Interferometry of ASTEROIDS

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ESAC - Madrid - Aug 25, 2011

Outline

- Introduction: why to study asteroids and what do their physical properties tell us?
  - Main Belt Asteroids
  - Size, shape, density and internal structure
- Interferometry of asteroids
  - Data analysis models, potential targets.
  - First results of VLTI-MIDI observations.
  - Future projects/perspectives.

Asteroids of the main belt

Plotted here are the positions of the first 5000 asteroids every 5 days.

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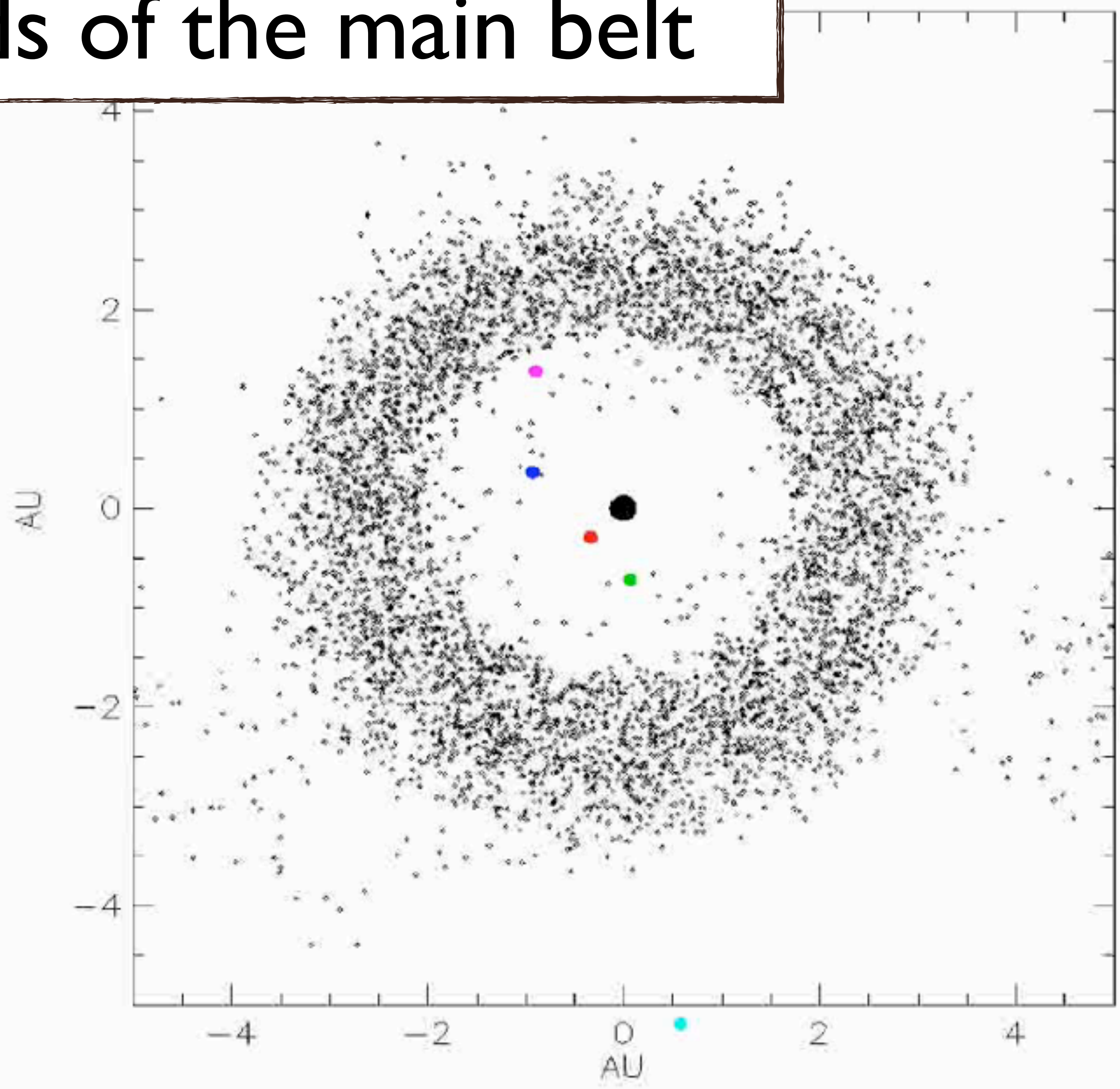


Near-Earth Asteroids (NEAs)

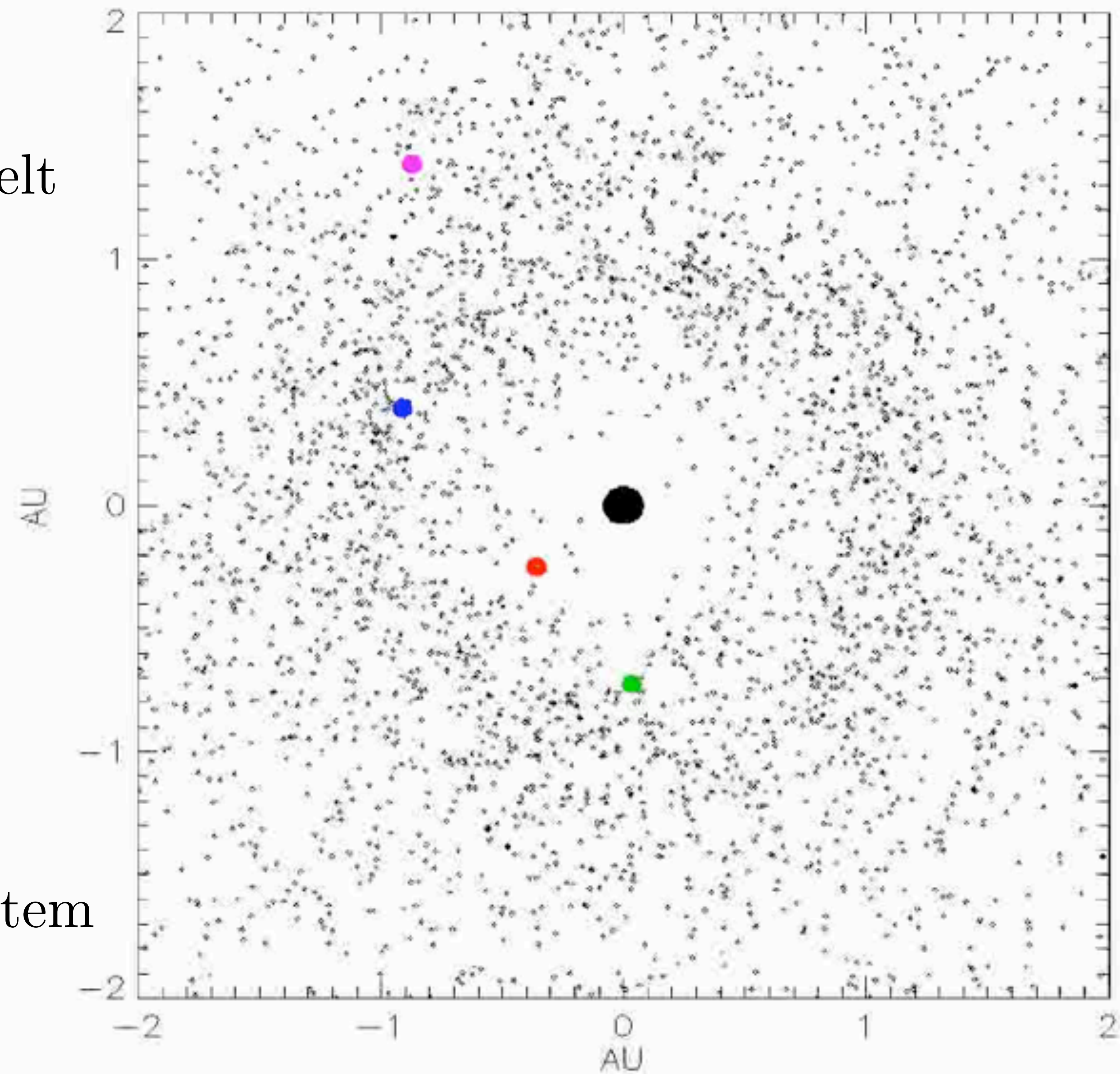
Some are from the main belt

Some are dead comets

dynamical lifetime: $\sim 10^7$y

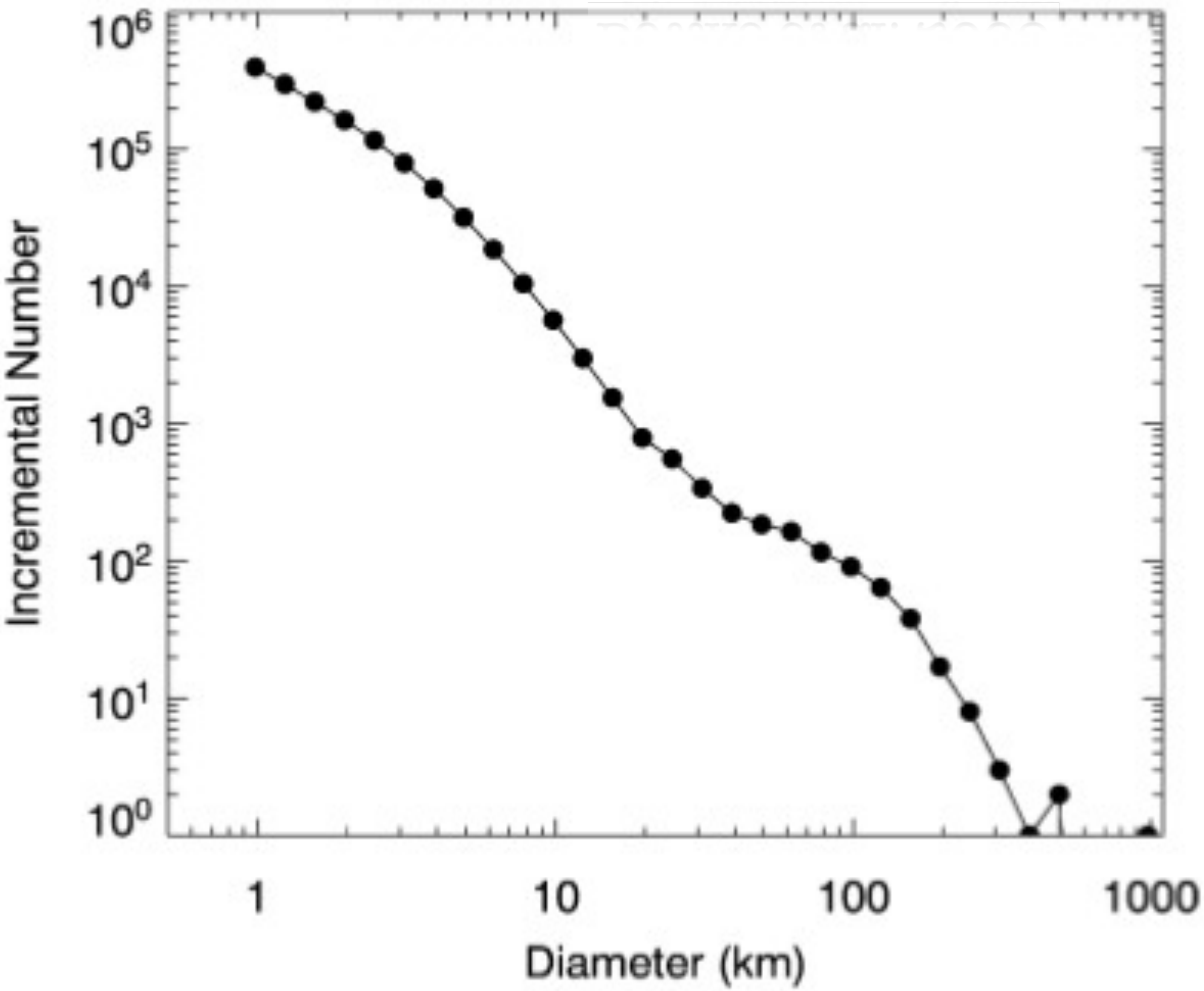
They meet they doom by

- crashing into the Sun
- ejection out the Solar System
- impacting a planet



Size distribution of main belt asteroids

Bottke et al. 2005



Assumption of spherical shapes

Size distribution of main belt asteroids

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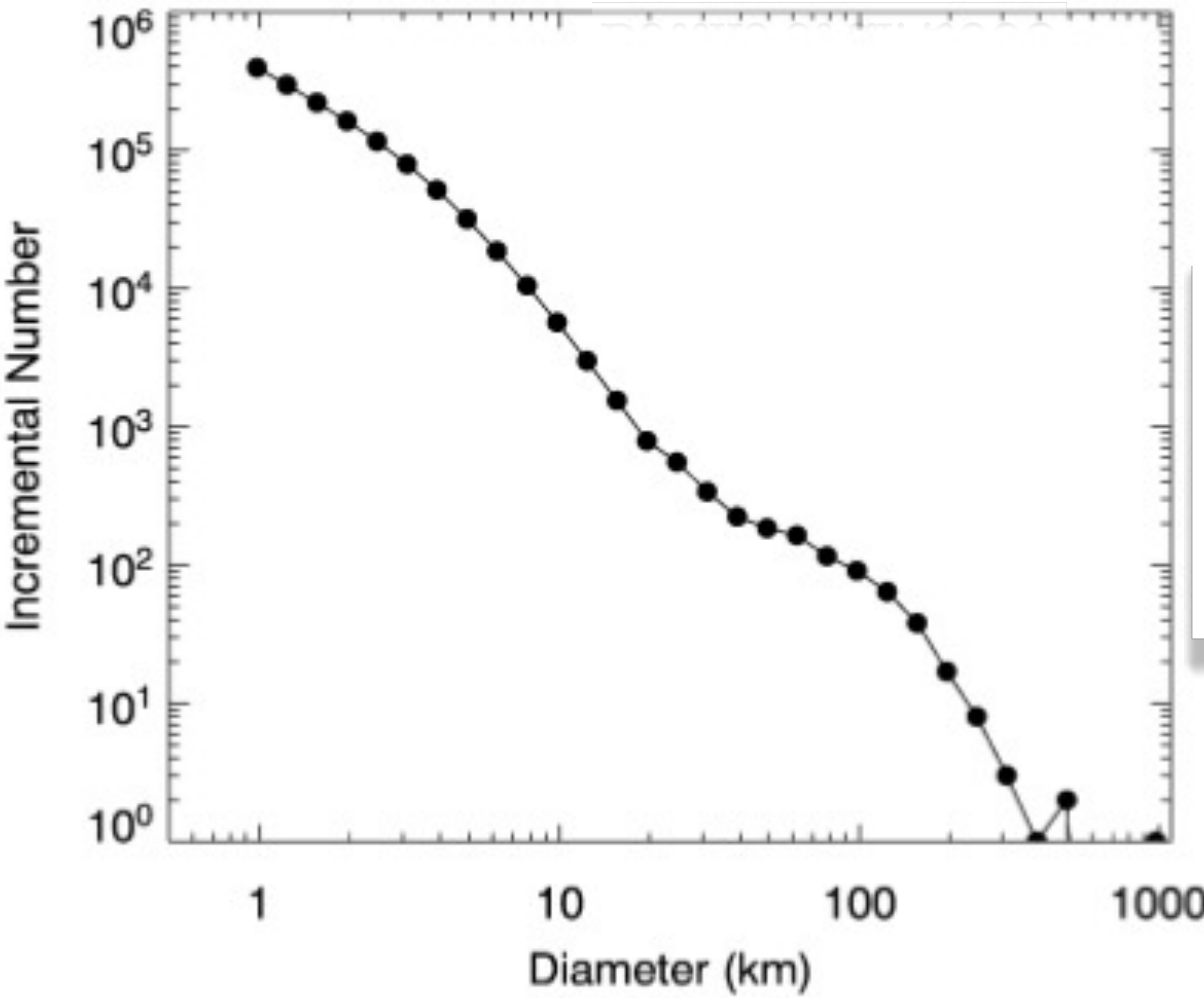

Assumption of spherical shapes

$$\theta(mas) = \frac{D(km)}{0.72\ \Delta(AU)}$$
$$\sim D \times \frac{1.5}{\Delta}$$

$\theta(mas) \sim D(km)$
at the center of the Belt

Size distribution of main belt asteroids

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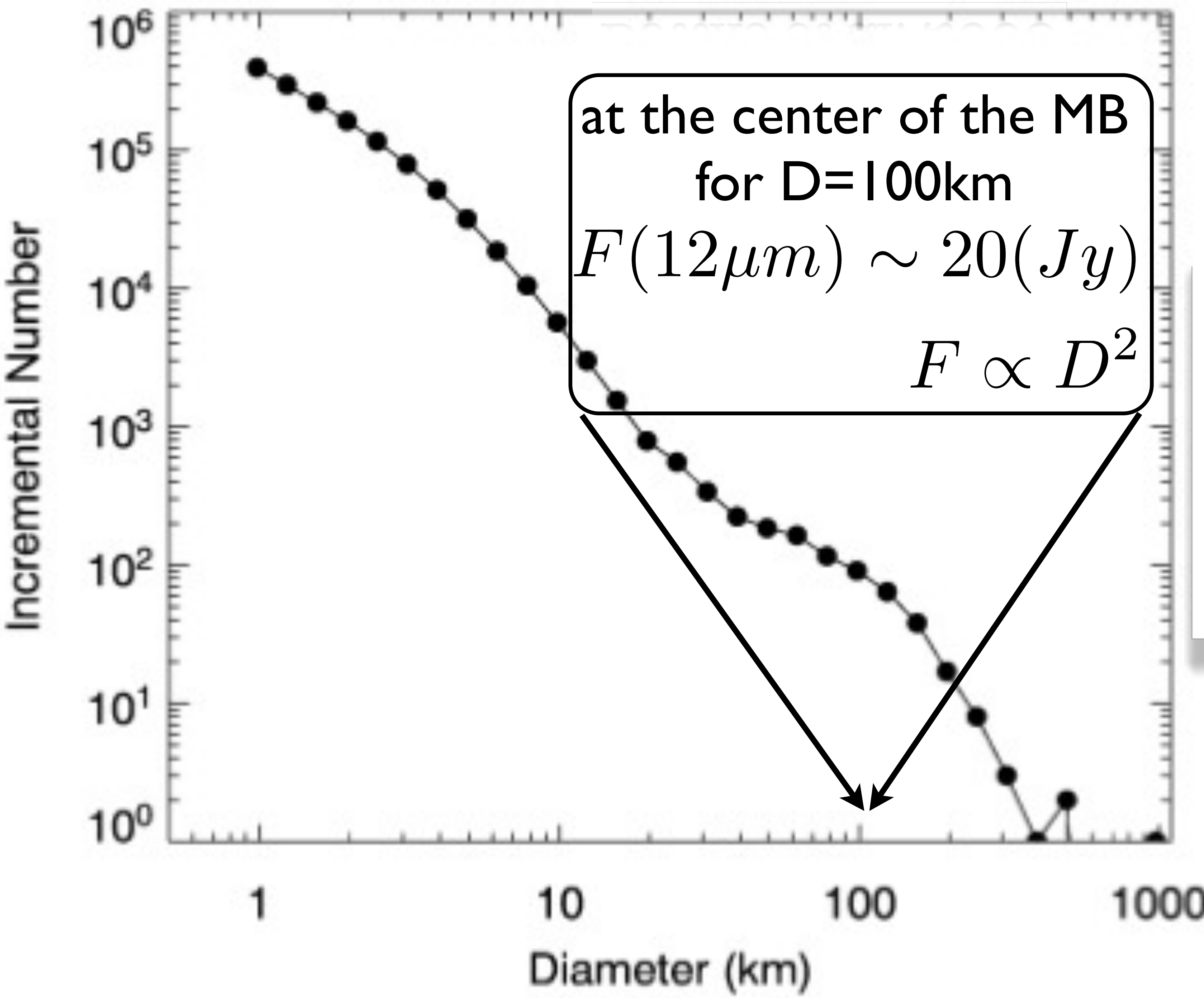

at the center of the MB
for D=100km

$$F(12\mu m) \sim 20(Jy)$$

$$F \propto D^2$$

Assumption of spherical shapes

$$\theta(mas) = \frac{D(km)}{0.72\ \Delta(AU)} \sim D \times \frac{1.5}{\Delta}$$

$\theta(mas) \sim D(km)$
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NEAs: size distribution

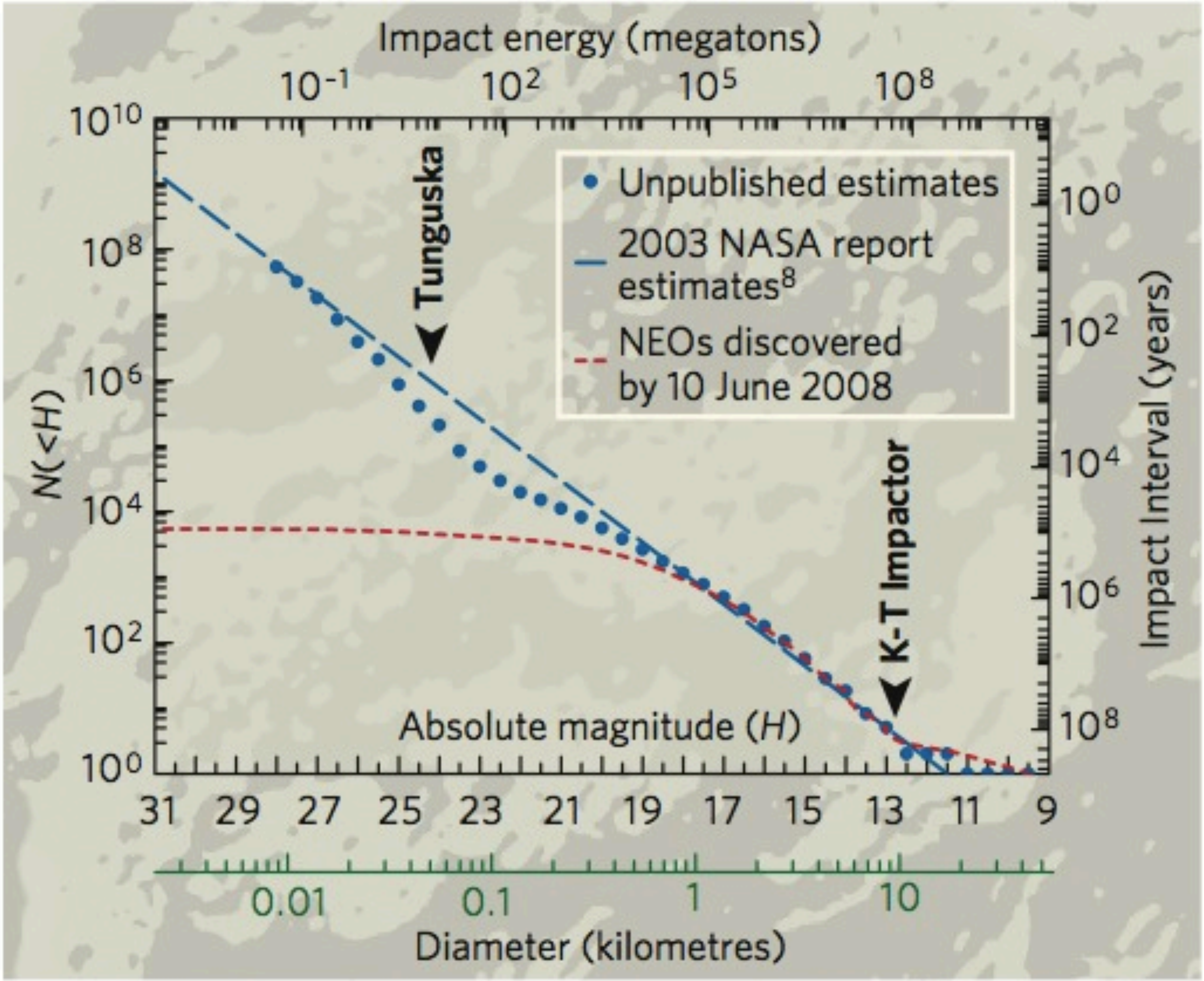
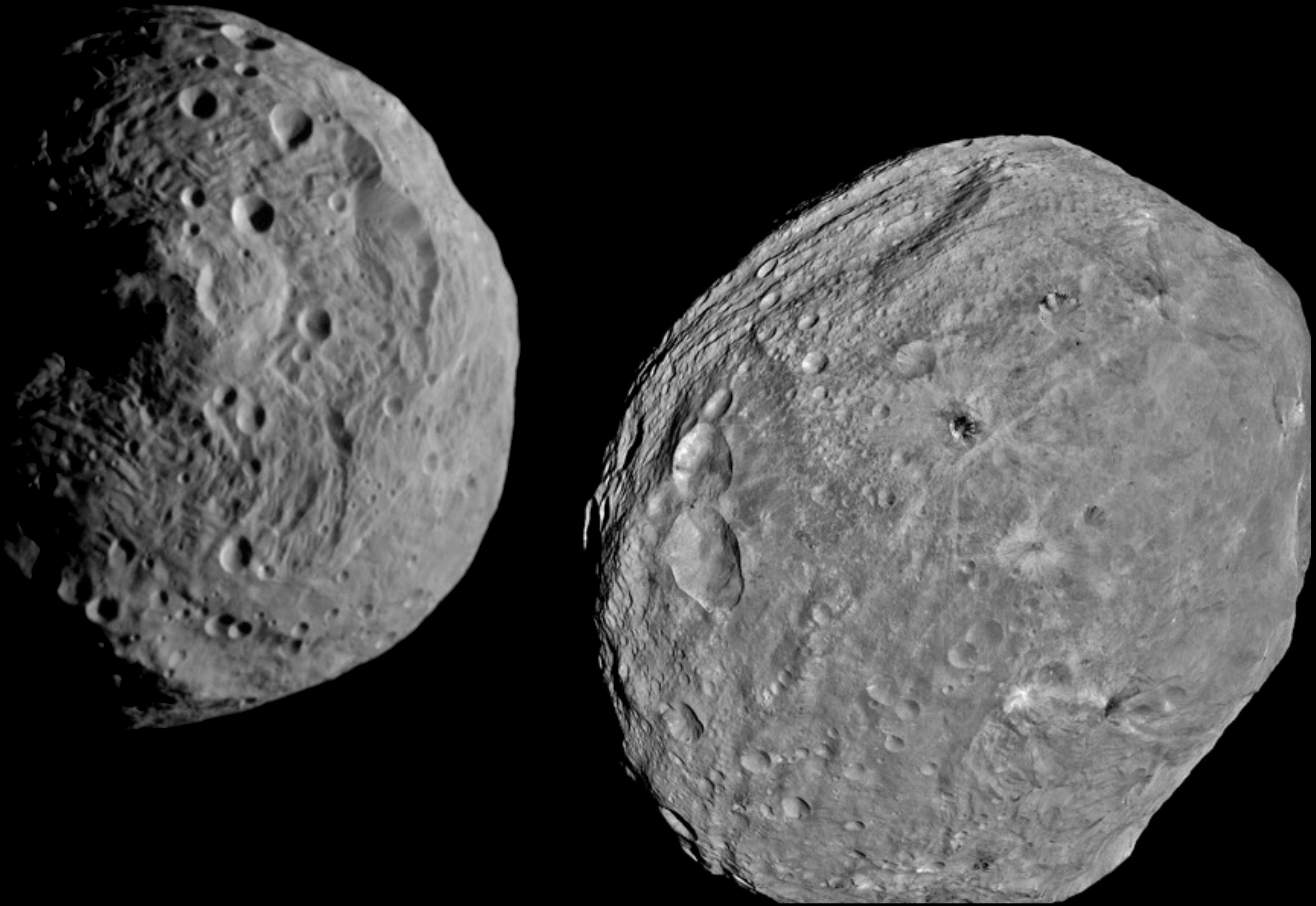


