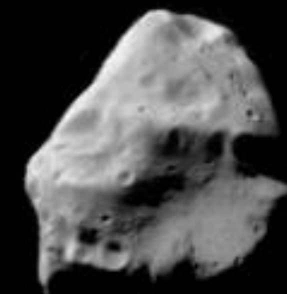
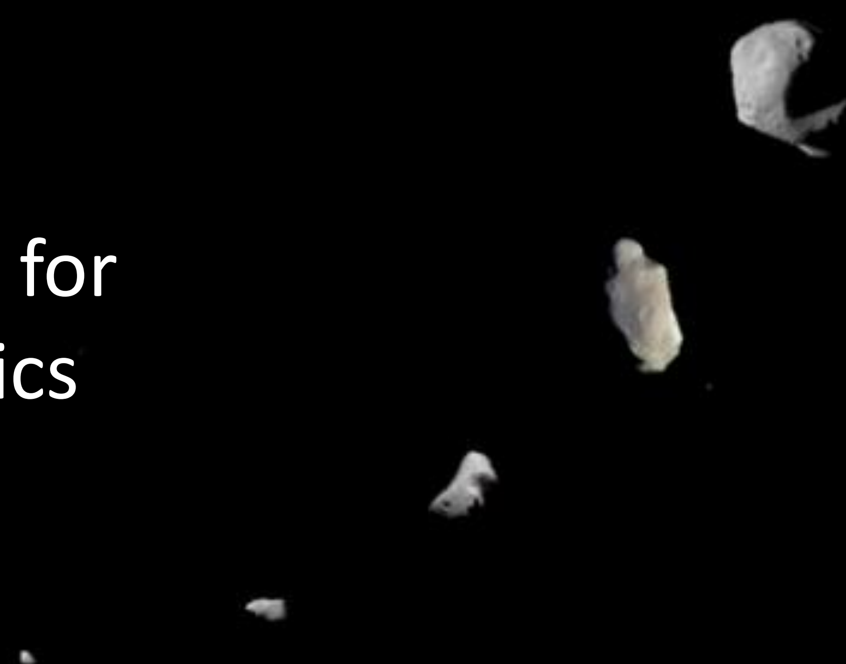
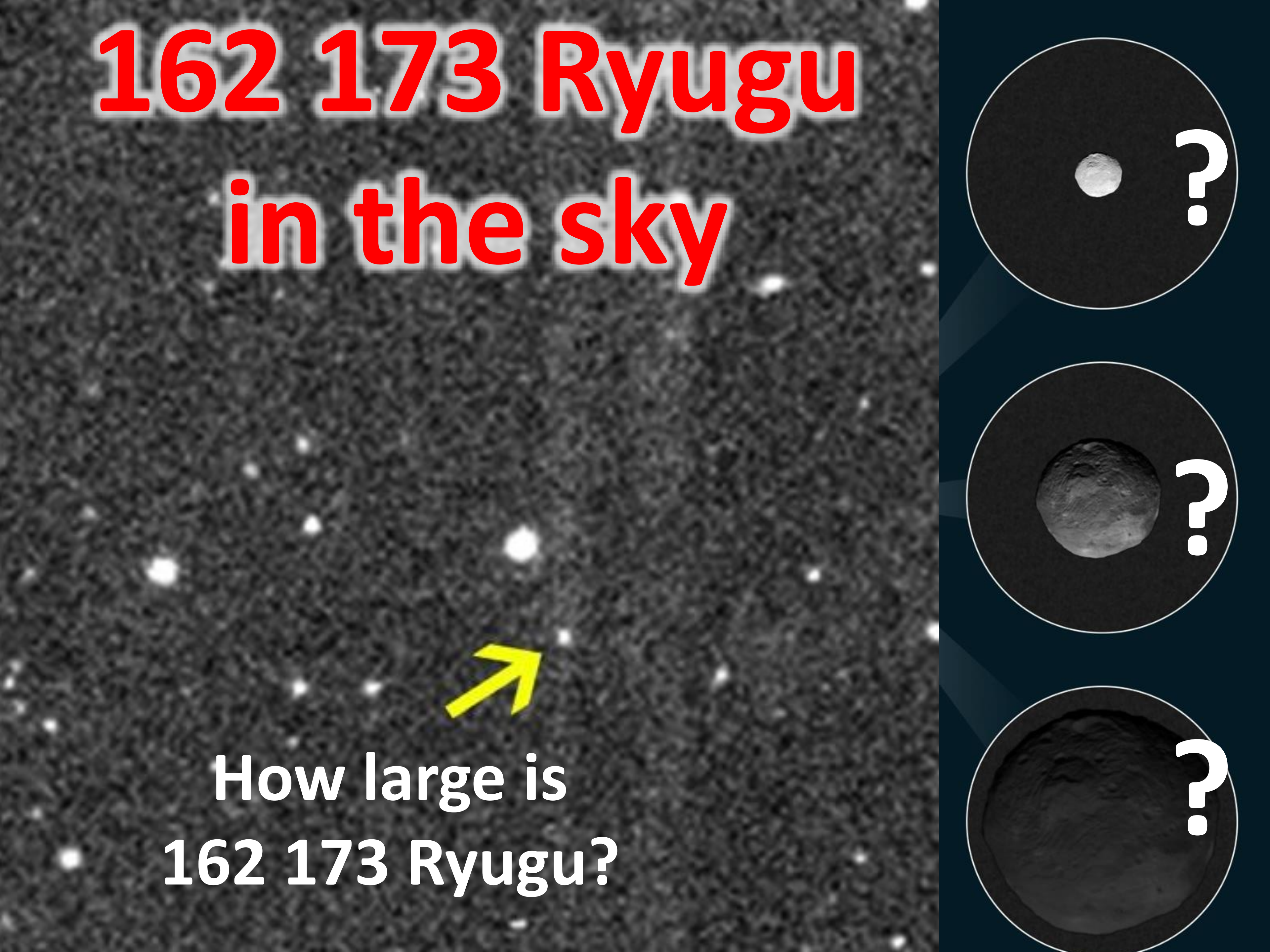
Asteroids in the thermal infrared



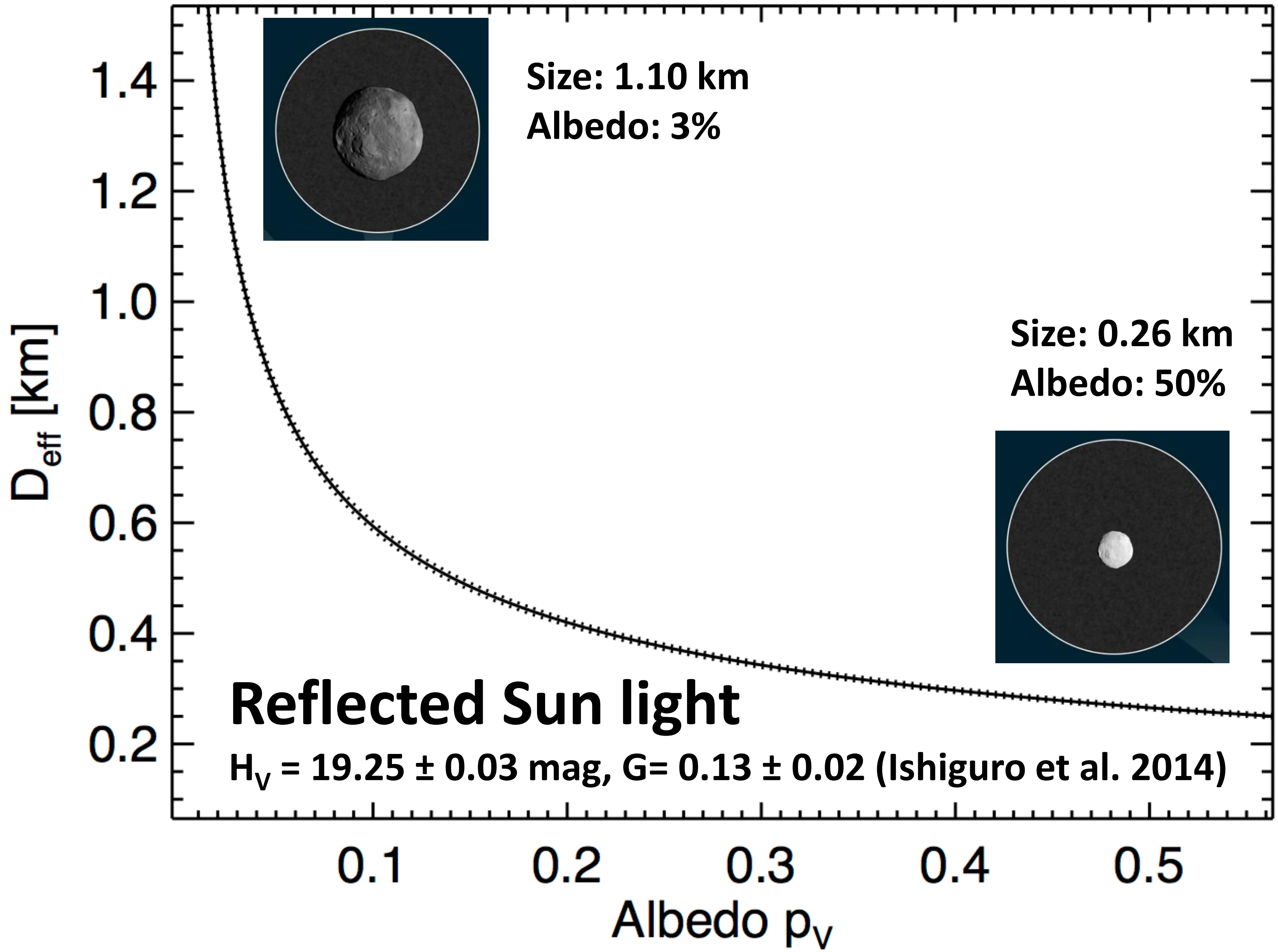
Thomas Müller
Max Planck Institute for extraterrestrial Physics
Garching, Germany



