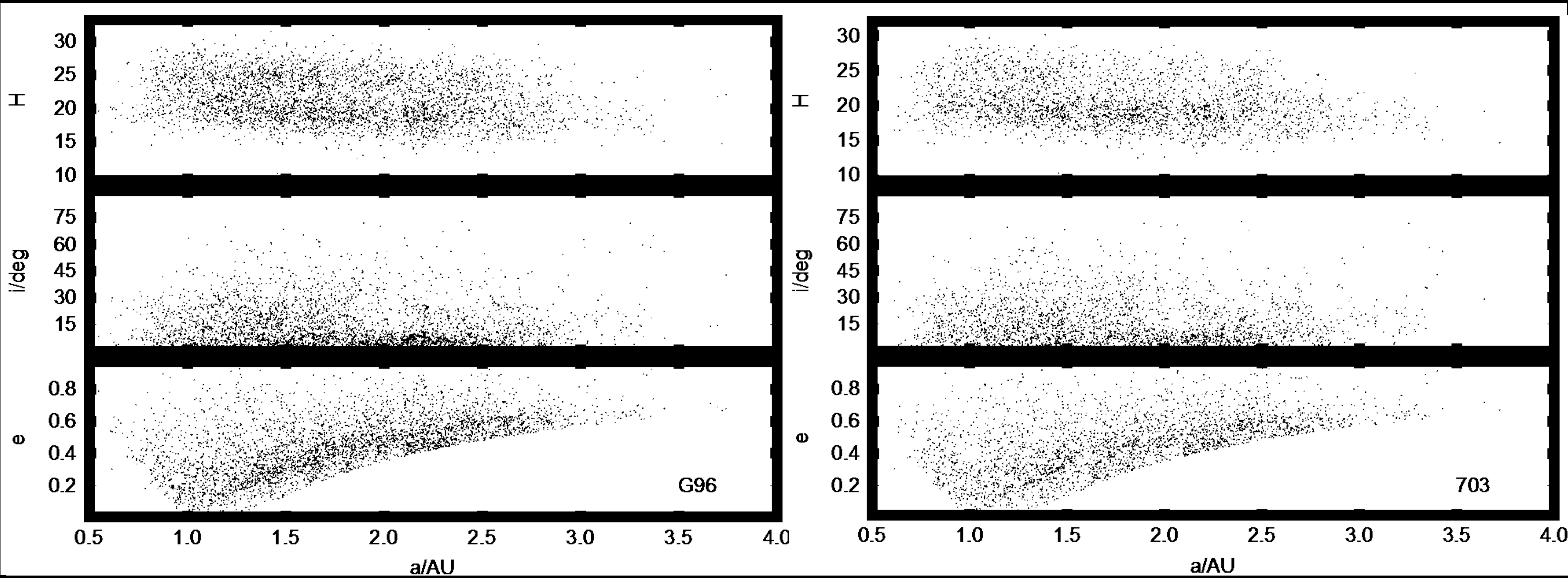


- **We add NEO components with weighting parameters to get combined NEO model population.**

# NEO Detections by CSS's 2005-2012

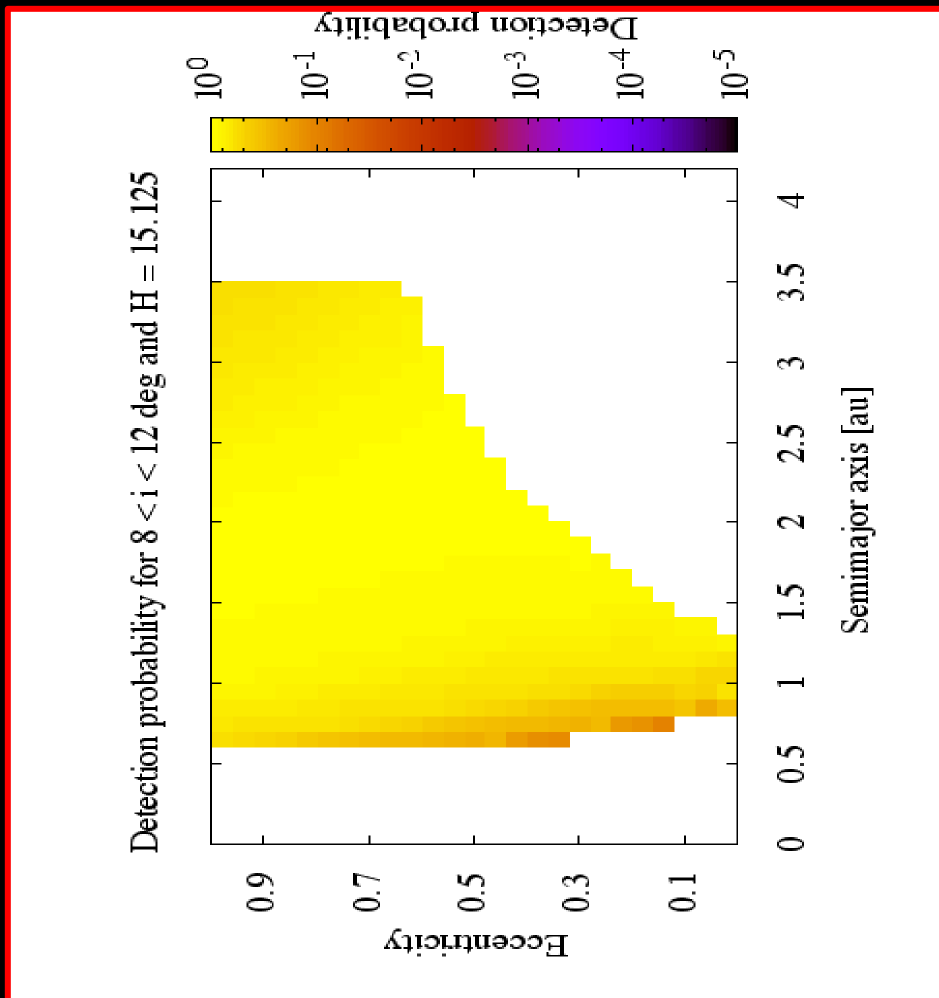
**Mt. Lemmon (G96)**
**Narrow and deep**

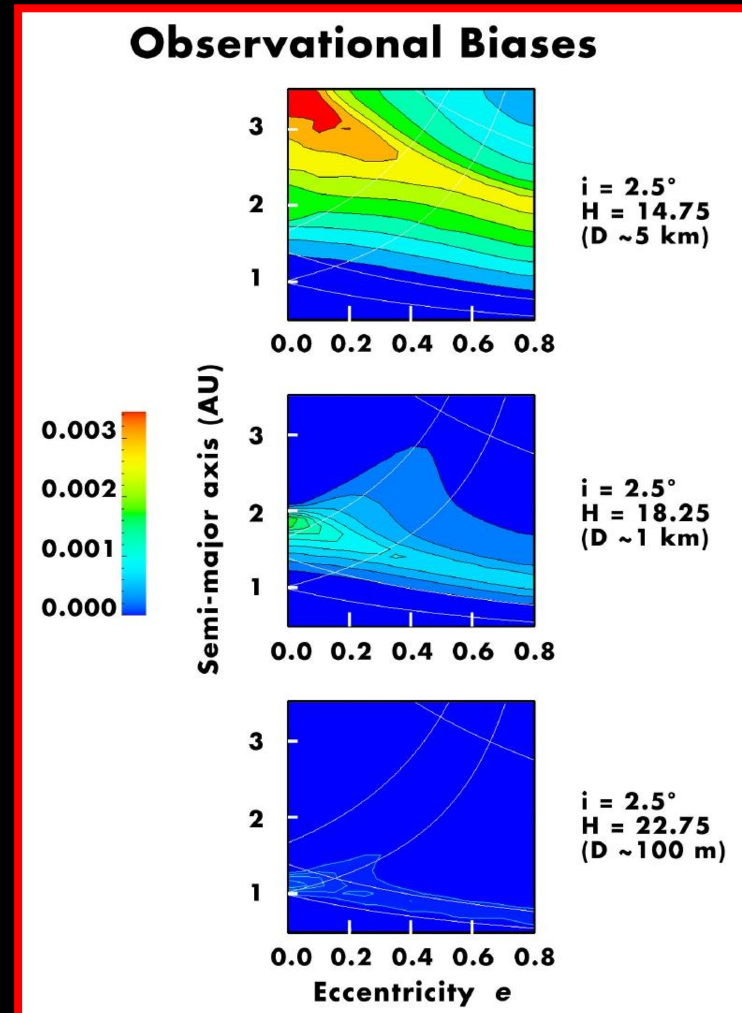
**Catalina (703):**
**Wide and shallow**




- We want to compare different NEO probability distributions to > 4500 NEO detections by Catalina Sky Survey.
- Need to account for observational biases!

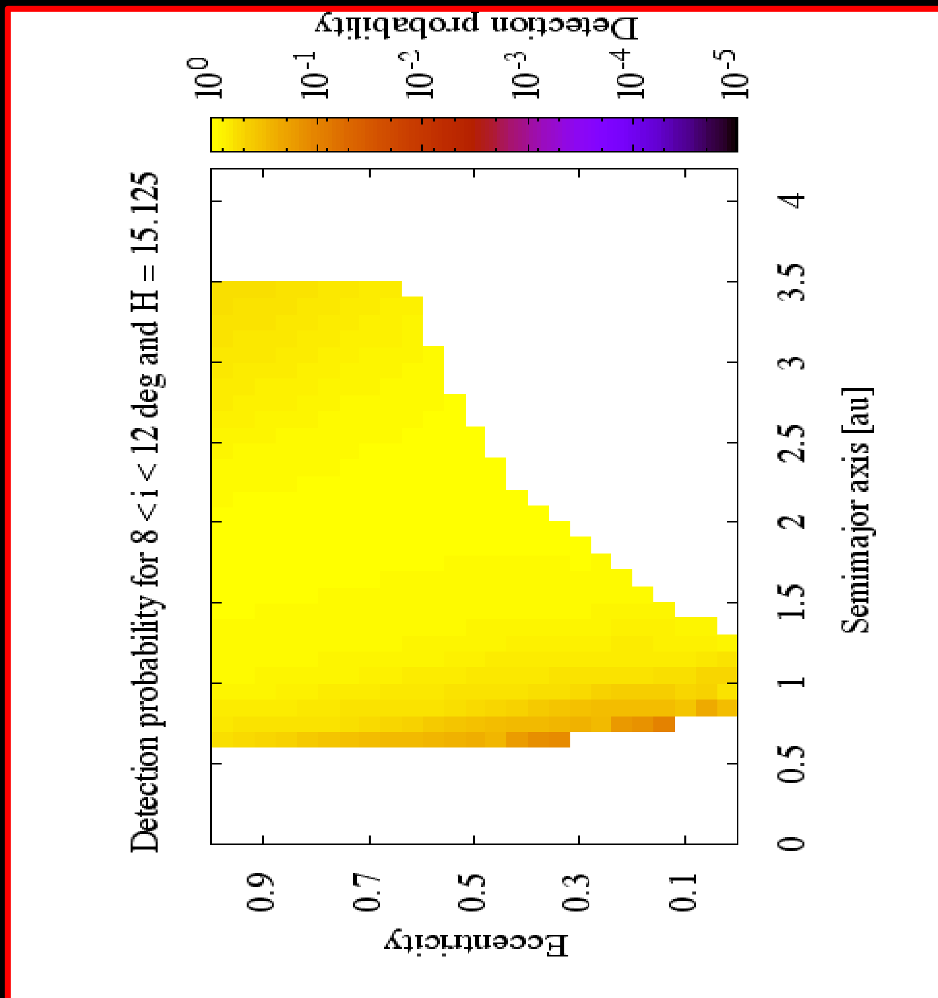
# Catalina Sky Survey Observational Biases

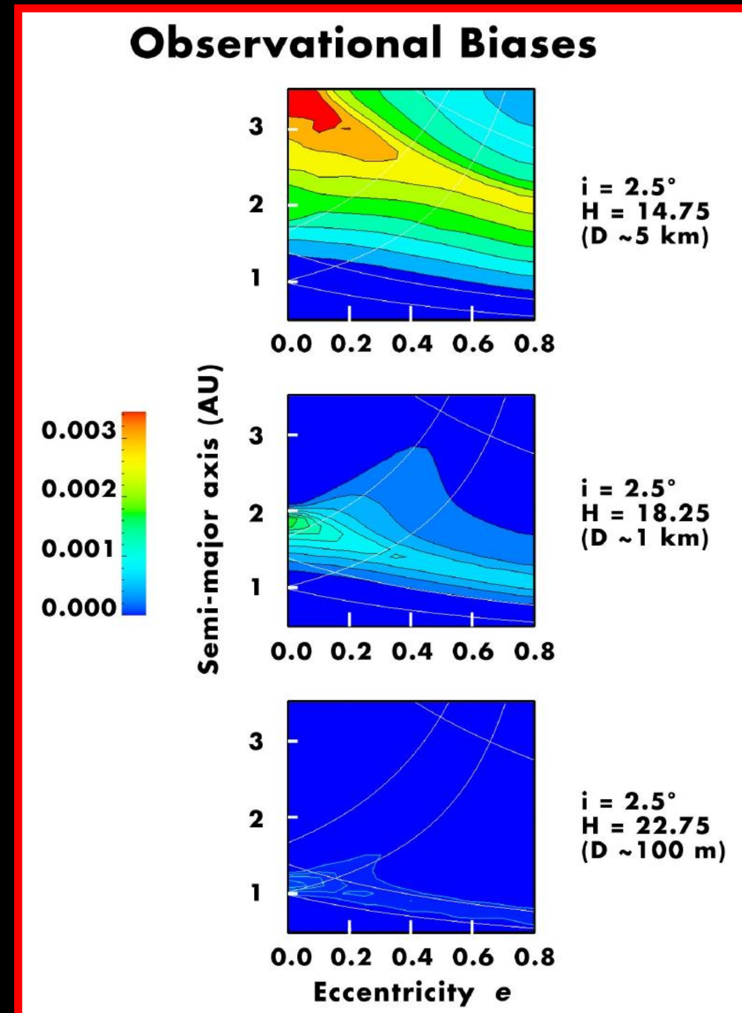



- Bright objects above limiting mag. even from far away. Dim objects most easily detected near the Earth.

# Catalina Sky Survey Observational Biases

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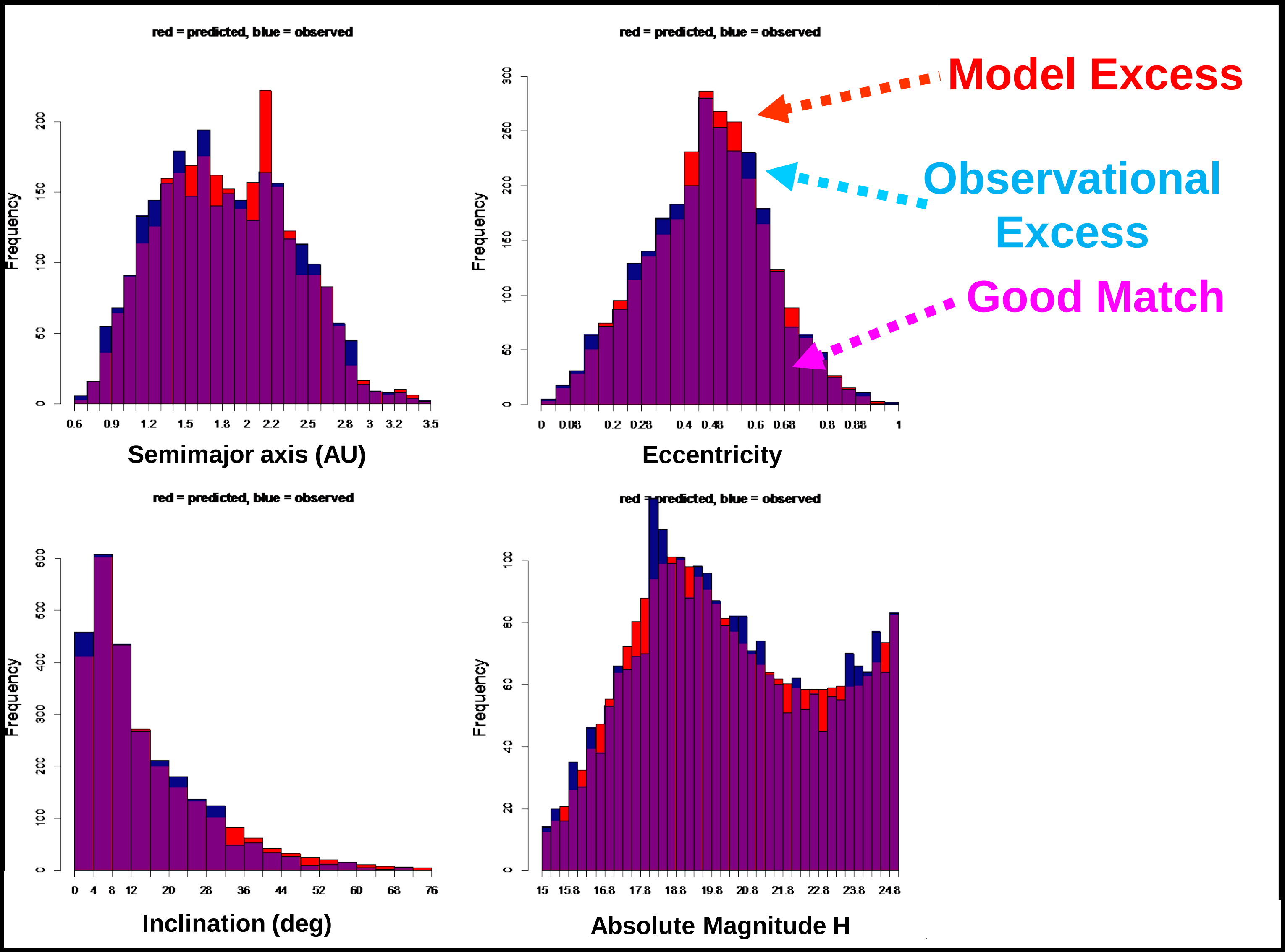
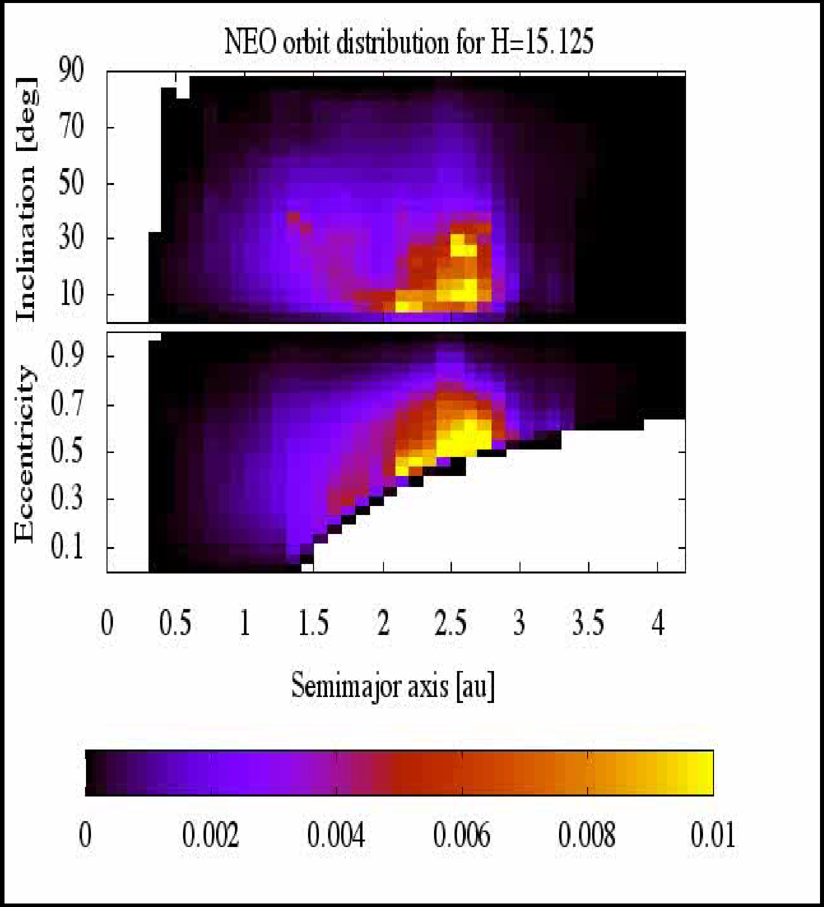
# NEO Model vs. Observations




- Excellent fits for orbits (*a*,*e*, *i*) and absolute magnitude (*H*).