Figure 1 | Estimate of the cumulative population of near-Earth objects (NEOs) versus size. *H* is the absolute magnitude

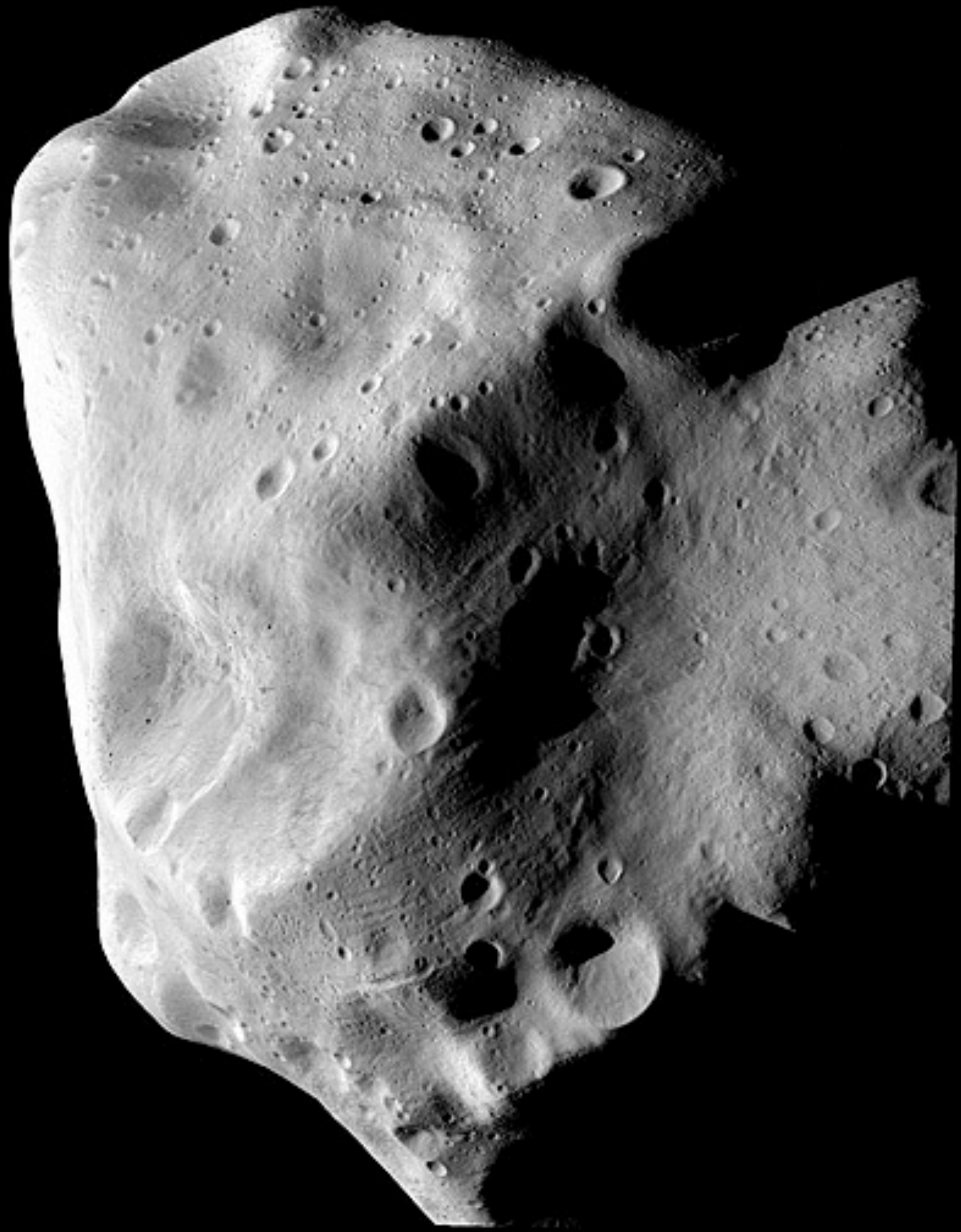
Images of asteroids from spacecrafts

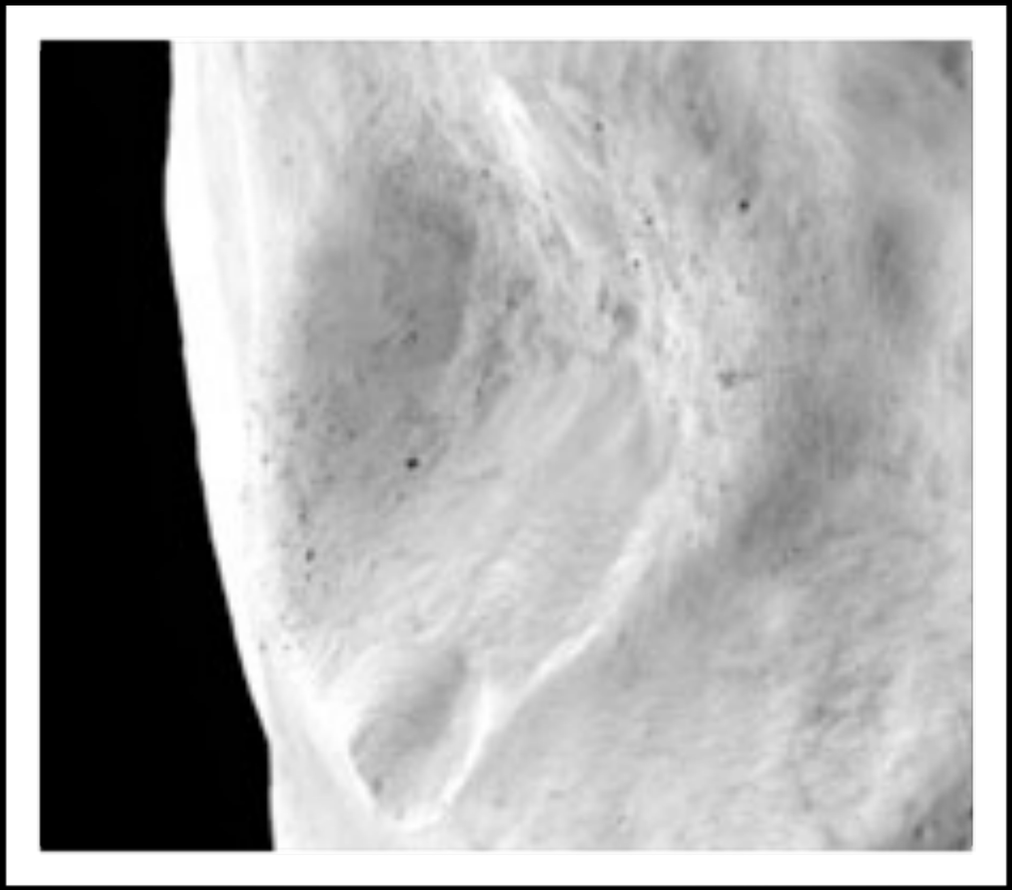
DAWN in orbit around (4) Vesta



Images of asteroids from spacecrafts

Rosetta flyby of 21 Lutetia





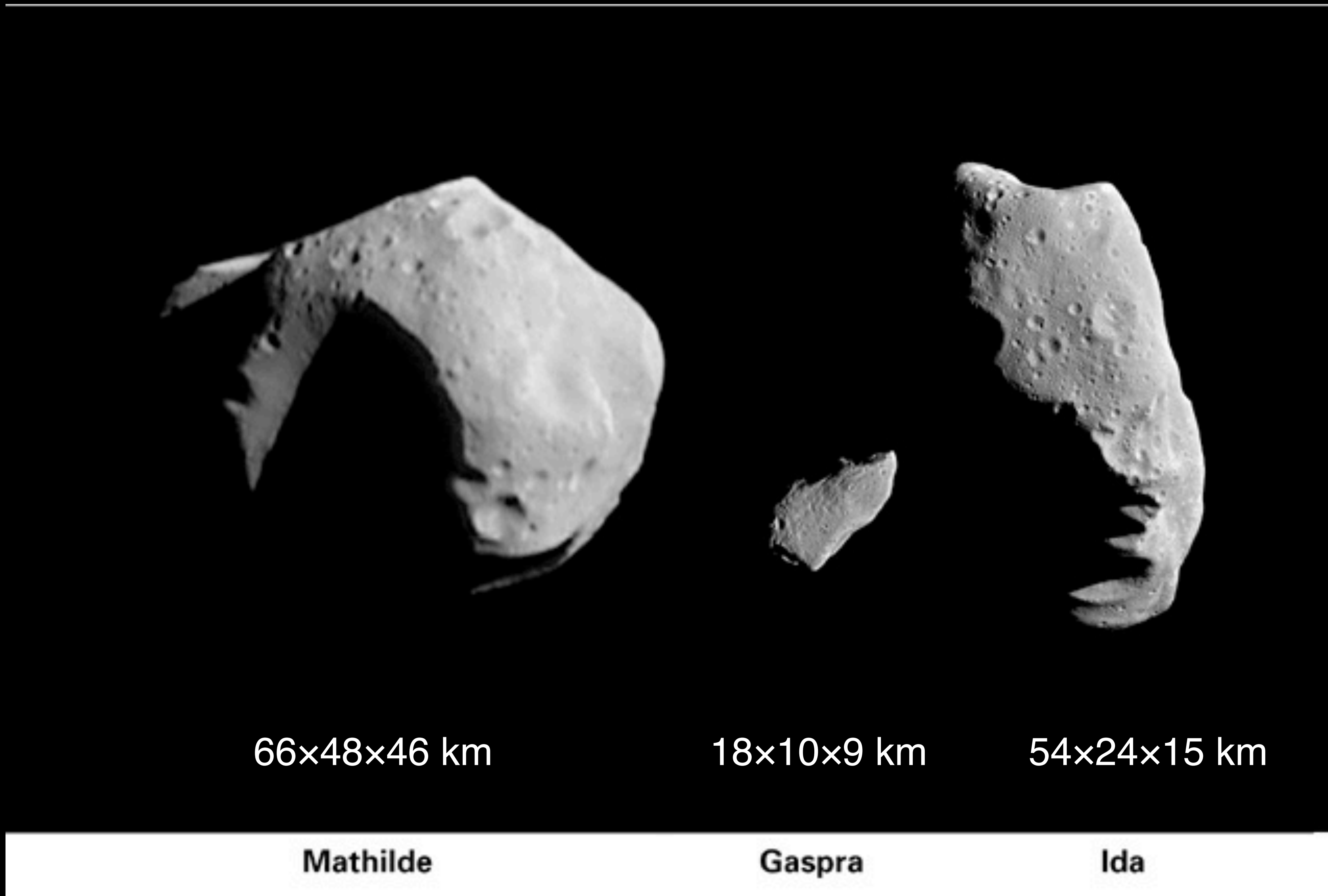
Covered with a regolith, estimated to be 600 m thick,

The regolith softens the outlines of many of the larger craters.

size: 132 × 101 × 76 km

mass: 1.7×10^{18} kg [pre Rosetta estimate: $(2.2\text{-}2.6) \times 10^{18}$ kg]

Images of asteroids from spacecrafts



Mission NEAR, 1998 (NASA)

Mission Galileo, 1993 (NASA)

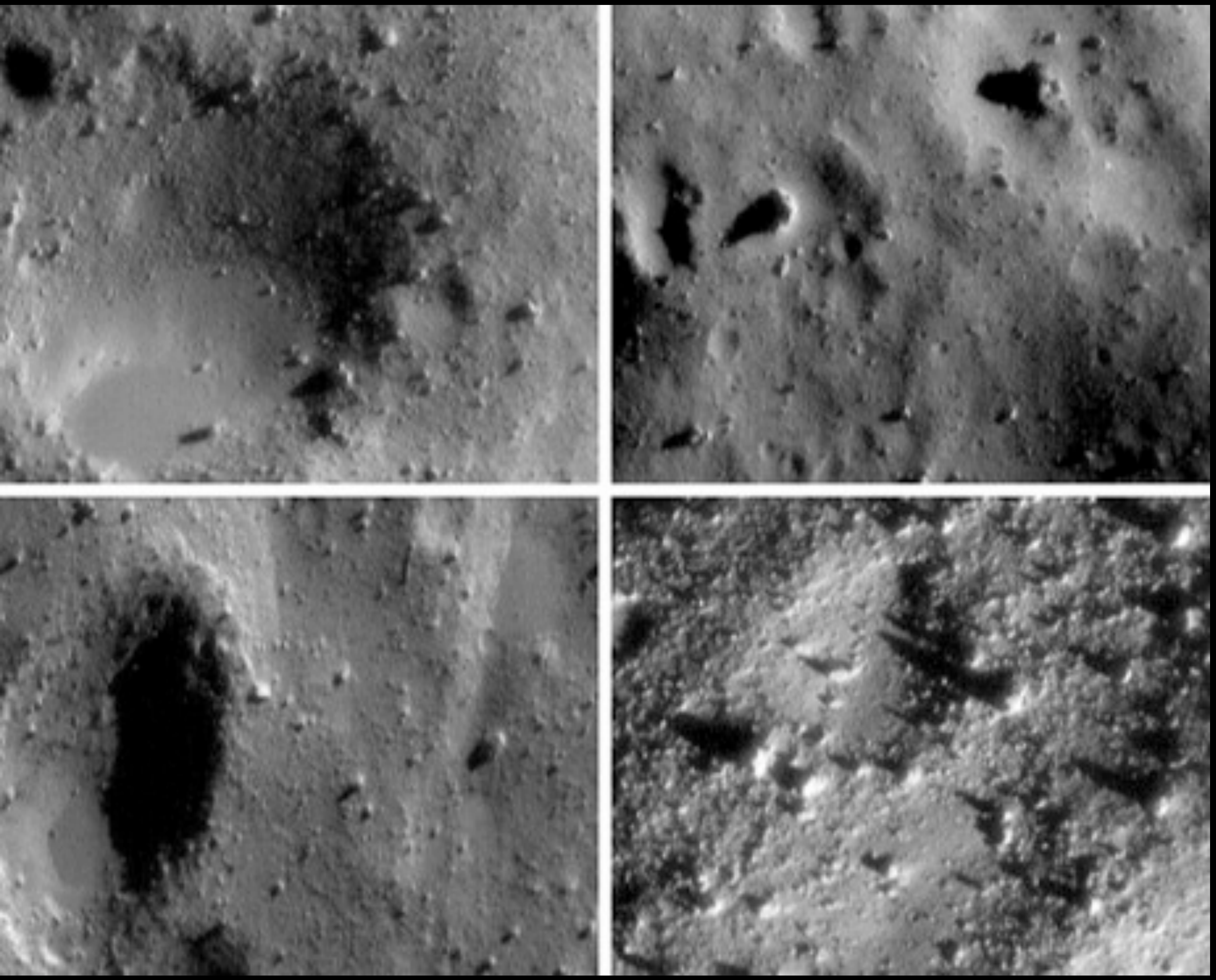
images from the NEAR shoemaker mission (NASA)

(433) Eros: size = 23 km

2^{nd} largest near-Earth asteroids

Discovered in Nice in 1898

First detailed images of the surface of an asteroid (433 Eros)



25143 Itokawa (viewed by Hayabusa)

Release 051101-1 ISAS/JAXA

Release 051101-2 ISAS/JAXA

size: 535 × 294 × 209 m
mass: $(3.58 \pm 0.18) \times 10^{10}$ kg
density: 1.9 ± 0.13 g/cm^3

Asteroids and the origin of our solar system

- Debris of the planet formation process
- Small → little alteration → conserve pristine material

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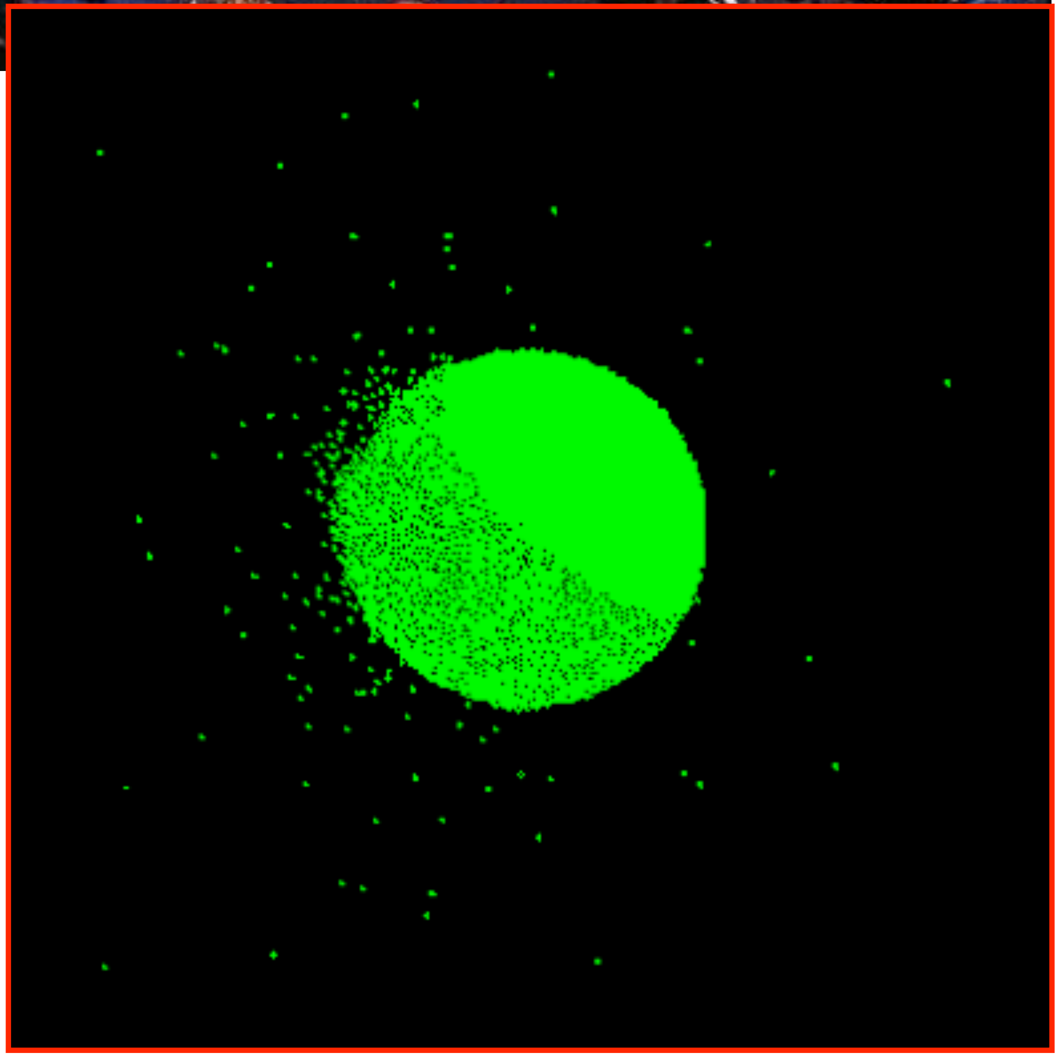
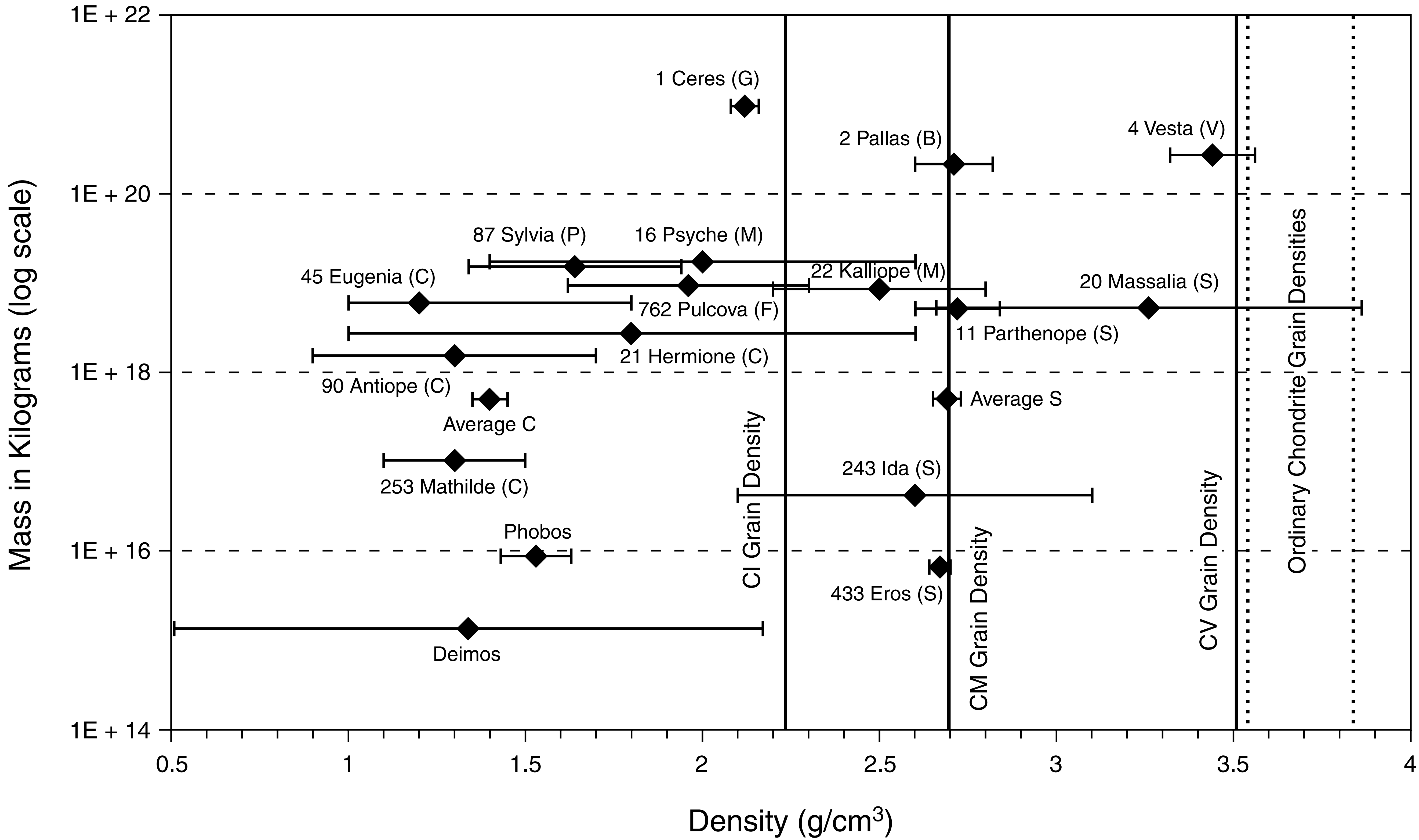


- Asteroids suffered collisional evolution.
- Sizes, shapes, and bulk densities tell us about their collisional histories