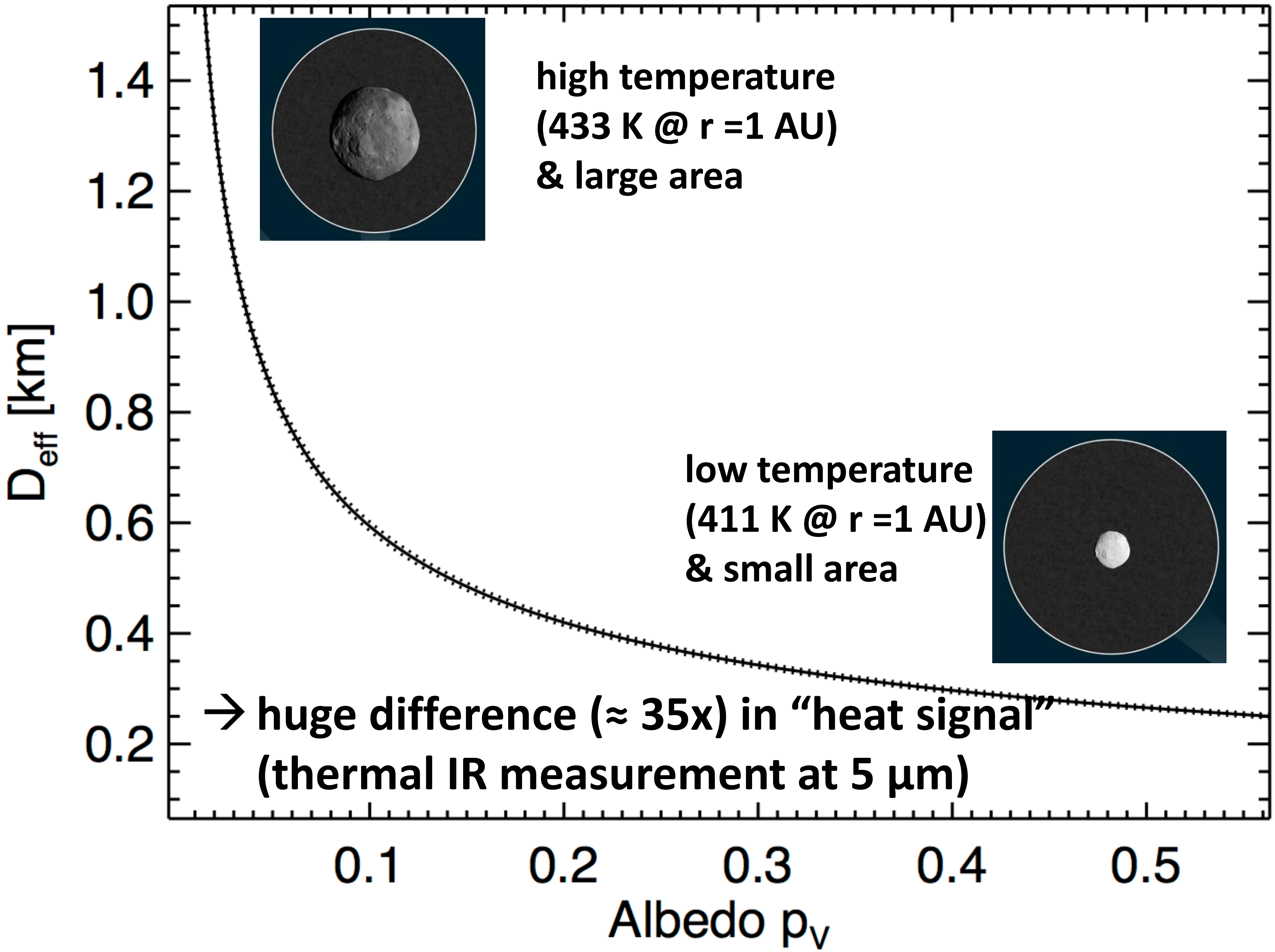

162 173 Ryugu
in the sky

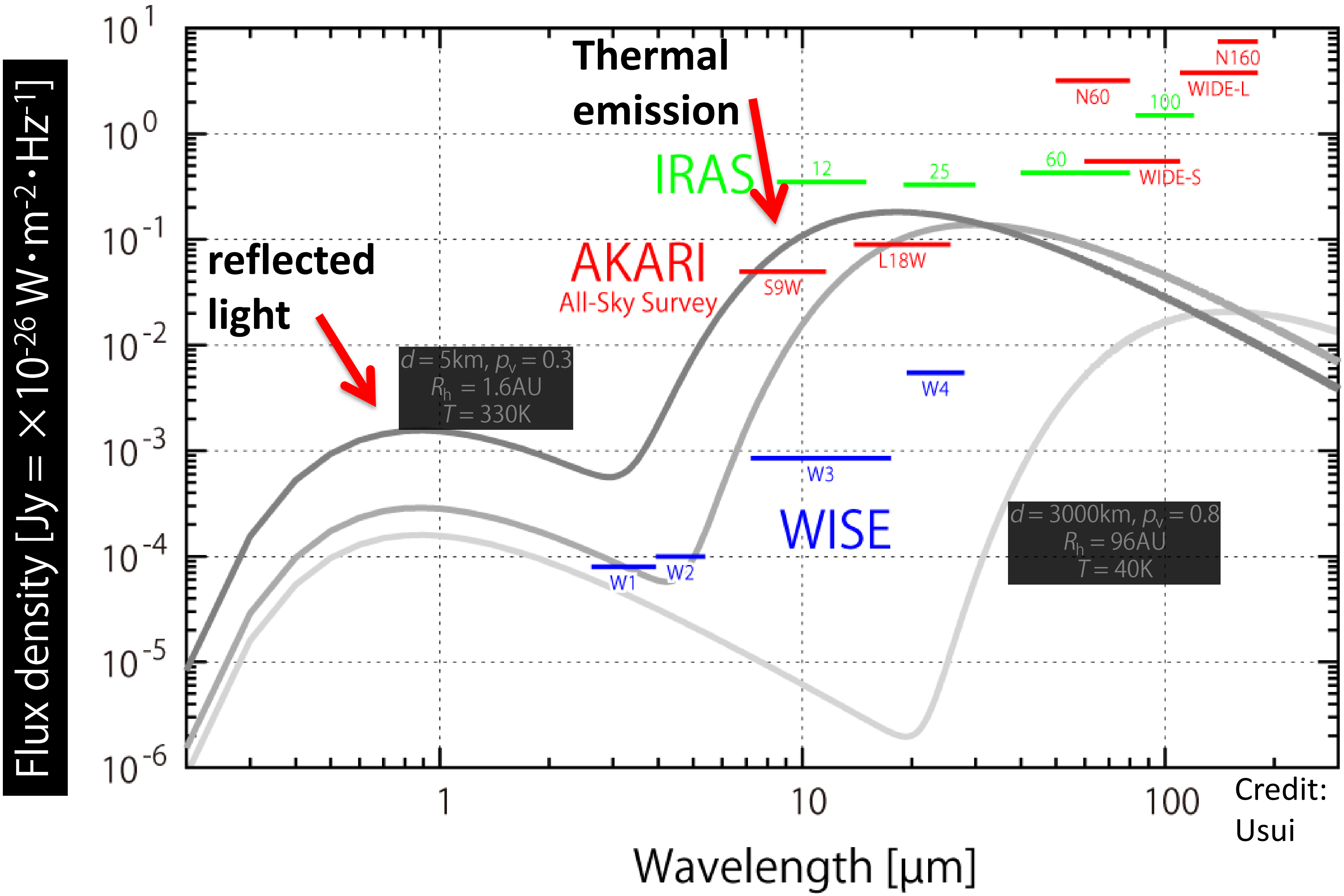

162 173 Ryugu
in the sky
How large is
162 173 Ryugu?
?
?
?

Radiometric Method Ryugu



Radiometric Method Ryugu





Neugebauer+1984; Ishihara+2010, Yamamura+2010; Wright+2010, Mainzer+2011

Ryugu Observations

- about 80 visual light curves, half are calibrated, some are very noisy, covering almost 10 years
- thermal data from AKARI (15 & 24 µm), ground-based Subaru- COMICS, Herschel-PACS (70 & 160 µm), Spitzer-IRS spectrum, covering phase angles from +22° ... +53°
- Spitzer-IRAC 3.6 & 4.5 µm light curves at two epochs + a series of short IRAC measurements spread over several months (phase angles from -89° ... -53°)
- no WISE data (too close to the Sun), maybe NEOWISE
- new light curve observations started again in summer 2016 and will continue until March 2017
- hopefully also Kepler-K2 in Sep/Oct 2017