# Debiased NEO Population

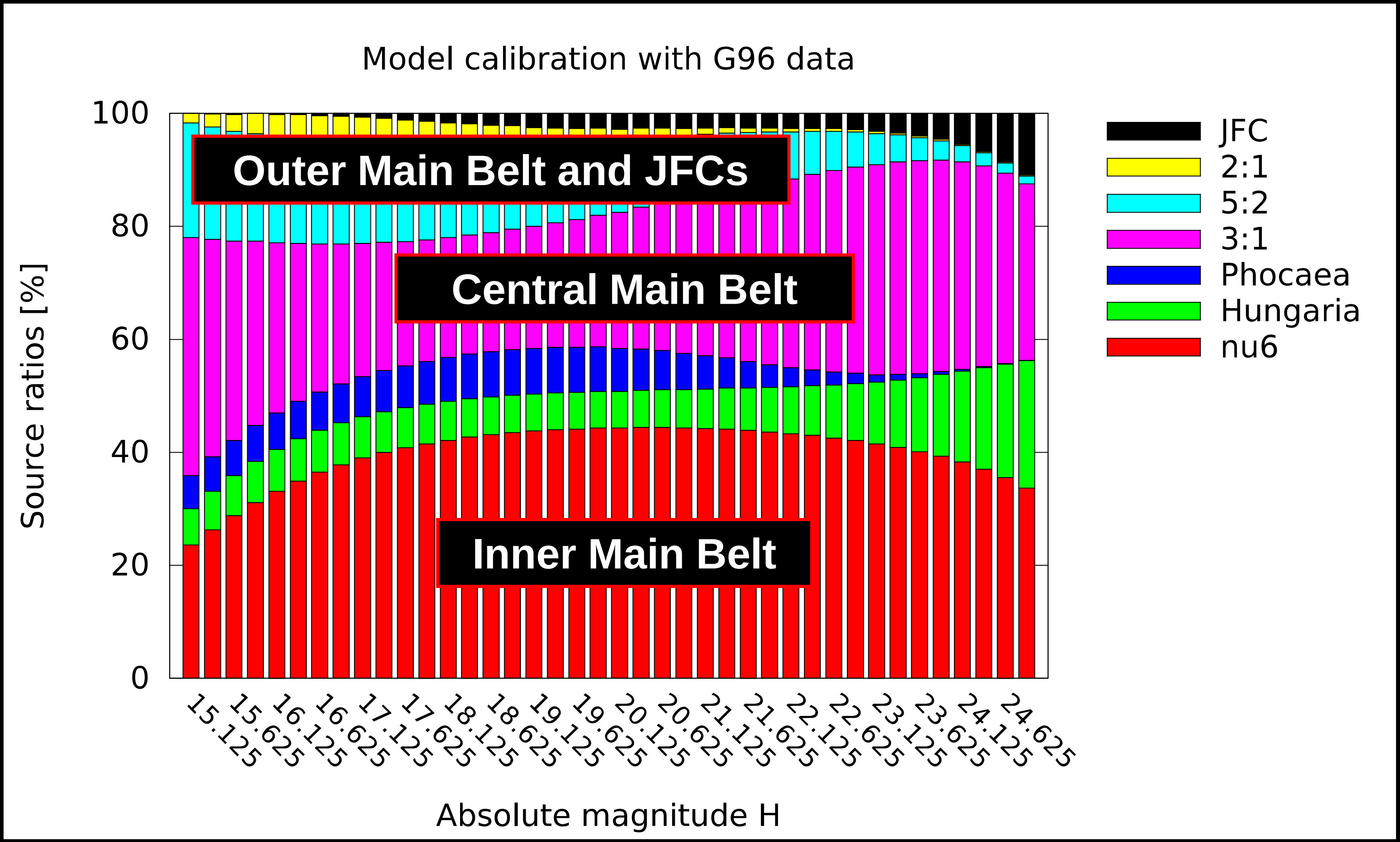



**Granvik et al. (2014)**
**15 < *H* < 25**

**Bottke et al. (2002)**
**13 < *H* < 22**

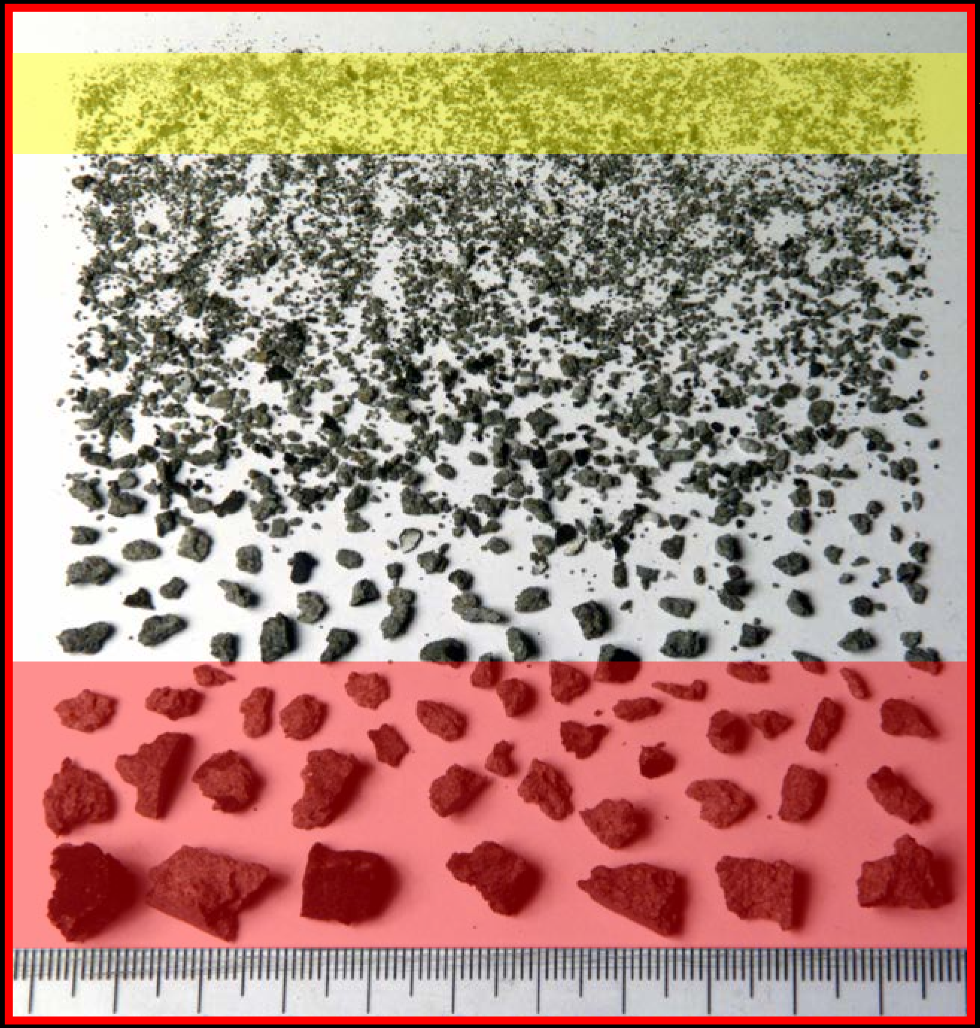
- **New NEO model for 15 < *H* < 25 (0.1 < *D* < 5 km). Similar overall shapes, yet more Amors and changes with *H*.**

# NEO Predicted Source




- **Source results fairly similar to Bottke et al. (2002). Most NEOs come from inner and central main belt.**

# Size Distribution



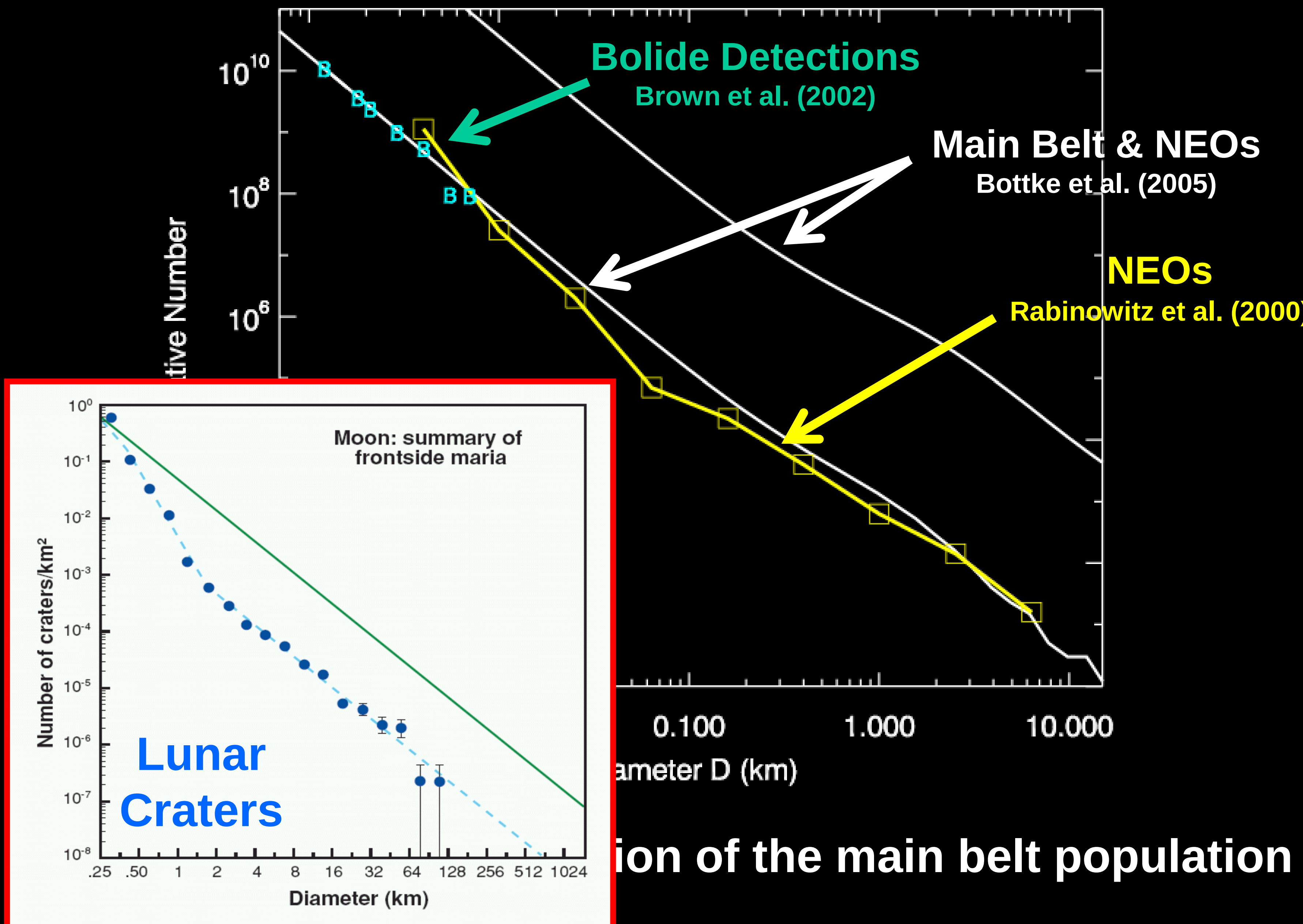
Almost none are known

*NEOs*

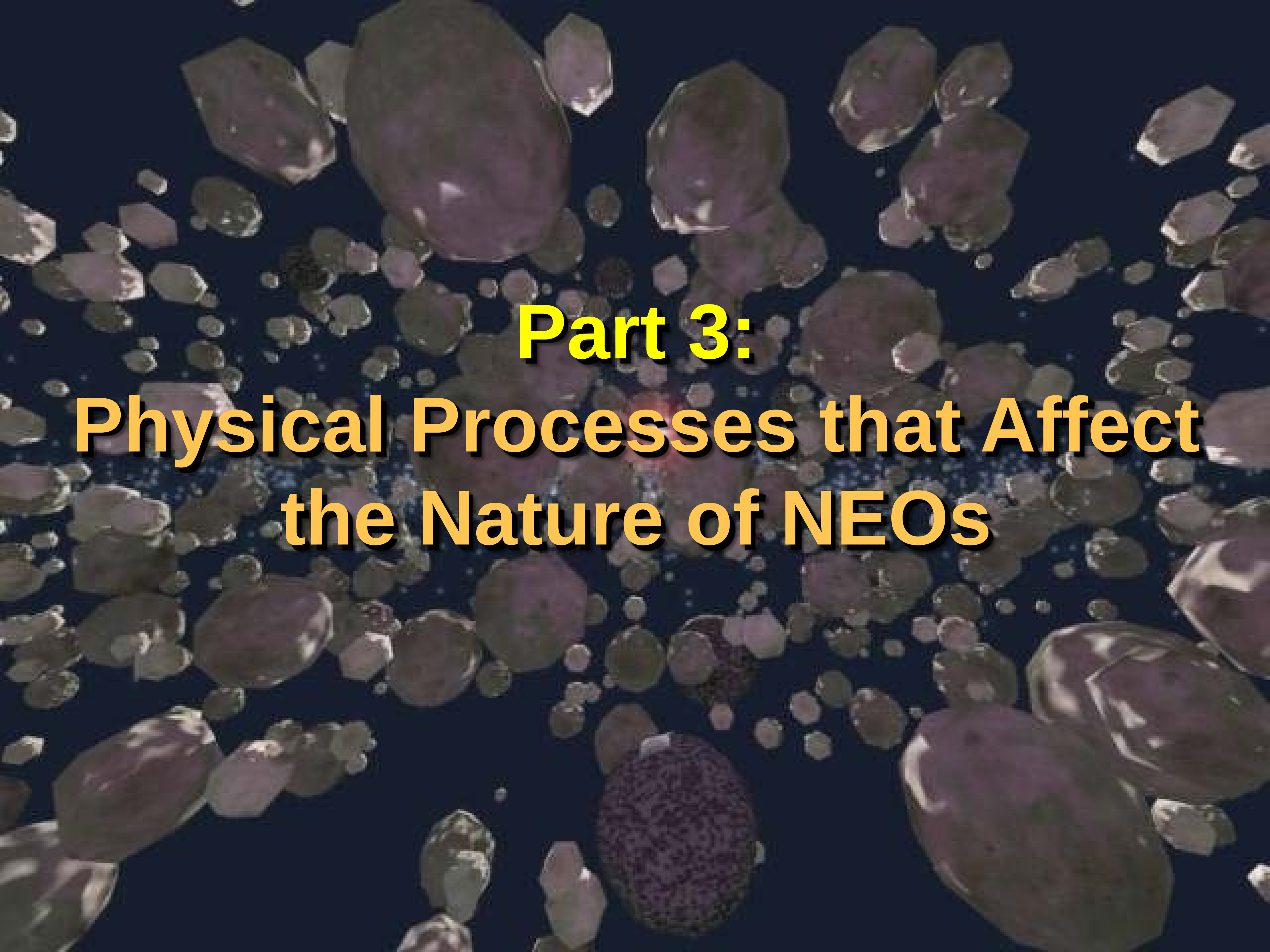
Most are known

- **Size distribution: Few big bodies, lots of small bodies…**

# Main Belt and NEO Size Distribution



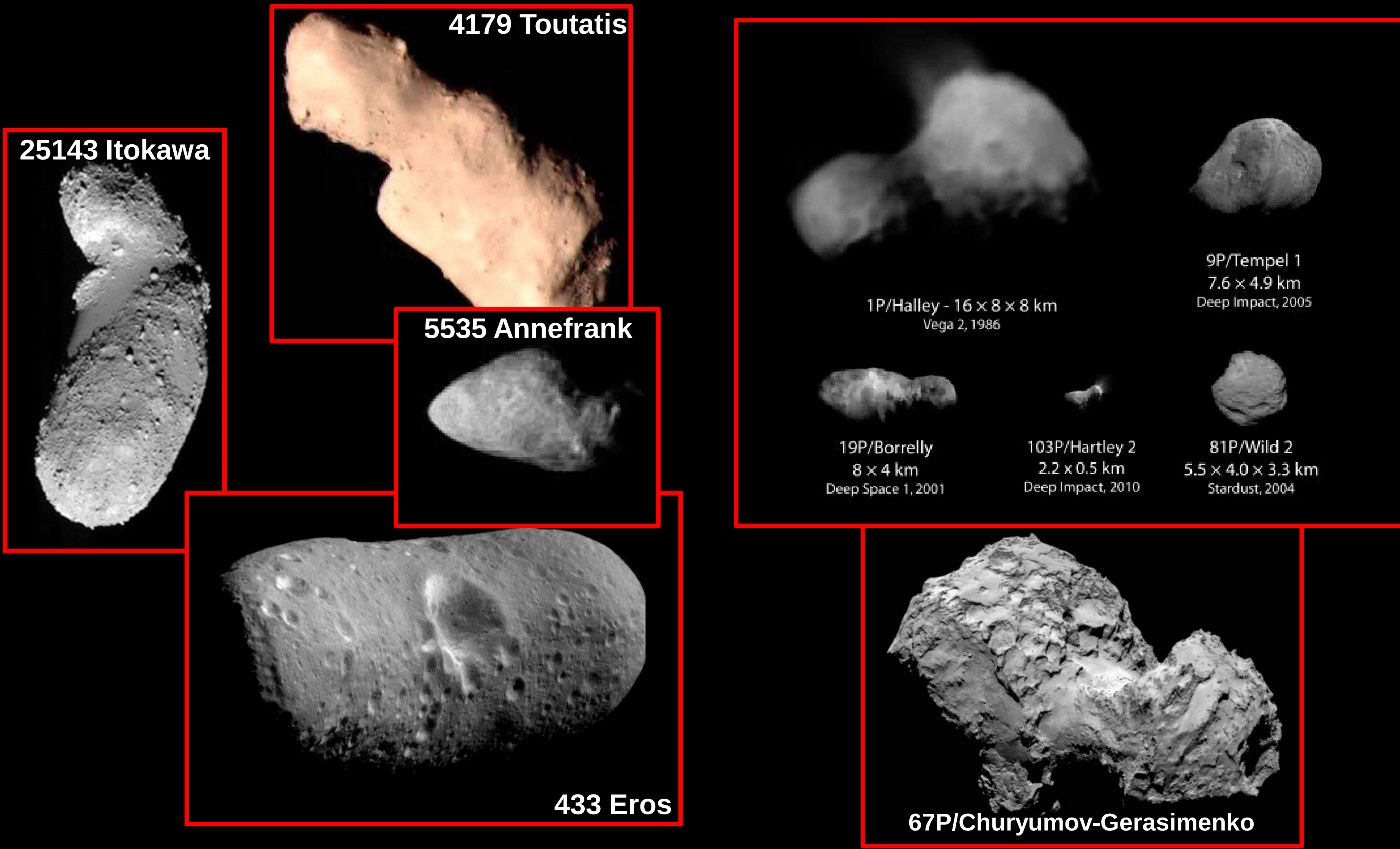

ion of the main belt population



# Part 3:

# Physical Processes that Affect the Nature of NEOs

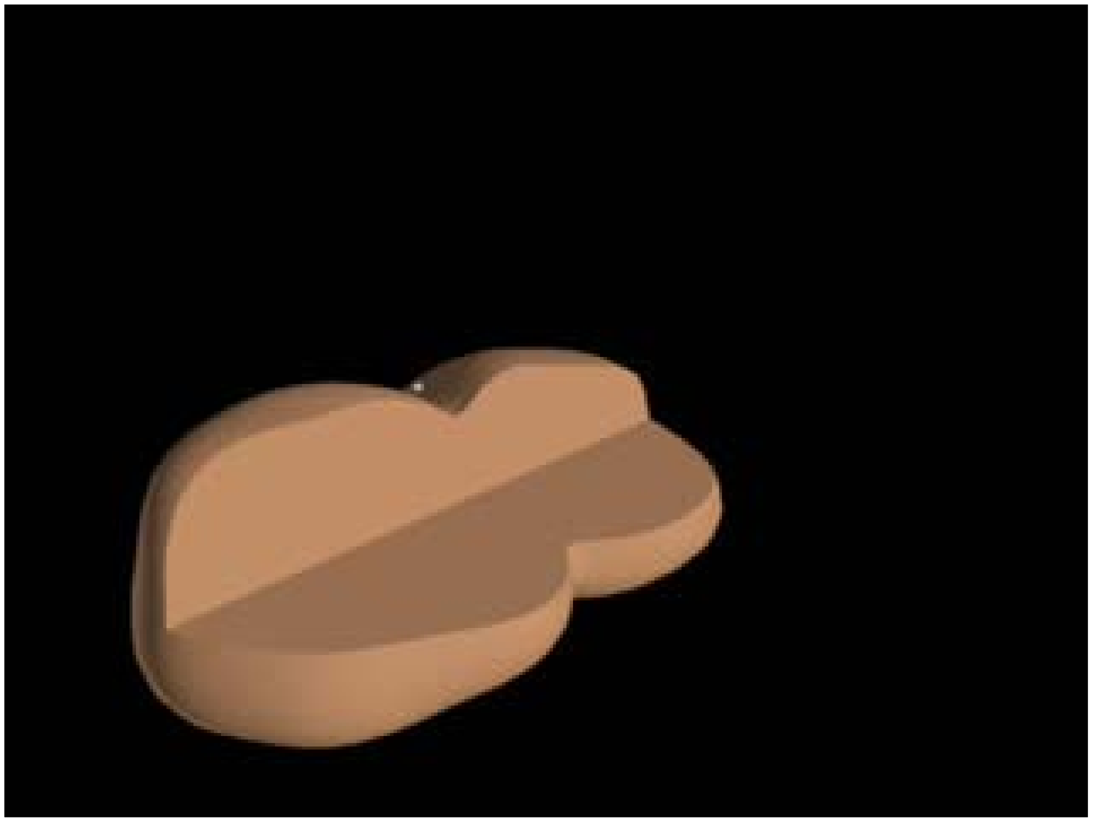
# NEOs: Many Shapes and Sizes




- Many NEOs appear to be collisional byproducts (e.g., contact binaries, irregular elongated objects, etc.)