Simulation of disruption and reaccumulation by P. Michel

Densities of asteroids & meteorite analogs



Britt et al. 2002

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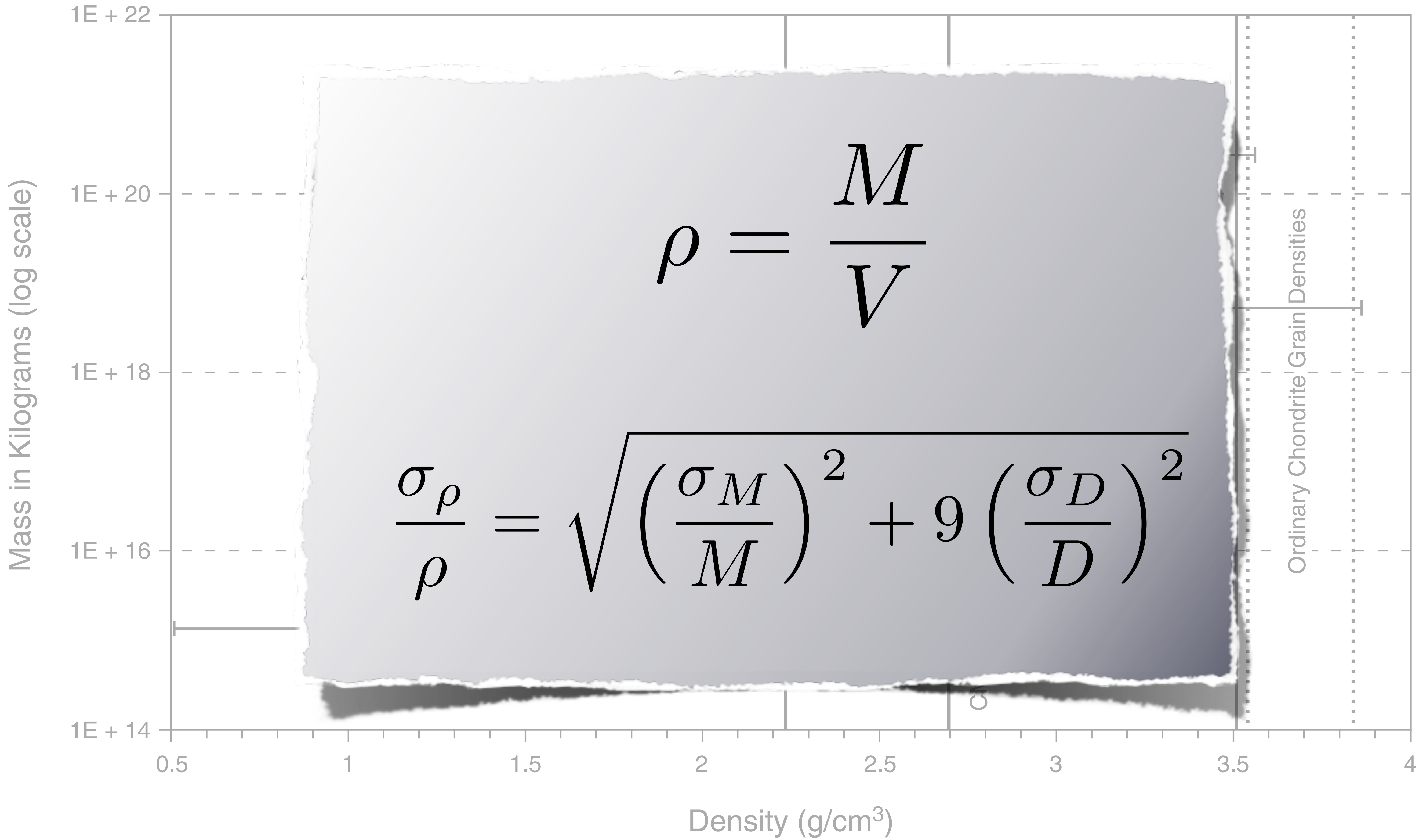
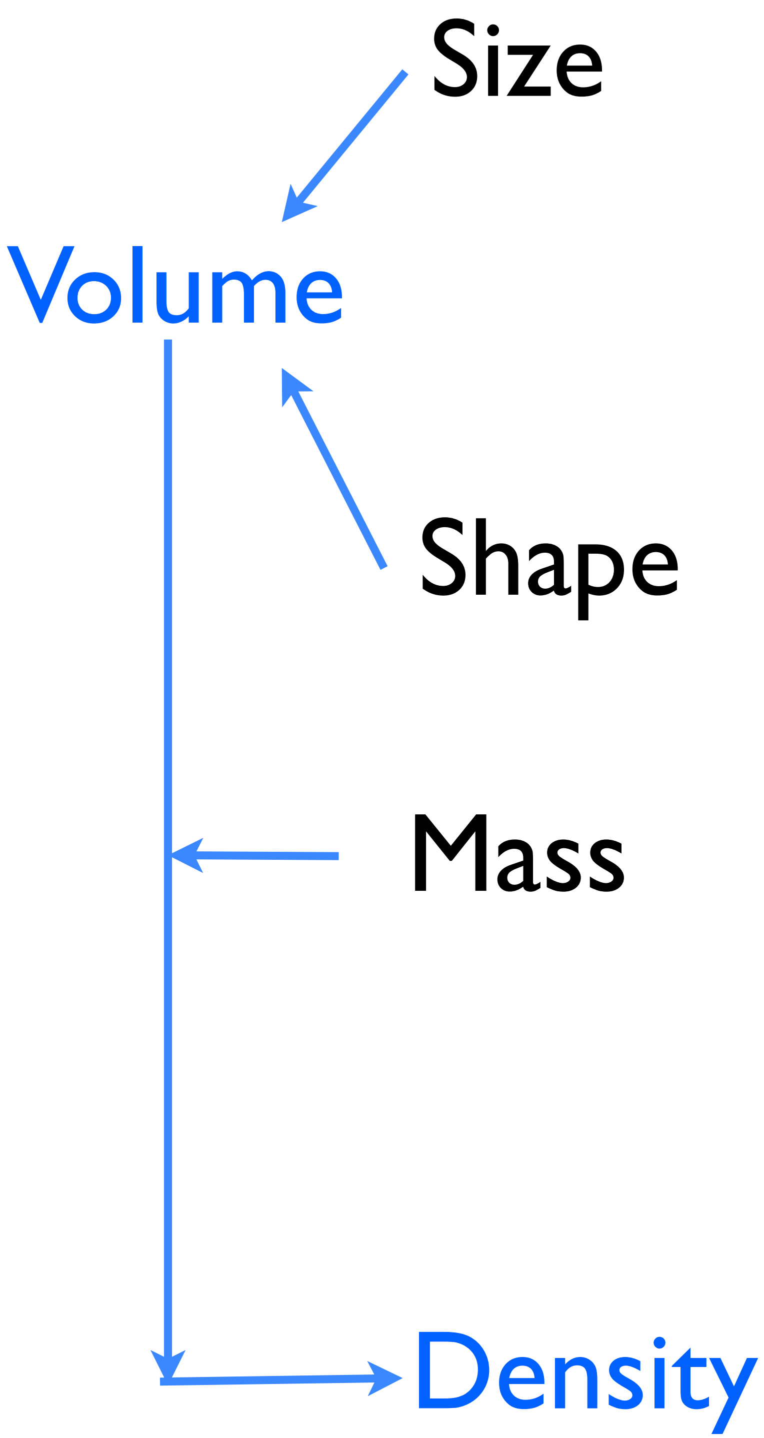


$$\rho = \frac{M}{V}$$

$$\frac{\sigma_\rho}{\rho} = \sqrt{\left(\frac{\sigma_M}{M}\right)^2 + 9\left(\frac{\sigma_D}{D}\right)^2}$$

Britt et al. 2002

Methods of physical characterization



Methods of physical characterization

Size ← Radiometry in the thermal infrared ($F_{IR} \propto D^2$)

Size, Shape ← Stellar occultation timing →

Shape ← Visible photometry (lightcurves)

Size → Volume

Shape → Volume

Mass

Volume, Mass → Density

Methods of physical characterization

Size

Radiometry in the thermal infrared ($F_{IR} \propto D^2$)

Volume

Stellar occultation timing

Visible photometry (lightcurves)

Shape

Asteroid-asteroid perturbation

Asteroid-planet (mars) perturbation

Asteroid-spacecraft perturbation

Mass

Density

Methods of physical characterization

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Size → Volume; Shape → Volume

Mass ← Asteroid-asteroid perturbation

Mass ← Asteroid-planet (mars) perturbation

Mass ← Asteroid-spacecraft perturbation

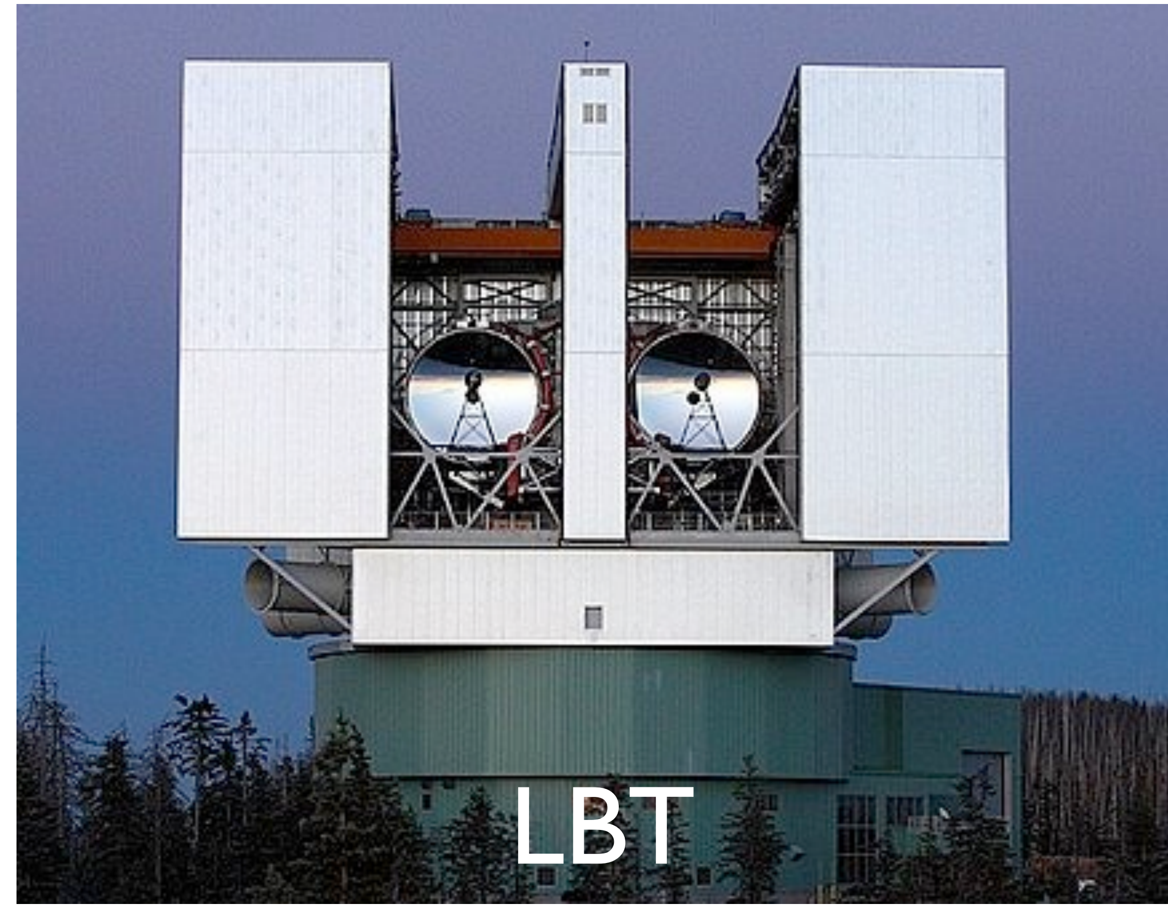
Mass ← Period and semimajor axis of asteroid satellites

$$\frac{P^2}{a^3} = \frac{4\pi^2}{GM}$$

↑ Adaptive optics, visible photometry

Volume, Mass → Density

Optical interferometers



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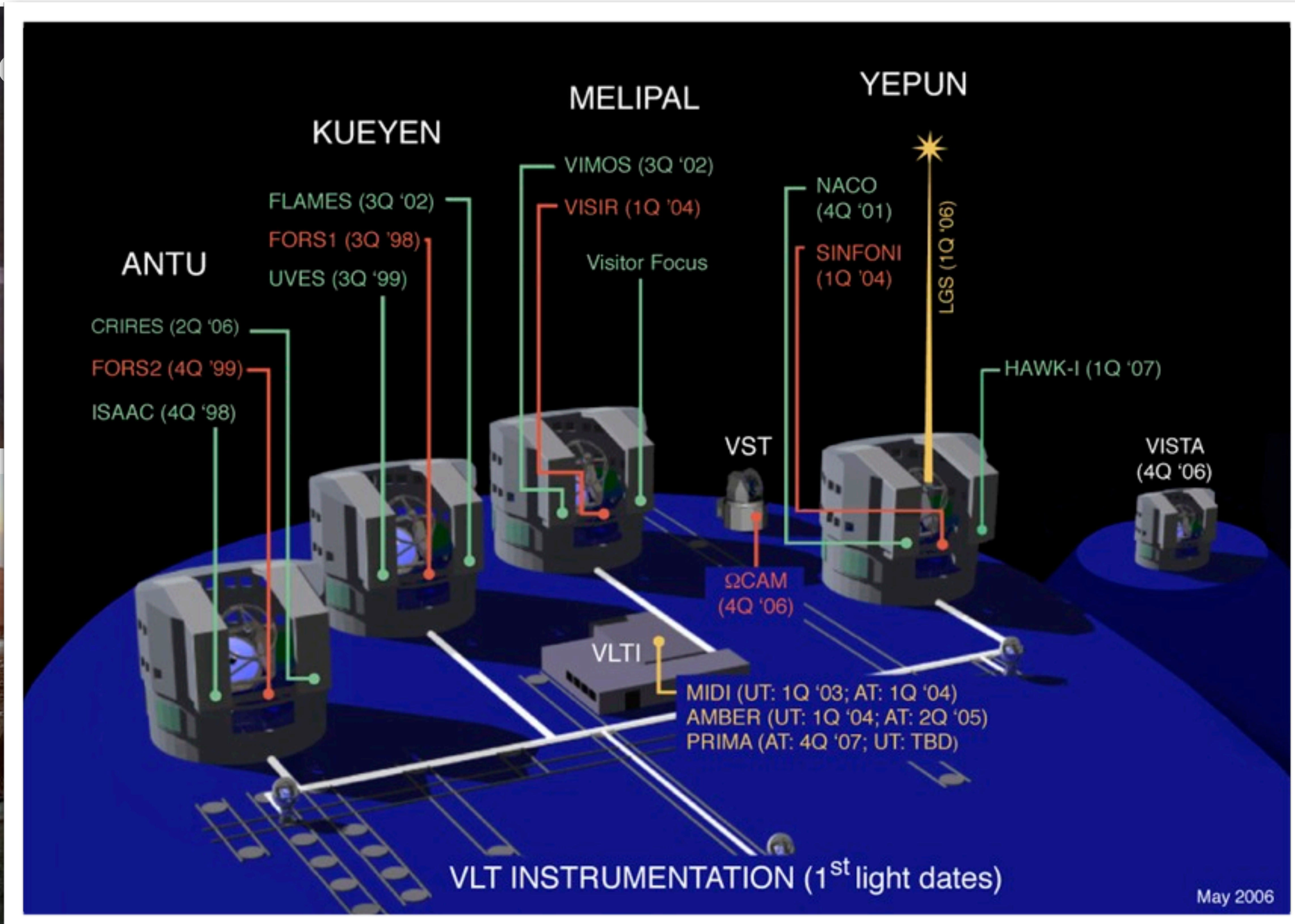


Interferometry and physical characterization of asteroids

Size → from 1 visibility →

Volume

Shape

Mass

Density

Interferometry and physical characterization of asteroids

Size → from 1 visibility →

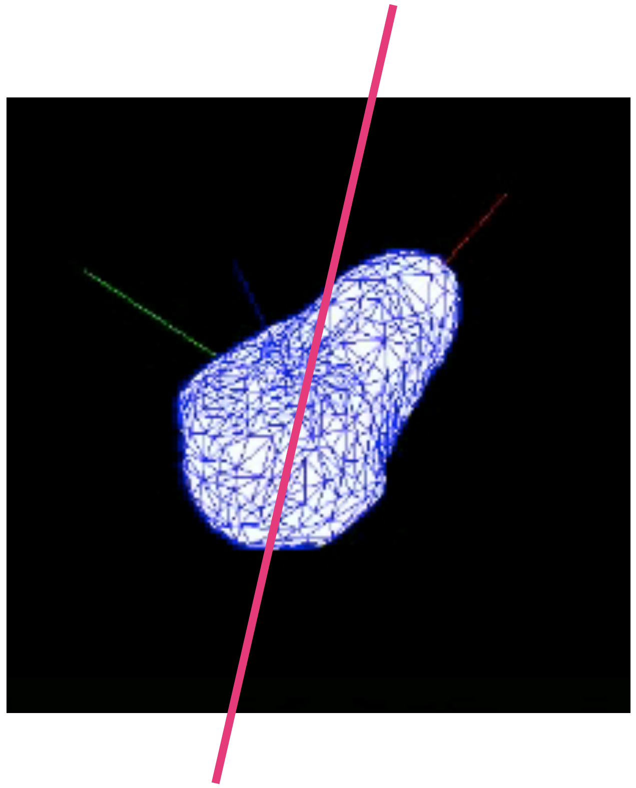
Volume

visibility as a function of time as the asteroid rotates →

Shape

Mass

Density



Interferometry and physical characterization of asteroids

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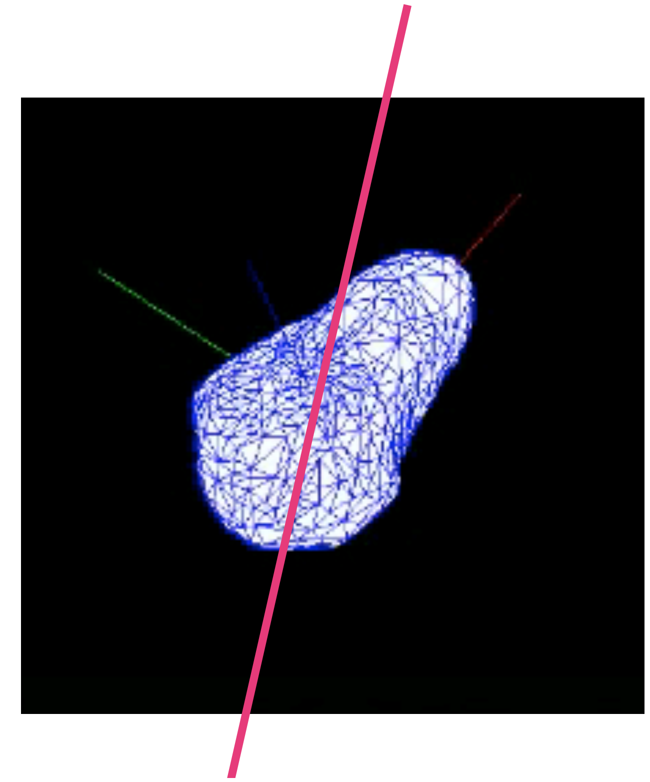


Volume

Shape → visibility as a function of time as the asteroid rotates →

Mass → Asteroid satellites: *P* from lightcurves and *a* from the visibility at (some) epochs →

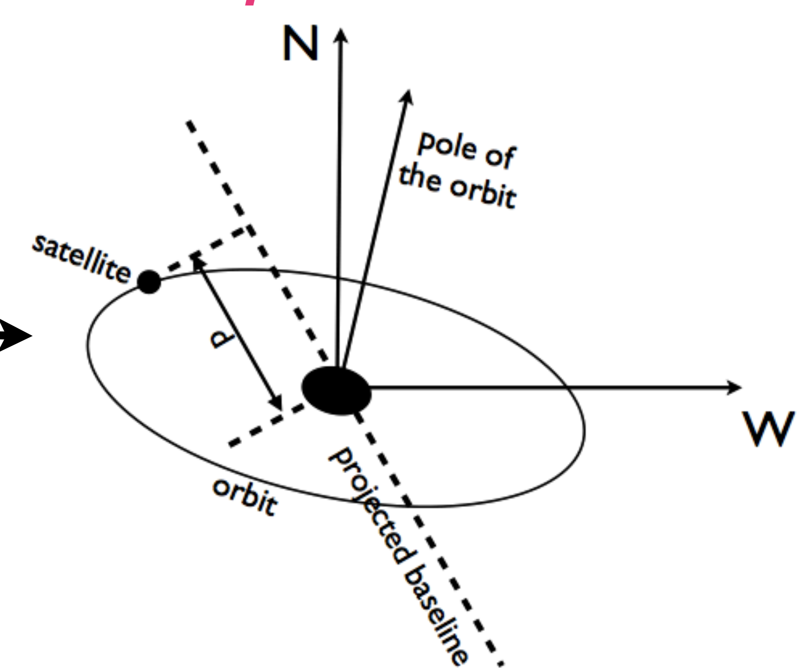


Figure 4 Geometry of the orbit on the plane of the sky at the time of interferometric measurement.

$$\frac{P^2}{a^3} = \frac{4\pi^2}{GM}$$

Density

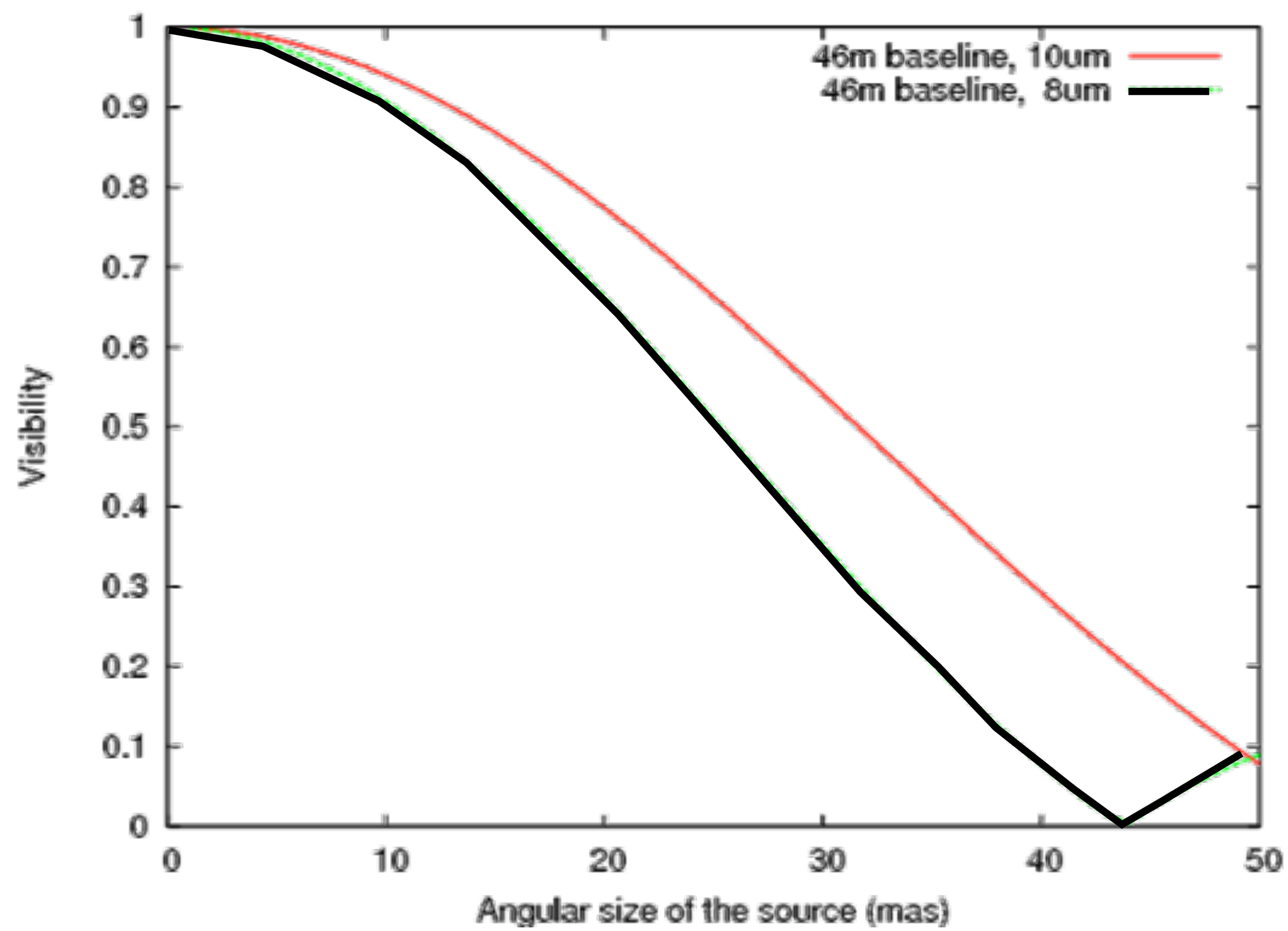
Simple geometric models (1) uniform disk

Visibility $$|V_\theta(u)| = |2J_1(\pi\theta u)/(\pi\theta u)|$$

first order Bessel function of first kind

Interferometric visibility of a uniform disk of diameter θ

as function of θ, where u = B/λ



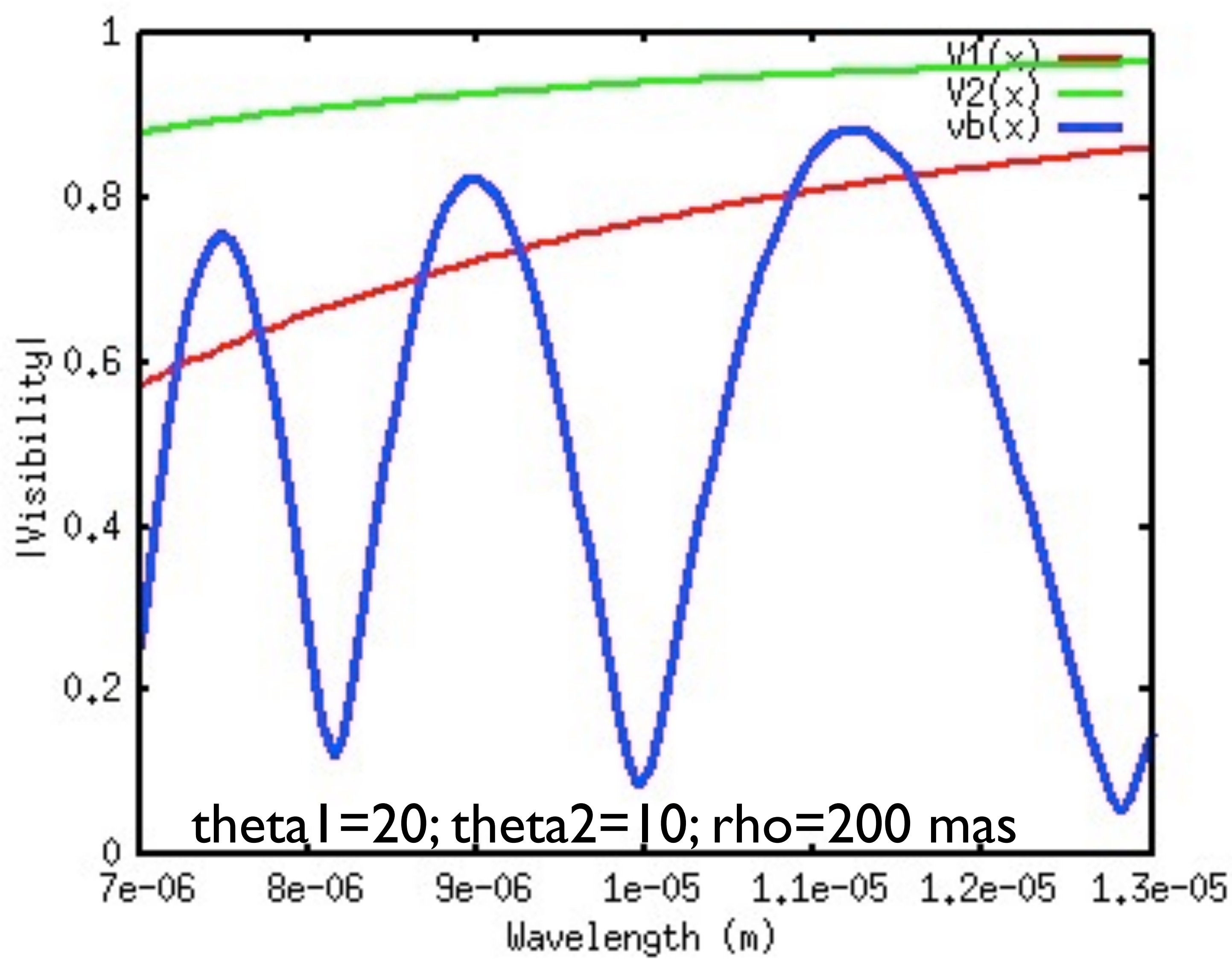
Simple geometric models (2) binary model