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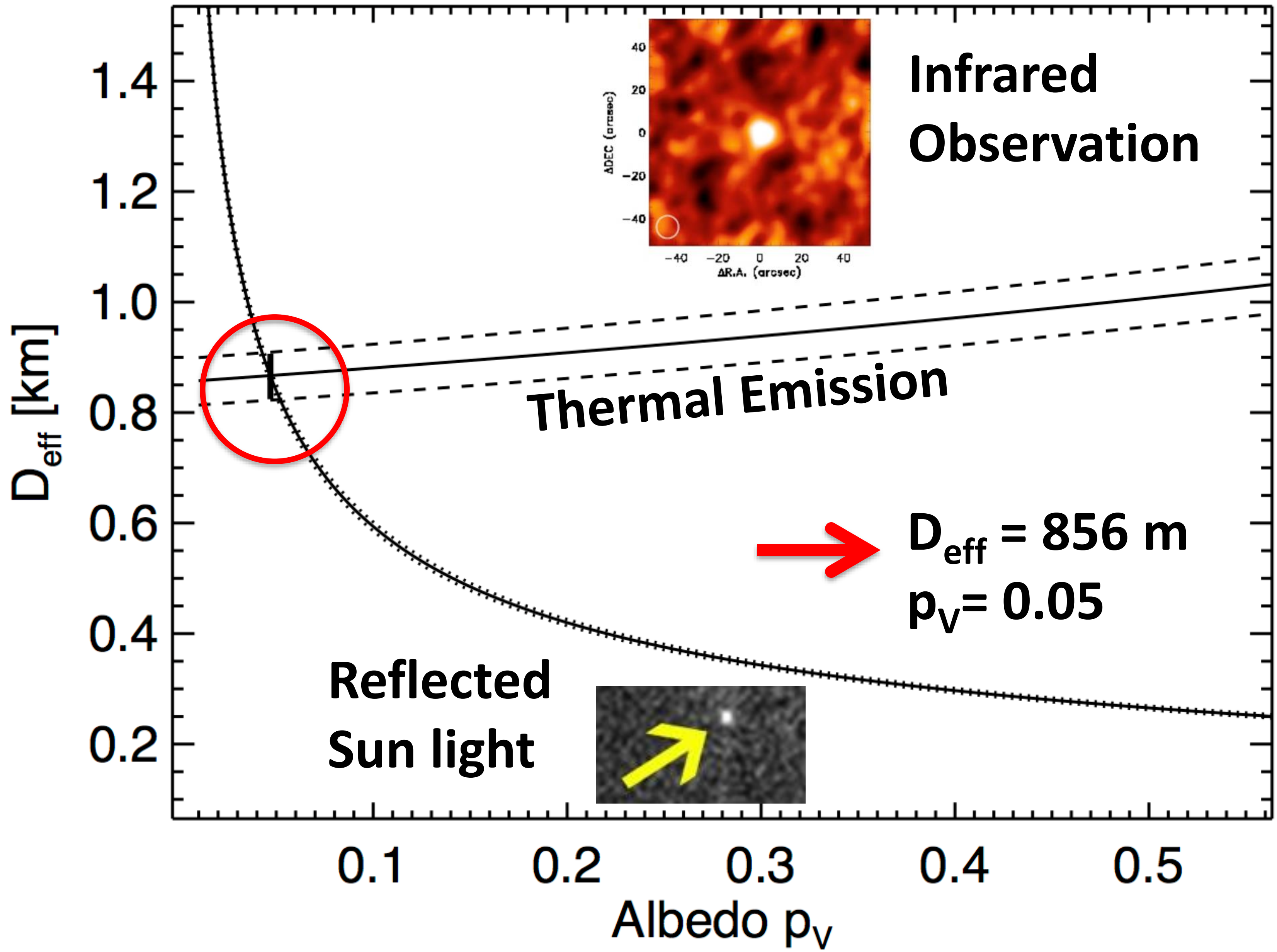
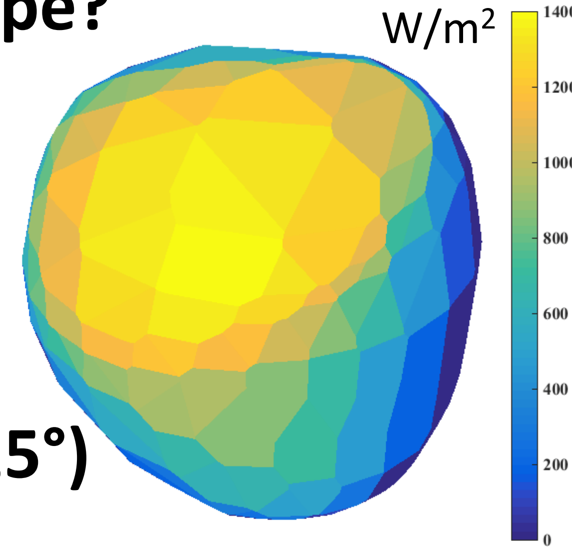
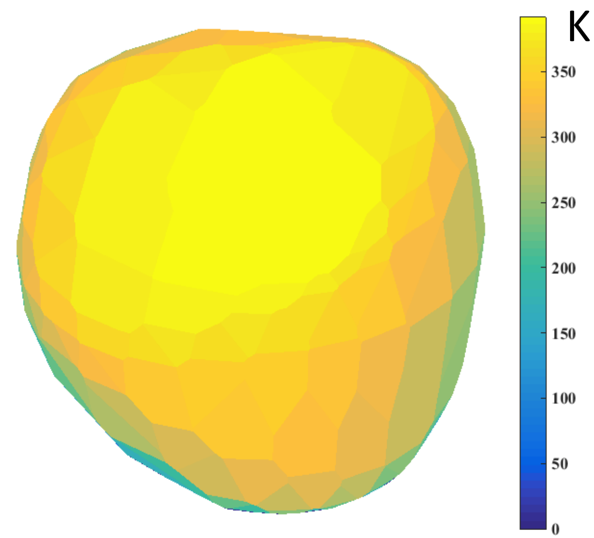
Radiometric Method Ryugu



Radiometric results: Ryugu

- size: 850-880 m, close to spherical shape?
- albedo p_V: 0.044-0.050
- thermal inertia: 150-300 $Jm^{-2}s^{-0.5}K^{-1}$
- surface roughness: very low, rms of surface slopes below 0.1
- spin axis $(\lambda, \beta)_{ecl}$ = (310°...340°, -40°±15°)
- P_{sid}= 7.6326 h, principle-axis rotation
- grain sizes: 1-10 mm (based on heat conductivity of 0.1-0.6 WK^{-1})



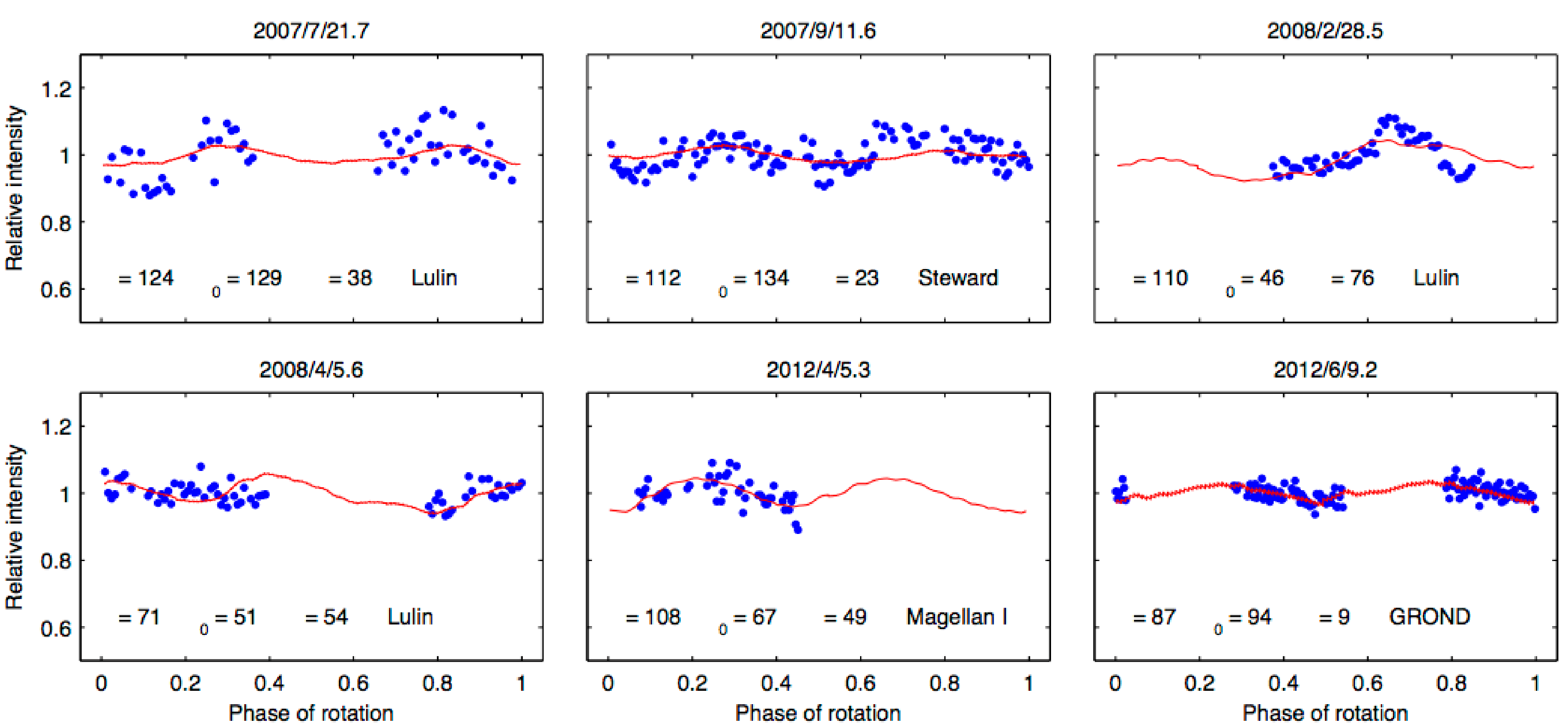


Hayabusa-2 Mission Target Asteroid 162173 Ryugu (1999 JU_3): Searching for the Object's Spin-Axis Orientation★