# Collisions and Asteroids

= Maximum Damage



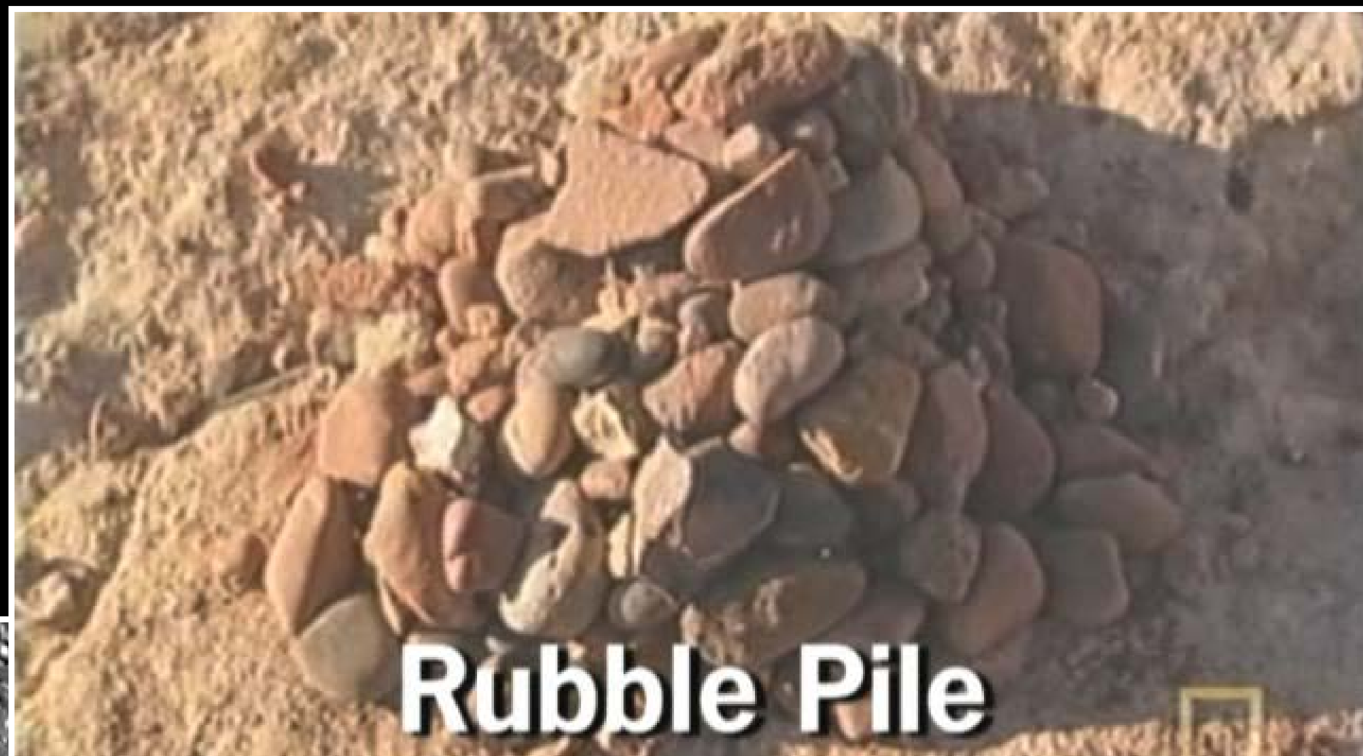
Asphaug et al. (1996)

- Impacts produce shock waves that fragment asteroid interiors
- Only a fraction of material is sent flying away from impact site

# Impacts Into Rocks

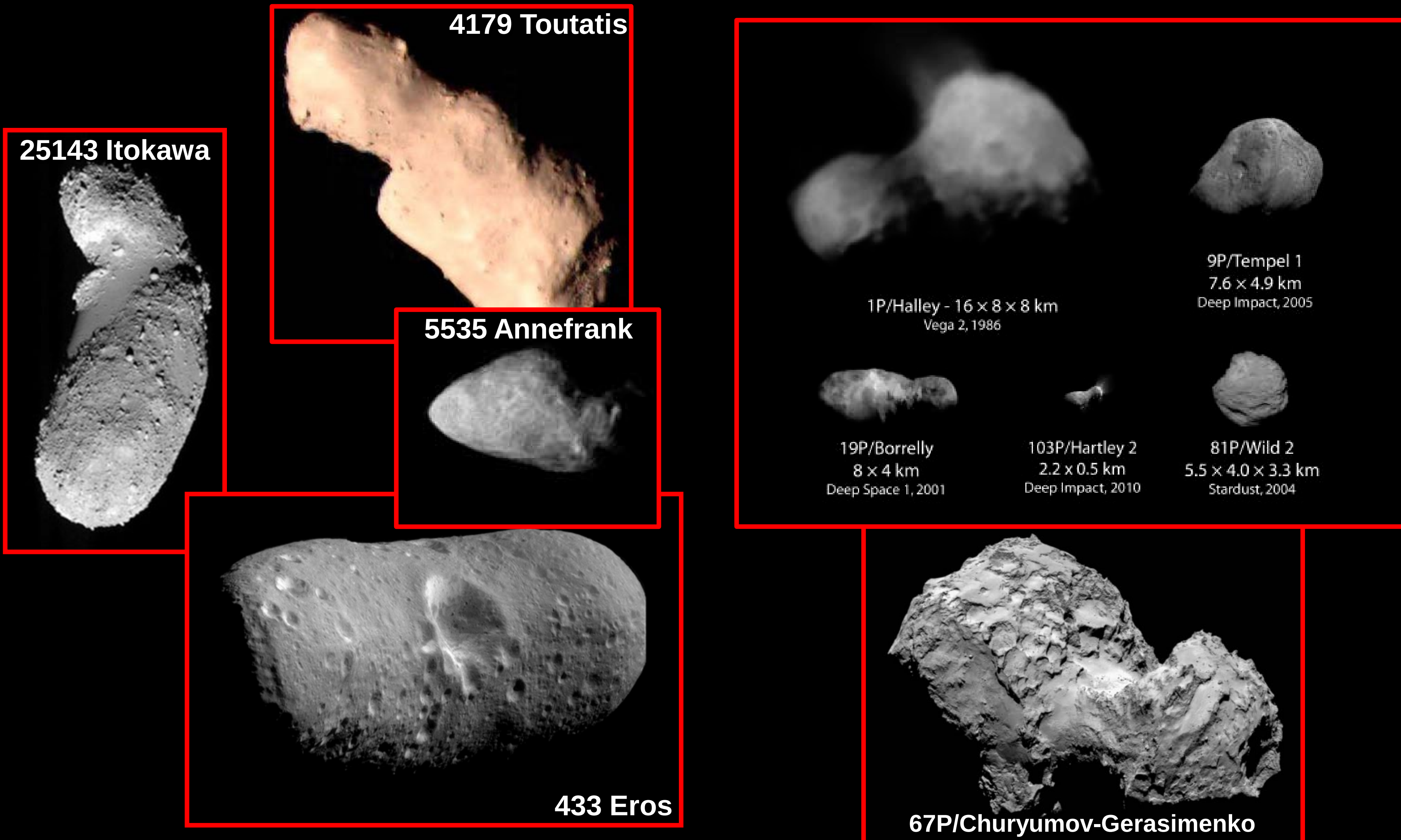

“Naked Science,” National Geographic, 2004

# Impacts Into Rubble Pile



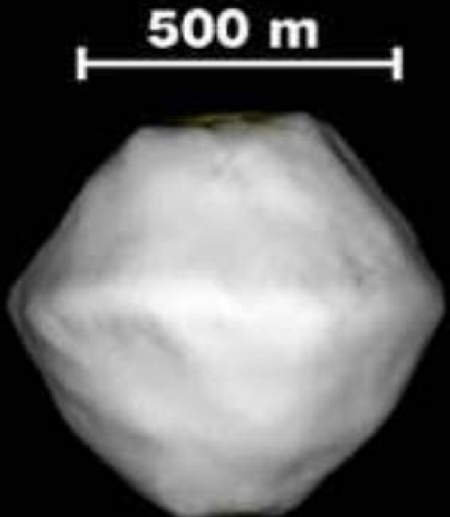

“Naked Science,” National Geographic, 2004

# NEOs: Many Shapes and Sizes

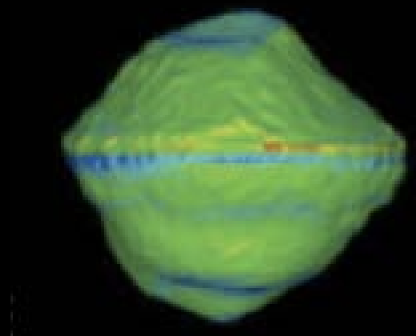



- **Many NEOs appear to be collisional byproducts (e.g., contact binaries, irregular elongated objects, etc.)**

# Radar Observation: Many "Top-Like" NEOs

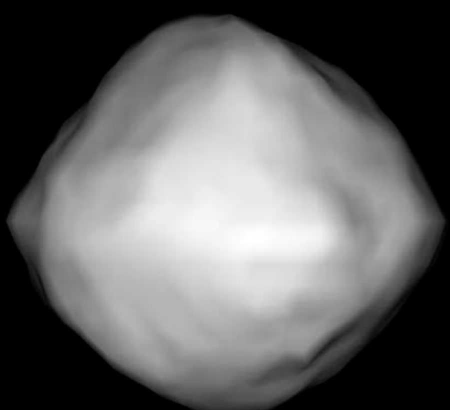



Triple Asteroid 1994 CC
Brosovic et al. 2011

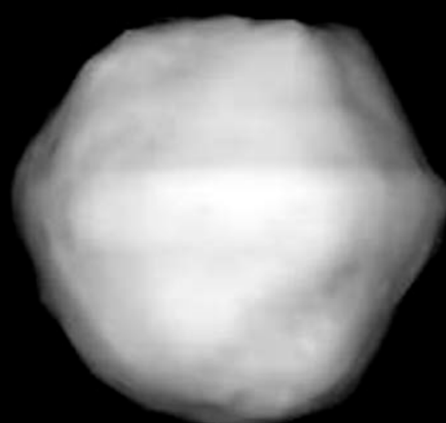


Binary Ast 1999 KW4
Ostro et al. 2005

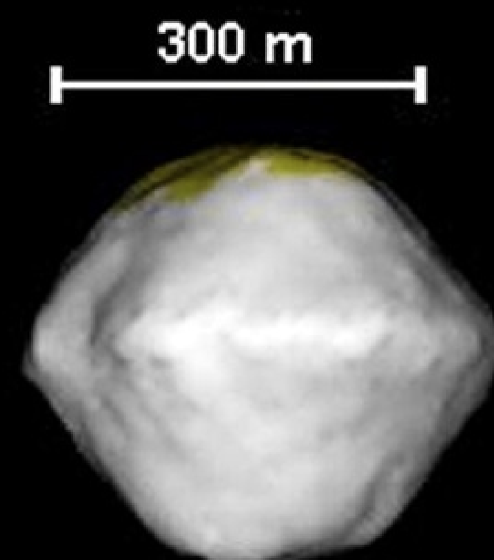

Triple Asteroid 1996 SN263
Becker et al. 2008



Single Asteroid RQ36
Howell et al. 2008, ACM



Binary Asteroid 2004 DC
Taylor et al. 2008, ACM

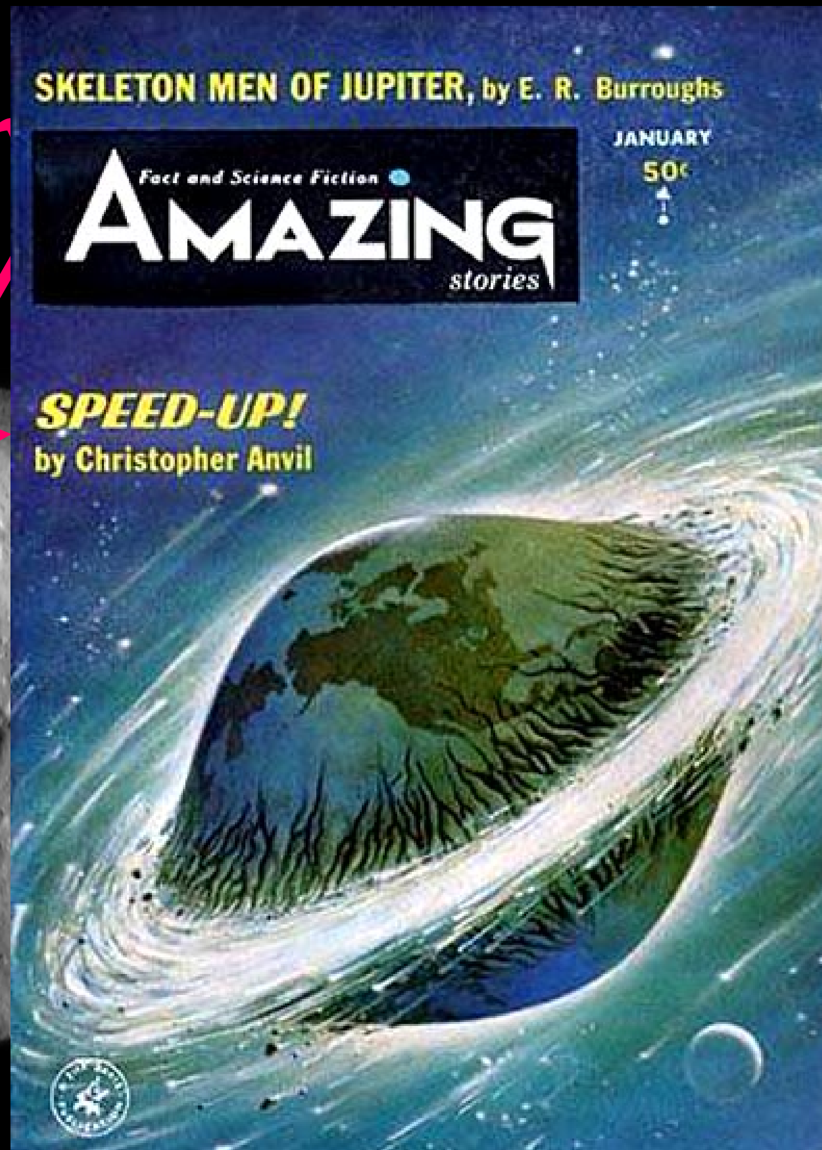



Single Asteroid 1998 EV5
Busch et al. 2011

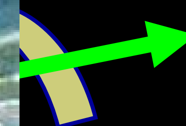
# Spin-Up & Down By The YORP Effect

$d\tau = \mathbf{r}$

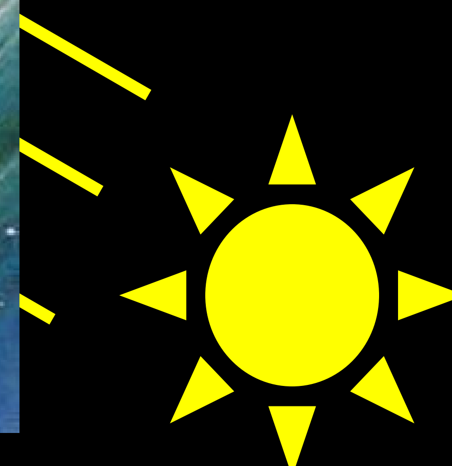
Normal to Surface




…bed and reemitted
…nt produces a
…e in the asteroid's
…te and obliquity.