Visibility

$$|V_b(u)| = \frac{\sqrt{V_{\theta_1}^2 I_{\theta_1}^2 + V_{\theta_2}^2 I_{\theta_2}^2 + 2V_{\theta_1} I_{\theta_1} V_{\theta_2} I_{\theta_2} \cos(2\pi u \rho)}}{I_{\theta_1} + I_{\theta_2}}$$

Interferometric visibility of a binary of components of sizes θ1 and θ2 separated by a distance rho

as function of lambda in meters



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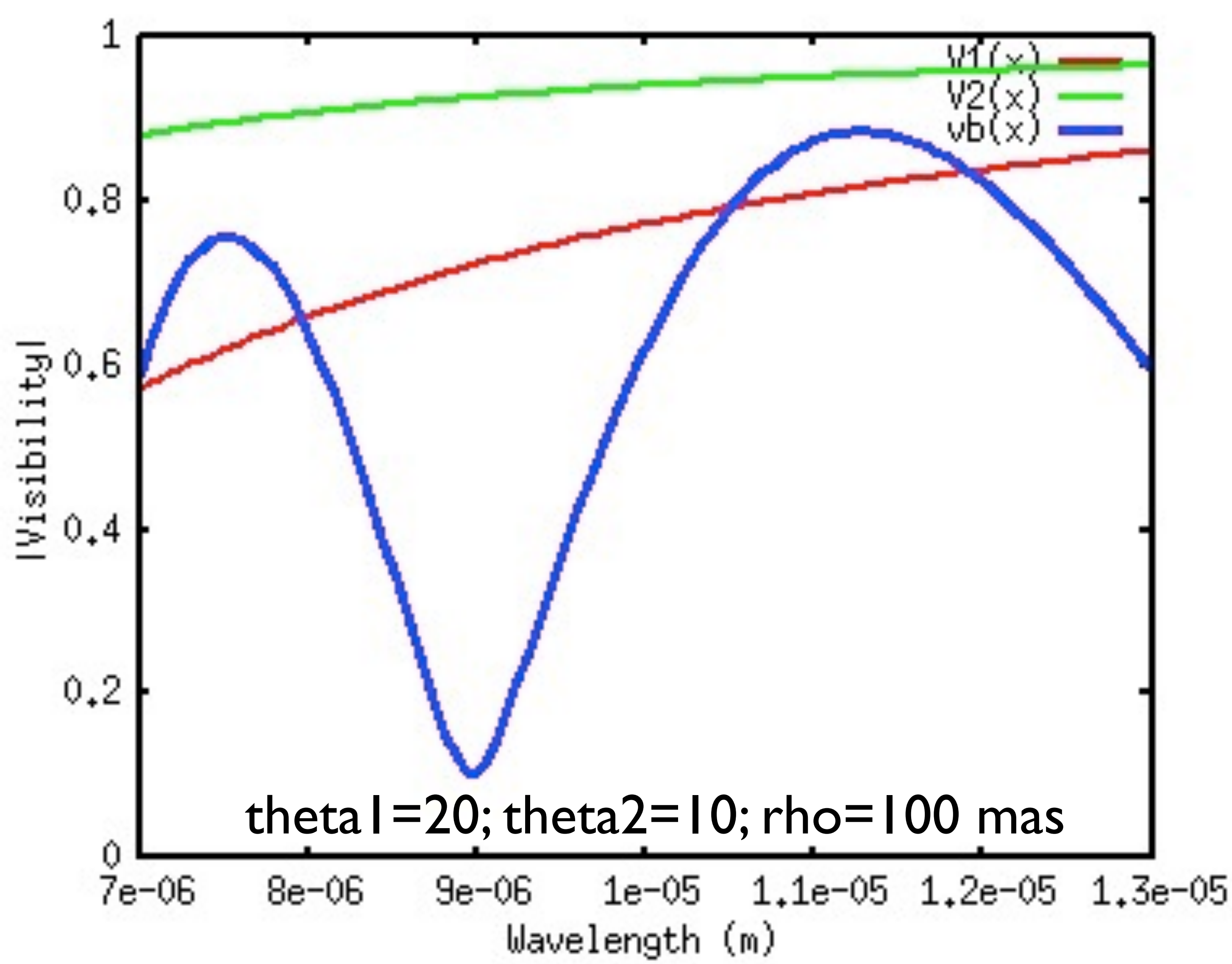

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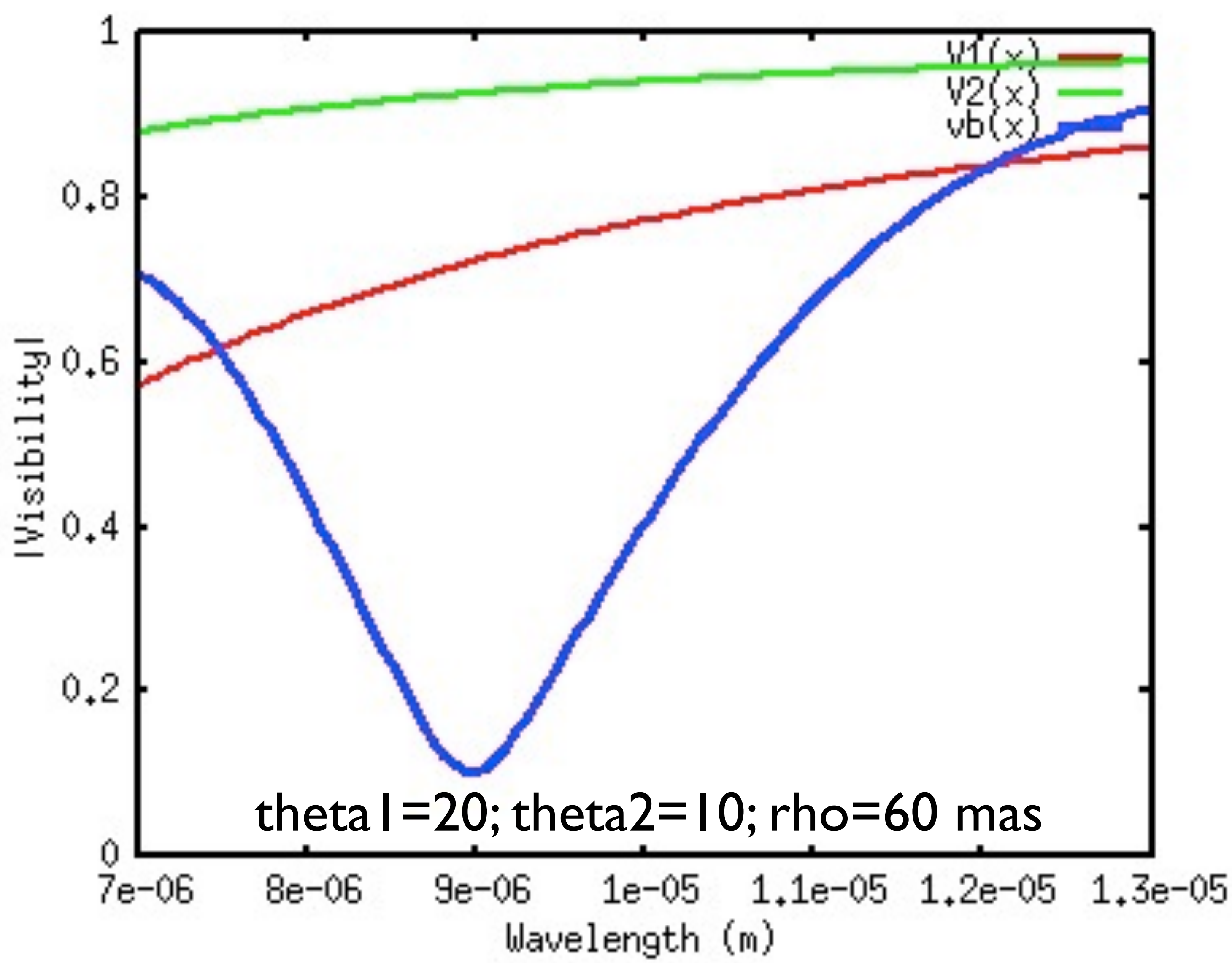

Results from interferometry

The VLTI of the ESO

- Coherent combination of the light from telescopes (distance between them B) of the VLT
- Resolution $\theta \sim \lambda/B$
  - MIDI $\lambda \in [8,13]\mu m$
  - AMBER $\lambda \in [1.2,2.5]\mu m$
  - VLTI $B \in [16,120]m$

$\theta_{MIDI} \in [15,100]mas$

$\theta_{AMBER} \in [3,25]mas$

Not sensitive enough for asteroids..

$\theta_{PRIMA} \in [3,25]mas$

K<9 (guide star) dual field (reference star and asteroid need to be within ~30”)

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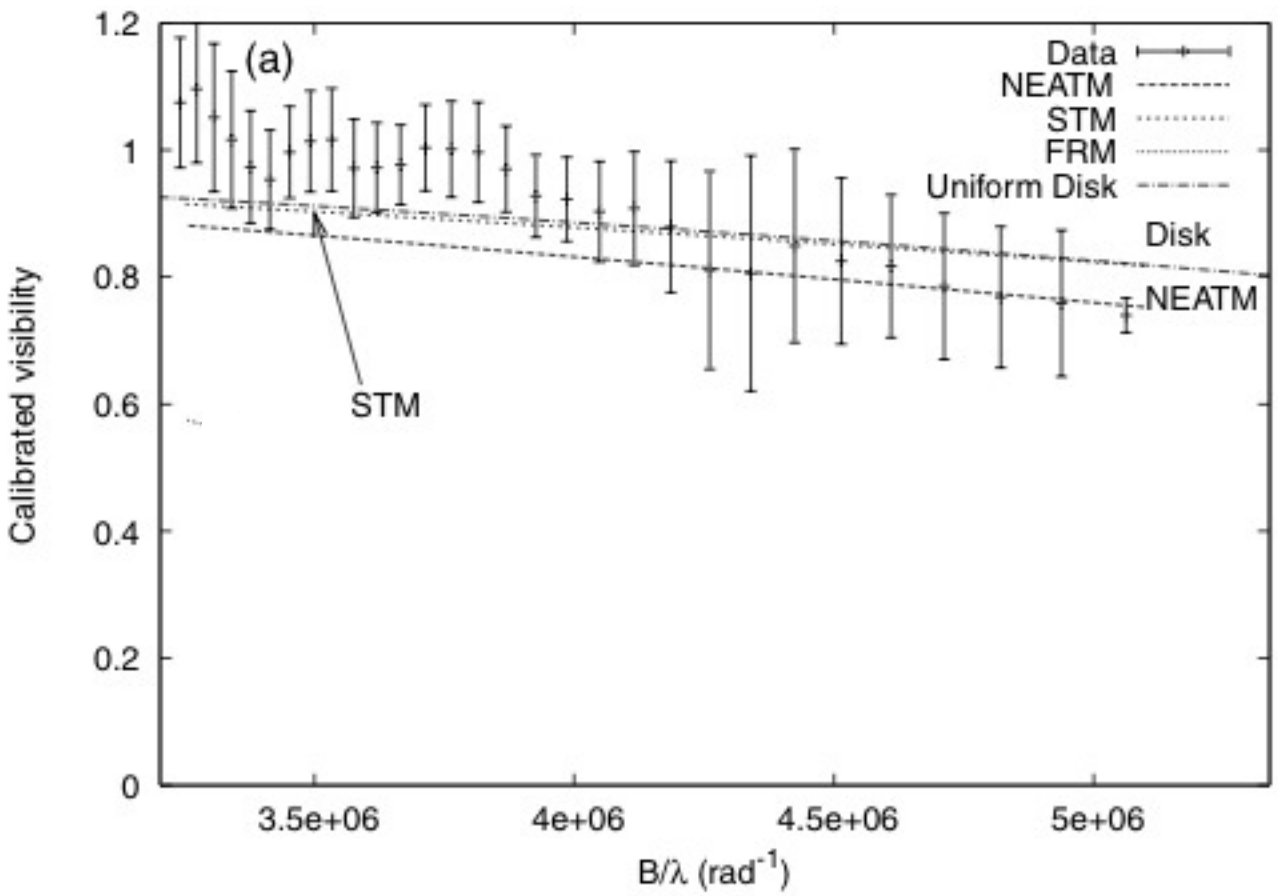
So far results for MIDI only

First successful observations of asteroids with MIDI-VLTI

Obtained fringes on

- 951 Gaspra (a testbed)
- 234 Barbara (complex shape)
  - long rotation period (26.5 hr, Schober 1981; Harris & Young 1983) suggestive of a possible binary system.
    - interferometric observations by Delbo et al 2009
- 41 Daphne (complex shape)
  - Matter et al 2011 (almost in press)

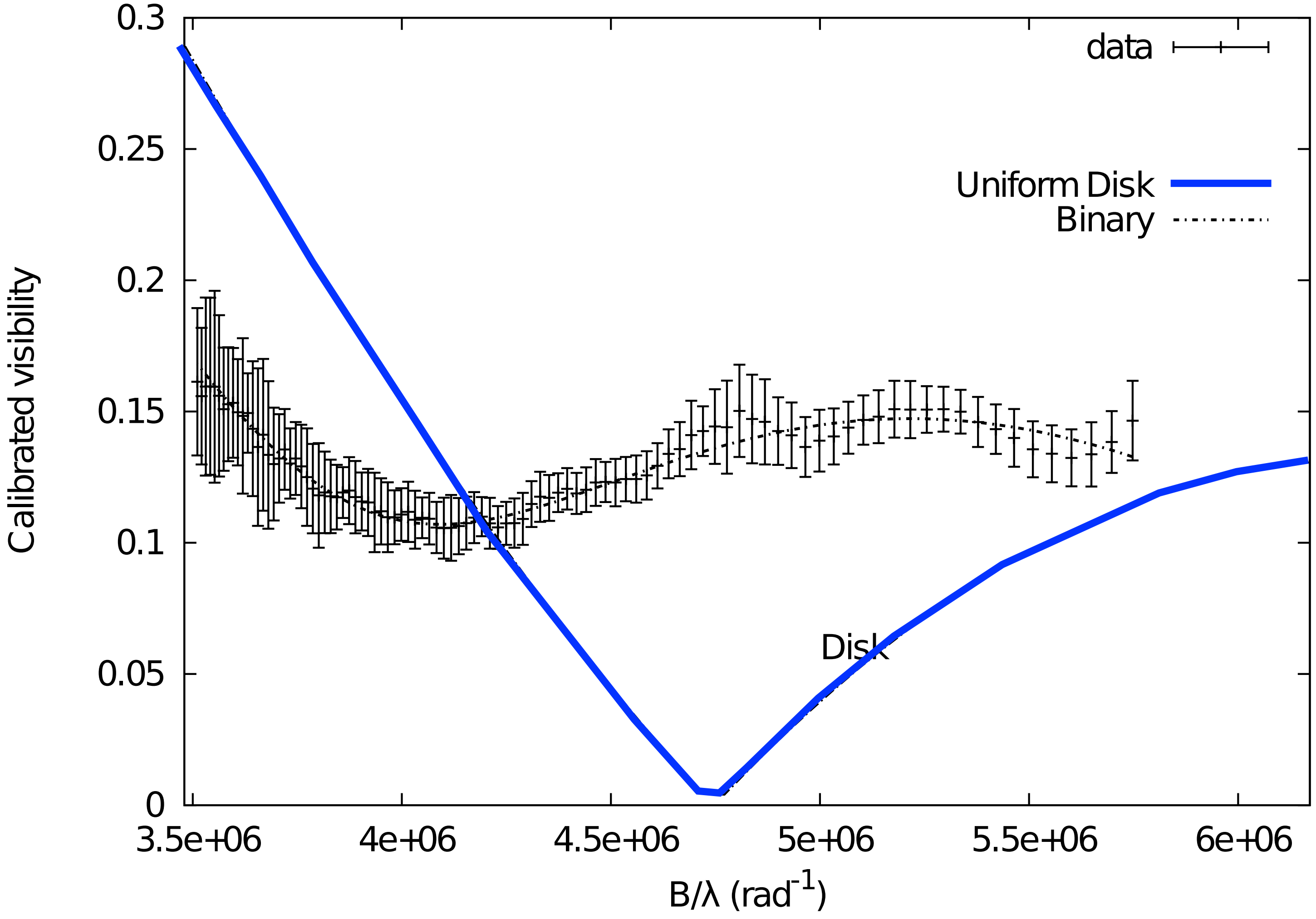
Results for Gaspra: size



Uniform disk fit to visibility
d =11 ± 2 km.

d=13 ± 2 or 11 ± 2 km
expected value from Thomas et al. (1994) in-situ observations depending of the spin-pole solution adopted

Results for Barbara: size and shape



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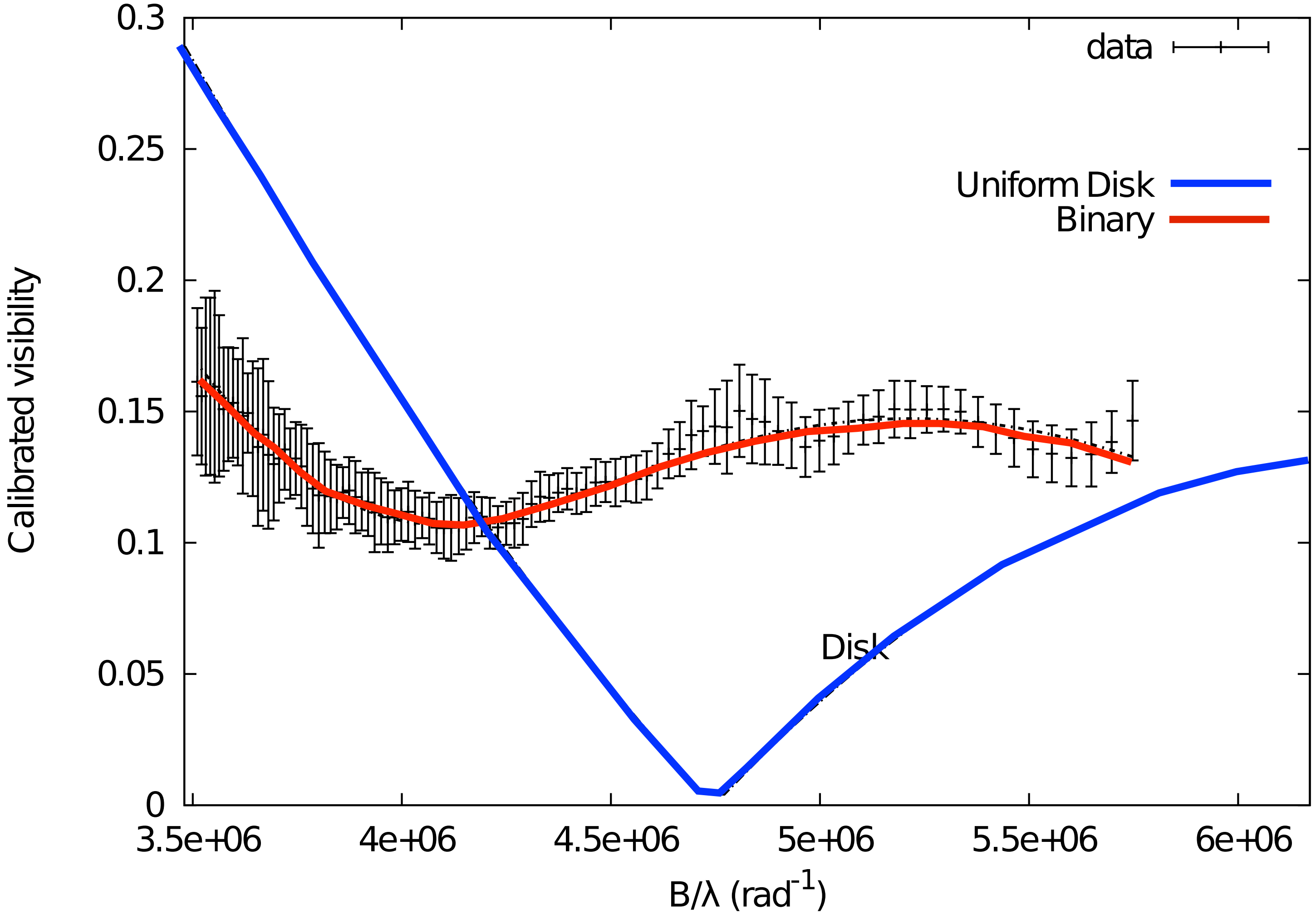

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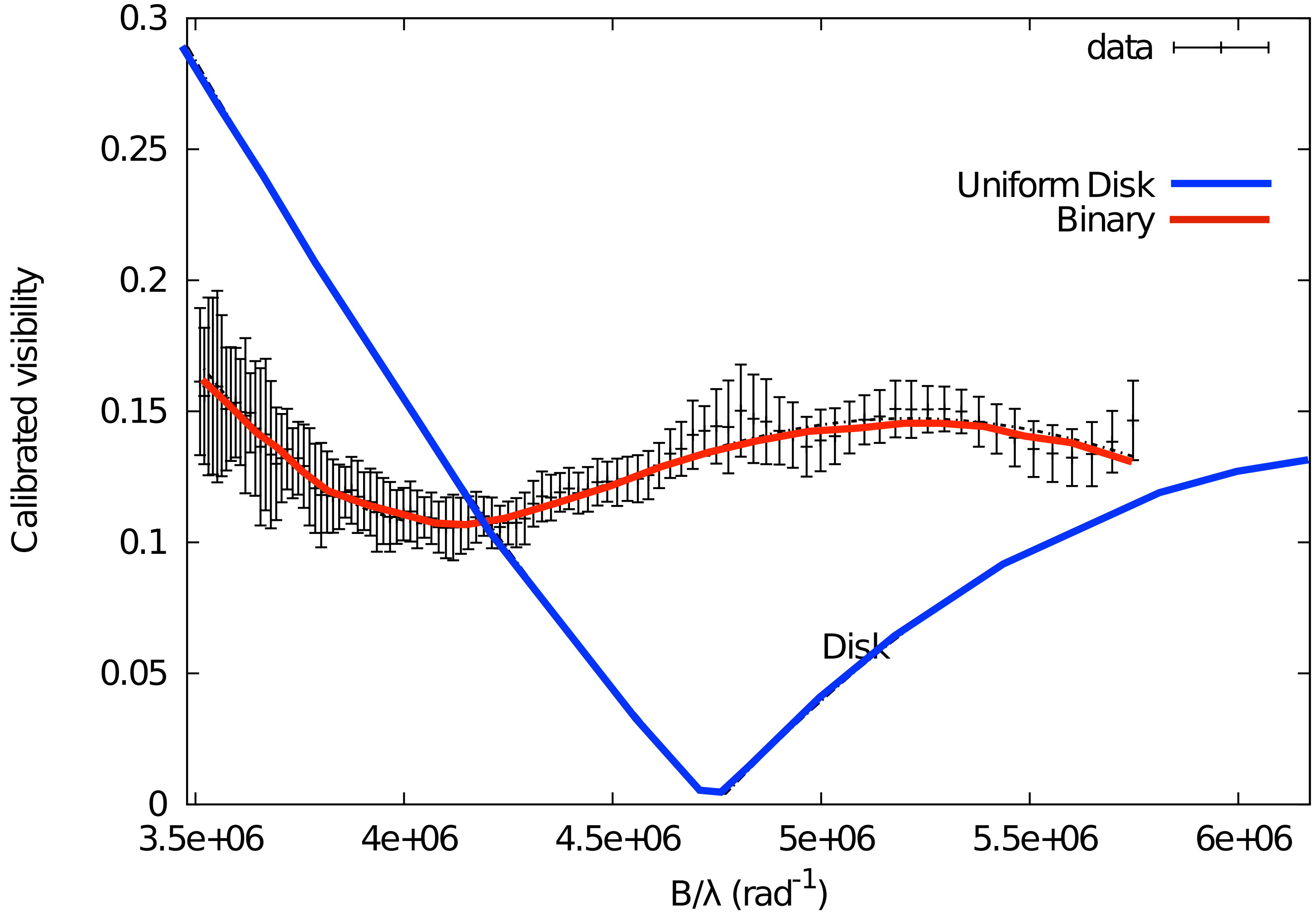

Asteroid	d (km)	Notes
Barbara	44.6 ± 0.3	poor fit
Barbara(1)	37.1 ± 0.5	primary
Barbara(2)	21.0 ± 0.2	satellite
	a (km)	
(1)–(2)	24.2 ± 0.2	separation

Note. Uncertainties are 1σ.