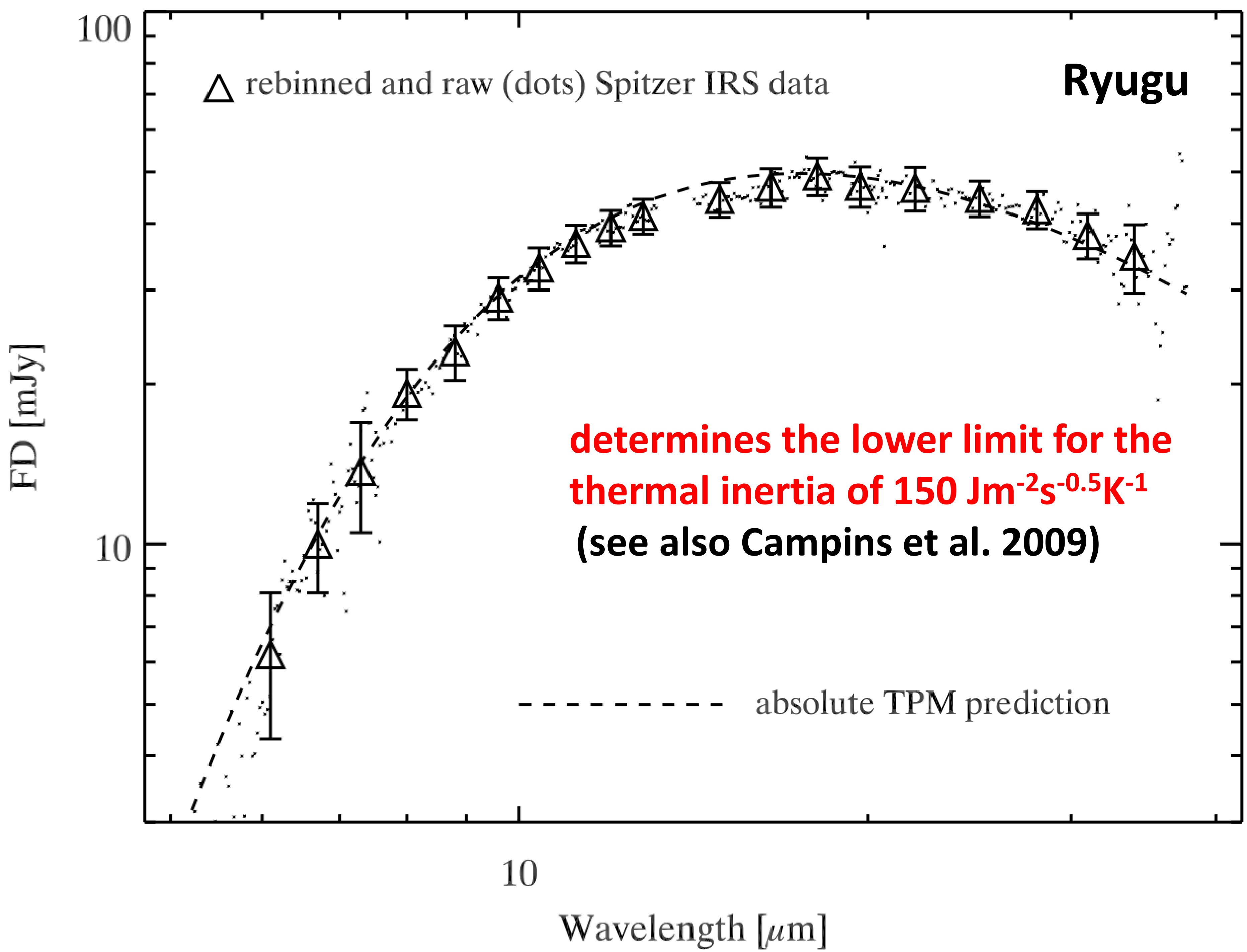
T. G. Müller[1], J. Ďurech[2], M. Ishiguro[3], M. Mueller[4], T. Krühler[1], H. Yang[3], M.-J. Kim[5], L. O'Rourke[6], F. Usui[7], C. Kiss[8], B. Altieri[6], B. Carry[9], Y.-J. Choi[5], M. Delbo[10], J. P. Emery[11], J. Greiner[1], S. Hasegawa[12], J. L. Hora[13], F. Knust[1], D. Kuroda[14], D. Osip[15], A. Rau[1], A. Rivkin[16], P. Schady[1], J. Thomas-Osip[15], D. Trilling[17], S. Urakawa[18], E. Vilenius[19], P. Weissman[20], P. Zeidler[21]

A&A accepted

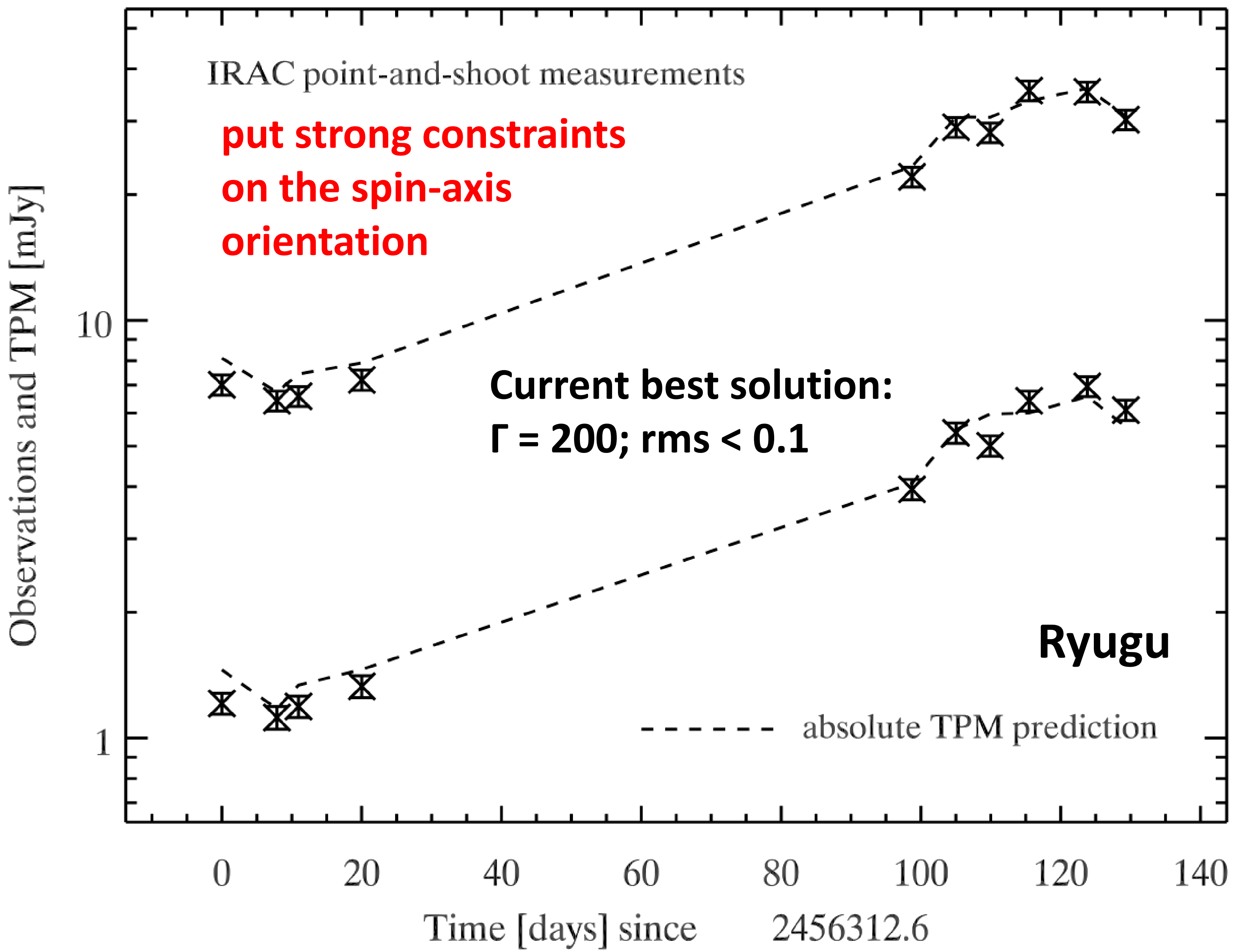
current visual light curves put only weak constraints on shape & spin properties of Ryugu