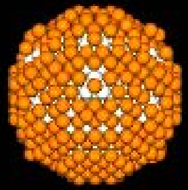
Spin pole



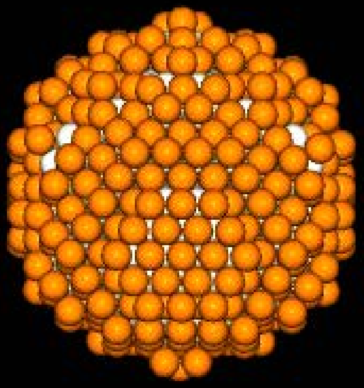
Rubincam (2000)

# NEO Evolution by YORP

**Top View**



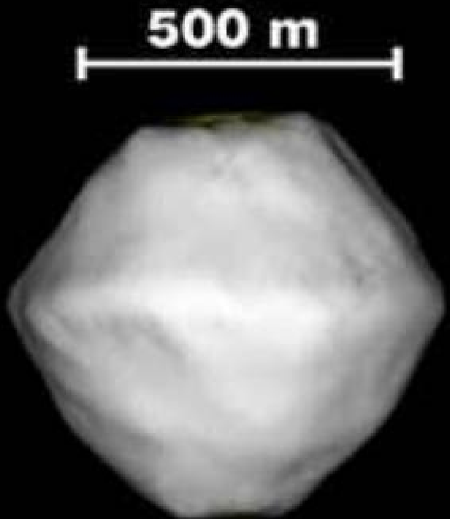
**Side View**



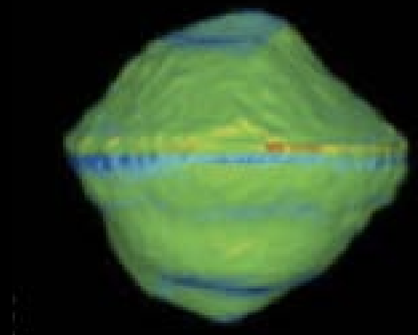
- **Spin up produces downslope movement toward equator and eventual mass shedding. Creation of binaries.**

Walsh et al. (2008)

# Radar Observation: Many “Top-Like” NEOs

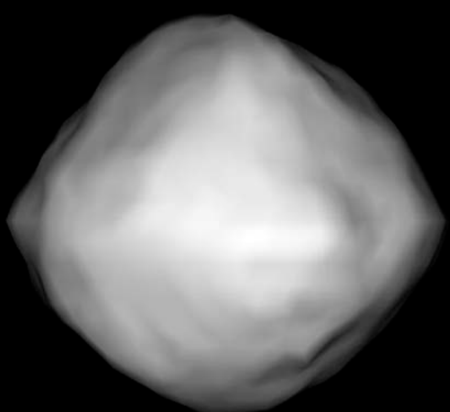



Triple Asteroid 1994 CC
Brosovic et al. 2011

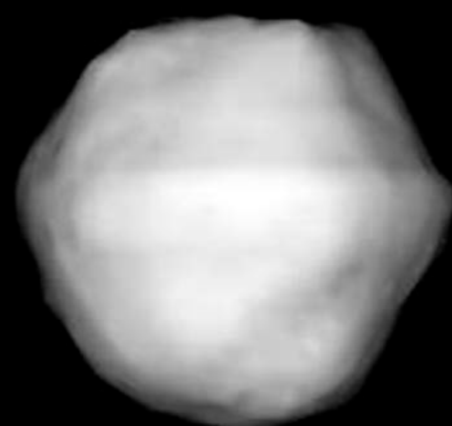


Binary Ast 1999 KW4
Ostro et al. 2005

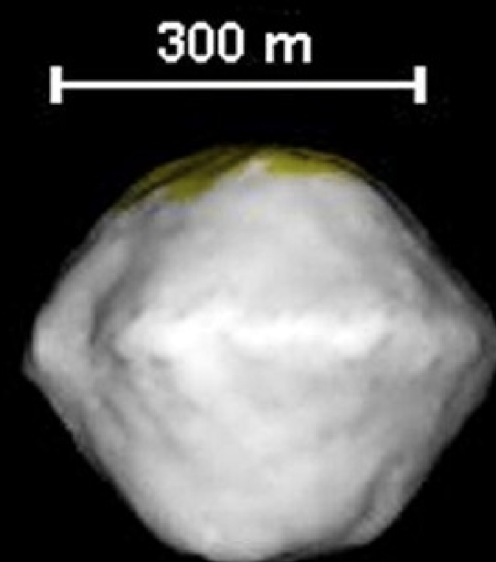

Triple Asteroid 1996 SN263
Becker et al. 2008



Single Asteroid RQ36
Howell et al. 2008, ACM

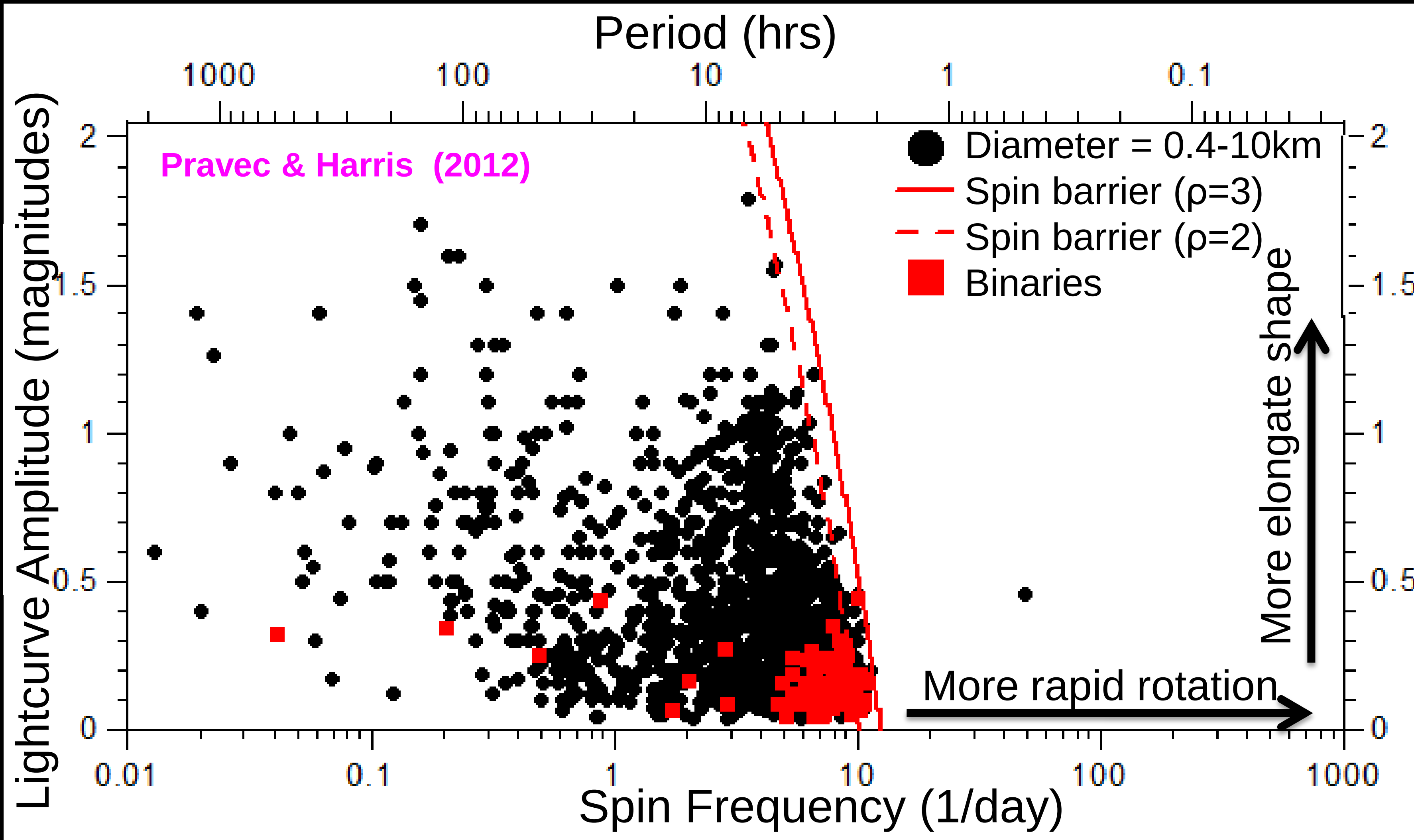


Binary Asteroid 2004 DC
Taylor et al. 2008, ACM



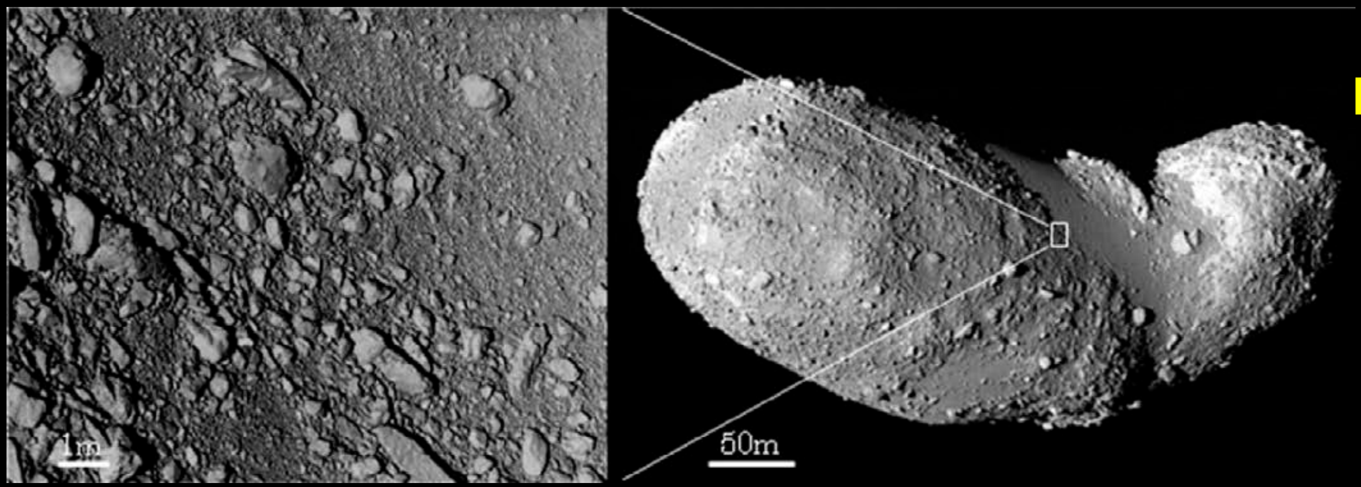

Single Asteroid 1998 EV5
Busch et al. 2011

# Binaries Spin Fast and Stay Spherical

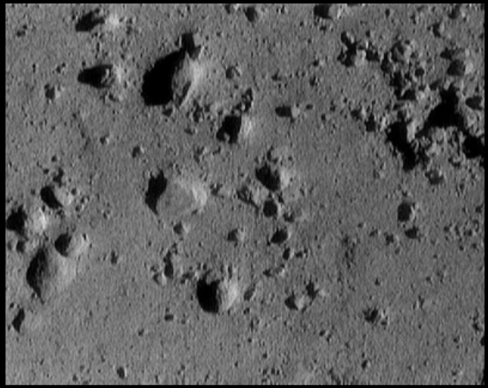



- Most asteroids do not exceed spin up limit. Most binaries are nearly spherical and are near spin up limit.

# Asteroid Regolith




Itokawa



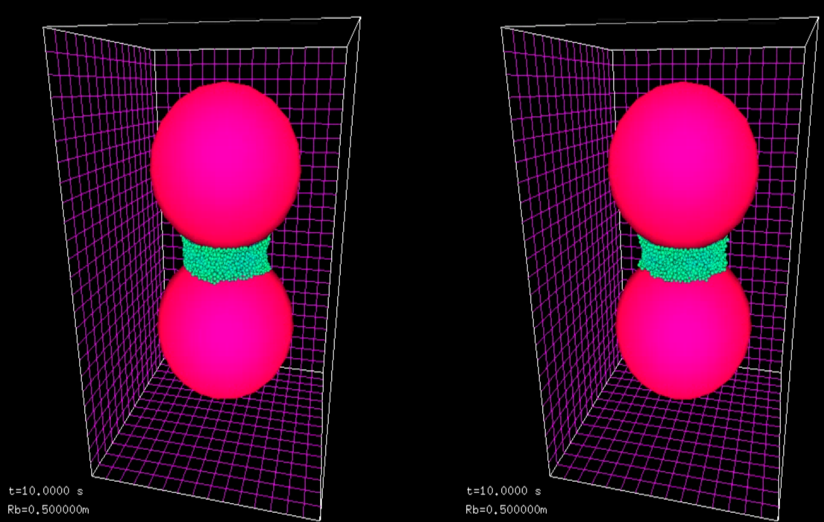
Eros

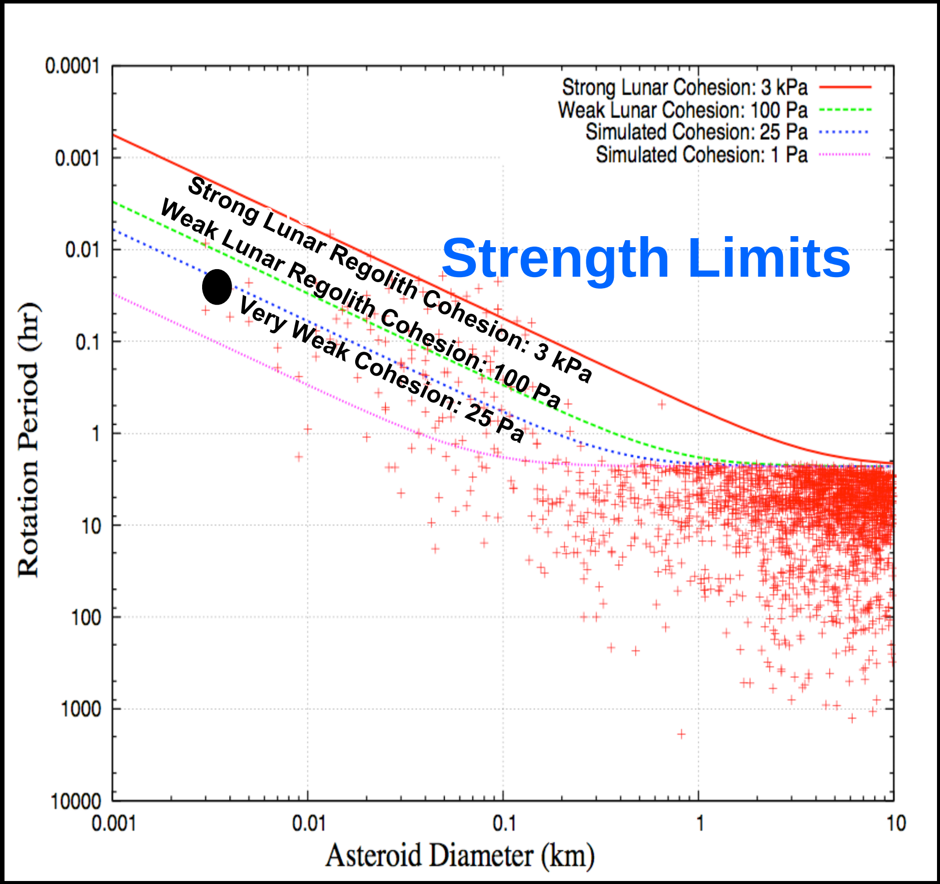
- **NEOs close up are size distributions of boulders and grains.**
  - **Measurements of Itokawa's surface suggest its constituents extend from microns to decameters with a ~1/$d^3$ size distribution**

# Cohesive Forces and Rubble Piles

- Fine grains (10 um) and cohesive forces (with possibly electrostatics) can act as a weak cement for larger blocks.

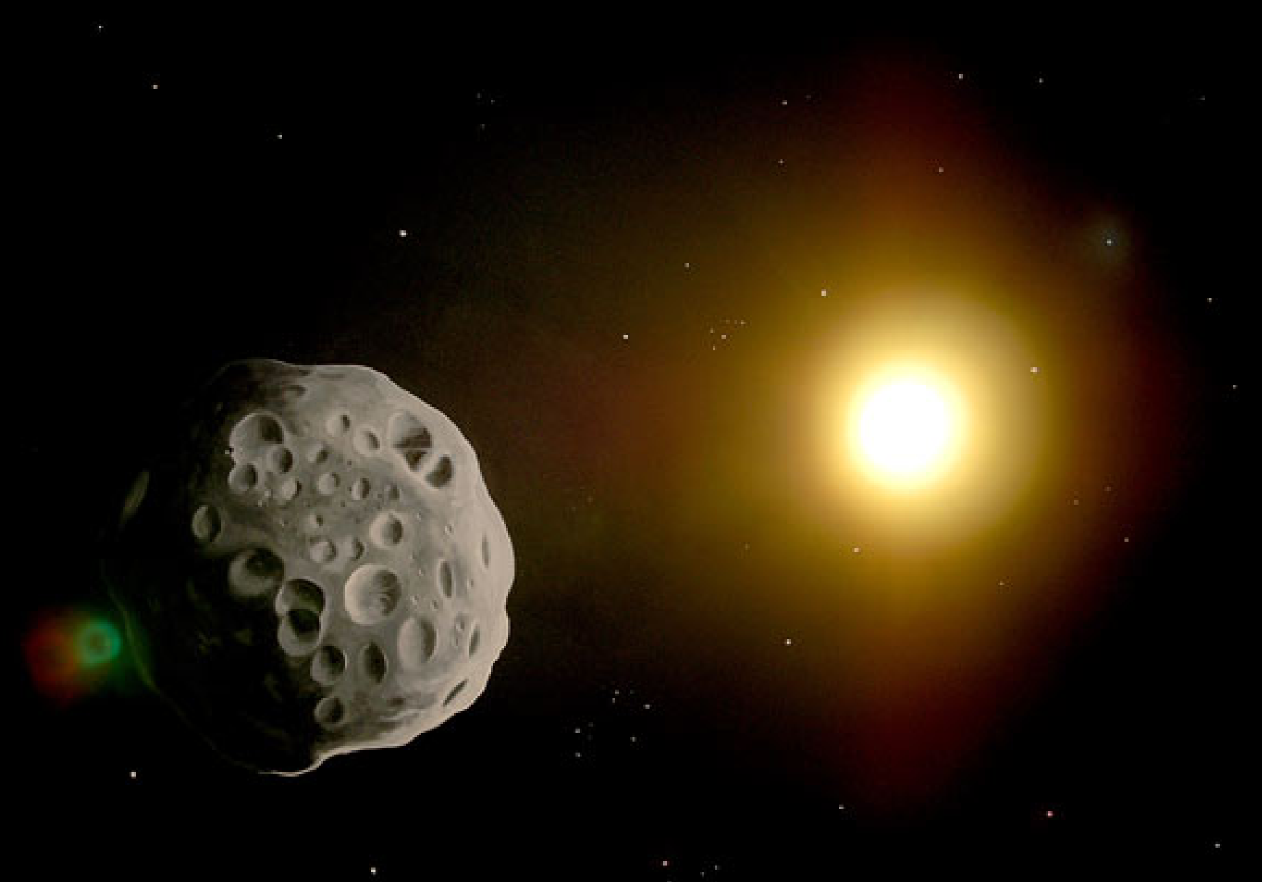
**Cohesionless Regolith** | **Cohesive Regolith**




Sample reference: Sanchez and Scheeres (2012)

# Thermal Effects on Asteroid Evolution



- Some asteroids shed mass and/or breakup close to Sun (e.g, 3200 Phaethon). Why?
- Very efficient YORP? Thermal cracking? Other?

Sample reference: Delbo et al. (2014)

# Effects of Extreme Heating


- **Melosh: Rock samples placed in "solar furnace" designed to simulate heat from nuclear blasts.**
- **35 kW delivered per unit area. Surface of samples quickly heated to several thousand deg. C.**

**Jay Melosh at the White Sands Missile Range, New Mexico**

# Effects of Extreme Heating: Serpentine


- **Experiments on serpentine (hydrated olivine), chosen to be analog for carbonaceous chondrite.**
- **Minerals are vaporizing, with water blasting chips out.**

**Jay Melosh at the White Sands Missile Range, New Mexico**

# Effects of Extreme Heating: Basalt

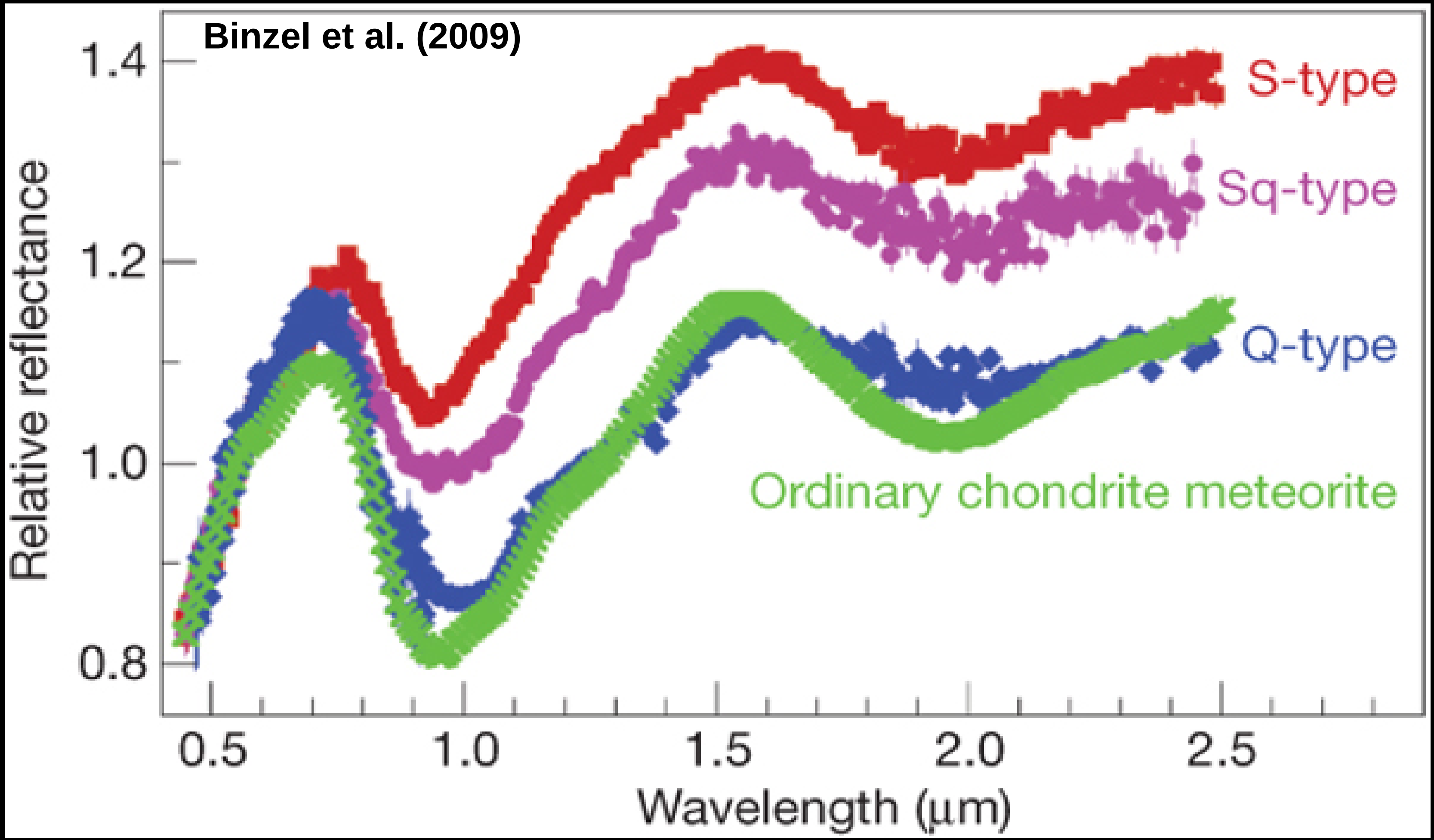


- **Experiments on drier basalt rock. Individual impulses from vaporized minerals are blasting out chunks of rock.**