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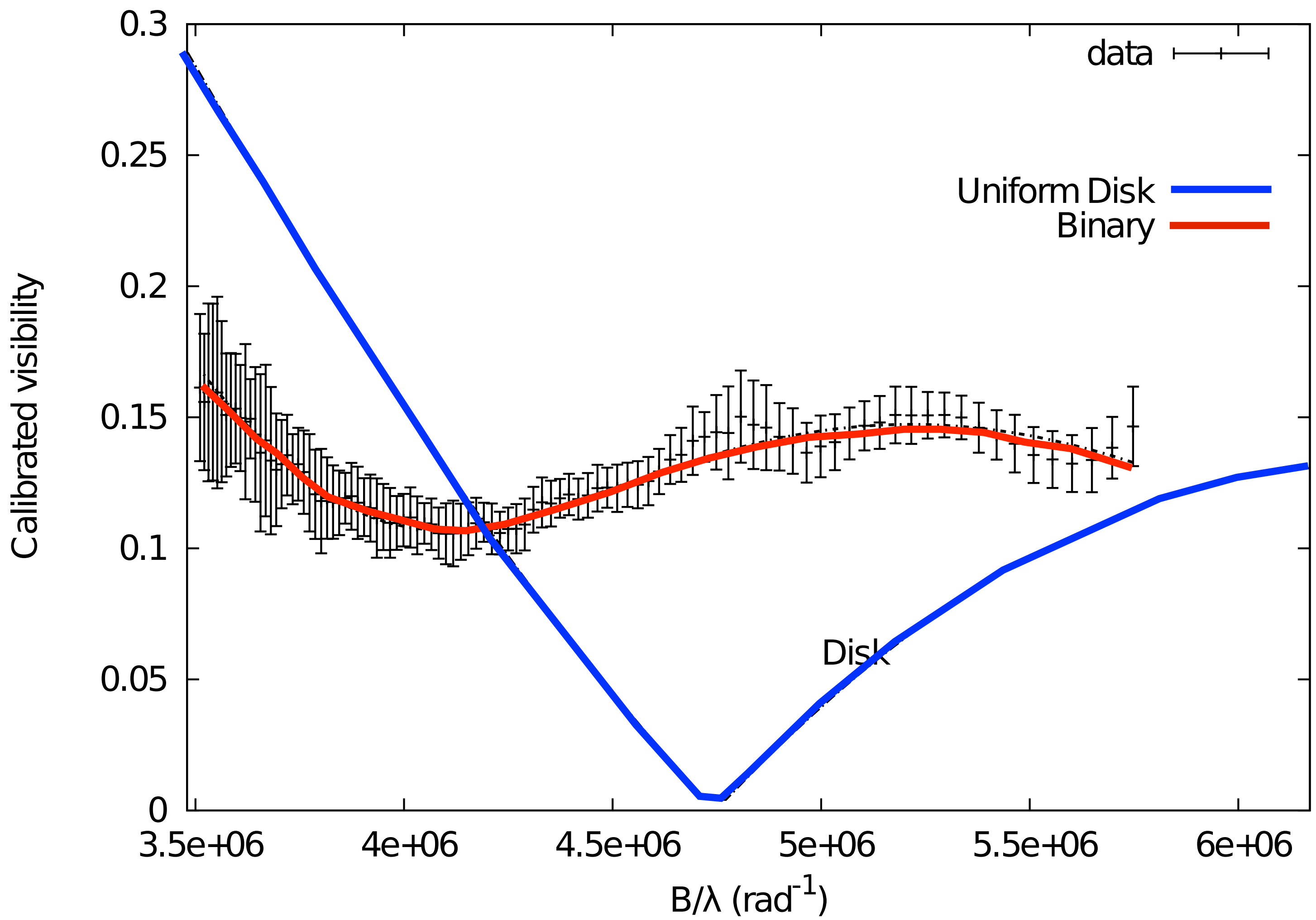

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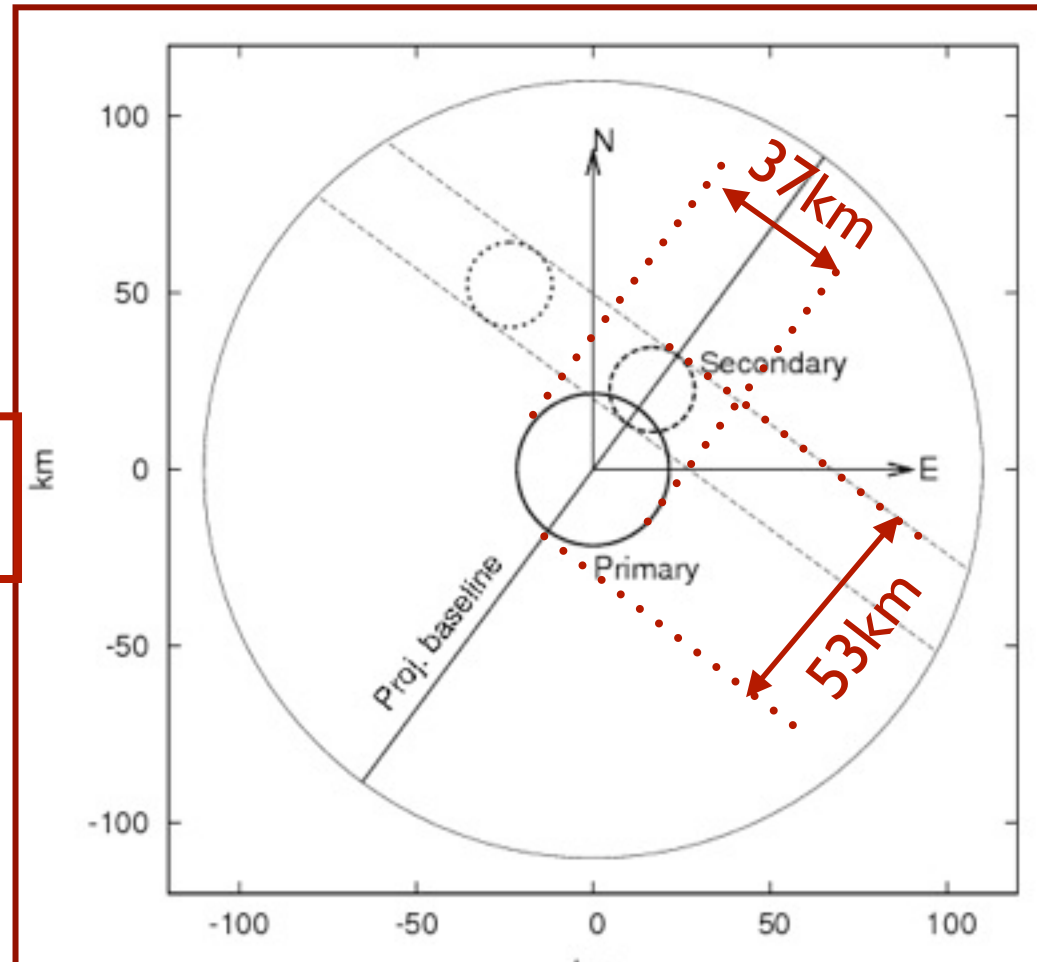
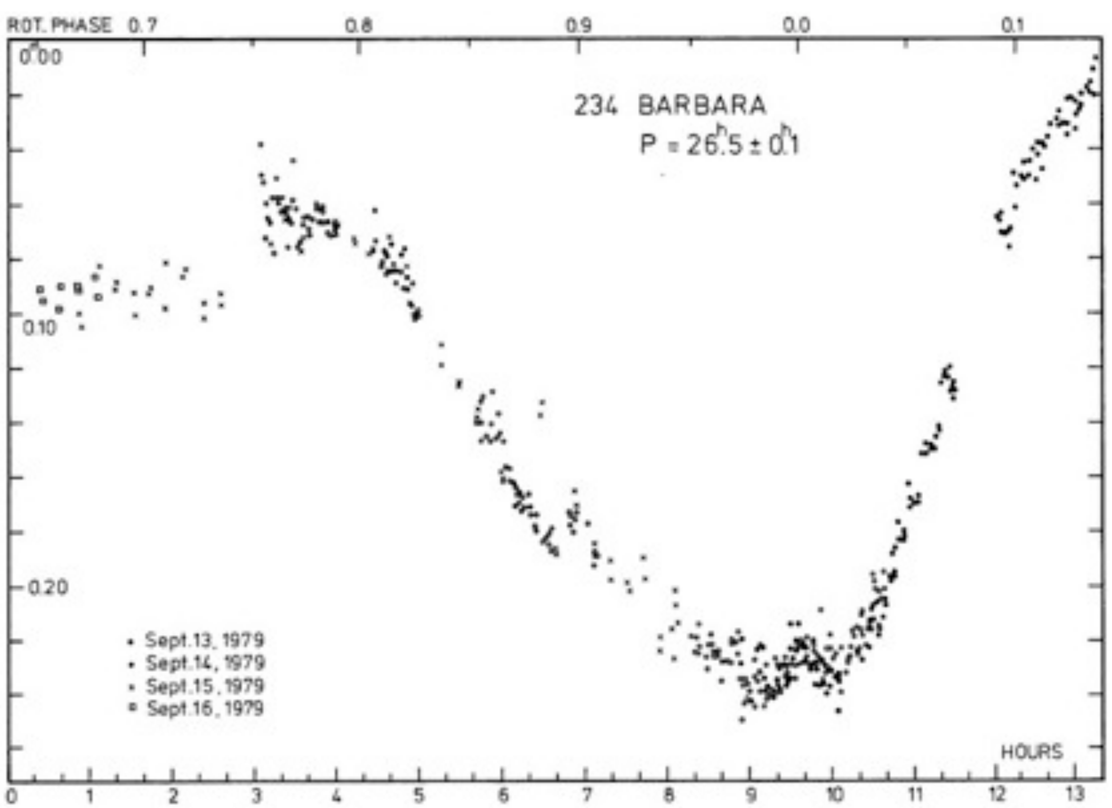
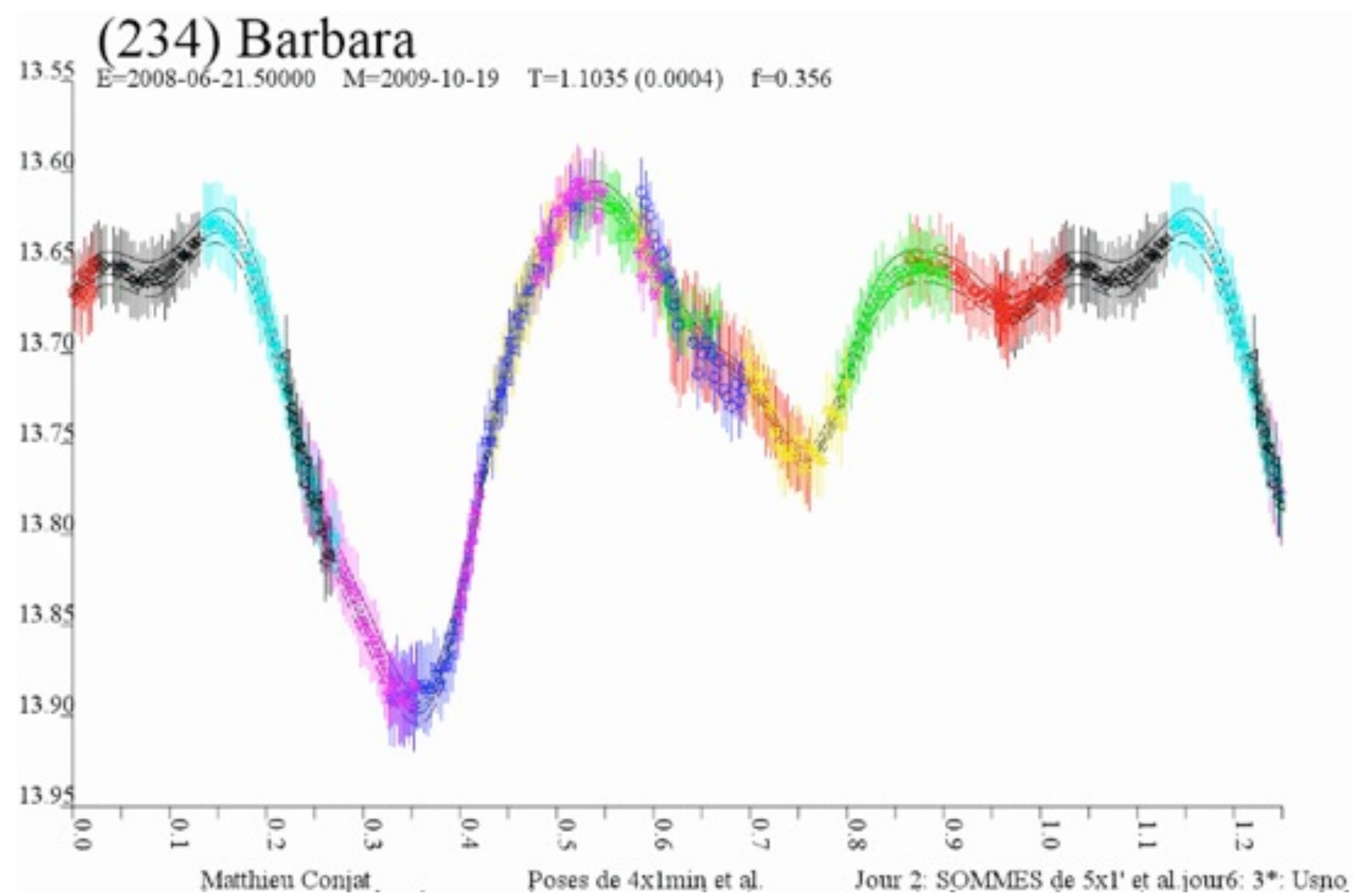
proposed geometric model

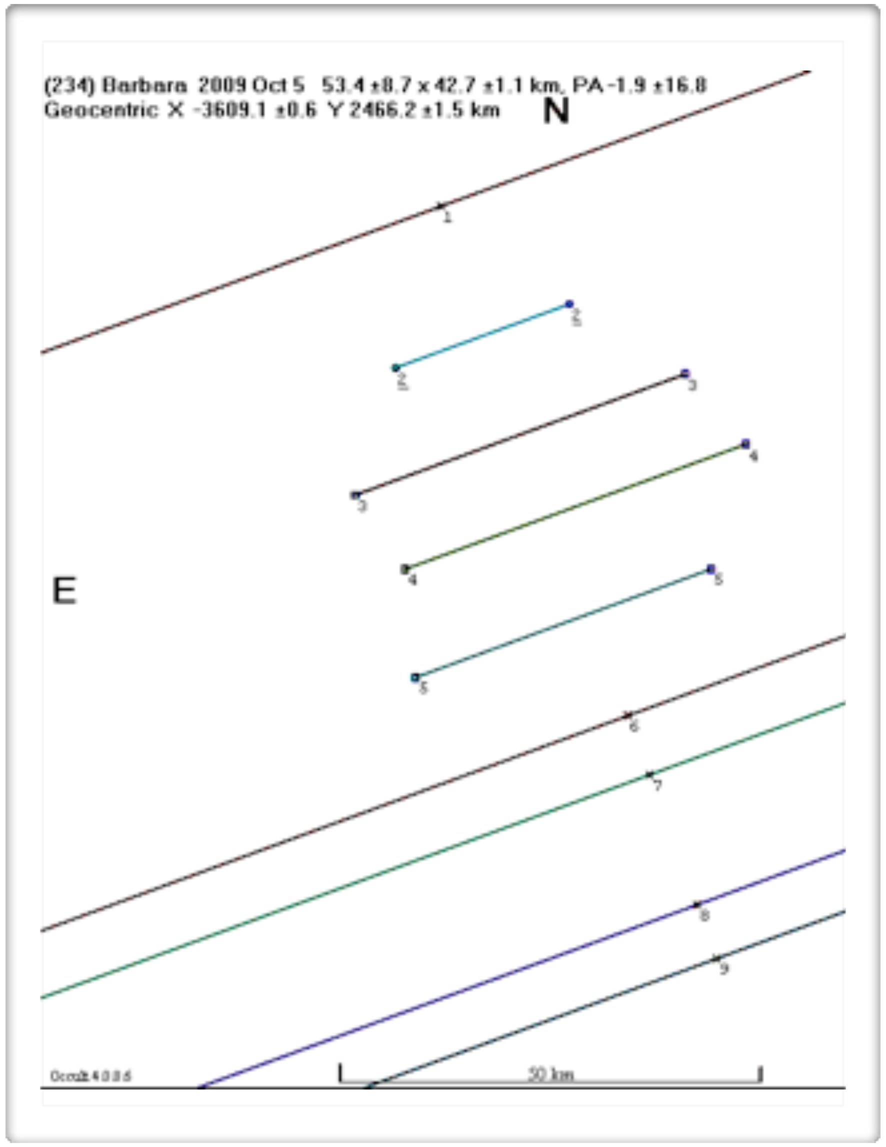


Barbara follow up: photometric lightcurves





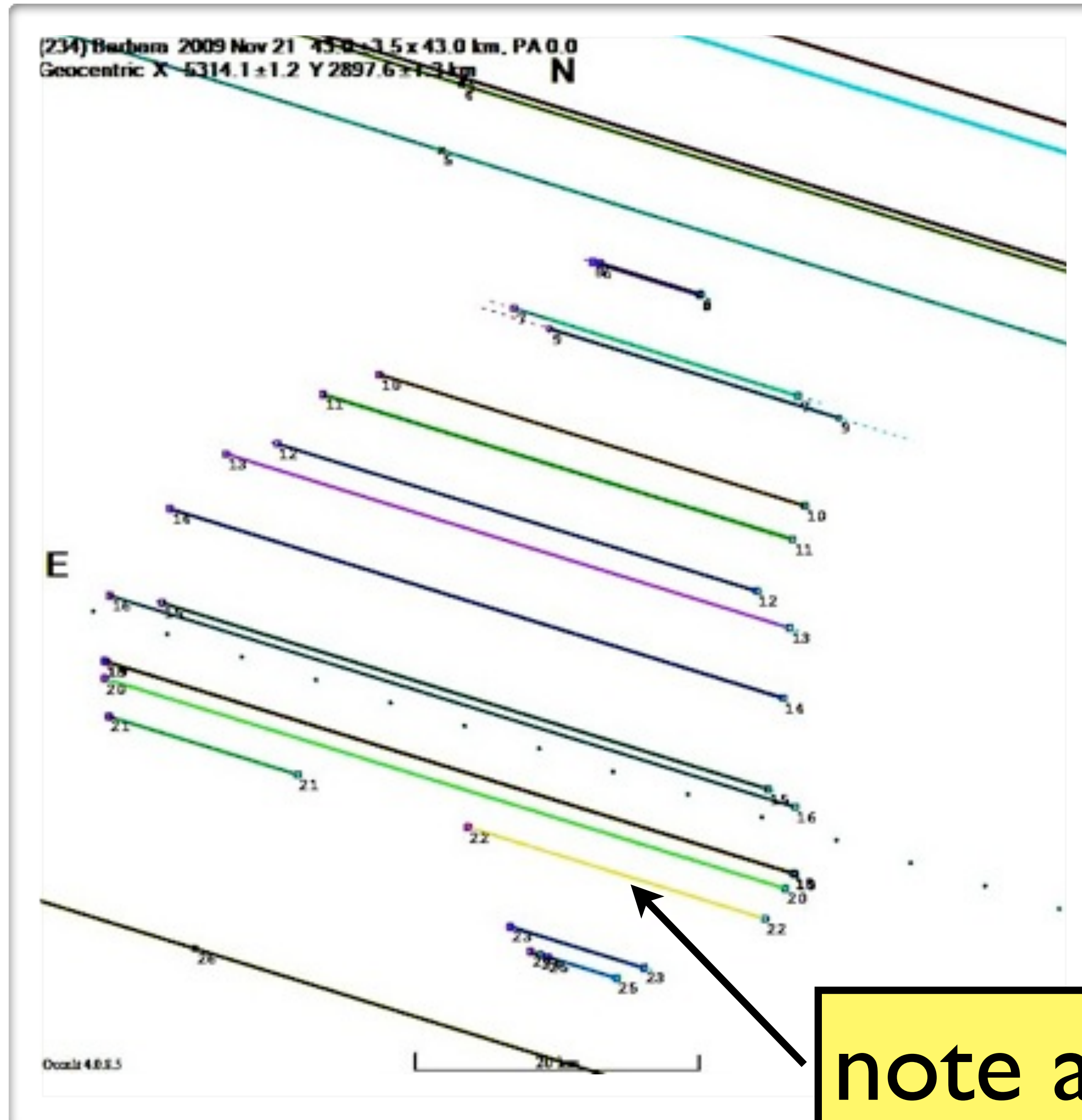
2009 occultation events



Stellar occultation 1

Oct 5, 2009
Ecliptic longitude, heliocentric: 77° ;
geocentric: 103°
Phase angle: 25°

(chord n. 2 is not precisely dated)
Source: http://www.euraster.net/results/2009/20091105-Barbara-crd_temp.gif



note also the double coord

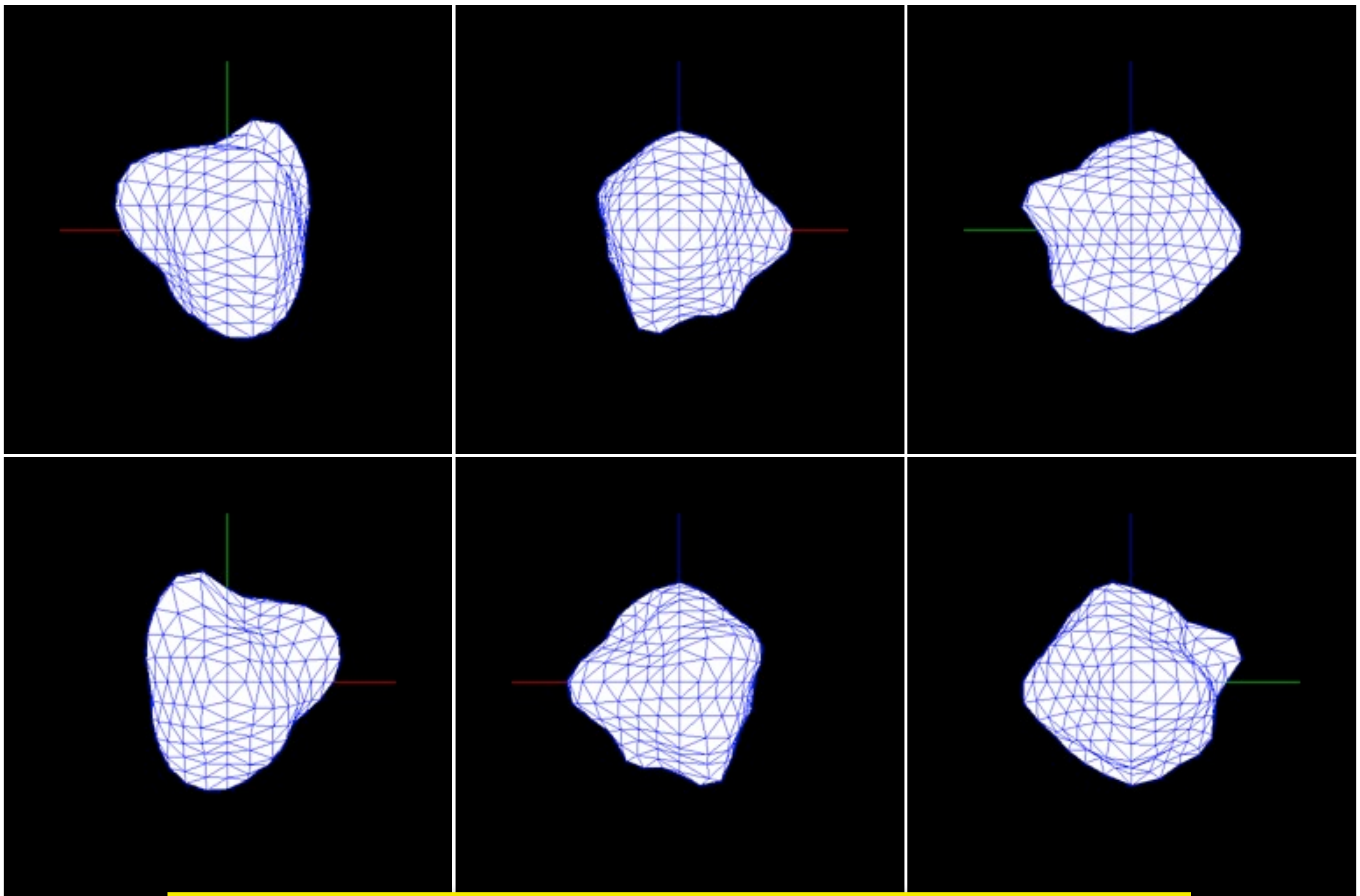
Stellar occultation 2

Nov 21, 2009
Ecliptic longitude, heliocentric: 89° ; geocentric: 107°
Phase angle: 18°