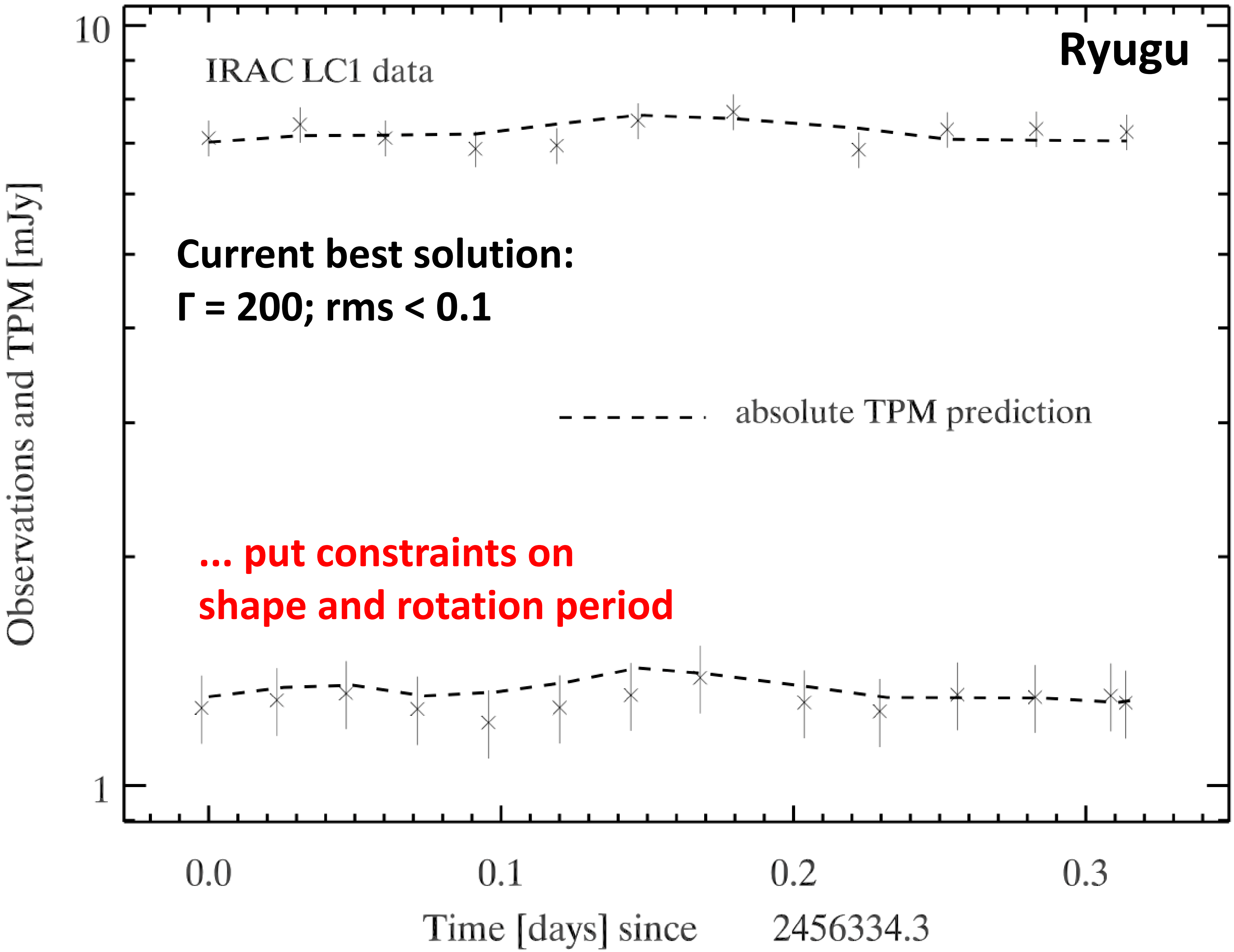


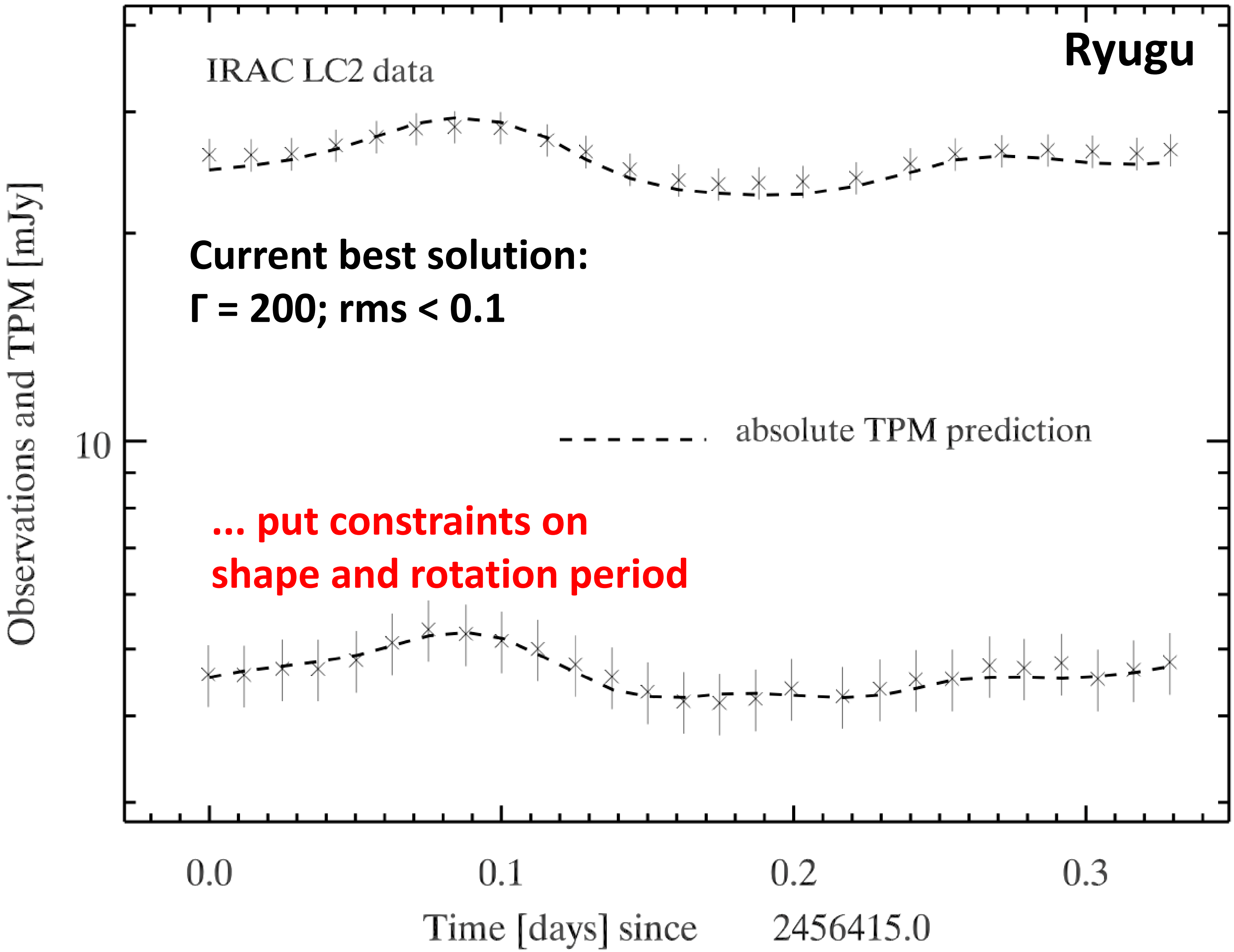
Comparison between the model (red curves) and the data (points) for a subset of visual lightcurves.



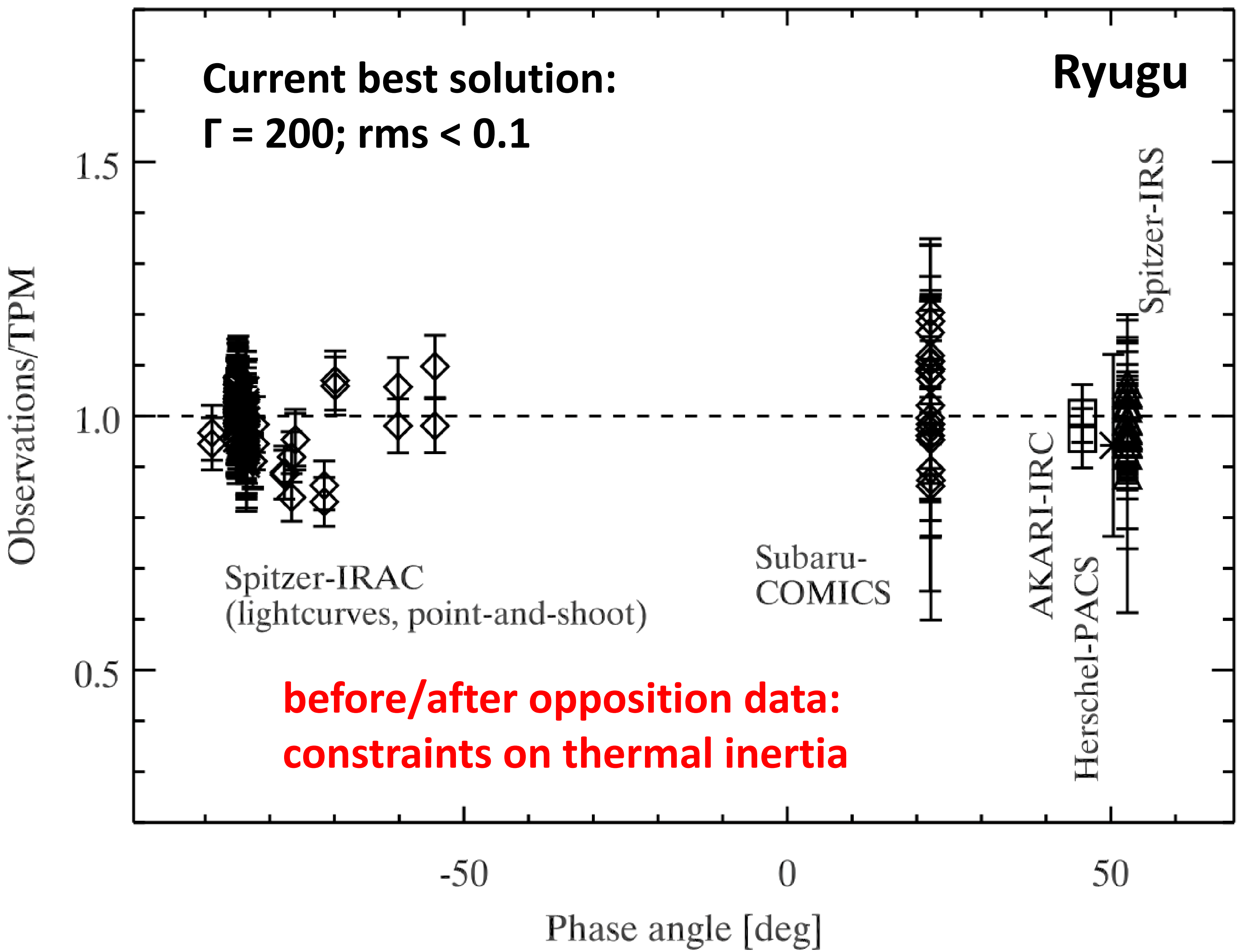
100
10
FD [mJy]
10
Wavelength [μm]
△ rebinned and raw (dots) Spitzer IRS data
Ryugu
determines the lower limit for the thermal inertia of 150 Jm-2s-0.5K-1
(see also Campins et al. 2009)
absolute TPM prediction


IRAC point-and-shoot measurements
put strong constraints
on the spin-axis
orientation
Current best solution:
Γ = 200; rms < 0.1
Ryugu
absolute TPM prediction
Observations and TPM [mJy]
10
1
0
20
40
60
80
100
120
140
Time [days] since 2456312.6