Jay Melosh at the White Sands Missile Range, New Mexico

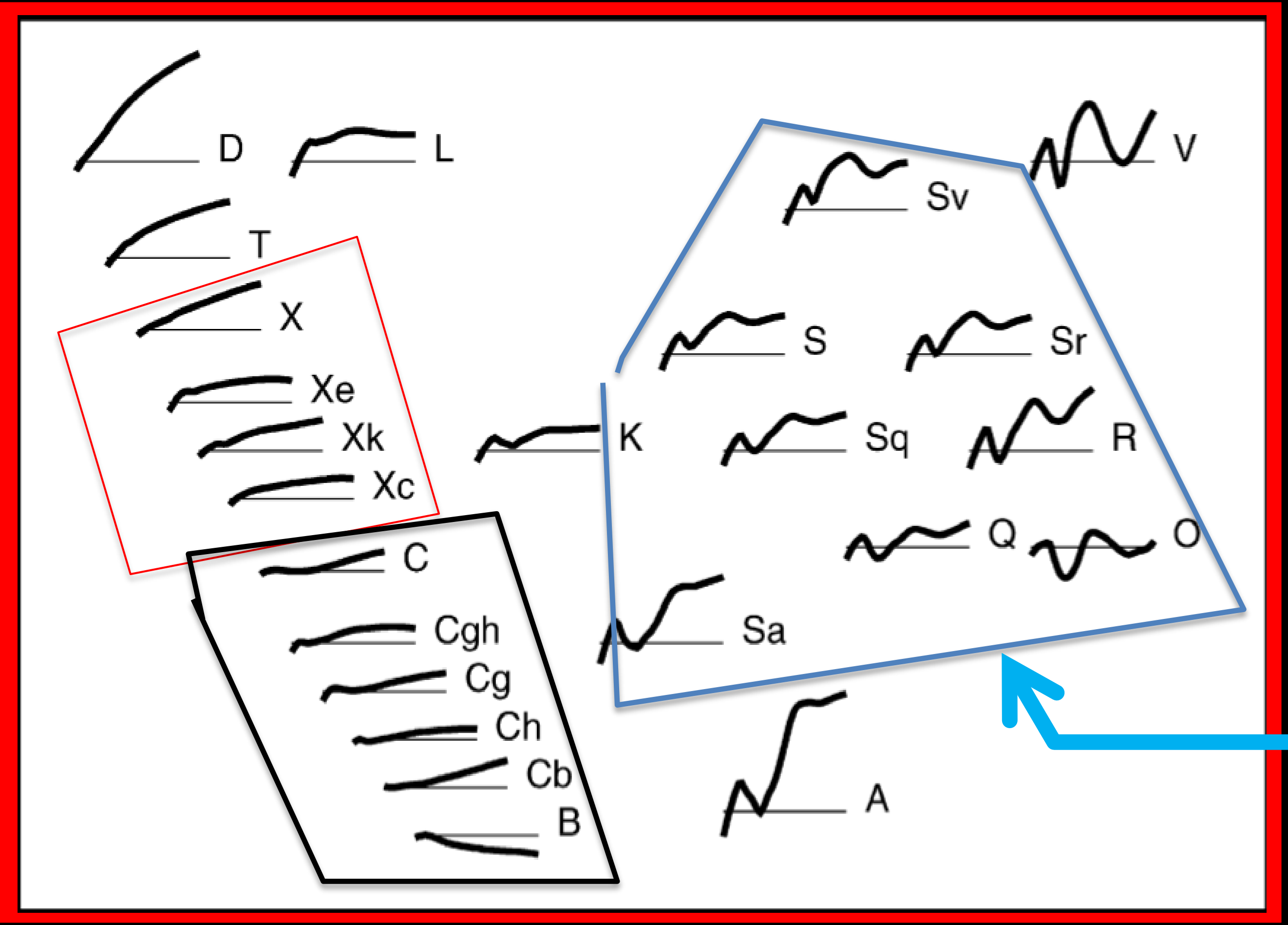
# Part 4:
# NEO Compositions and Albedos
## (Thanks to Dan Britt/Andy Rivkin)

# Asteroid Spectroscopy

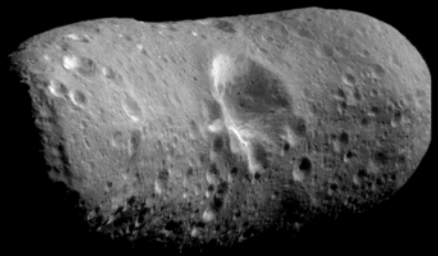



- **Asteroid composition can be estimated by analyzing the nature of sunlight reflected off of asteroid surfaces.**

# S/Q Complex Spectroscopy




433 Eros (S)



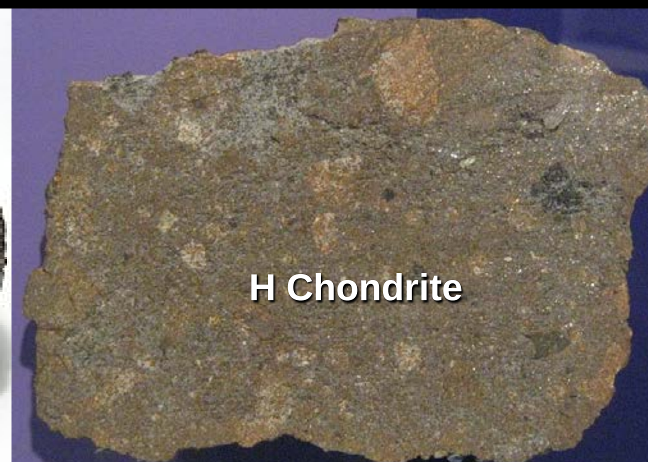
25143 Itokawa (S)

**S/Q complex:**
**Albedo ~0.2-0.3**
**Ordinary chondrites**

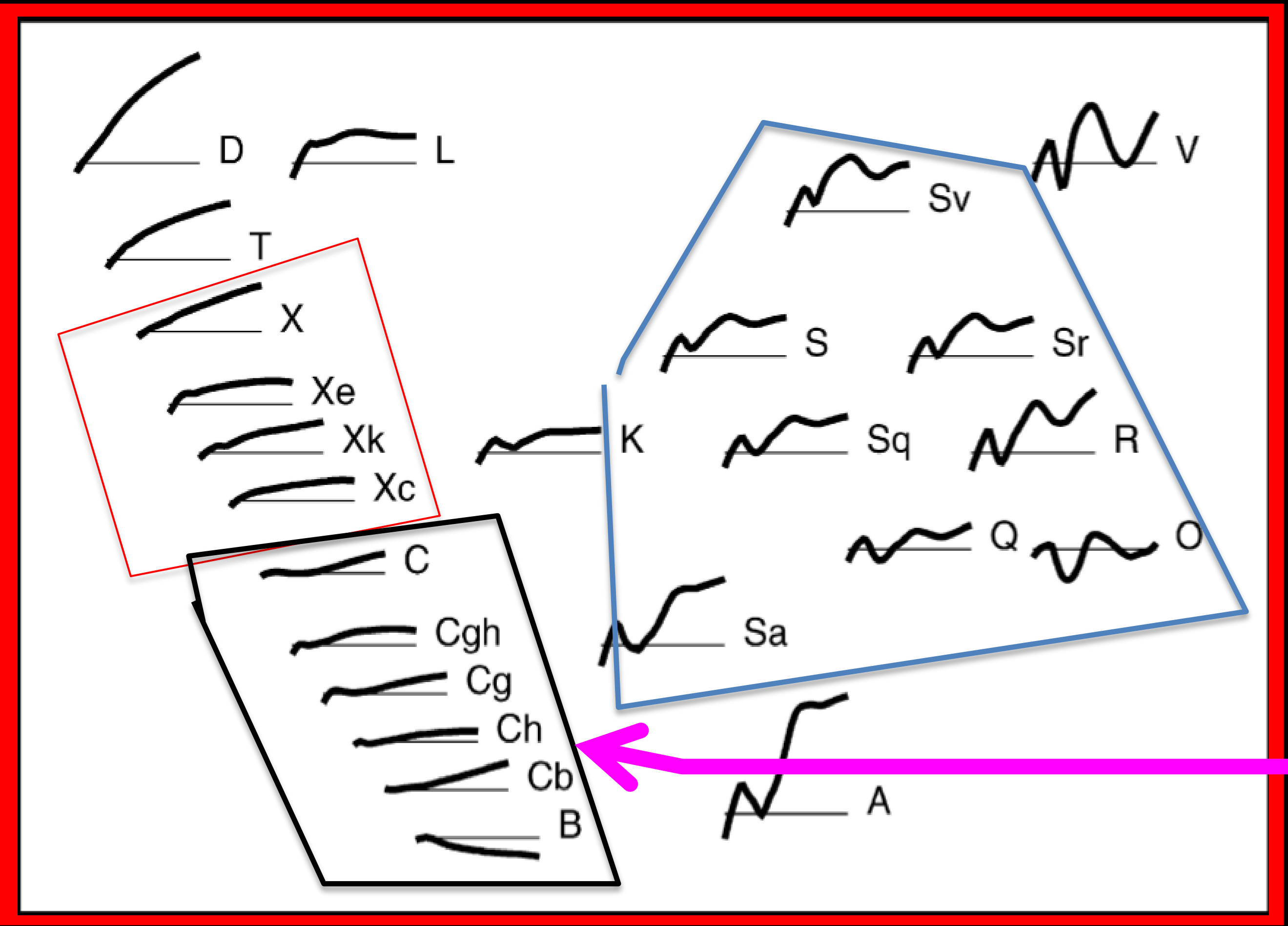
- **Taxonomy: Spectra used to organize asteroids into groups.**

# Meteorite Types

| Meteorite | % Silicates | % Metal | Characteristics |
|---|---|---|---|
| Chondrites (ordinary, enstatite) | 80 | 20 | Contain chondrules, olv, pyx, metal, sulfides, usually strong |


# C-Complex Spectroscopy



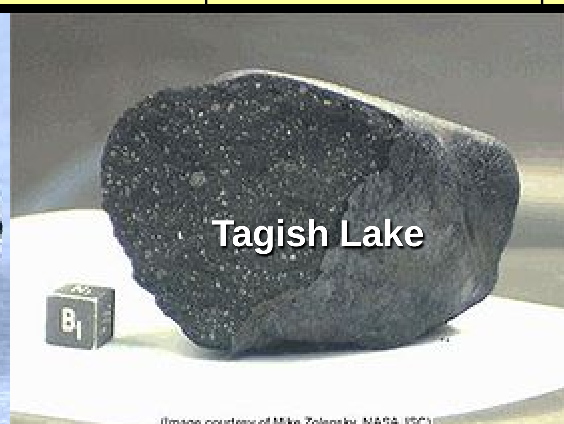

253 Mathilde (Cb)

**C complex:**
**Albedo ~0.04-0.08**
**CC meteorites**
**water/organics**

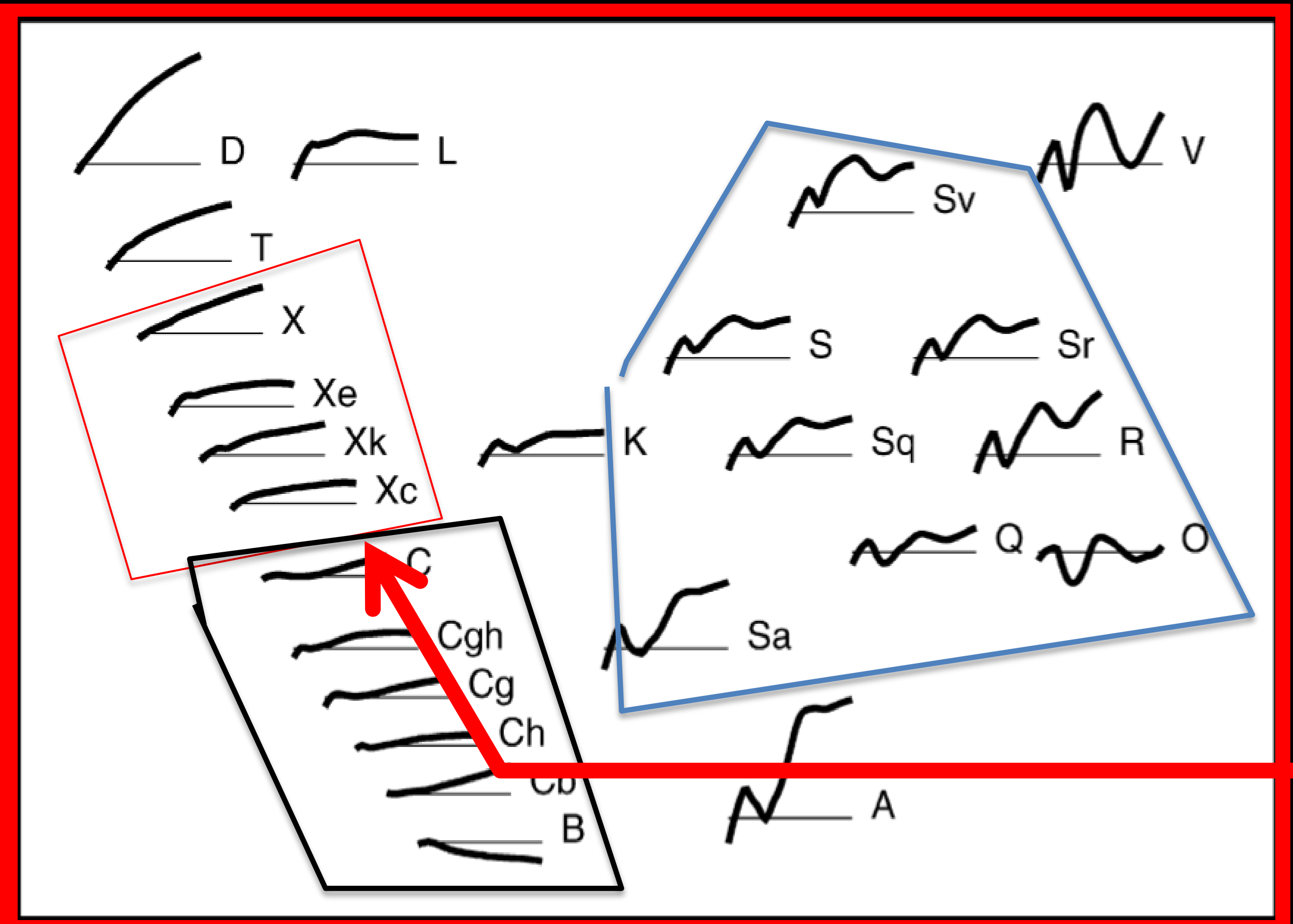
- **C-complex asteroids have few/no spectral bands. Hydration features common (e.g., phyllosilicates).**

# Meteorite Types

| Meteorite | % Silicates | % Metal | Characteristics |
|---|---|---|---|
| Chondrites (ordinary, enstatite) | 80 | 20 | Contain chondrules, olv, pyx, metal, sulfides, usually strong |
| Volatile-rich Carbonaceous Chondrites (CI, CM) | >99 | < 1 | Hydrated silicates, carbon compounds, refractory grains, very weak. |
| Other Carbonaceous (CO, CV, CK, CR, CH) | Highly variable | Highly variable | Highly variable, chondules, refractory grains, often as strong as ordinary chondrites |


# X-Complex Spectroscopy




21 Lutetia (Xc)

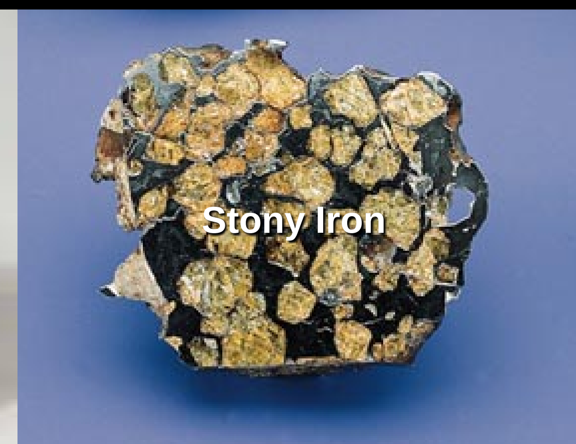
2867 Steins (Xe)

**X complex:**
**Albedo ~0.04-0.5**
**Iron meteorites or EC/CC meteorites or Aubrites or…**

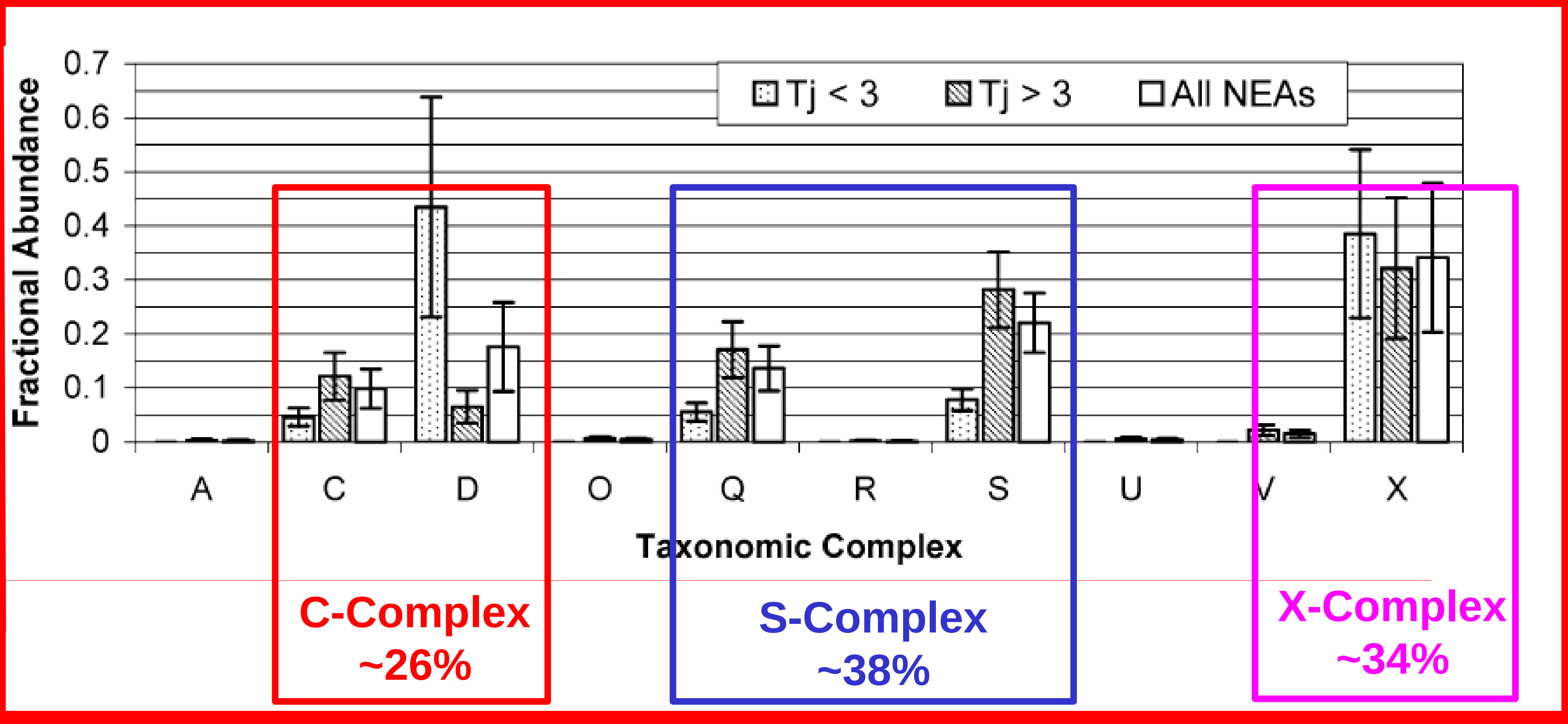
- **X-complex asteroids have few/no spectral bands. Albedo used as discriminant between enstatite/iron/carbonaceous.**