Source: http://www.asteroidoccultation.com/observations/Results/

Size from the MIDI-VLTI observations confirmed

KOALA shape model of Barbara from occultations and photometry



Tanga, Carry, Delbo et al, in preparation

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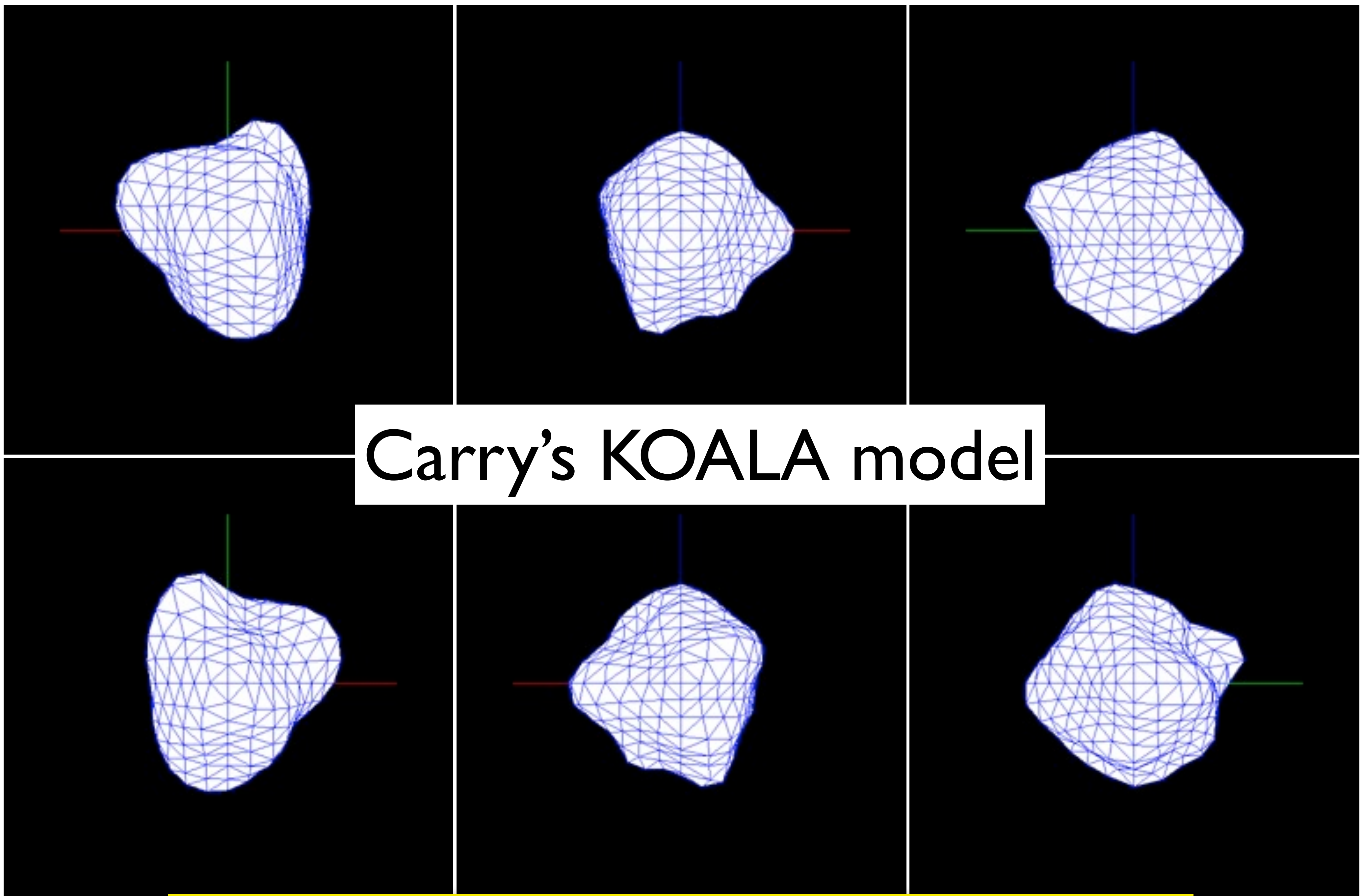

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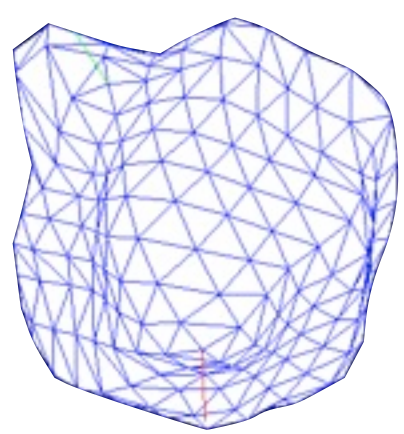
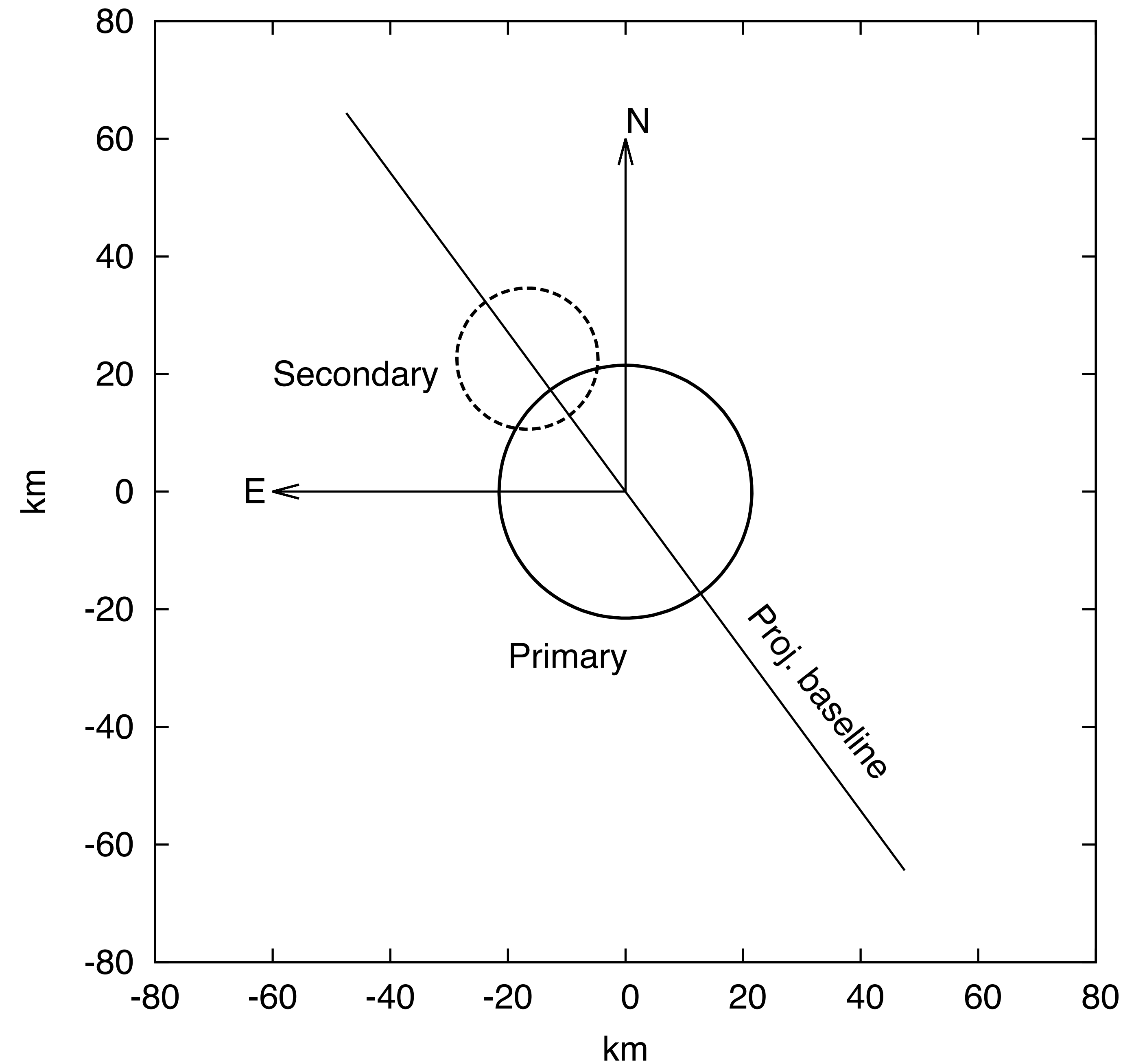
KOALA vs VLTI models

projected on the sky at the time of VLTI observations

KOALA model
from Tanga et al.



VLTI model
adapted from from Delbo et al. 2009



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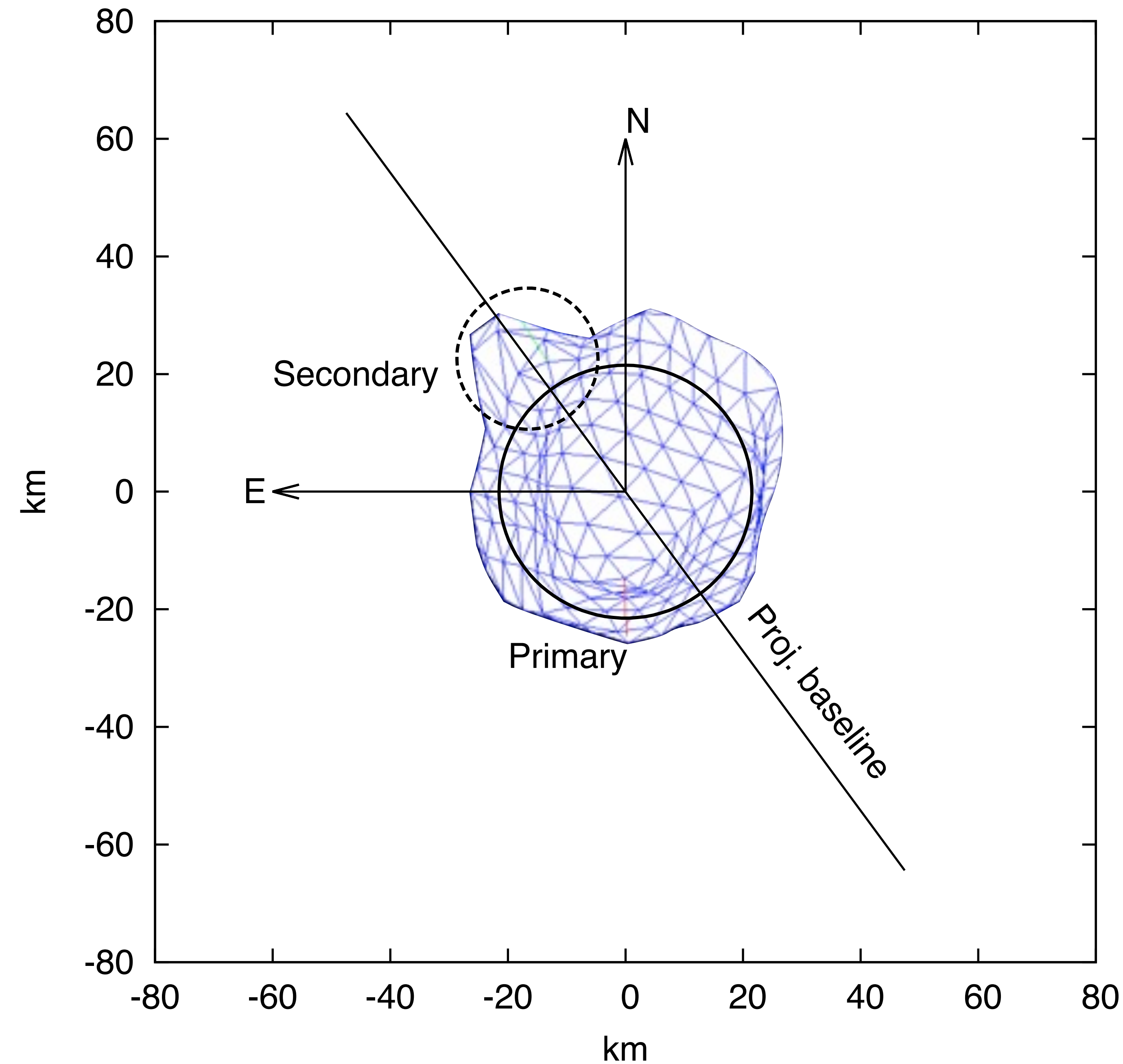
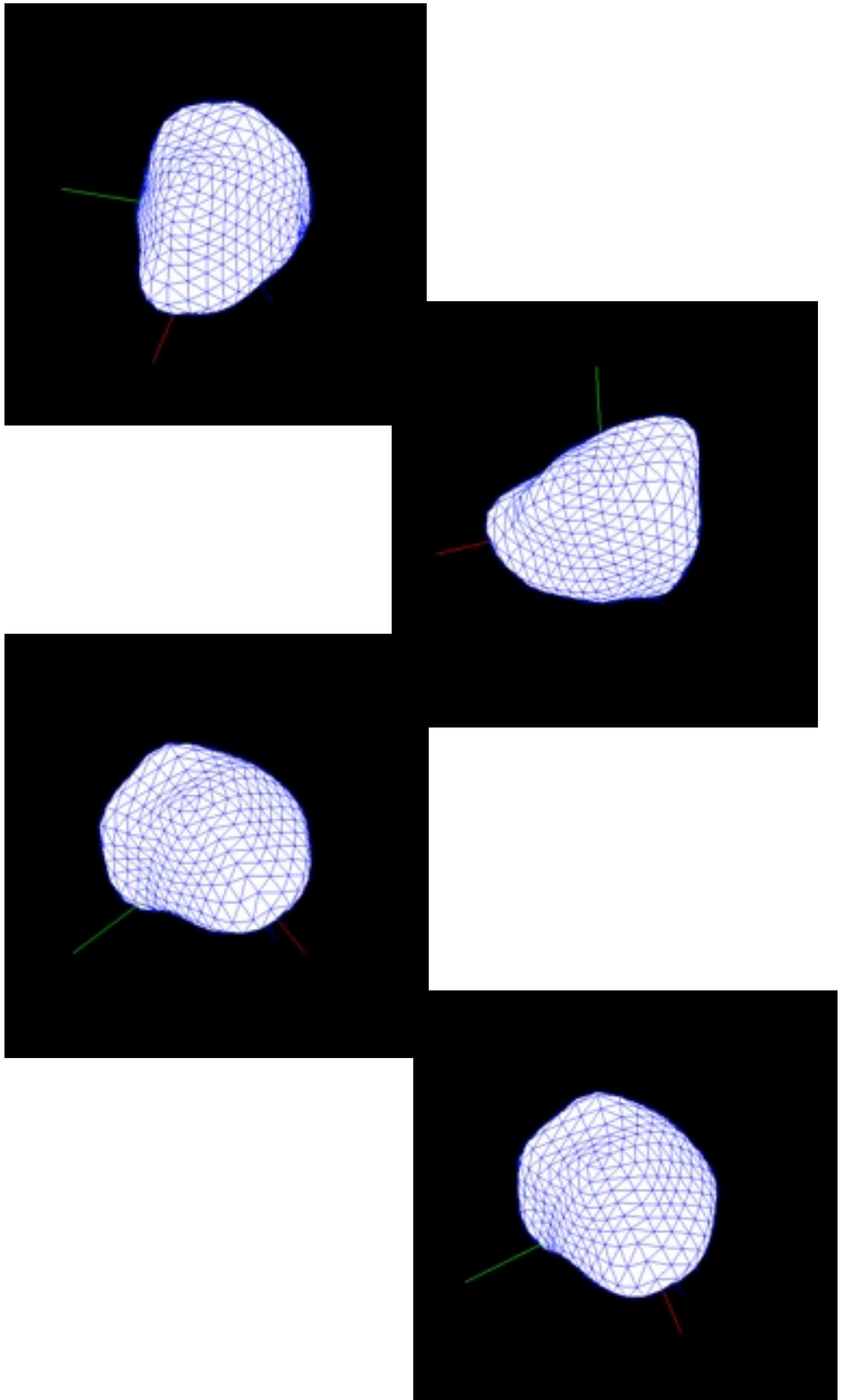
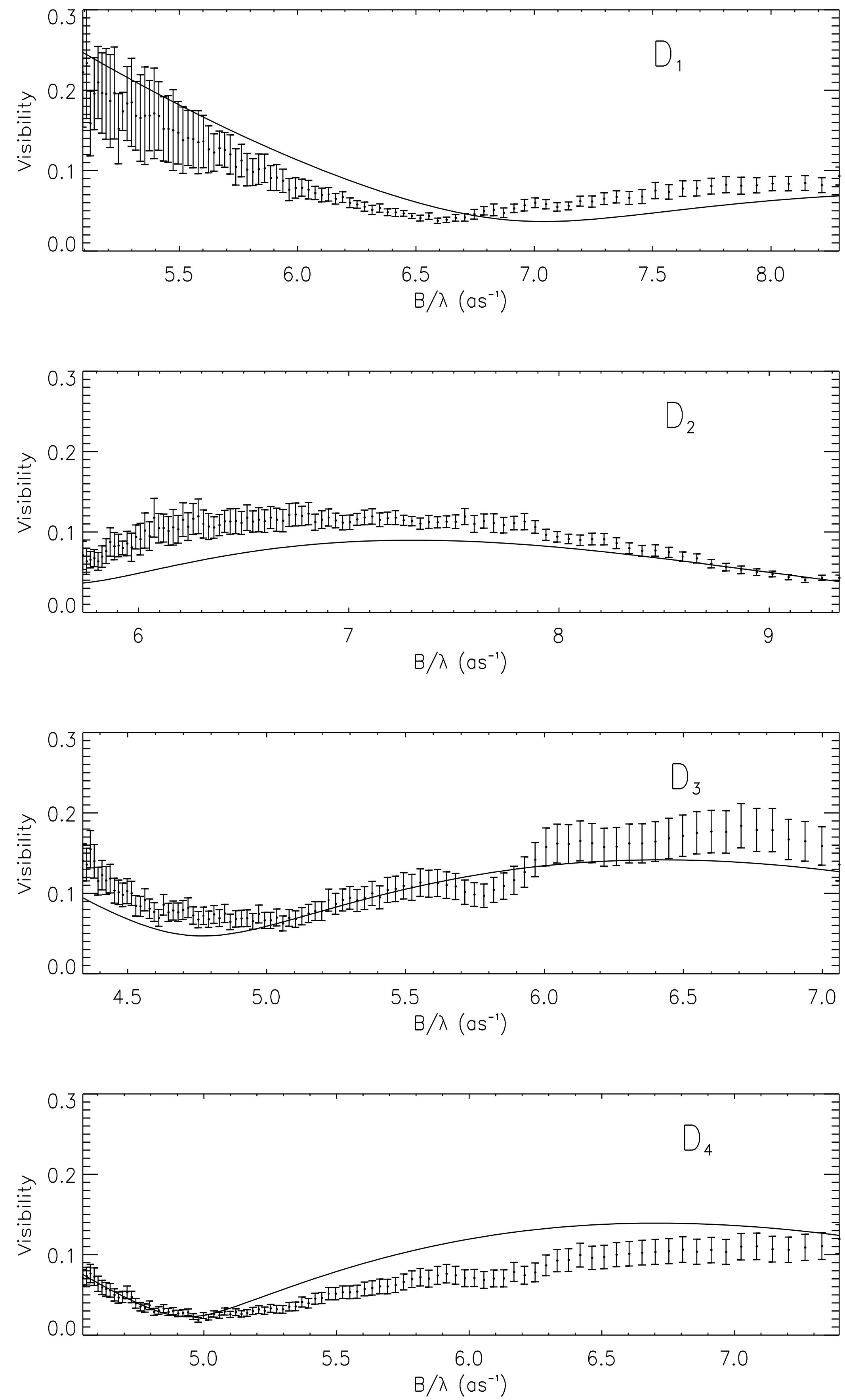


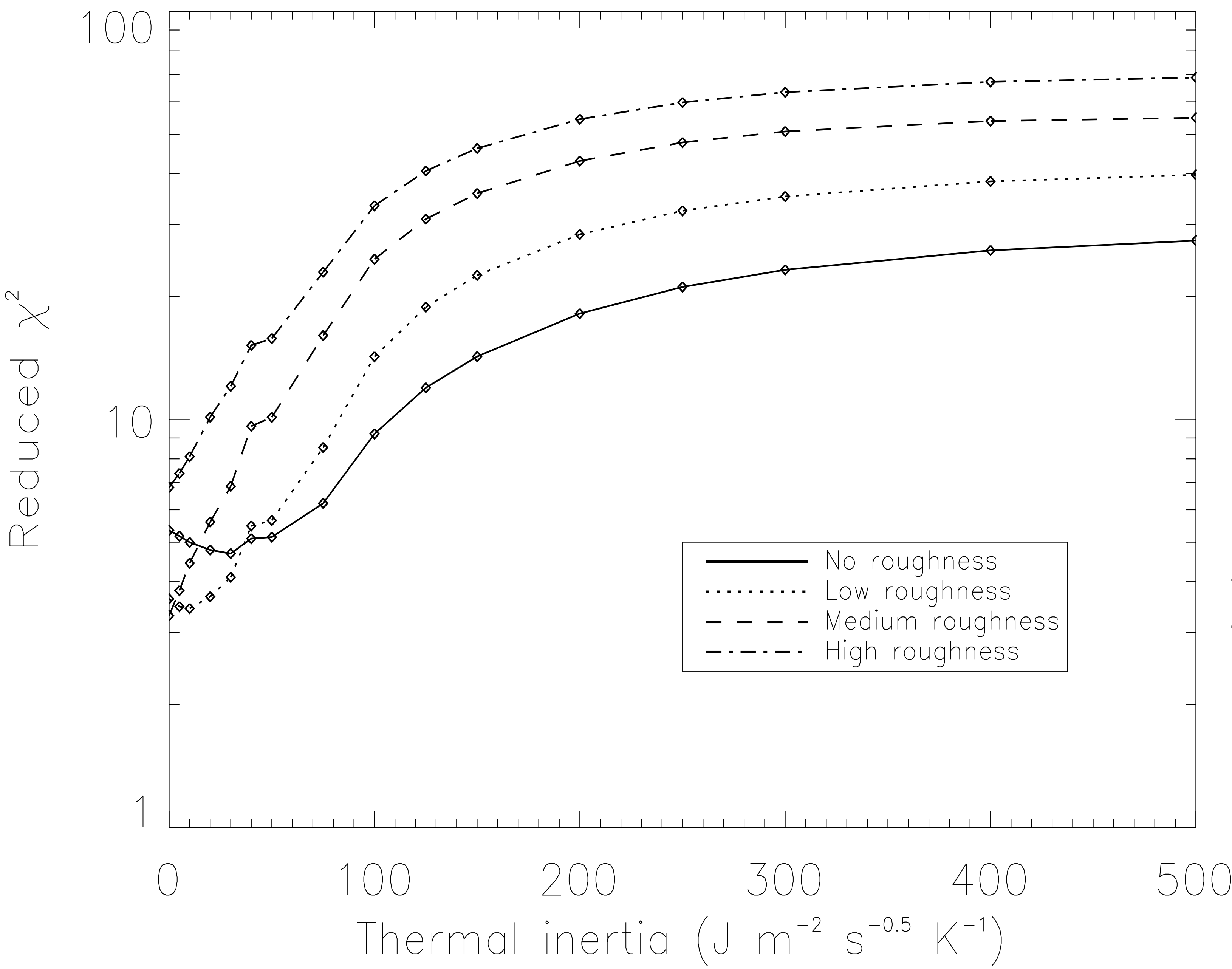
41 Daphne

Matter et al. Icarus, in press





41 Daphne: nature of the surface



Given a priori information about the shape, we constrained the thermal inertia.