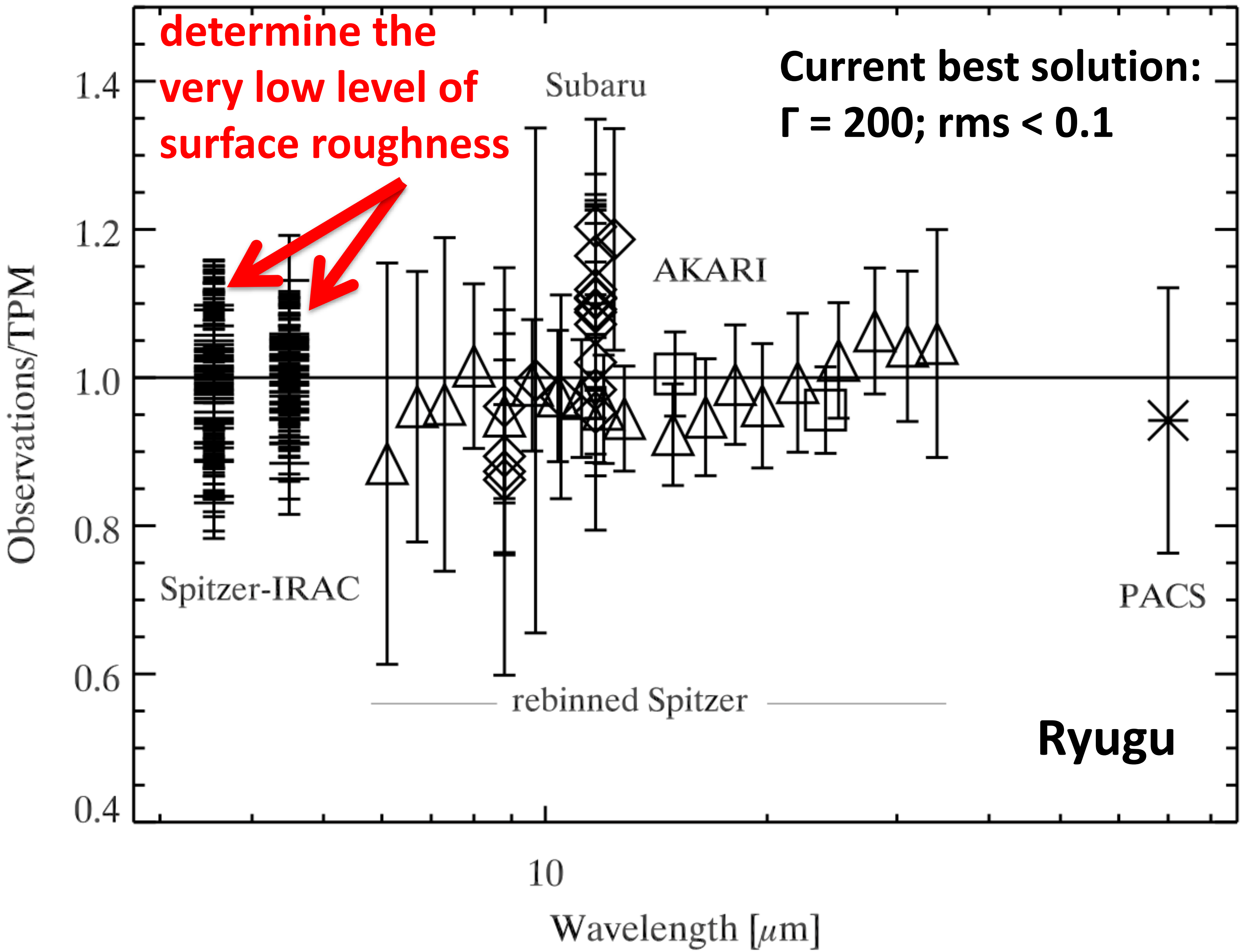

Ryugu
IRAC LC1 data
Current best solution:
Γ = 200; rms < 0.1
absolute TPM prediction
... put constraints on
shape and rotation period
Observations and TPM [mJy]
10
1
0.0
0.1
0.2
0.3
Time [days] since 2456334.3



Ryugu
IRAC LC2 data
Current best solution:
Γ = 200; rms < 0.1
absolute TPM prediction
... put constraints on
shape and rotation period
Observations and TPM [mJy]
10
0.0
0.1
0.2
0.3
Time [days] since 2456415.0

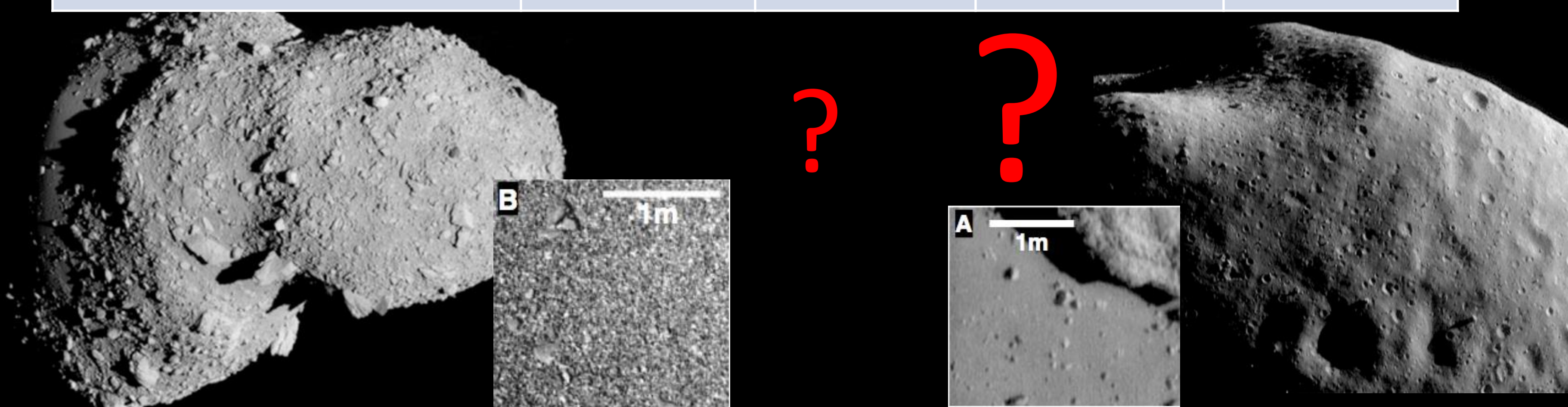


Current best solution:
Γ = 200; rms < 0.1
Ryugu
Observations/TPM
1.5
1.0
0.5
Spitzer-IRAC
(lightcurves, point-and-shoot)
Subaru-
COMICS
AKARI-IRC
Herschel-PACS
Spitzer-IRS
before/after opposition data:
constraints on thermal inertia
-50
0
50
Phase angle [deg]


determine the very low level of surface roughness
Current best solution:
Γ = 200; rms < 0.1
Subaru
AKARI
Spitzer-IRAC
PACS
rebinned Spitzer
Ryugu
Observations/TPM
1.4
1.2
1.0
0.8
0.6
0.4
10
Wavelength [μm]

Comparison of surface properties derived via radiometric techniques

	Itokawa	**Bennu**	**Ryugu**	**Eros**
Thermal inertia $[Jm^{-2}K^{-1}s^{-1/2}]$	700	550? 310?	200	150
model (measured) roughness	60° (50°?)	20°	5°	38° (25°)
references	Müller+14	reference model	Müller+16	Rozitis 16