# Meteorite Types

| Meteorite | % Silicates | % Metal | Characteristics |
|---|---|---|---|
| Chondrites (ordinary, enstatite) | 80 | 20 | Contain chondrules, olv, pyx, metal, sulfides, usually strong |
| Iron meteorites | < 5 | >95 | Almost all FeNi metal |
| Stony-irons | ≈50 | ≈50 | Mix of silicates and metal |



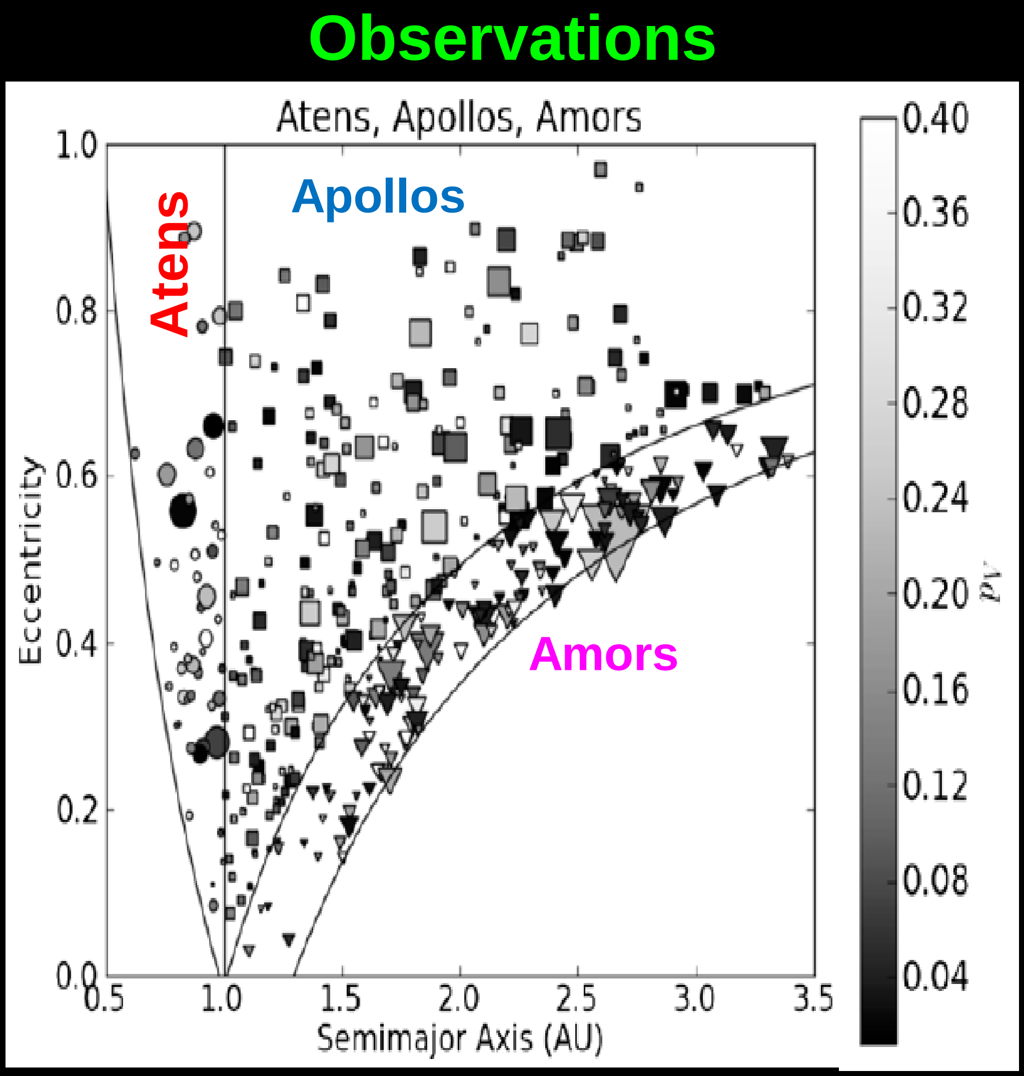
# Characterizing NEO Population: Spectra

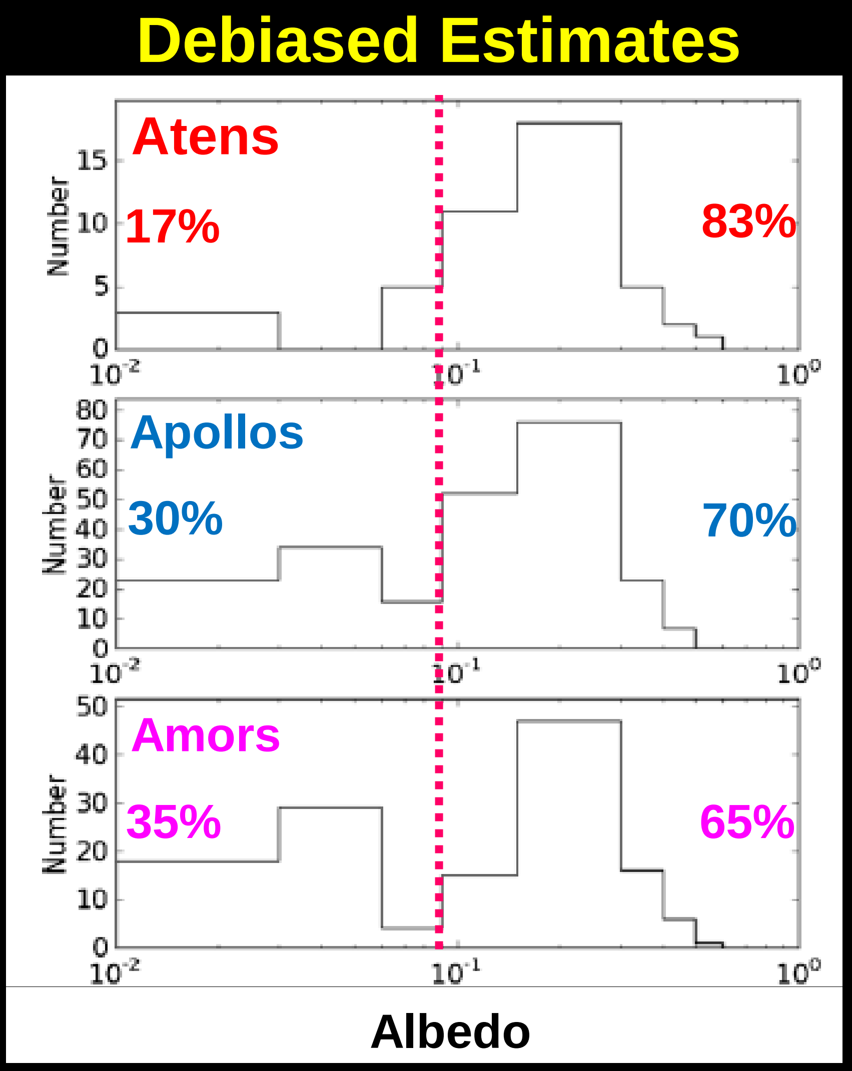



- Population: Debiased survey using available NEO spectra

Stuart and Binzel (2004)

# Characterizing NEO Population: Albedos

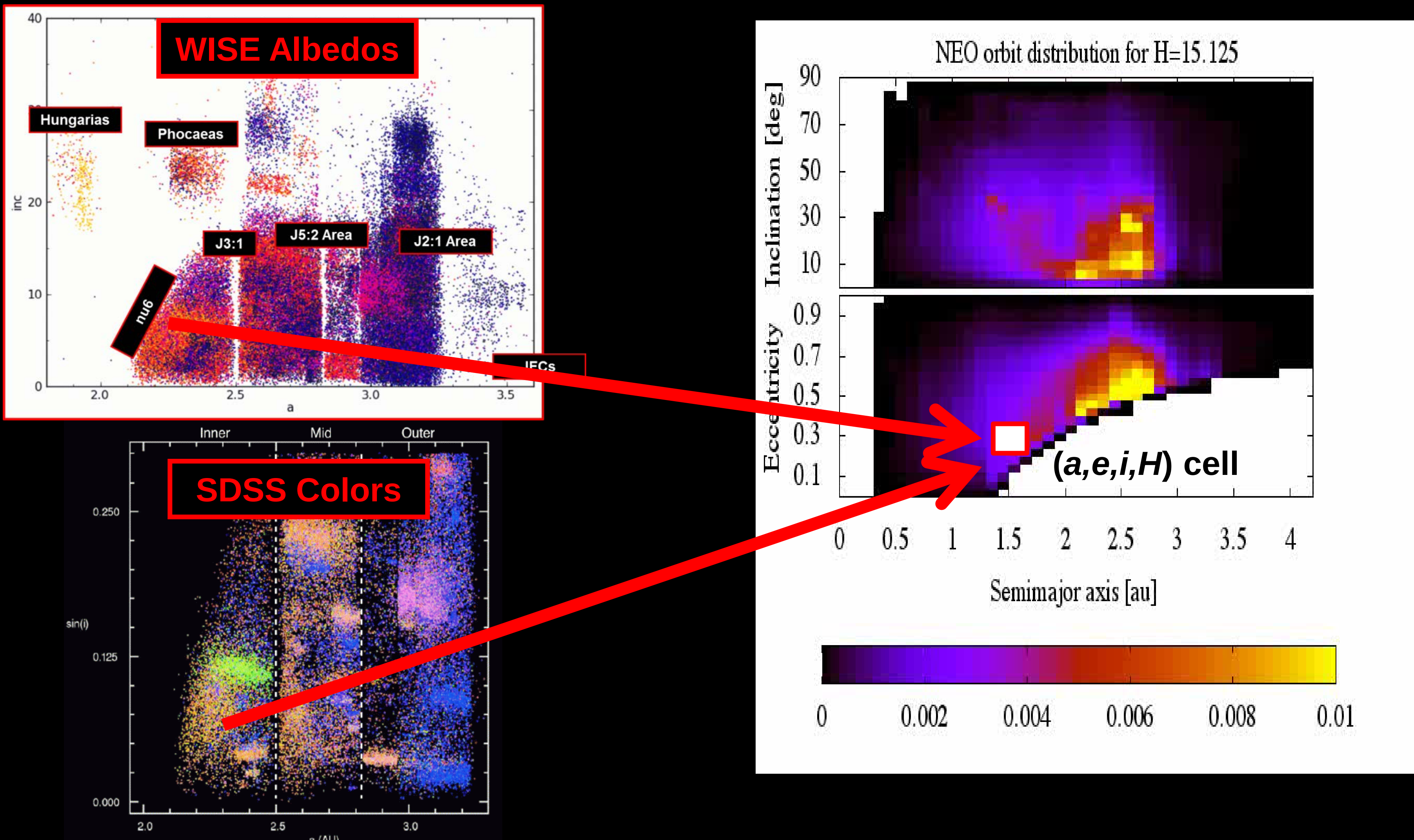



- ***NEOWISE*. Low albedos likely C-complex. High albedos are mostly S-complex. Most NEOs have albedo > 0.09.**

Mainzer et al. (2012)

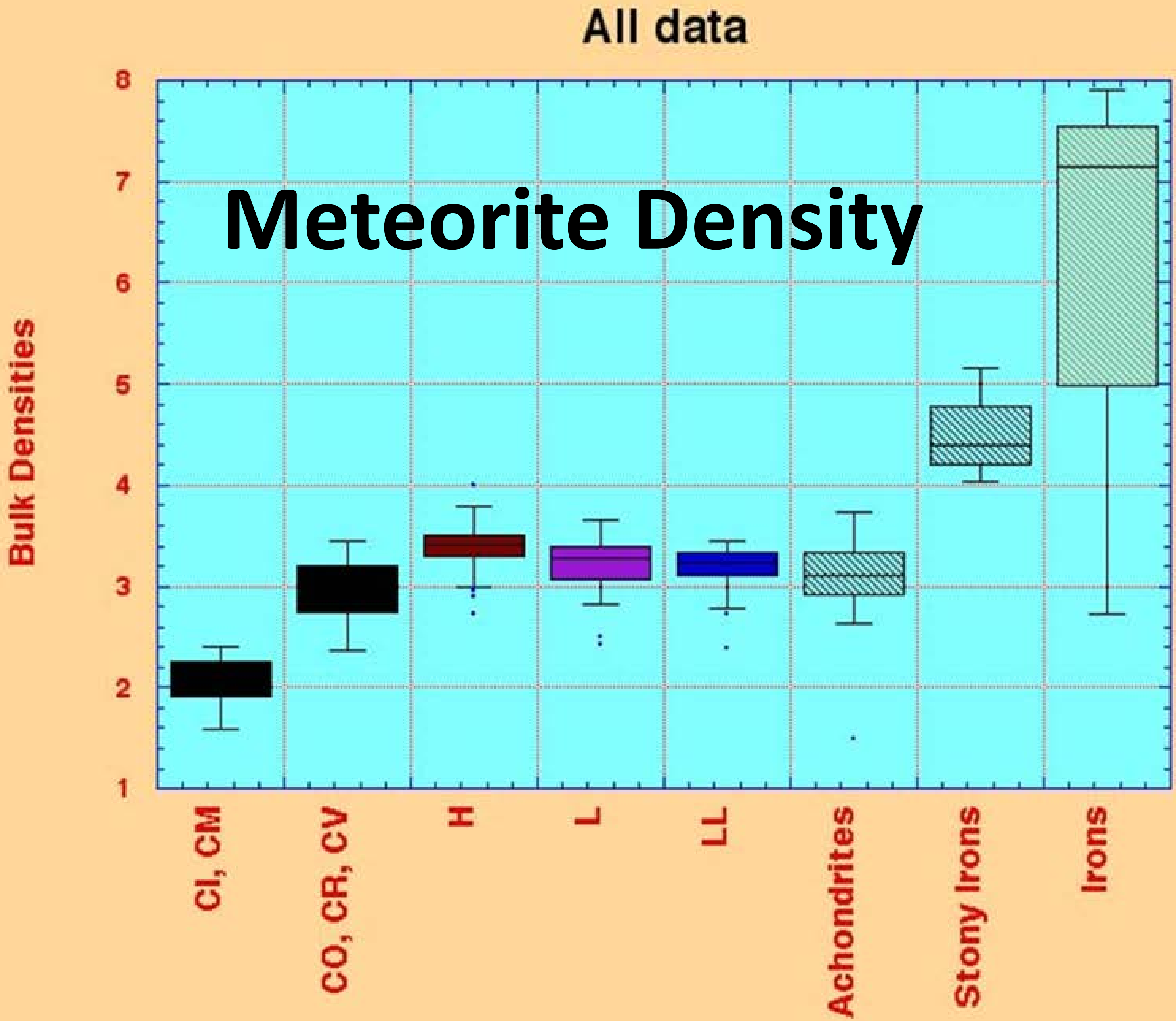
# Feed Forward: NEO Albedos and Colors



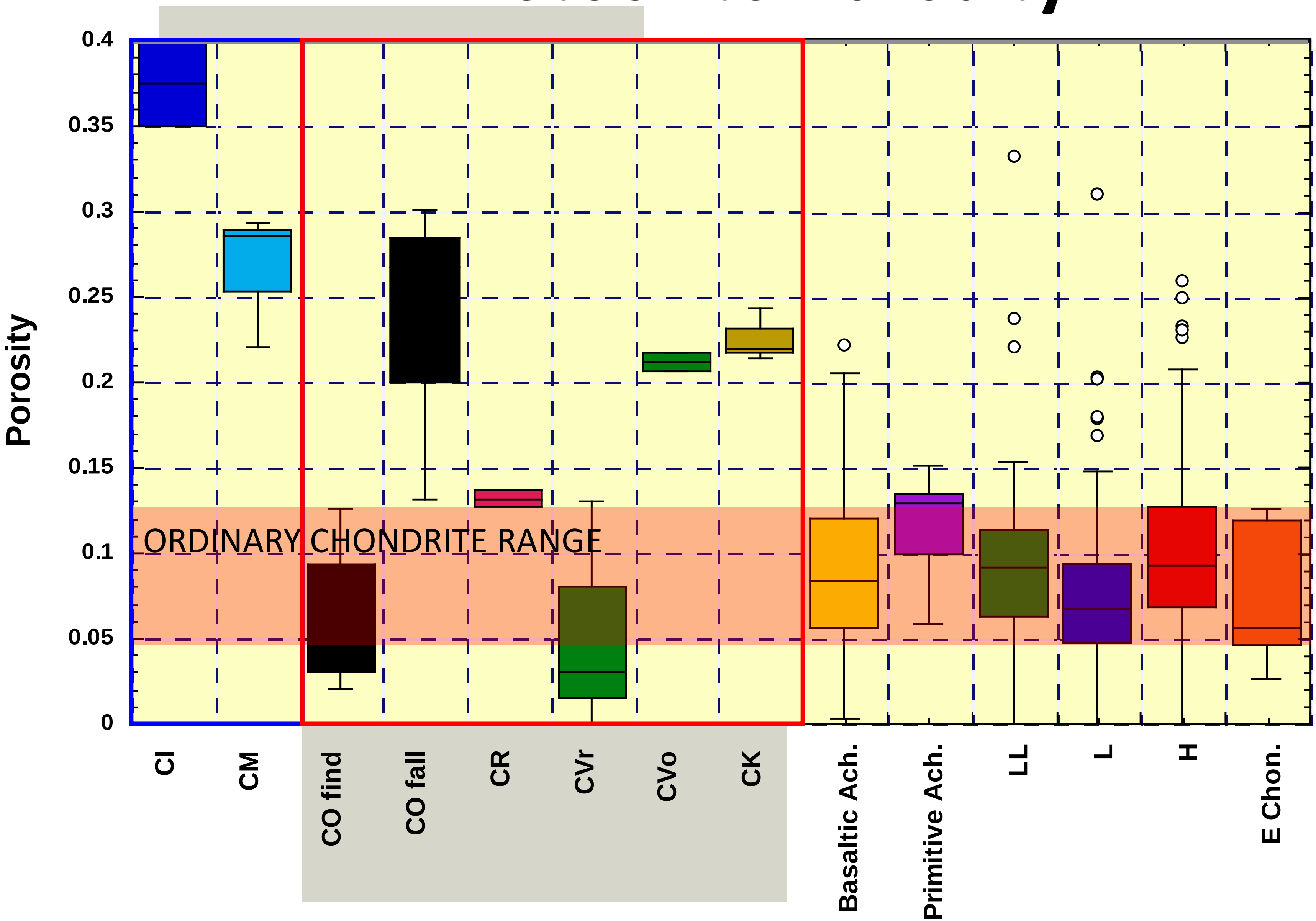

- Albedos and colors in source (from WISE and SDSS) can be fed forward to predict nature of NEOs in (*a*,*e*,*I*,*H*) cells.