$$\Gamma < 50\ J\ m^{-2}\ s^{-0.5}\ K^{-1}$$

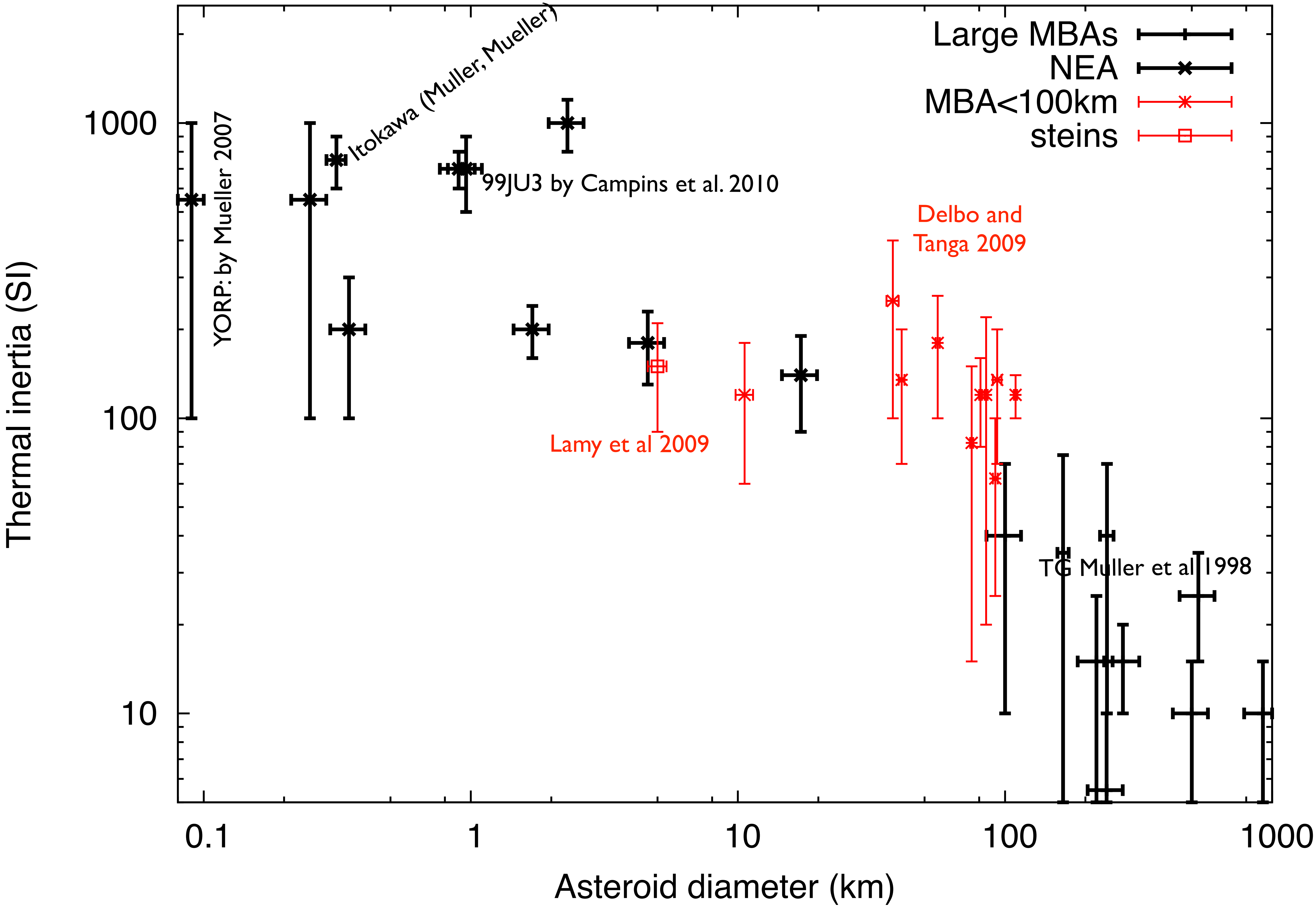
$$\Gamma \propto \sqrt{\kappa}$$

Smooth surface

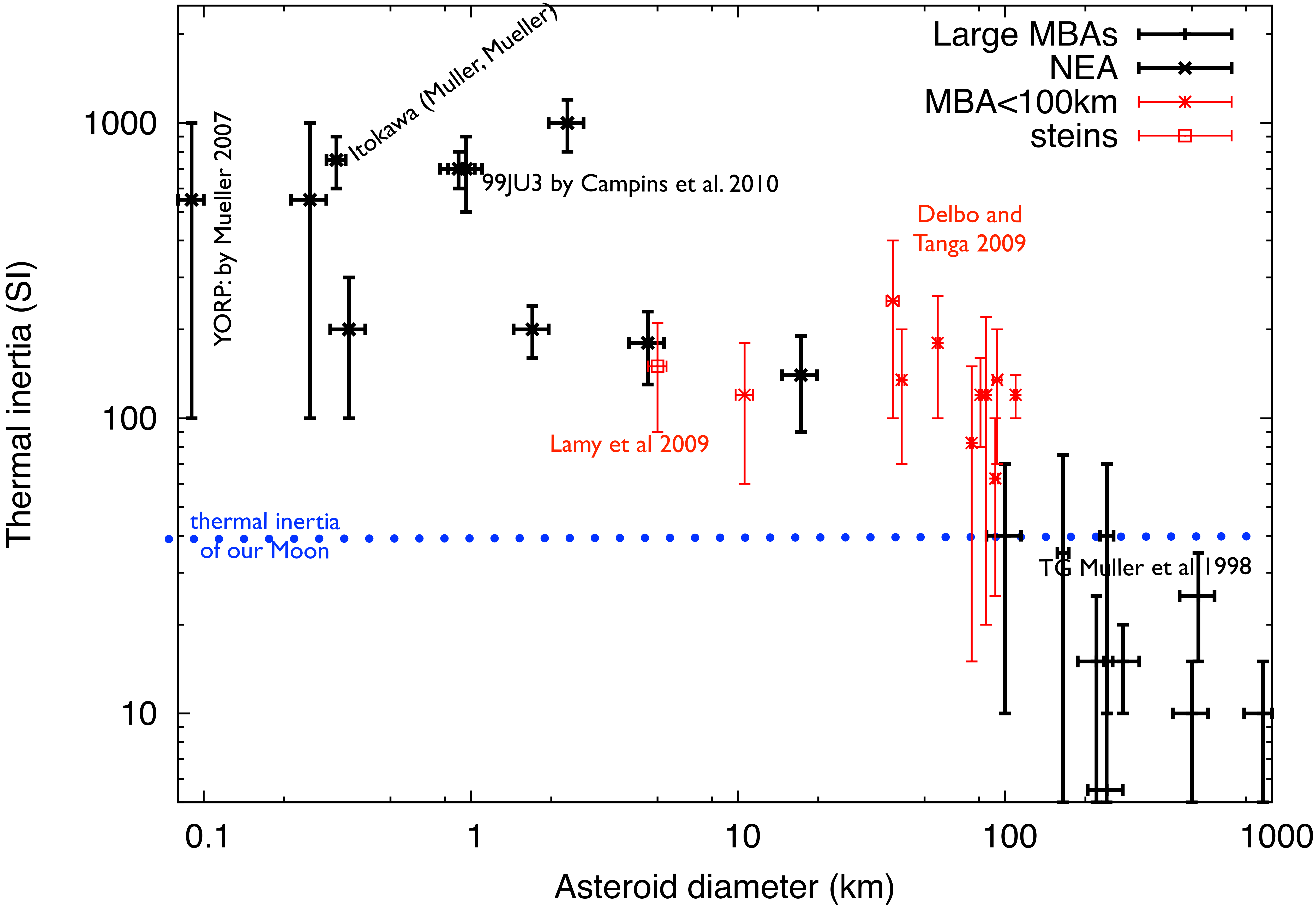
Conclusion: insulating layer of mature and thick regolith; craters smoothed out by regolith landslides?

From observations in the thermal IR at one epoch only

Matter et al. 2011



Large MBAs
NEA
MBA<100km
steins
Itokawa (Muller, Mueller)
YORP: by Mueller 2007
99JU3 by Campins et al. 2010
Delbo and Tanga 2009
Lamy et al 2009
TG Muller et al 1998
1000
100
10
0.1
1
10
100
1000
Thermal inertia (SI)
Asteroid diameter (km)



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thermal inertia of our Moon
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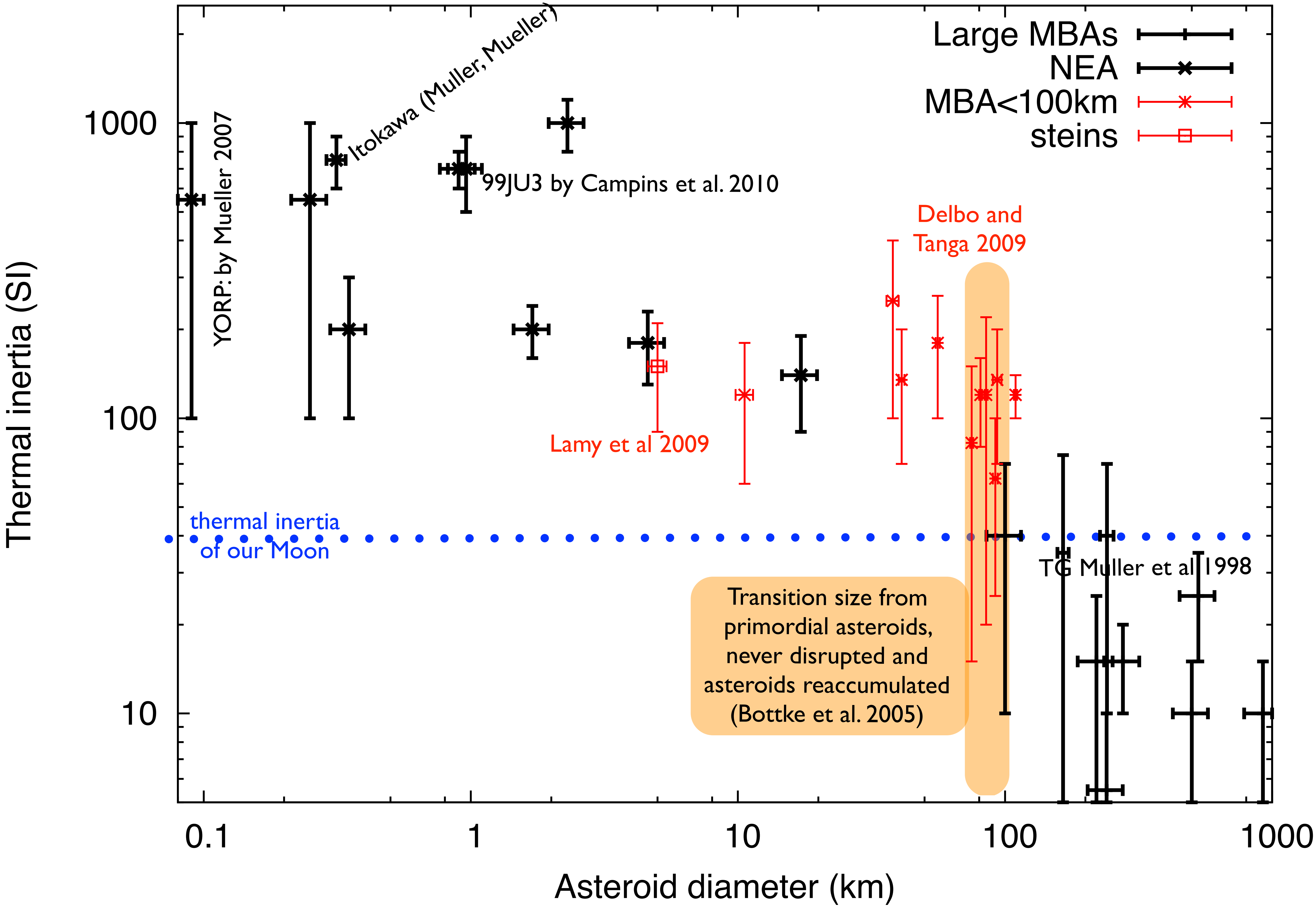
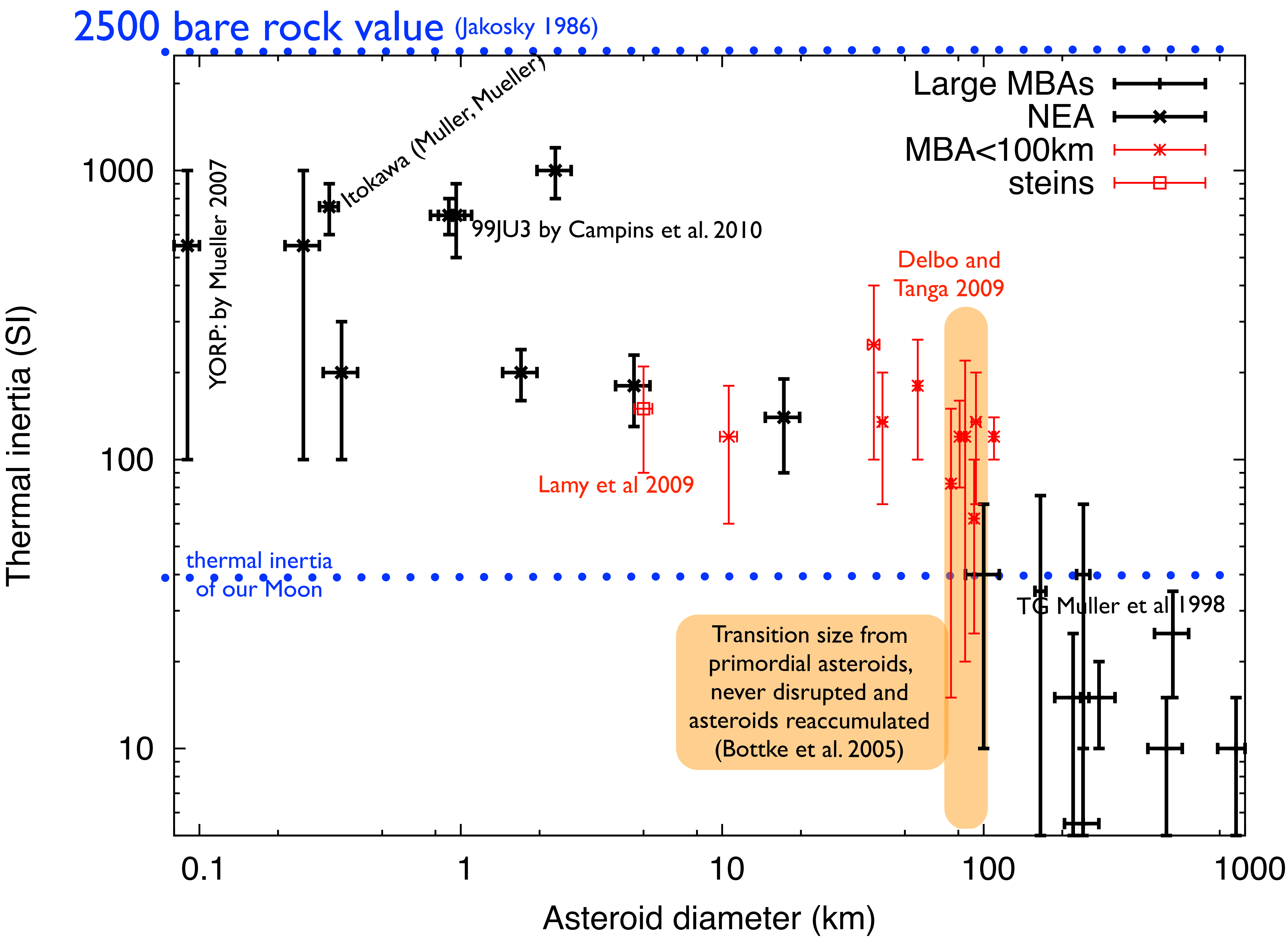
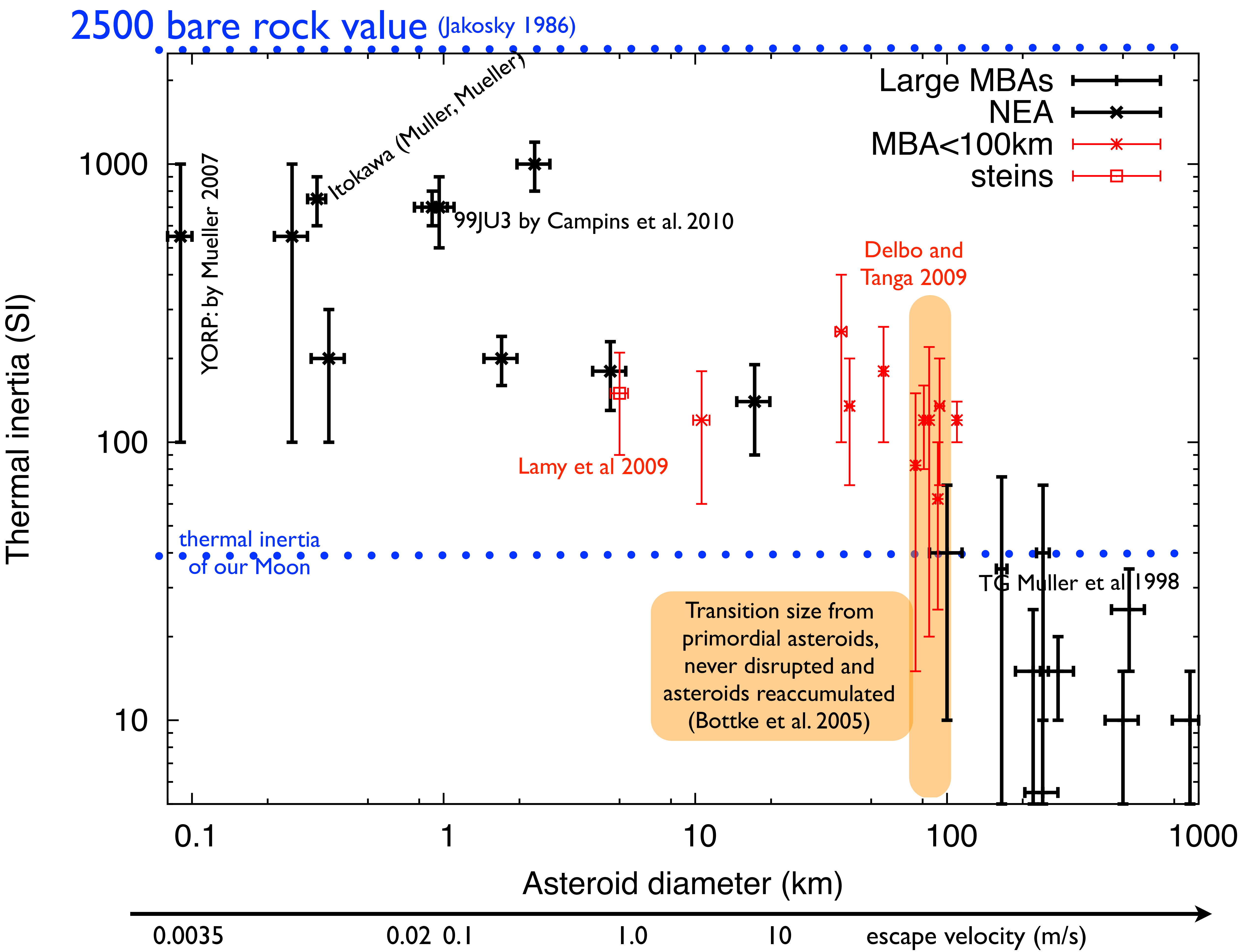
Thermal inertia (SI)
1000
100
10
0.1
1
10
100
1000
Asteroid diameter (km)



Large MBAs
NEA
MBA<100km
steins
1000
100
10
Thermal inertia (SI)
YORP: by Mueller 2007
Itokawa (Muller, Mueller)
99JU3 by Campins et al. 2010
Delbo and Tanga 2009
Lamy et al 2009
thermal inertia of our Moon
TG Muller et al 1998
Transition size from primordial asteroids, never disrupted and asteroids reaccumulated (Bottke et al. 2005)
0.1
1
10
100
1000
Asteroid diameter (km)



2500 bare rock value (Jakosky 1986)
Large MBAs
NEA
MBA<100km
steins
1000
100
10
Thermal inertia (SI)
YORP: by Mueller 2007
Itokawa (Muller, Mueller)
99JU3 by Campins et al. 2010
Delbo and Tanga 2009
Lamy et al 2009
thermal inertia of our Moon
TG Muller et al 1998
Transition size from primordial asteroids, never disrupted and asteroids reaccumulated (Bottke et al. 2005)
0.1
1
10
100
1000
Asteroid diameter (km)



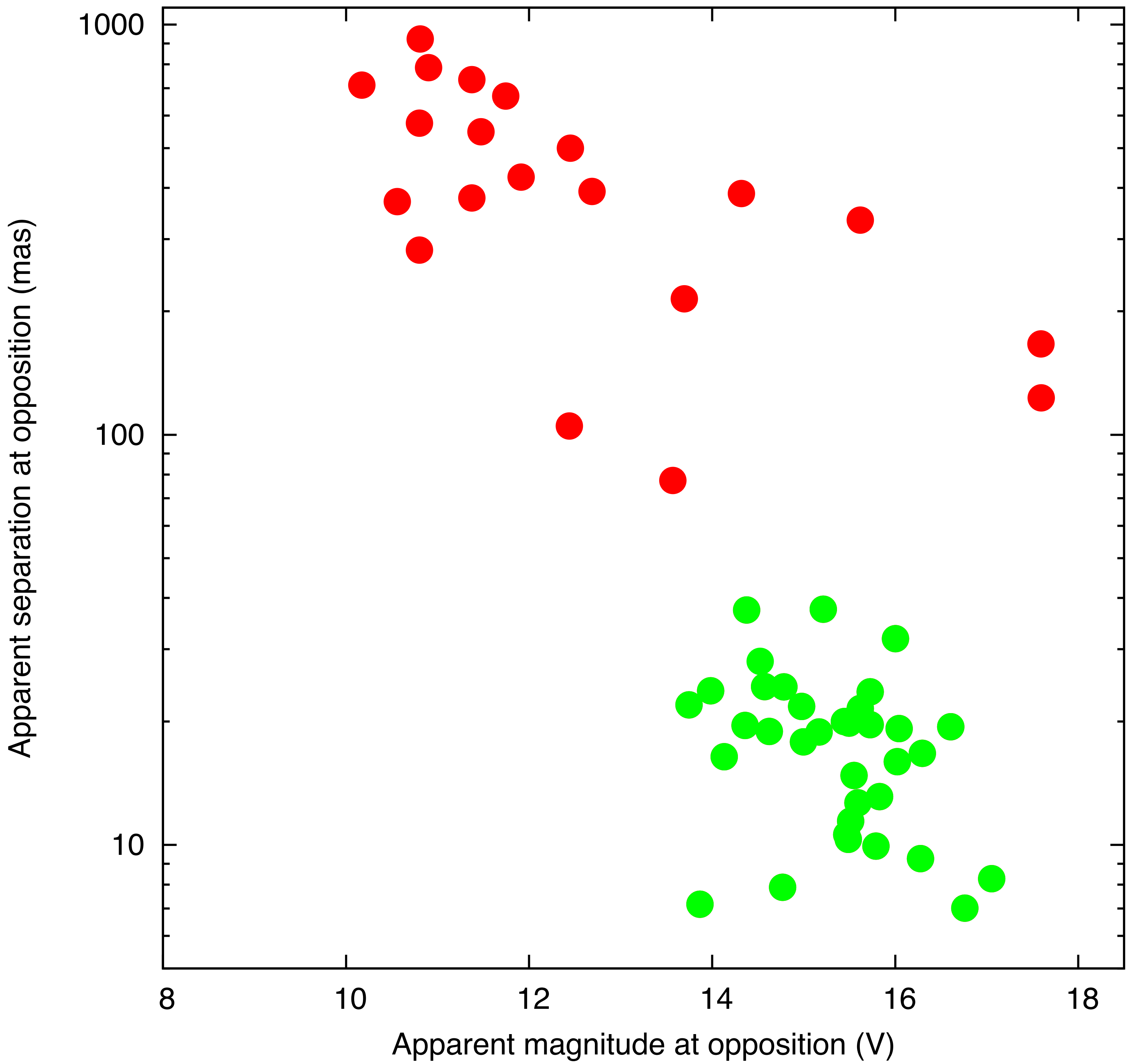
2500 bare rock value (Jakosky 1986)
Large MBAs
NEA
MBA<100km
steins
1000
100
10
Thermal inertia (SI)
YORP: by Mueller 2007
Itokawa (Muller, Mueller)
99JU3 by Campins et al. 2010
Delbo and Tanga 2009
Lamy et al 2009
thermal inertia of our Moon
TG Muller et al 1998
Transition size from primordial asteroids, never disrupted and asteroids reaccumulated (Bottke et al. 2005)
0.1
1
10
100
1000
Asteroid diameter (km)
0.0035
0.02 0.1
1.0
10
escape velocity (m/s)