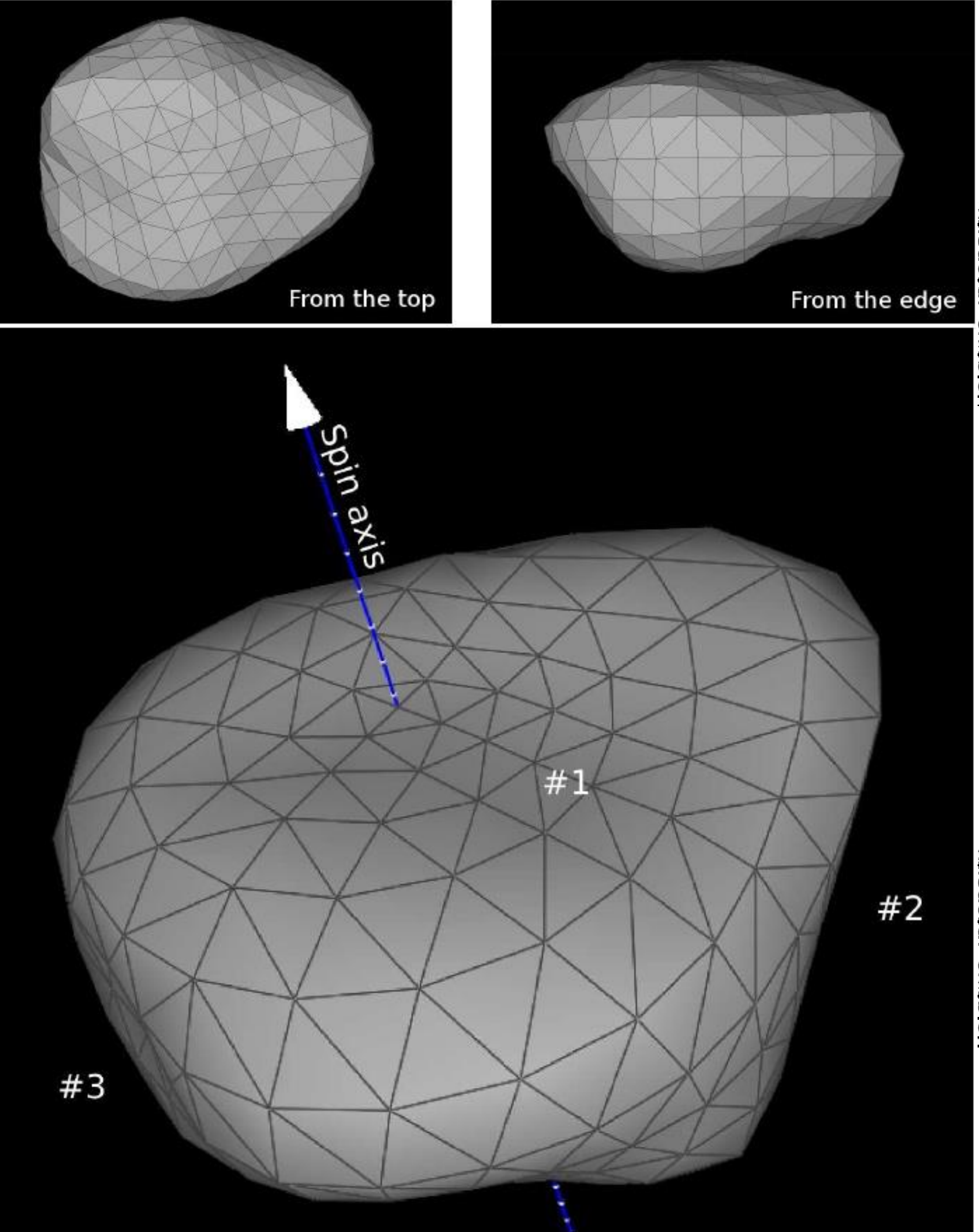


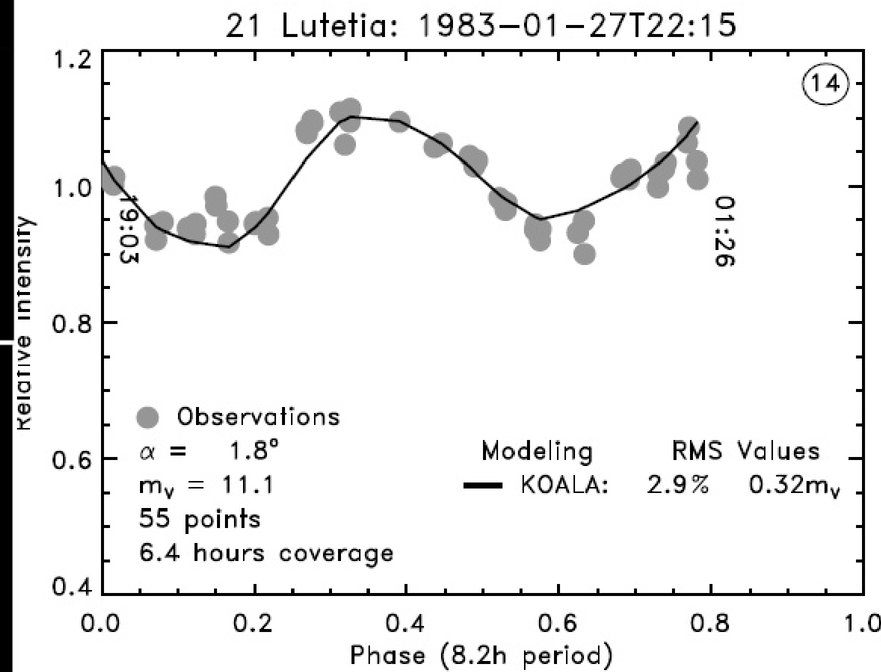
Large main-belt asteroids

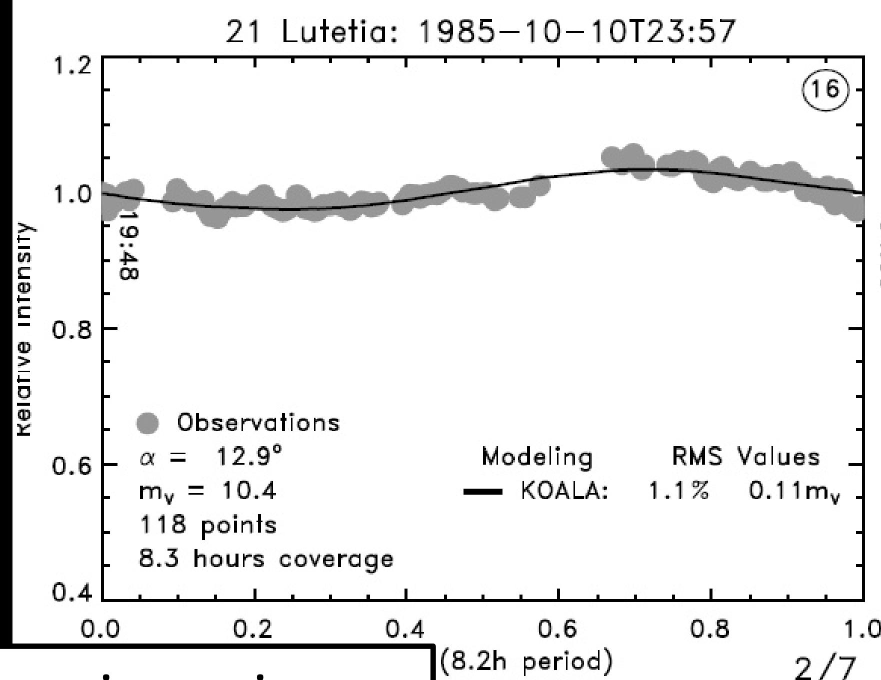
Motivation:

- density determination for Gaia mass sample: requires high-quality size and shape information
- size-albedo properties for large samples (like for the AKARI catalogue; Usui+2011, 2013, 2014; Hasegawa+2013)
- thermal properties for IRAS, AKARI, WISE-detected objects
- asteroids as far-IR/submm/mm absolute flux calibration standards for ISO, AKARI, Spitzer, Herschel, ALMA, IRAM, APEX, etc. (Müller+2002, 2005, 2014; Stansberry+2007; ...)

- MBAs have no atmosphere, no dust storms, are (almost) IR featureless, have low-conductivity surfaces, shape and spin information, predictable daily/seasonally variations ...