Parker et al. (2008); Masiero et al. (2011; 2013)

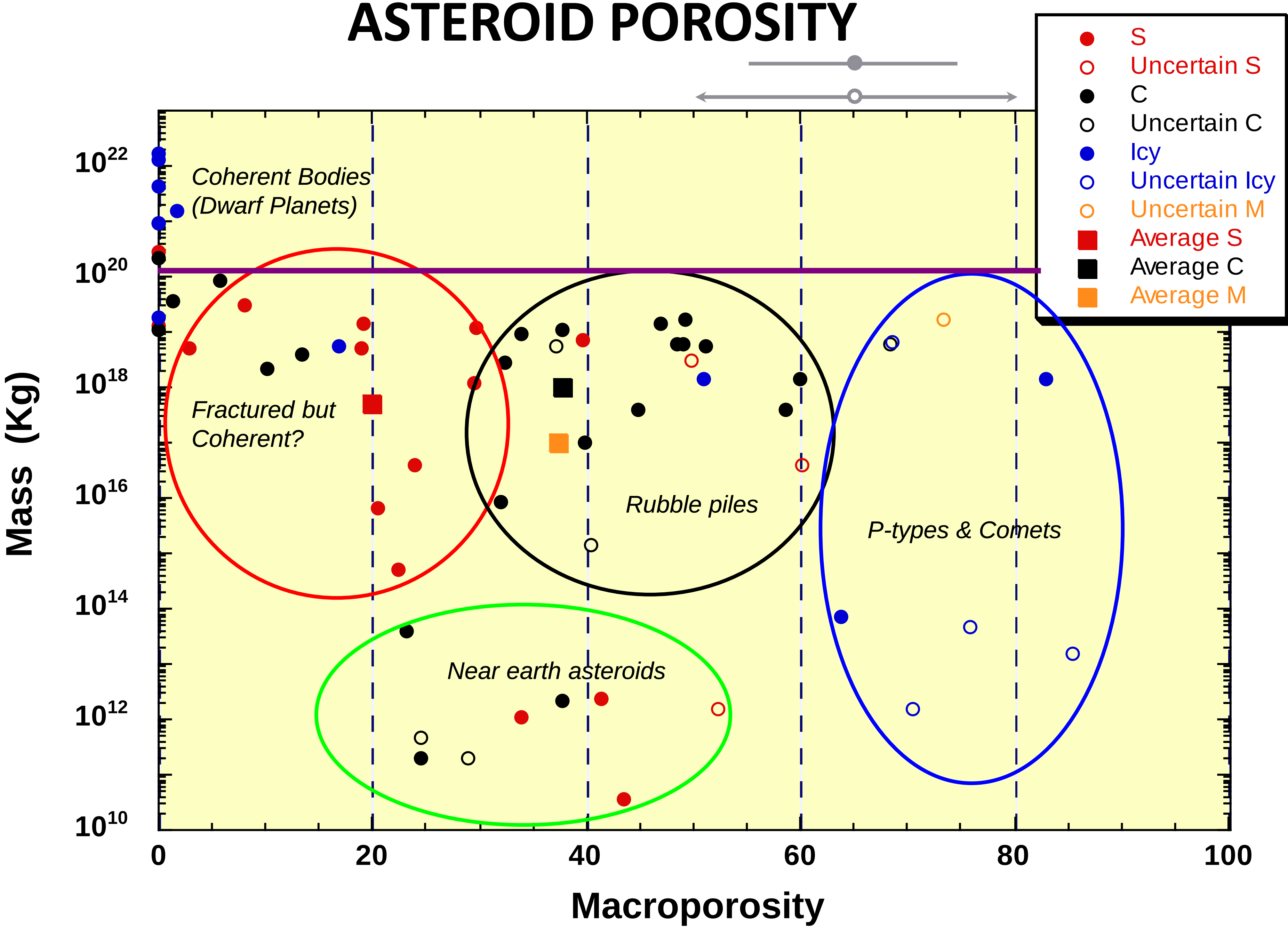
# Meteorite Density



# Meteorite Porosity

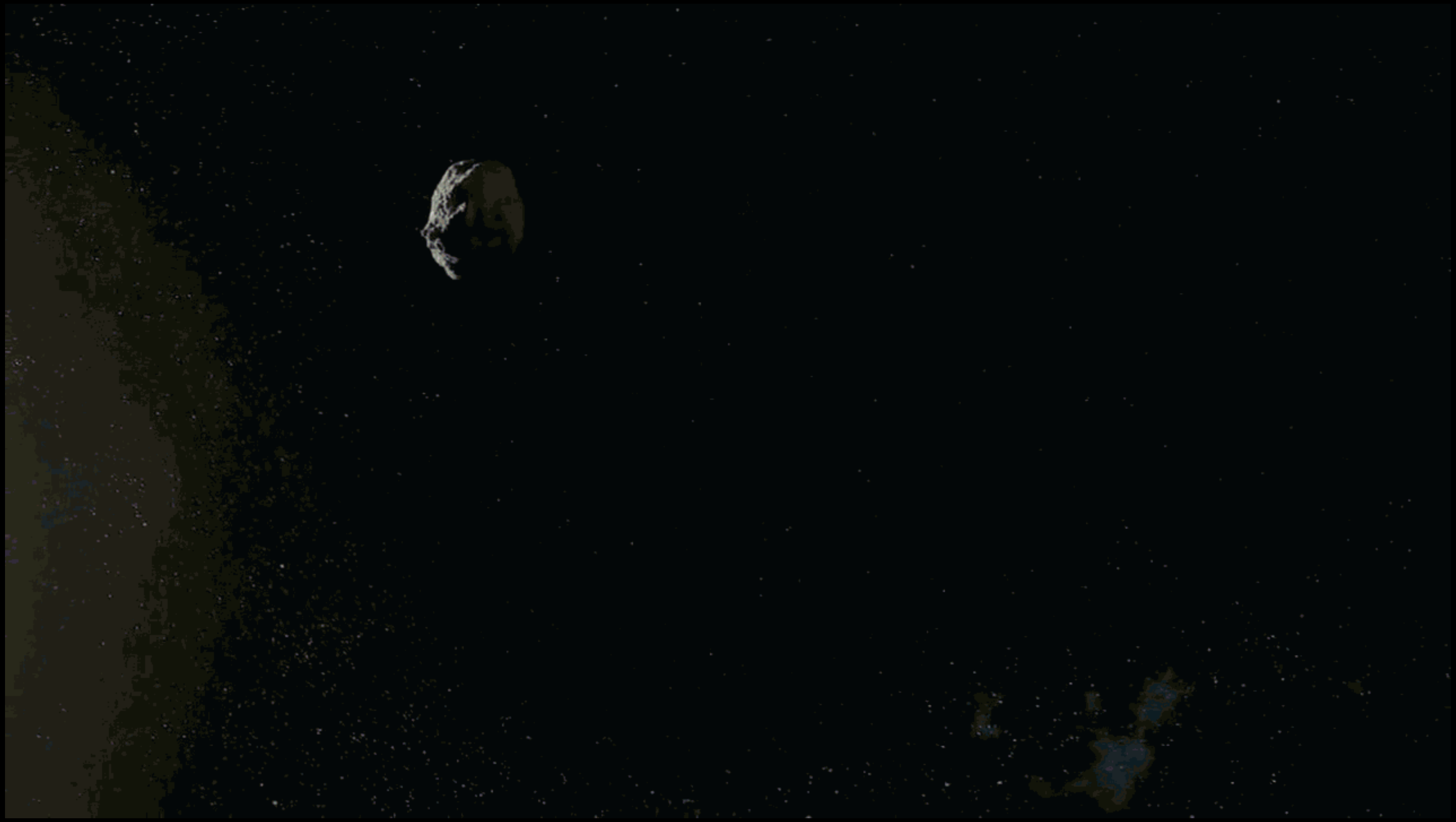


# ASTEROID POROSITY



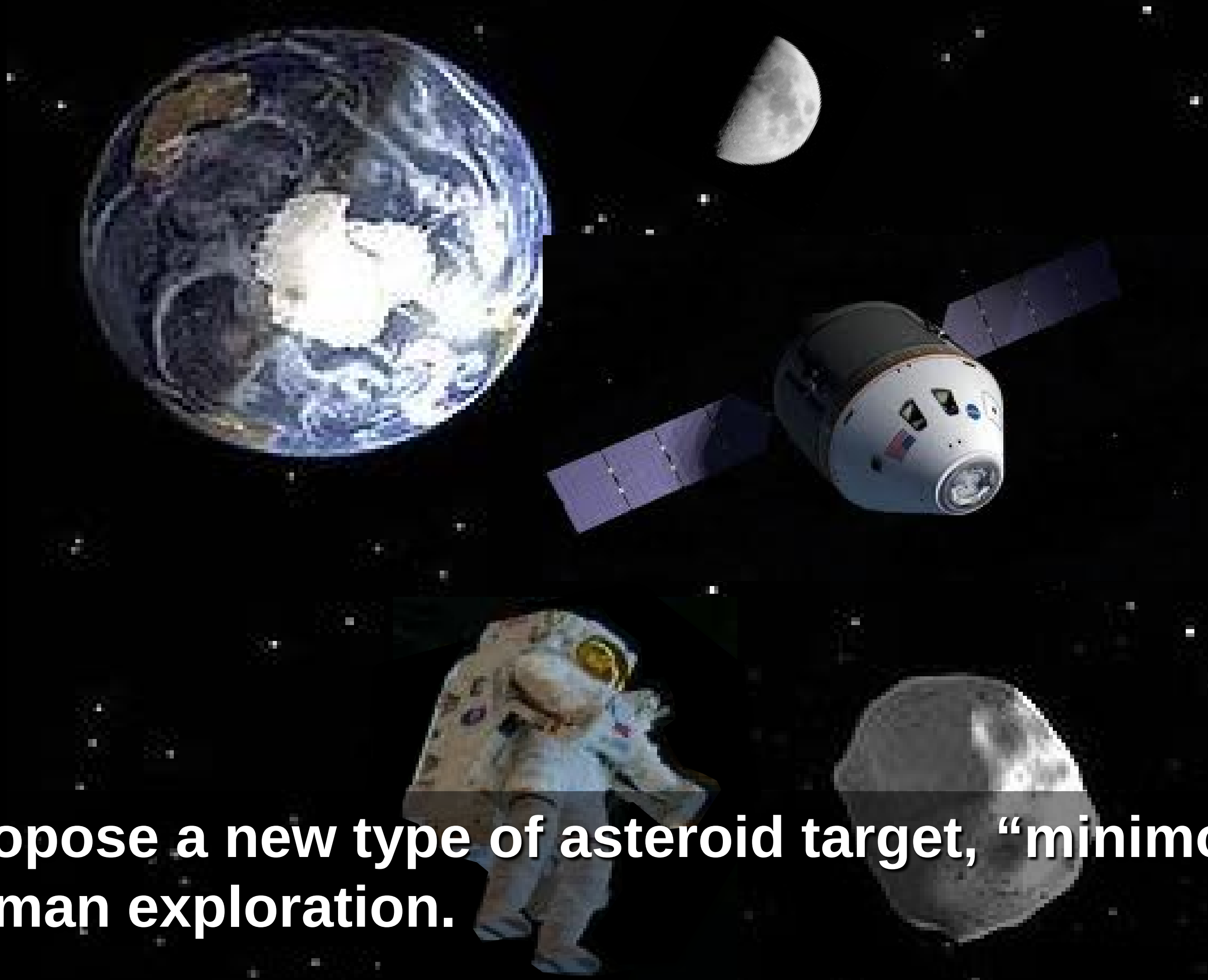
# Part 5:
# Minimoons

# Human Visits to Near-Earth Asteroids



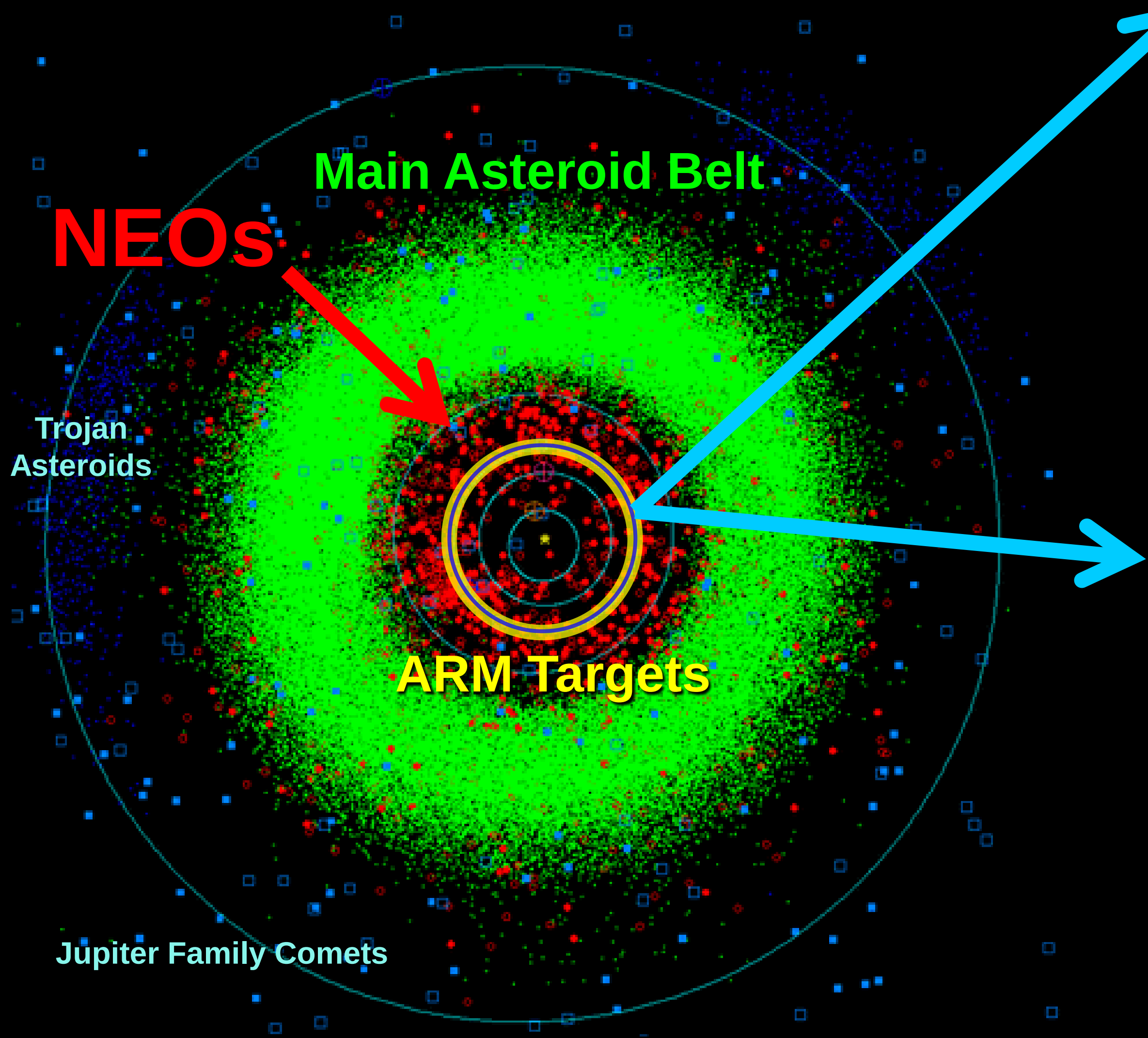
- A new concept for human exploration of NEAs: "Asteroid Redirect Mission (ARM)".
- *Are there any other alternatives that are inexpensive?*

# New Asteroid Targets: "Minimoons"

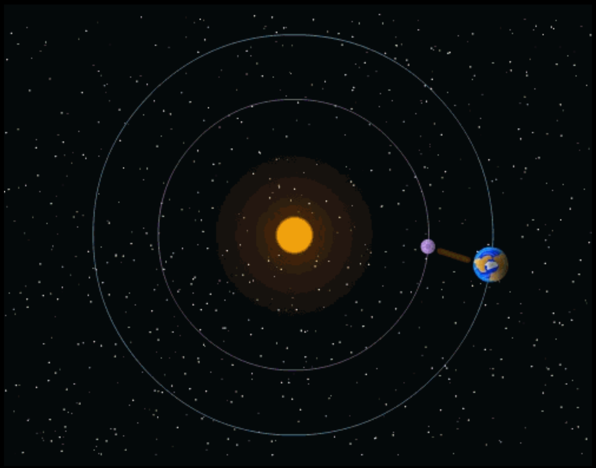


- We propose a new type of asteroid target, "minimoons", for human exploration.
- Minimoons are a new idea and have great promise. They could help achieve NASA's goals at lower costs and risk.

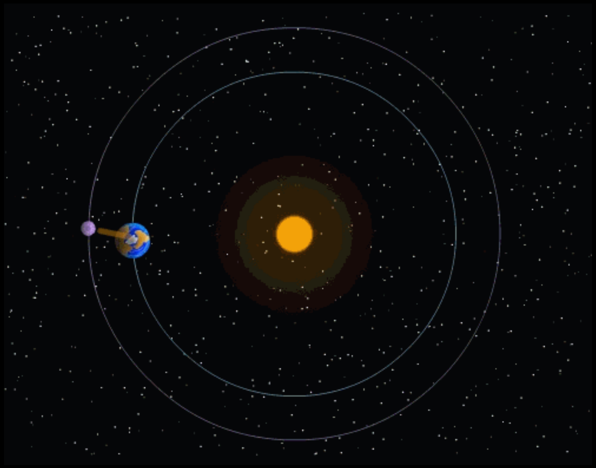
# NEOs, ARM Targets, and Lagrange Points




Lagrange Point 1 (L1)



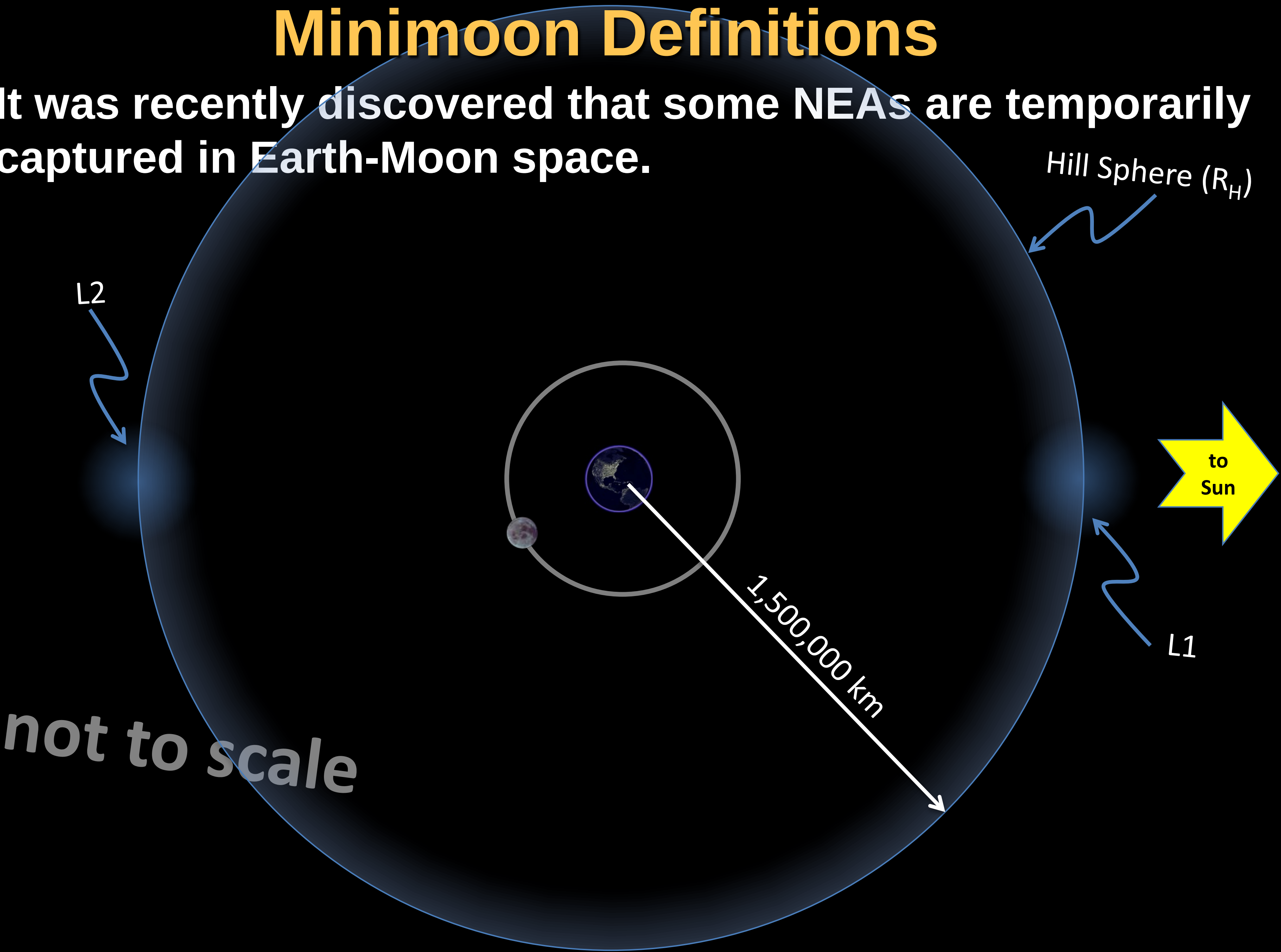
Lagrange Point 2 (L2)



- L1 and L2 are about 4 lunar distances from the Earth.