Future projects

Asteroids with satellites

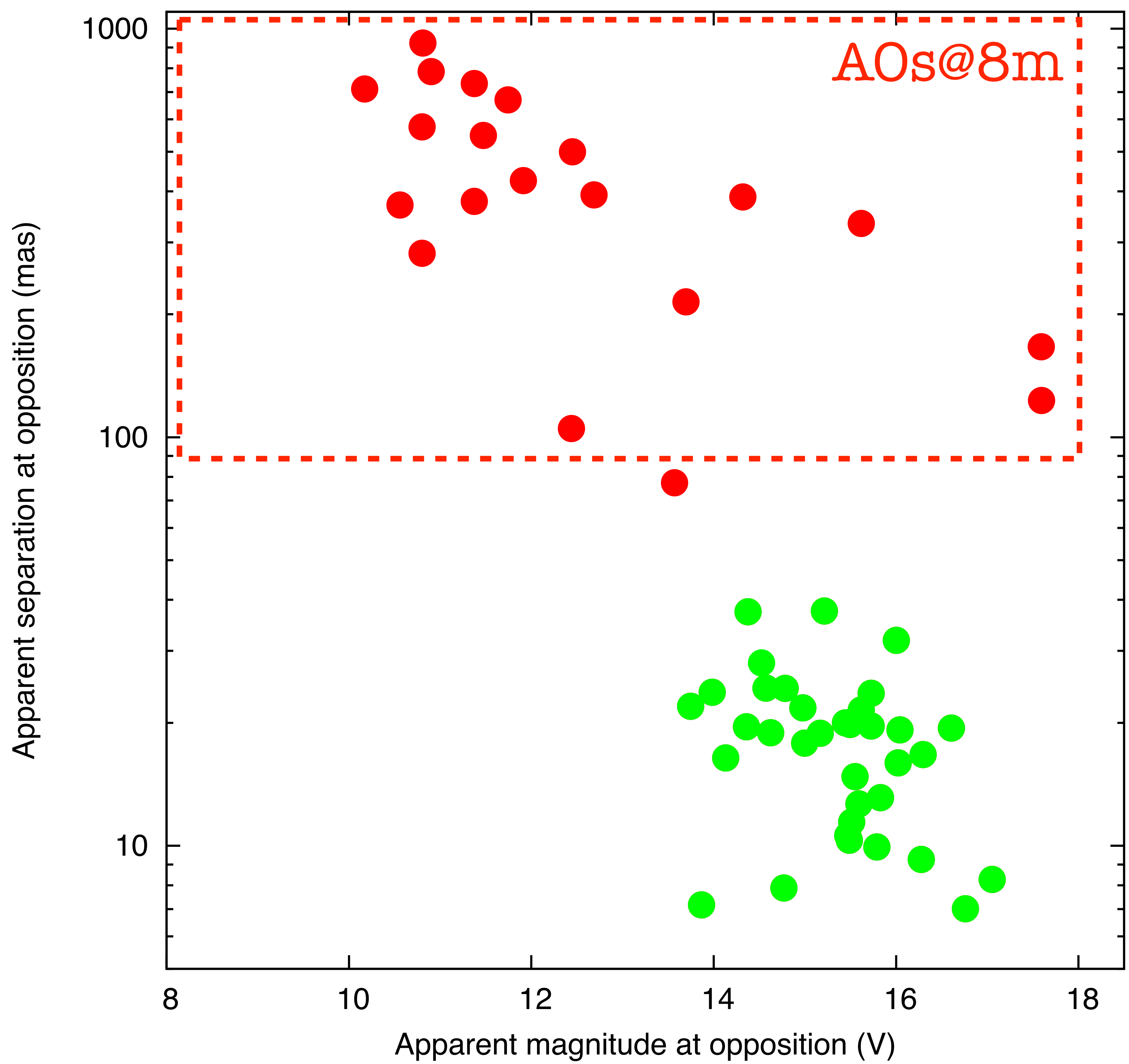
● discovered by AOs

● discovered by photometry: transits and eclipses



Asteroids with satellites

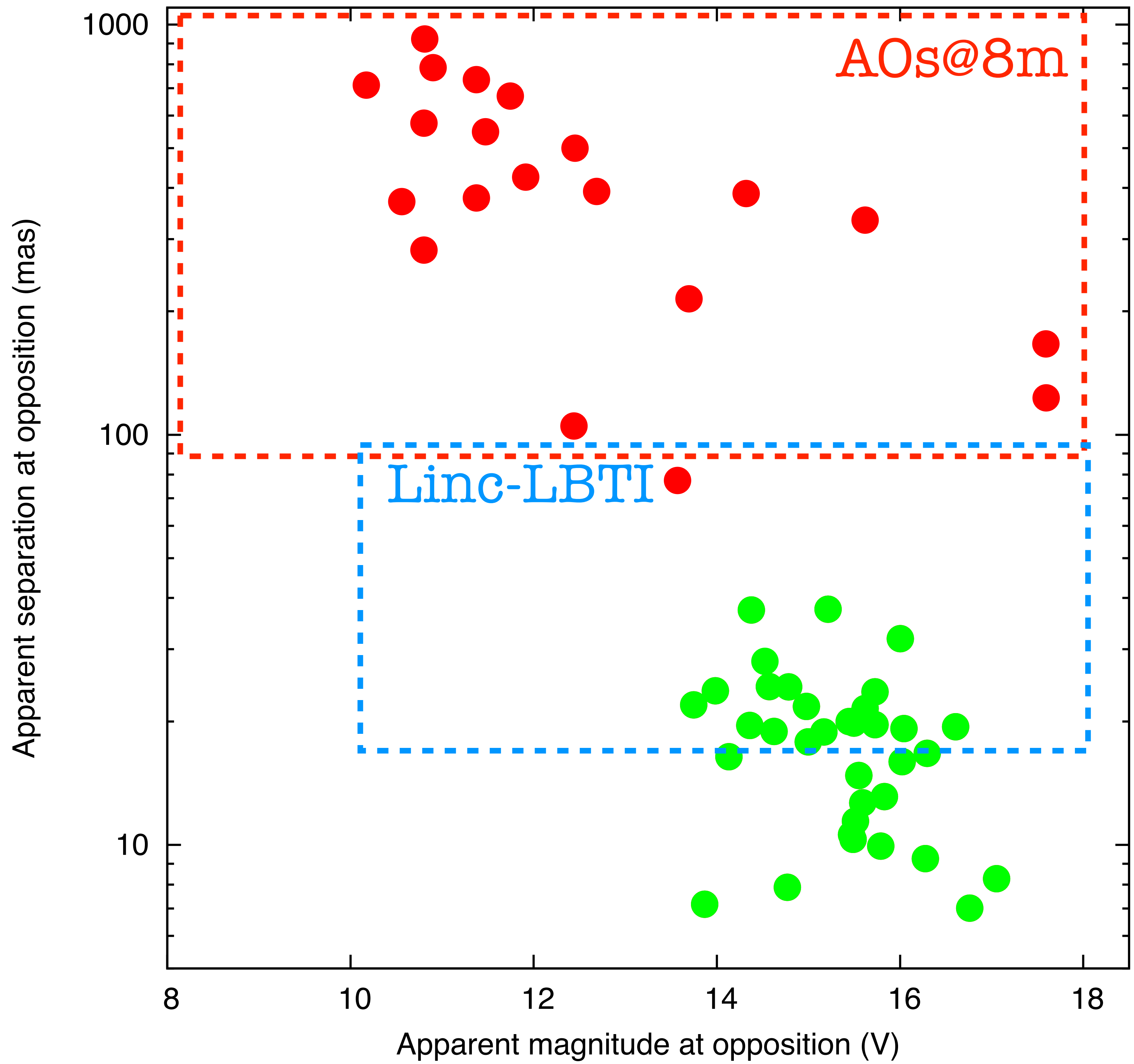
- discovered by AOs
- discovered by photometry: transits and eclipses



Asteroids with satellites

discovered by AOs

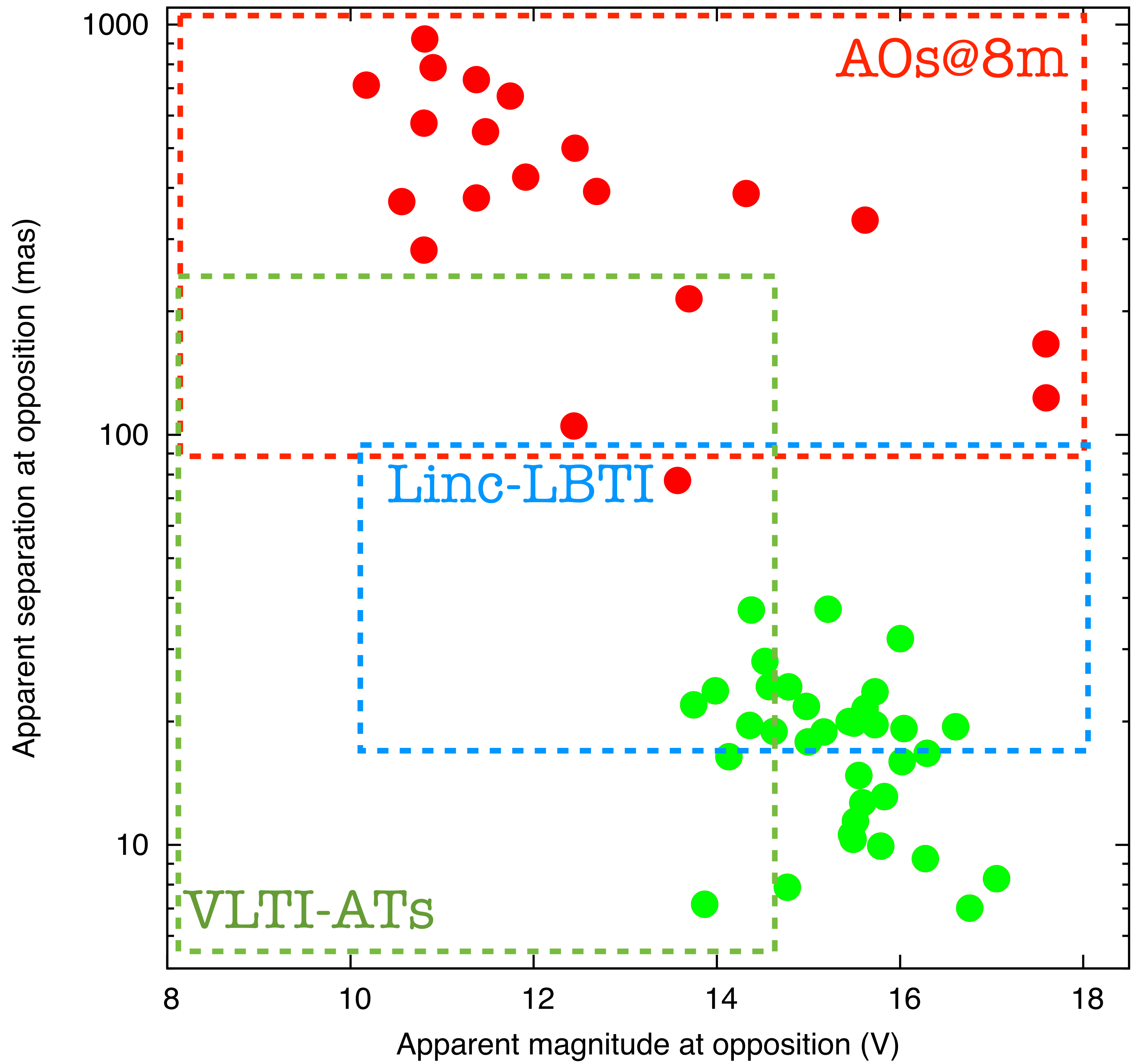
discovered by photometry: transits and eclipses



Asteroids with satellites

discovered by AOs

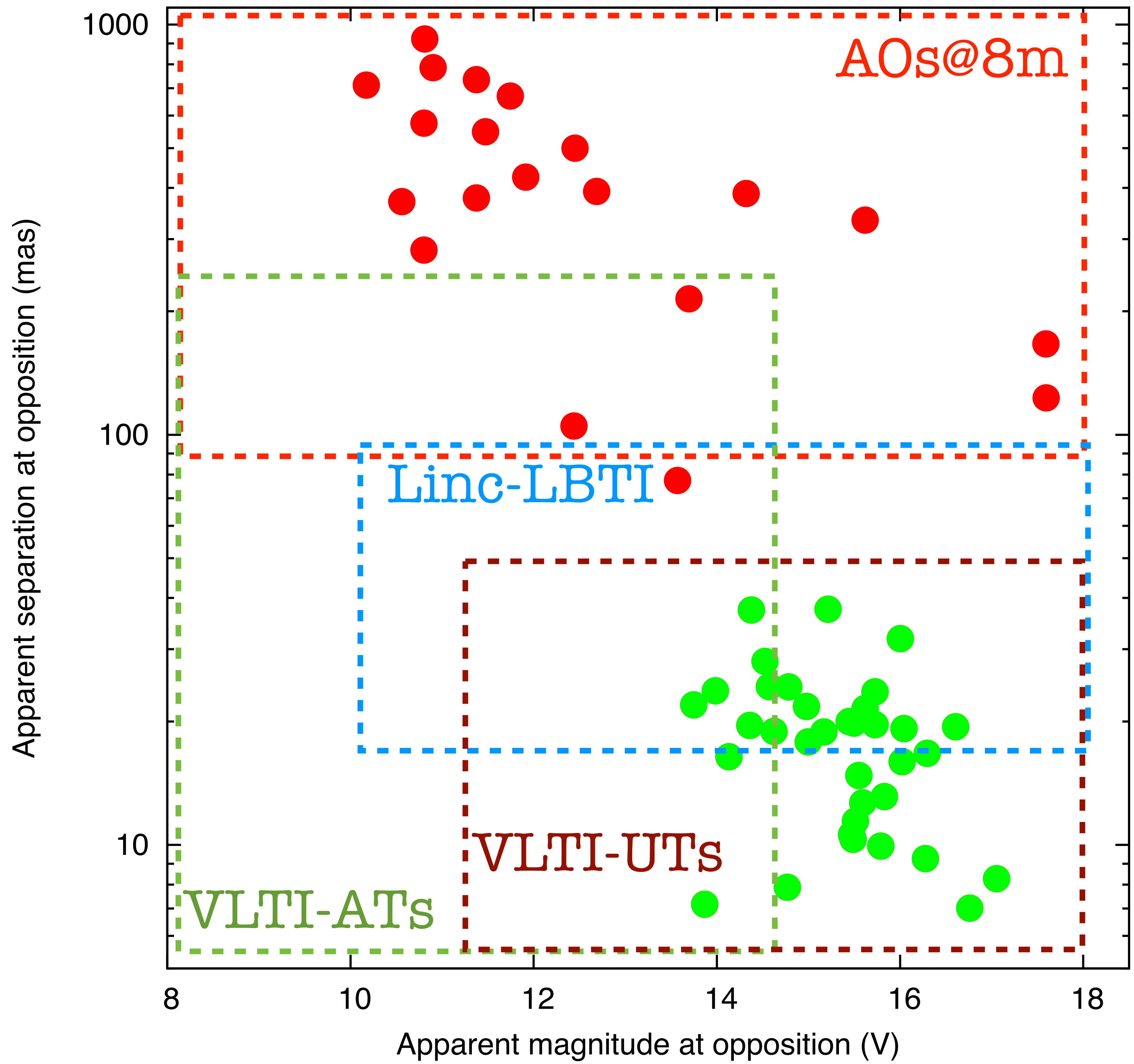
discovered by photometry: transits and eclipses



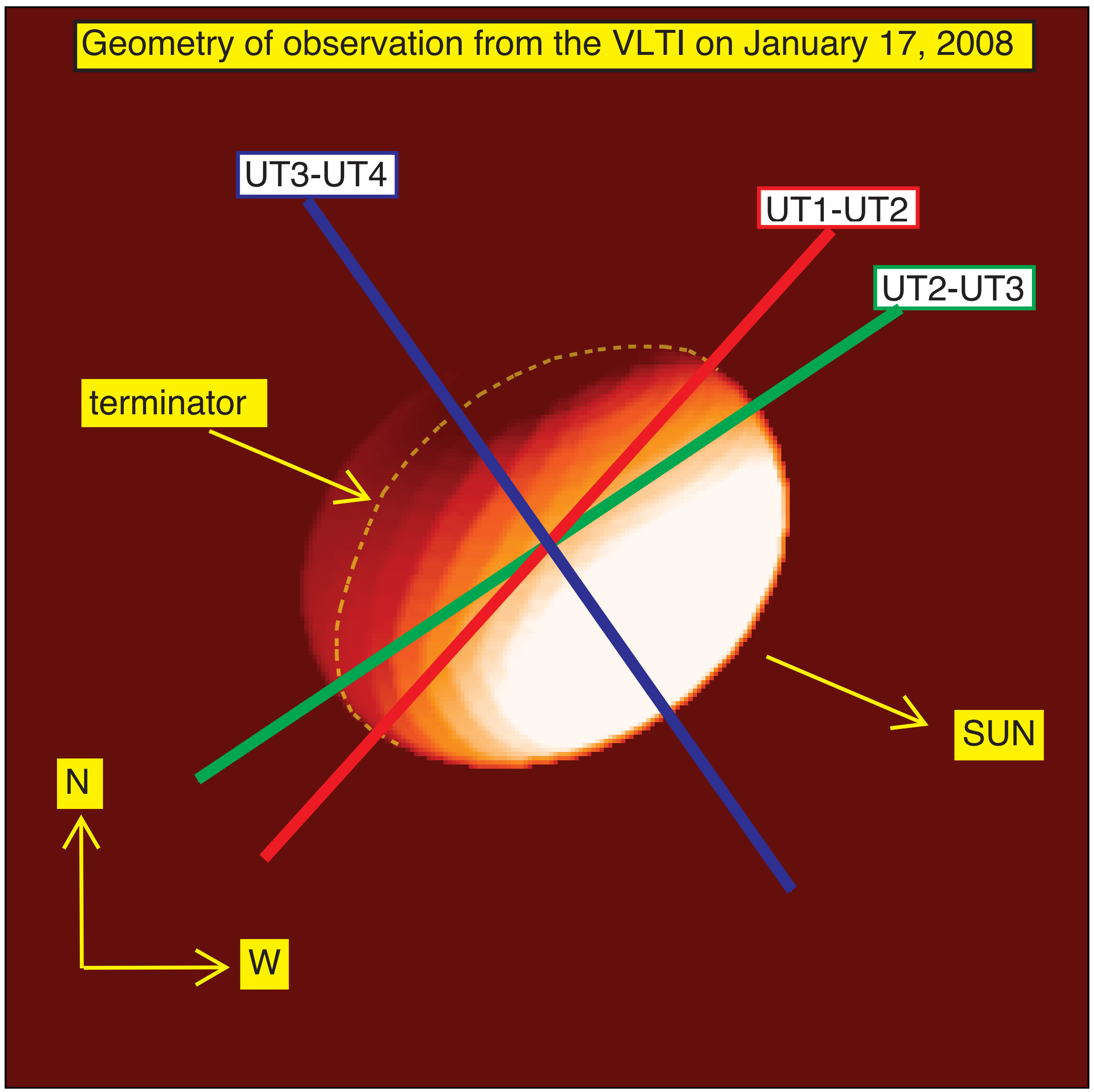
Asteroids with satellites

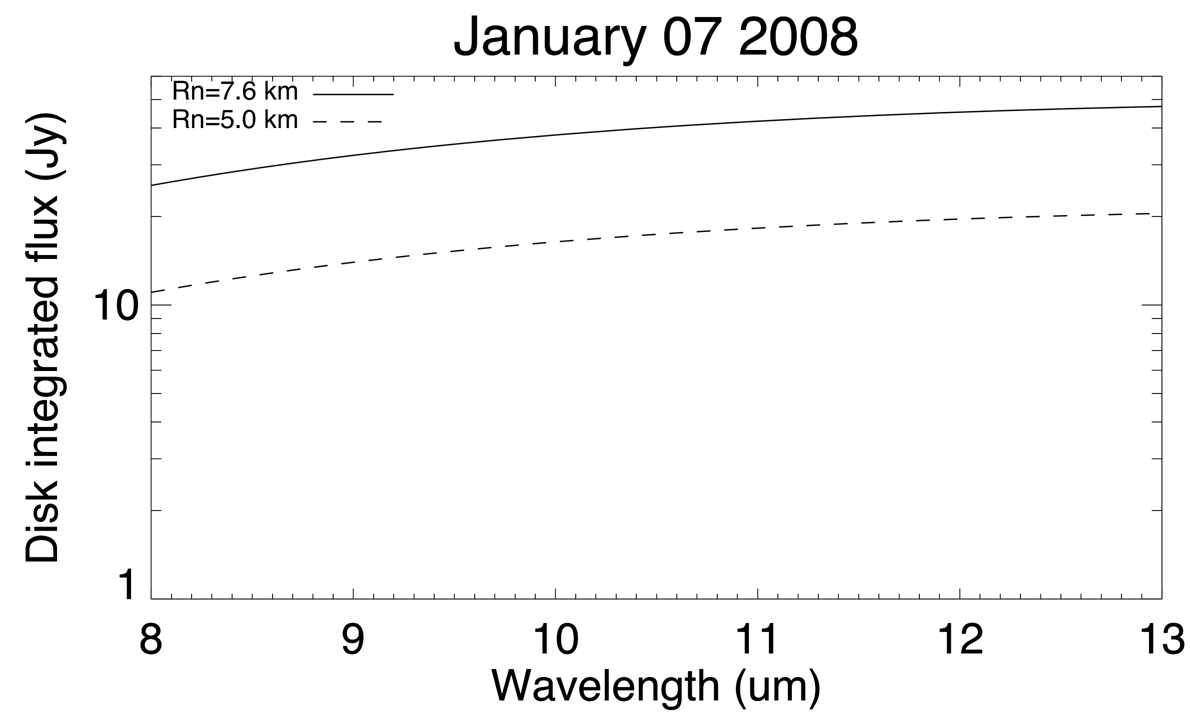
discovered by AOs

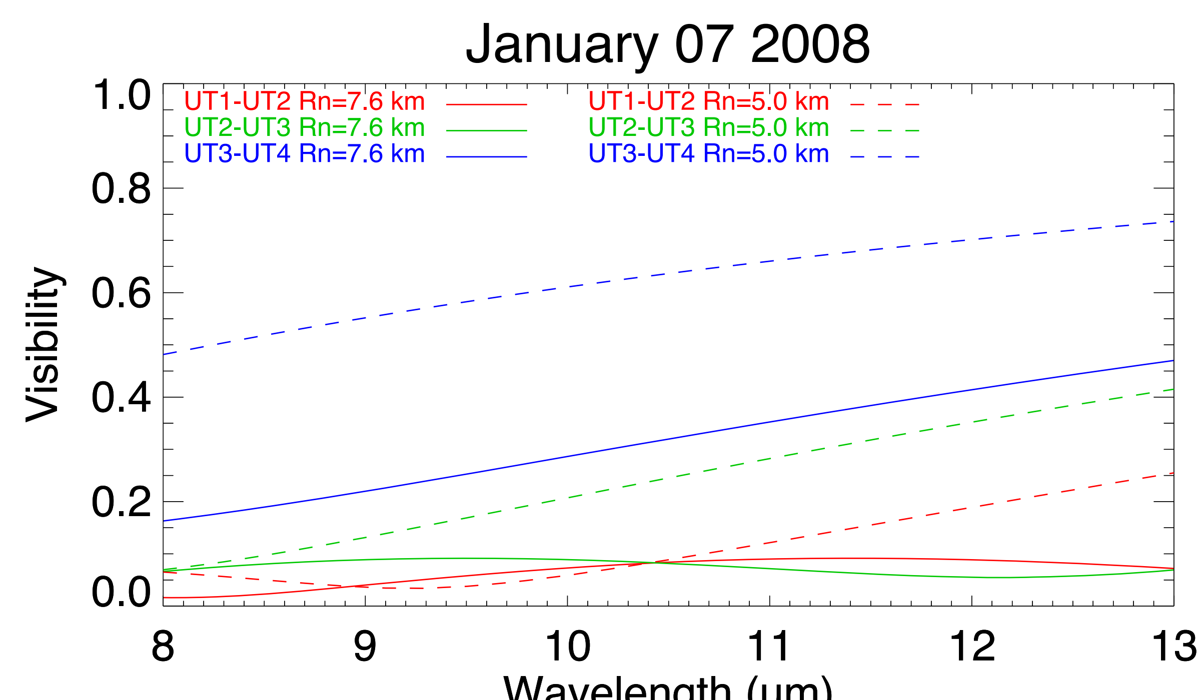
discovered by photometry: transits and eclipses



Comets: 8P Tuttle

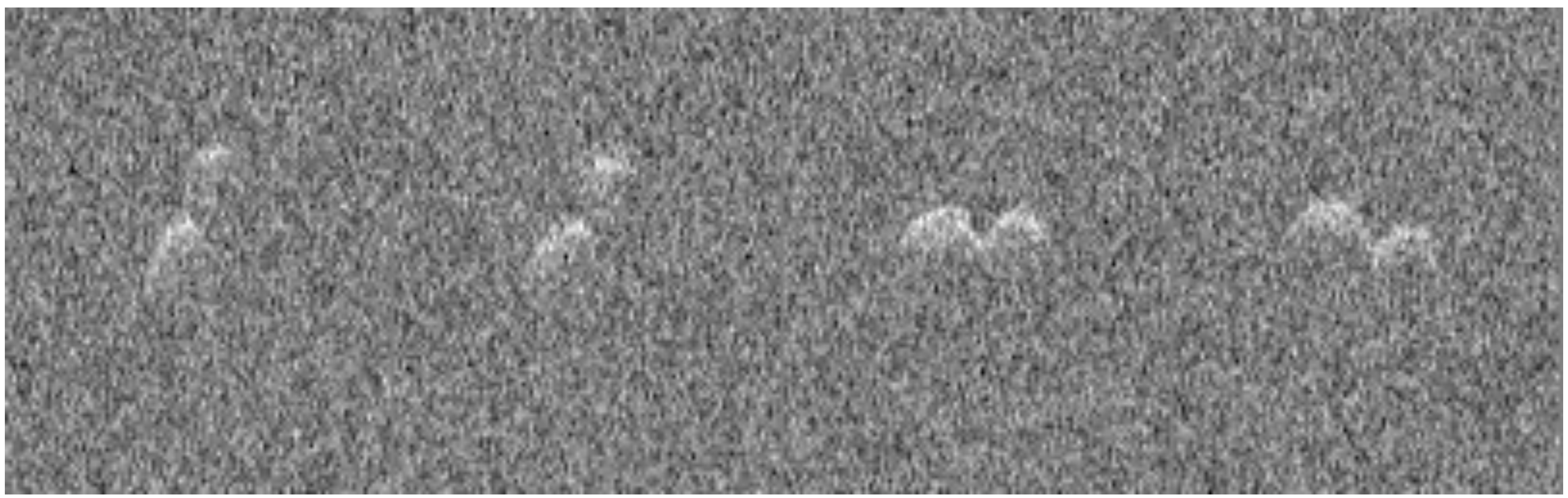




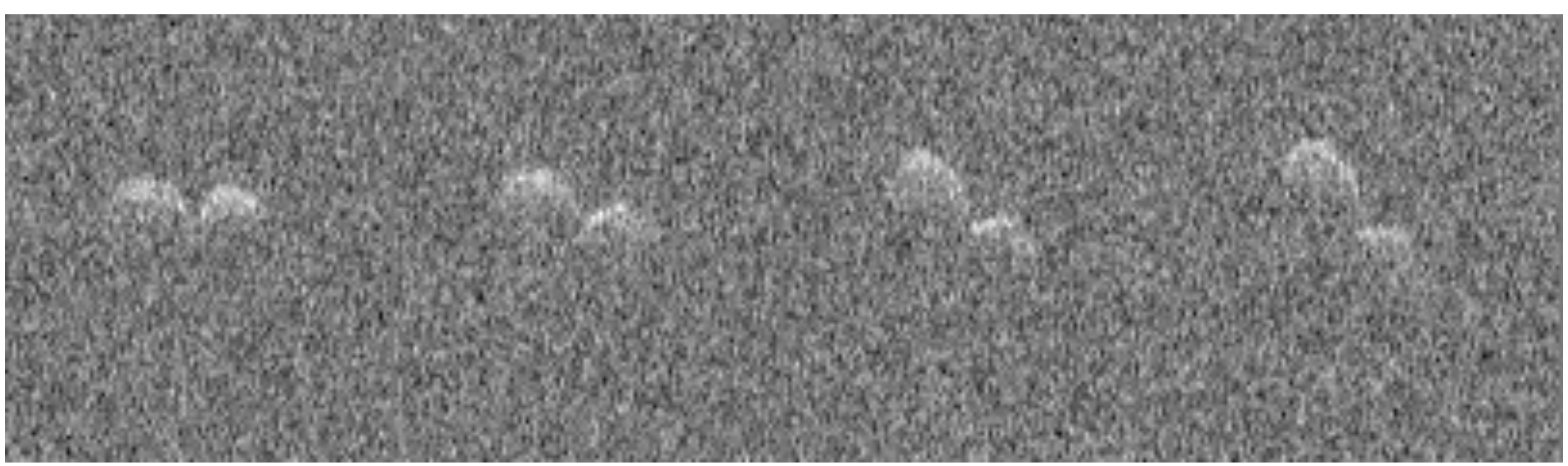


Radar delay-doppler imaging of the first bilobate comet

2008 Jan 3.9



2008 Jan 4.9



Conclusions

- Measured the sizes and shapes of some asteroids.
- (Determined surface properties of asteroids)
- Observations of close binaries underway... important future prospects.
- Active comet nuclei can be observed.