# Minimoon Definitions

- It was recently discovered that some NEAs are temporarily captured in Earth-Moon space.

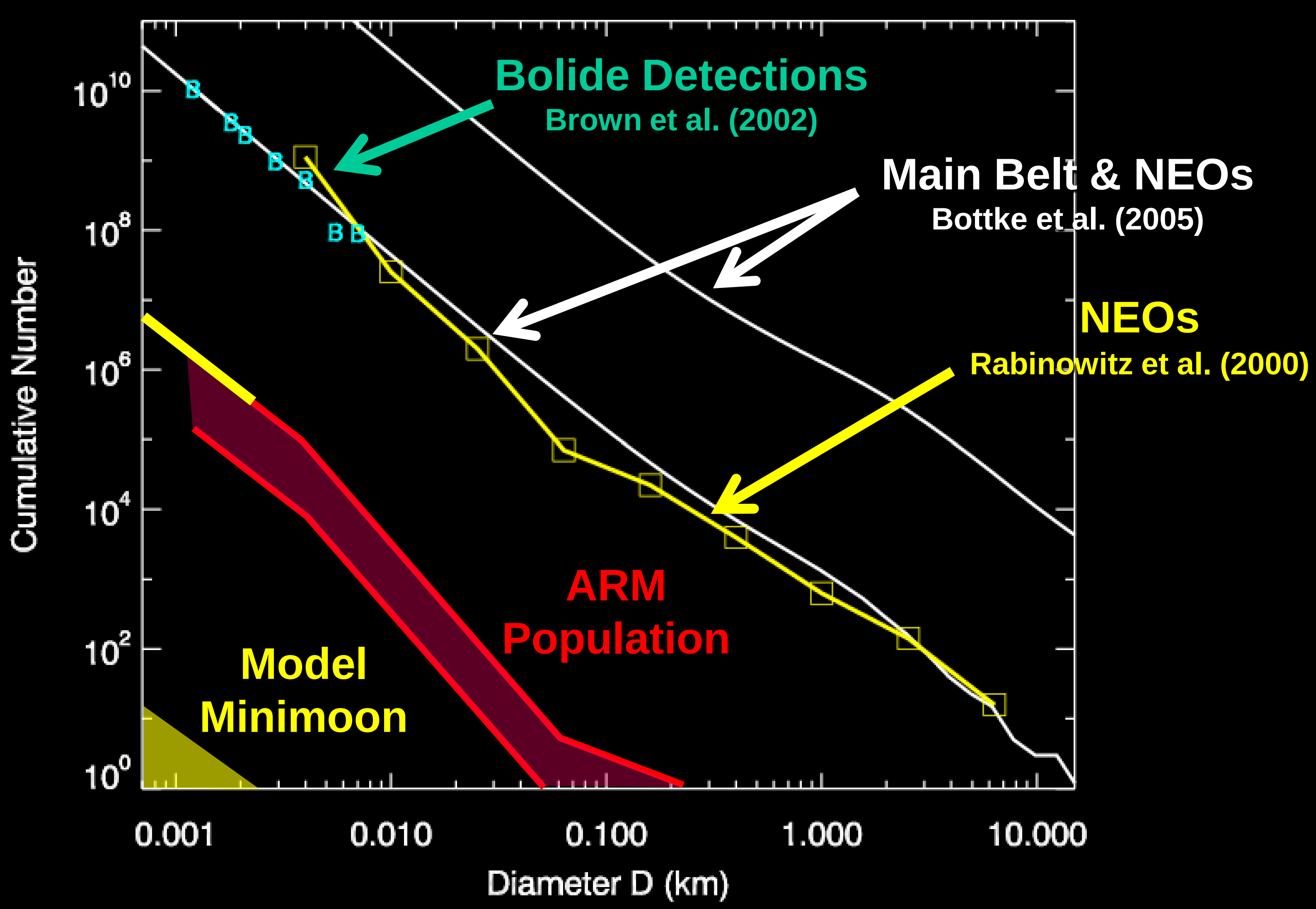


# Trajectory of a Long-Lived Minimoon


- **We define "minimoons" as bodies that make a complete orbit around Earth. Some make many!**

**Granvik et al. 2012; Icarus**

# Minimoon Population




***Several meter-sized minimoons are in steady state***

# How Many Minimoons Are There at Any Time?


2


dozen

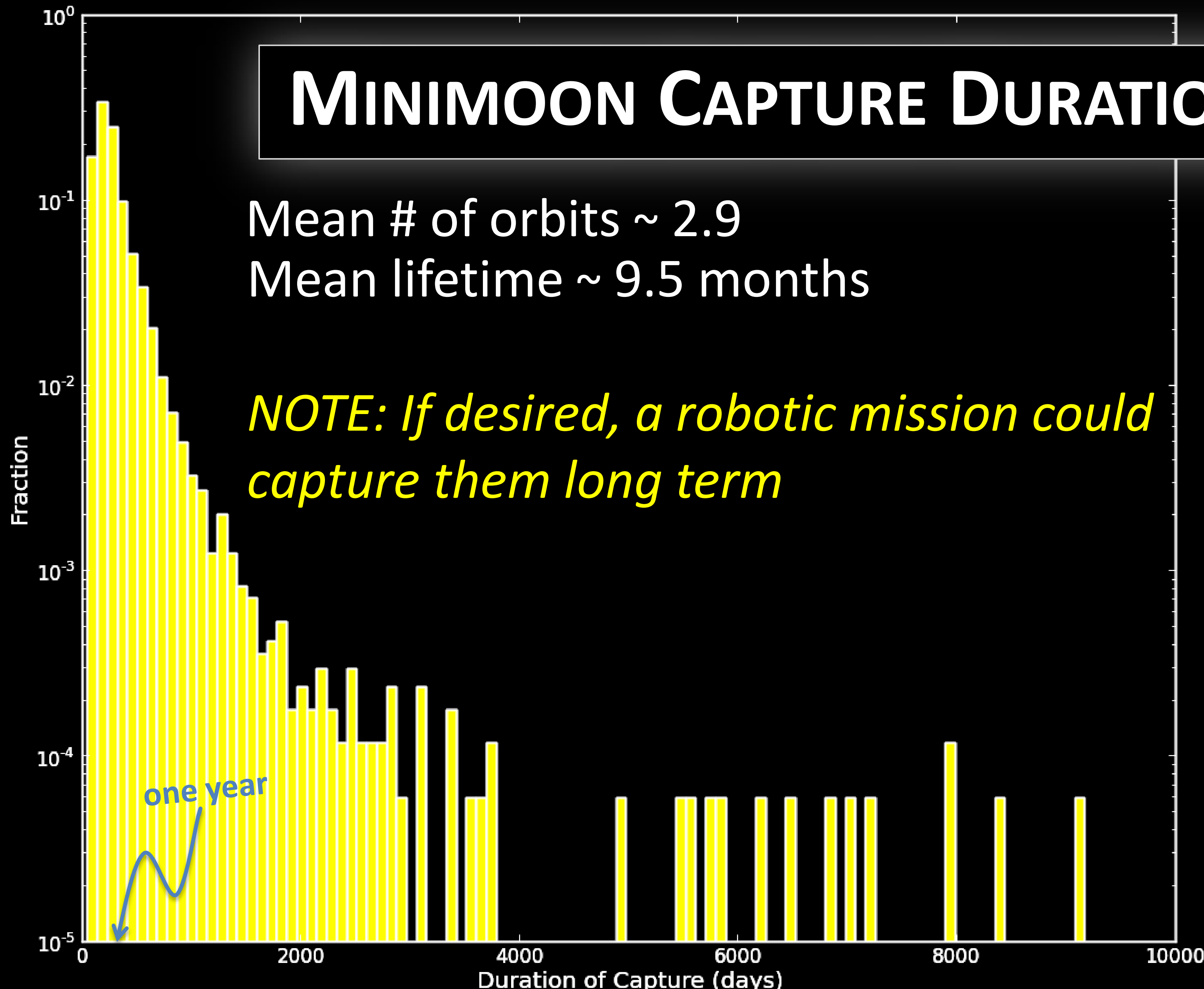

one every 50 years

- There is always something to visit, but a detailed observational and theoretical study is needed to understand the population!

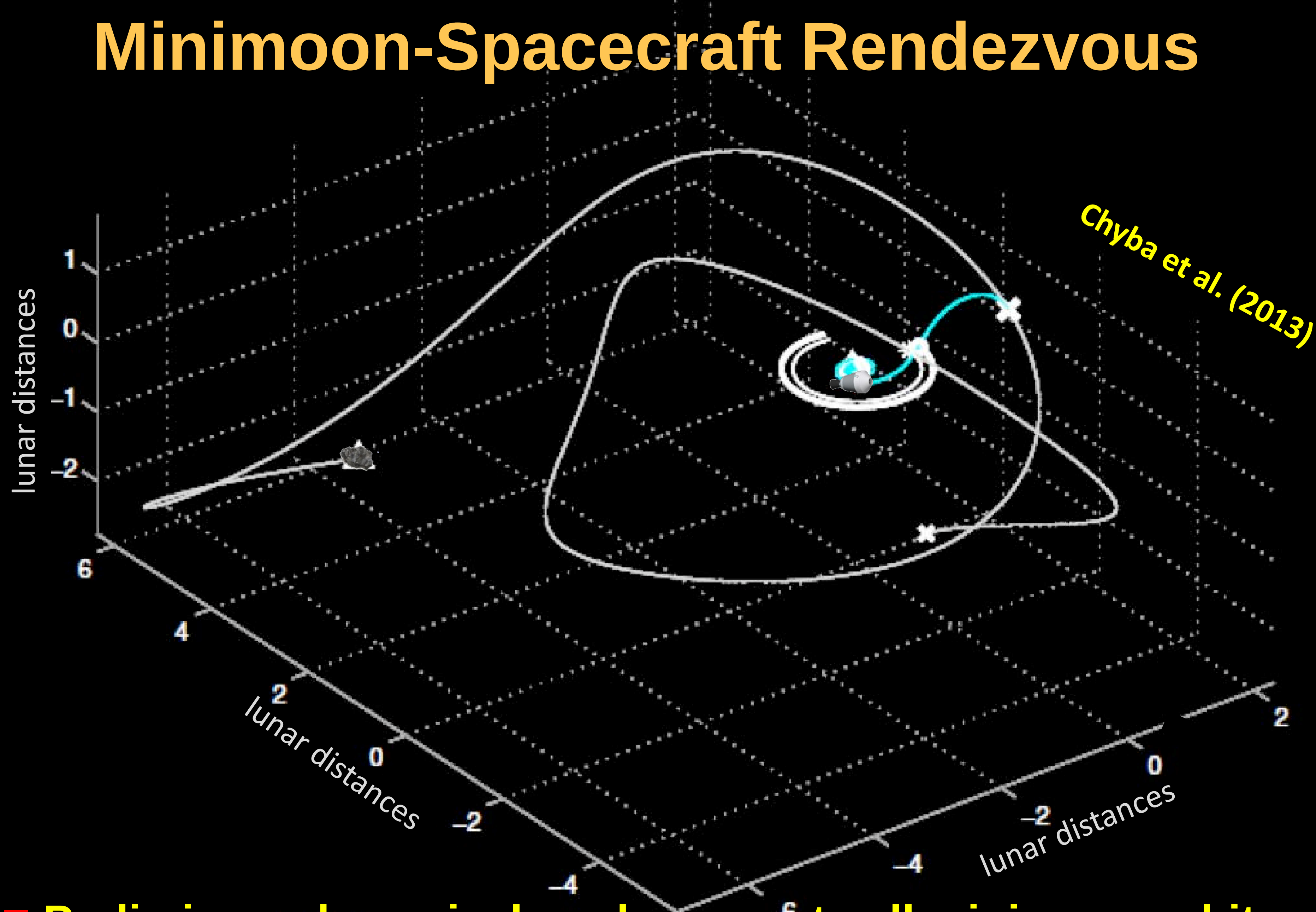
# MINIMOON CAPTURE DURATION

Mean # of orbits ~ 2.9
Mean lifetime ~ 9.5 months

*NOTE: If desired, a robotic mission could capture them long term*

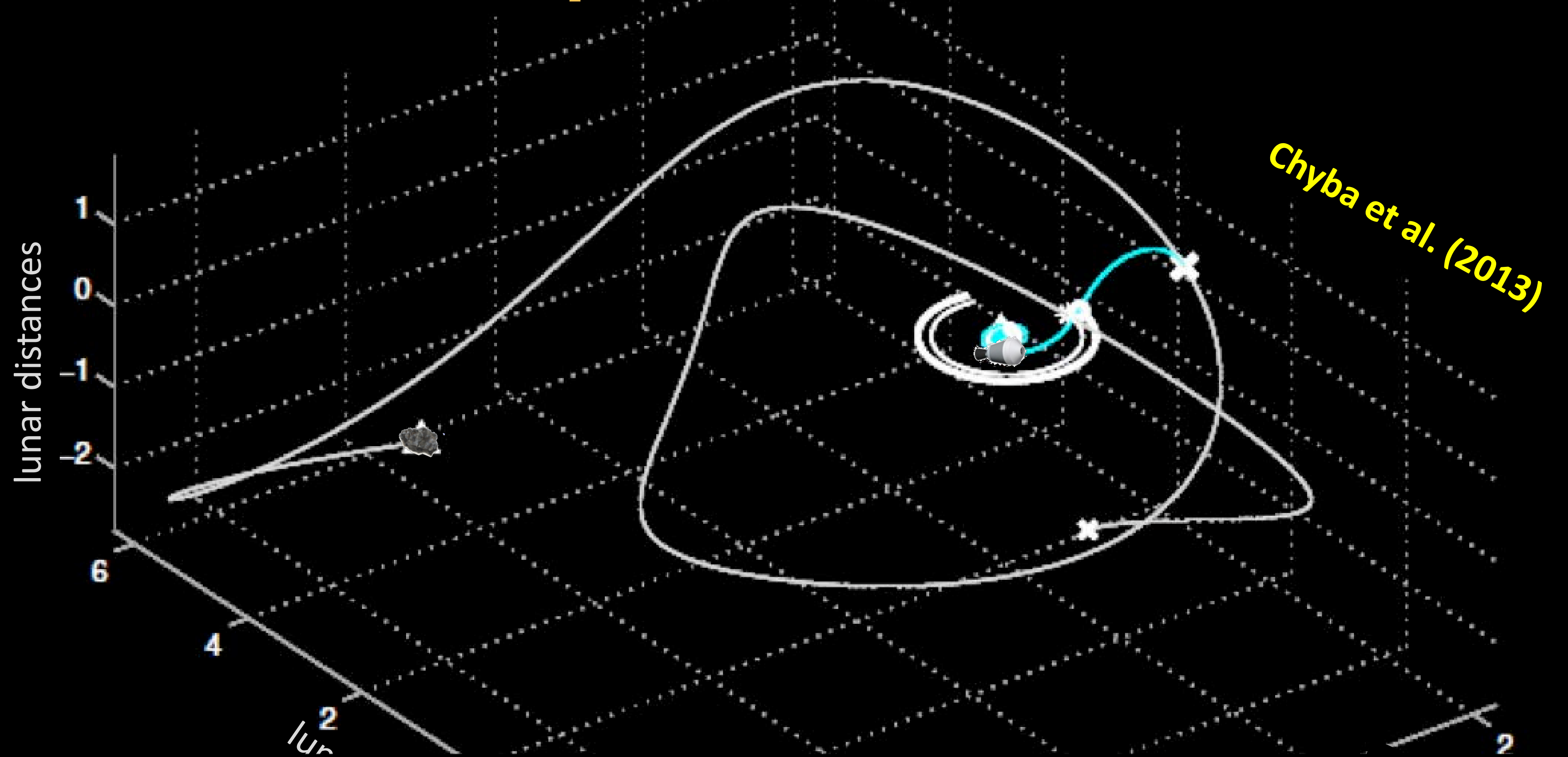


# Minimoon-Spacecraft Rendezvous




- Preliminary dynamical work suggests all minimoon orbits reachable by spacecraft from geosynchronous orbit.

# Minimoon-Spacecraft Rendezvous

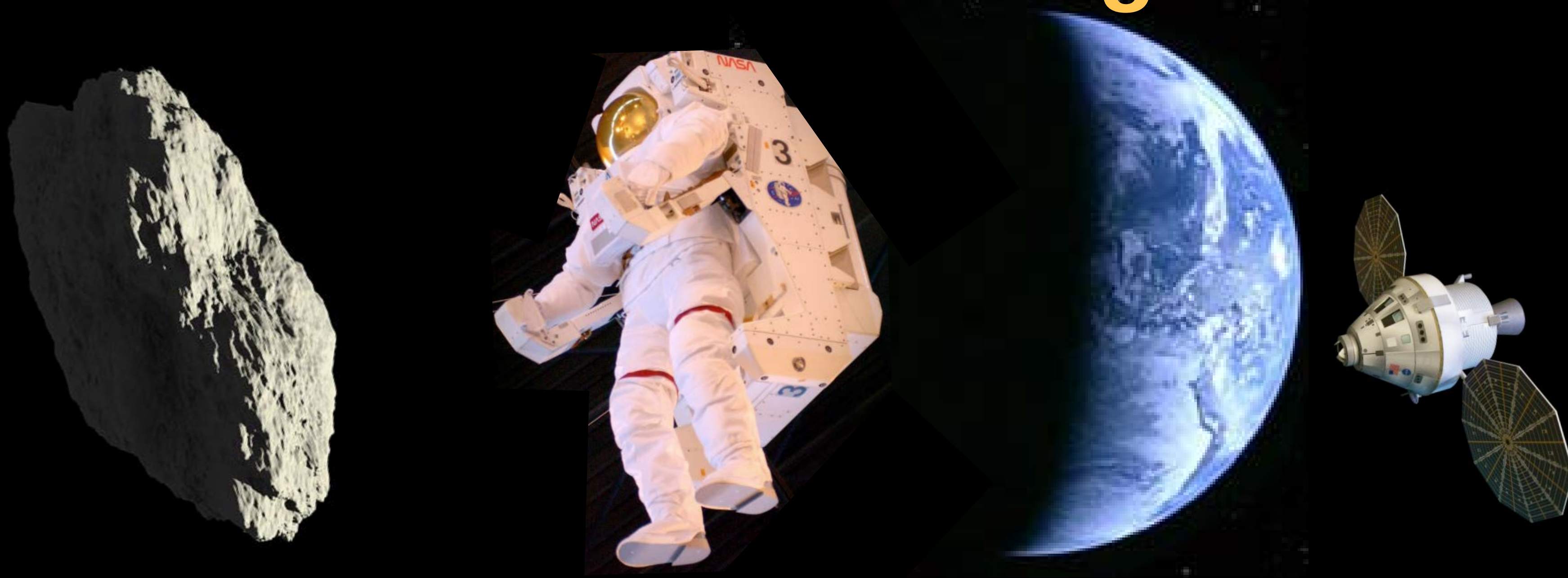



- **For human mission planning:**
  - – **Visit a long-term stable minimoon.**
  - – **If none suitable, use precursor to stabilize minimoon (mini-ARM?)**
  - – **Or, allow flexible flight plan for Orion to visit targets of opportunity**

# Minimoon-Orion Rendezvous

- **Preliminary estimates suggest an Orion-minimoon rendezvous mission might last many weeks.**
  - **Much depends on the orbit; some minimoons easier targets than others.**

# Minimoon Advantages



- Minimoons are already temporarily captured!
- Nearby targets for human missions that are reachable with Orion and scientifically interesting.
- Minimoons detectable with existing assets.

**Minimoons warrant an in-depth study!**