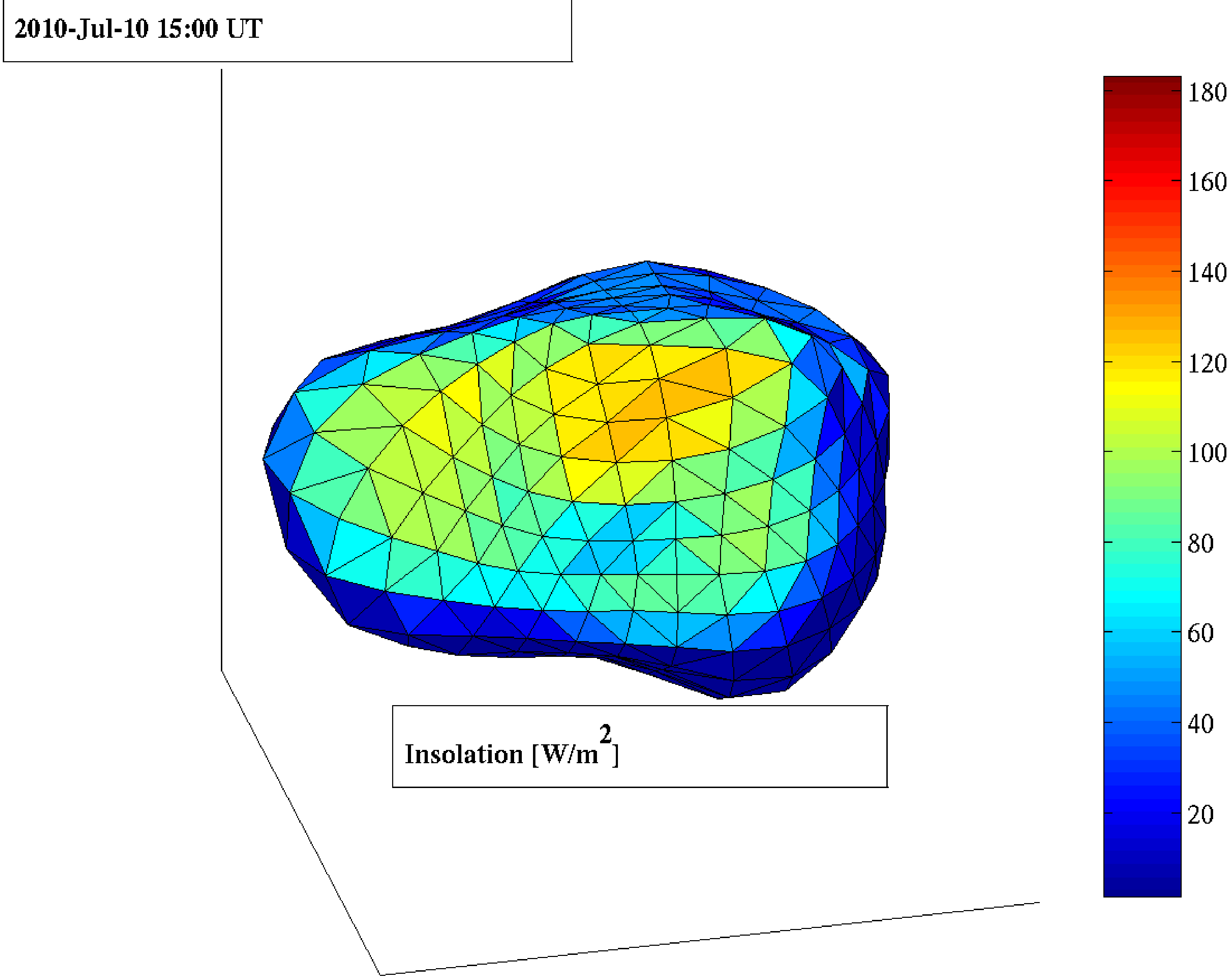


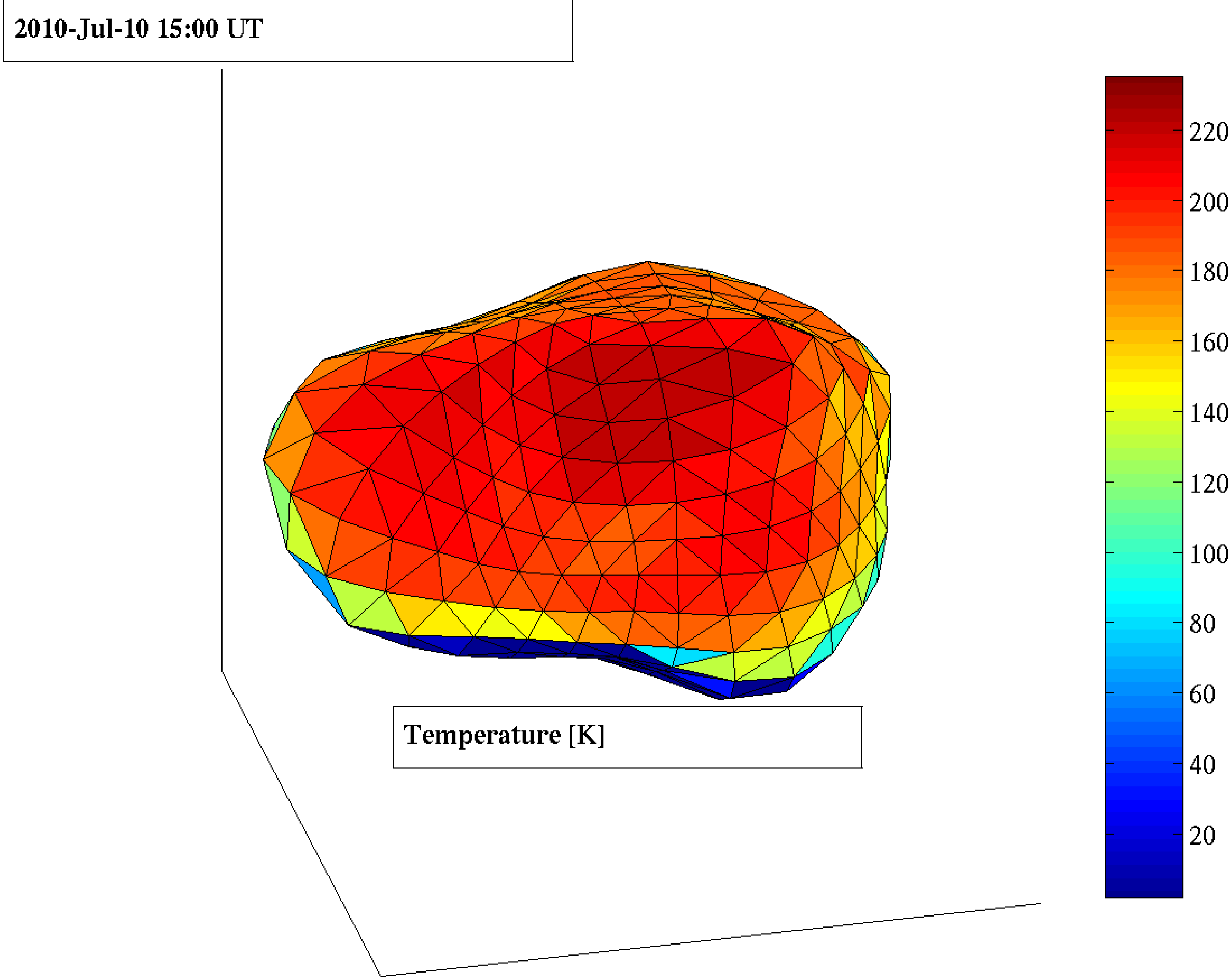




2/7

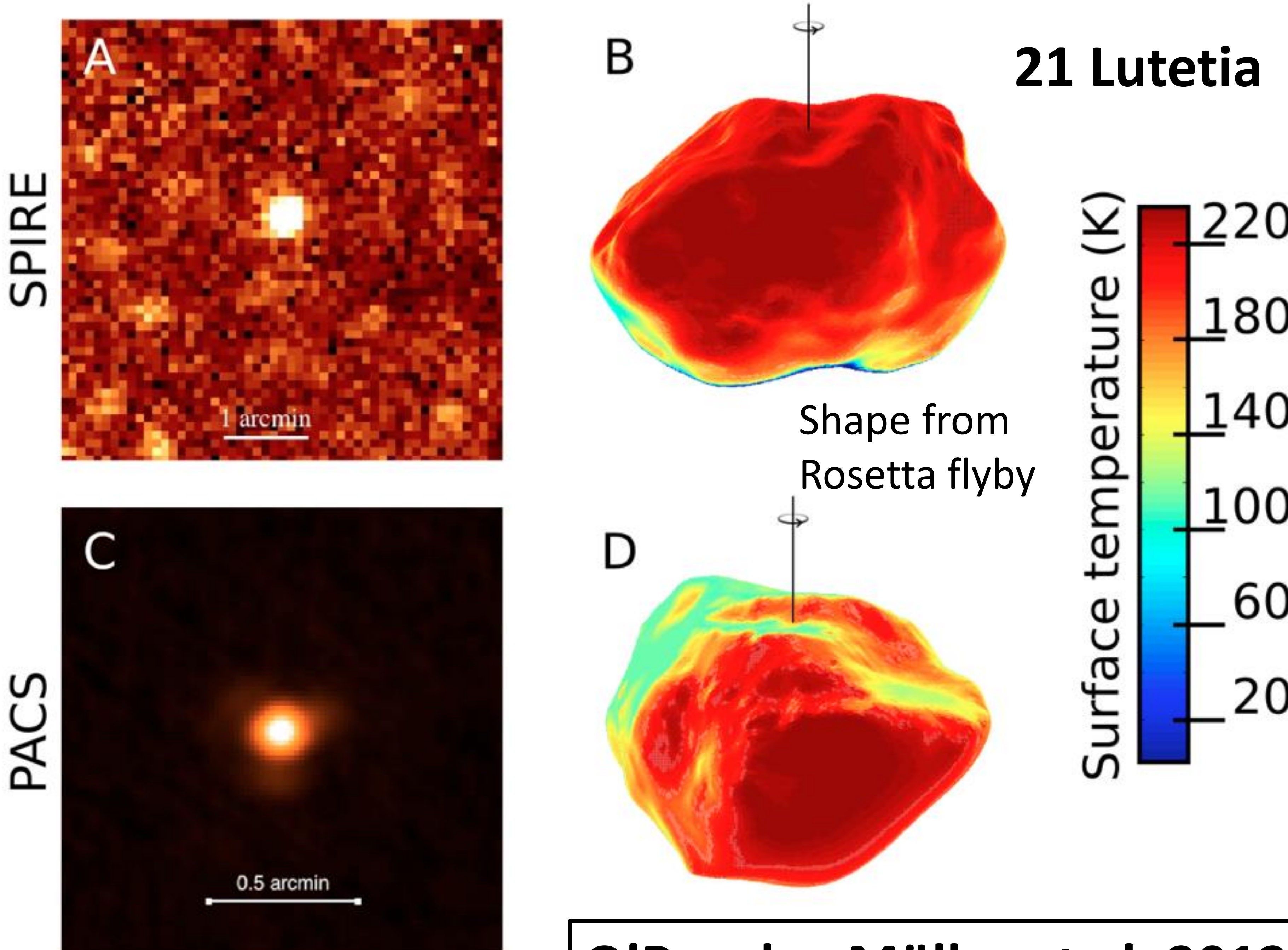
Shape and spin properties from lightcurve inversion


2010-Jul-10 15:00 UT
Insolation [W/m2]
180
160
140
120
100
80
60
40
20

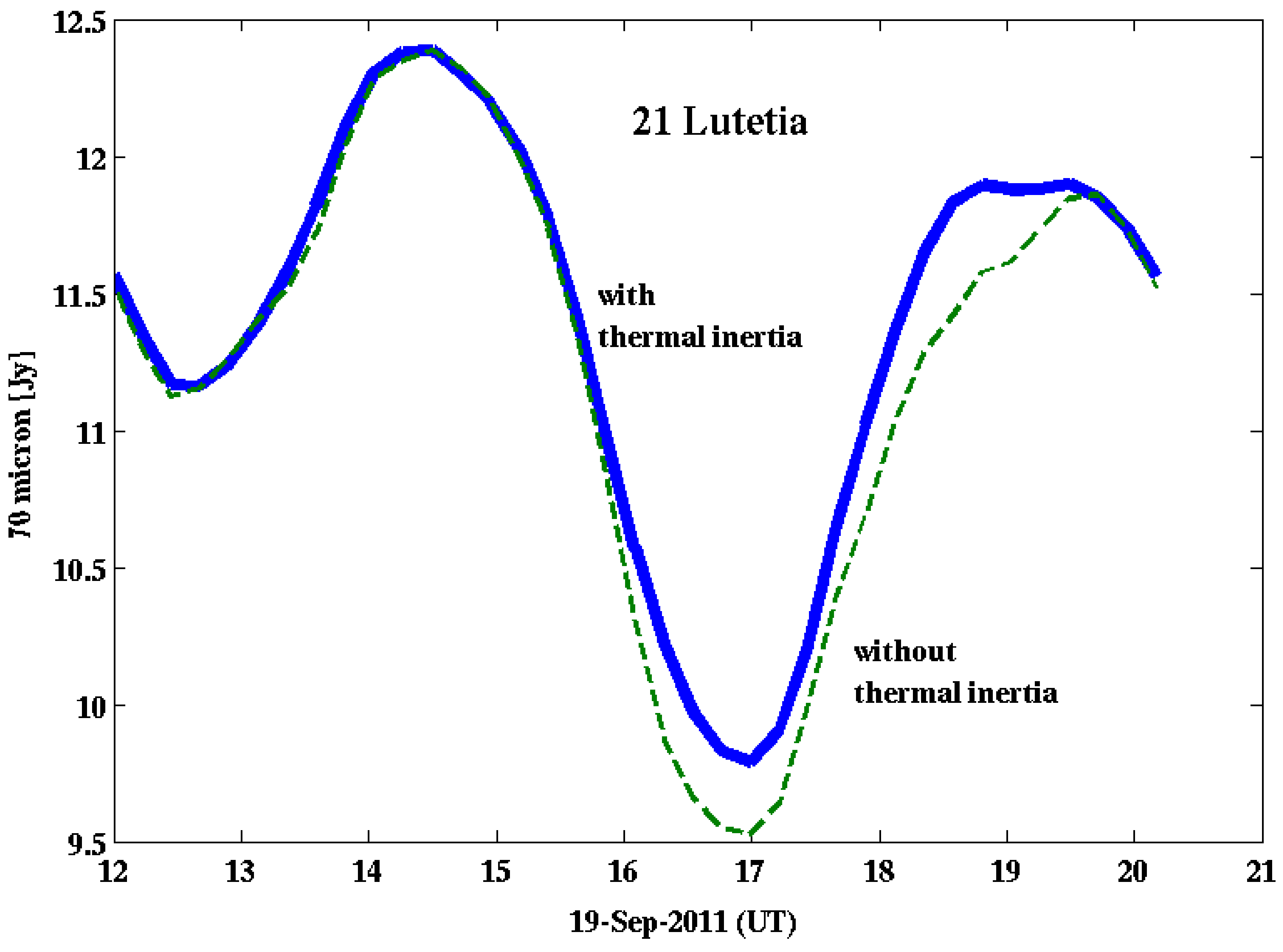


2010-Jul-10 15:00 UT
Temperature [K]
220
200
180
160
140
120
100
80
60
40
20

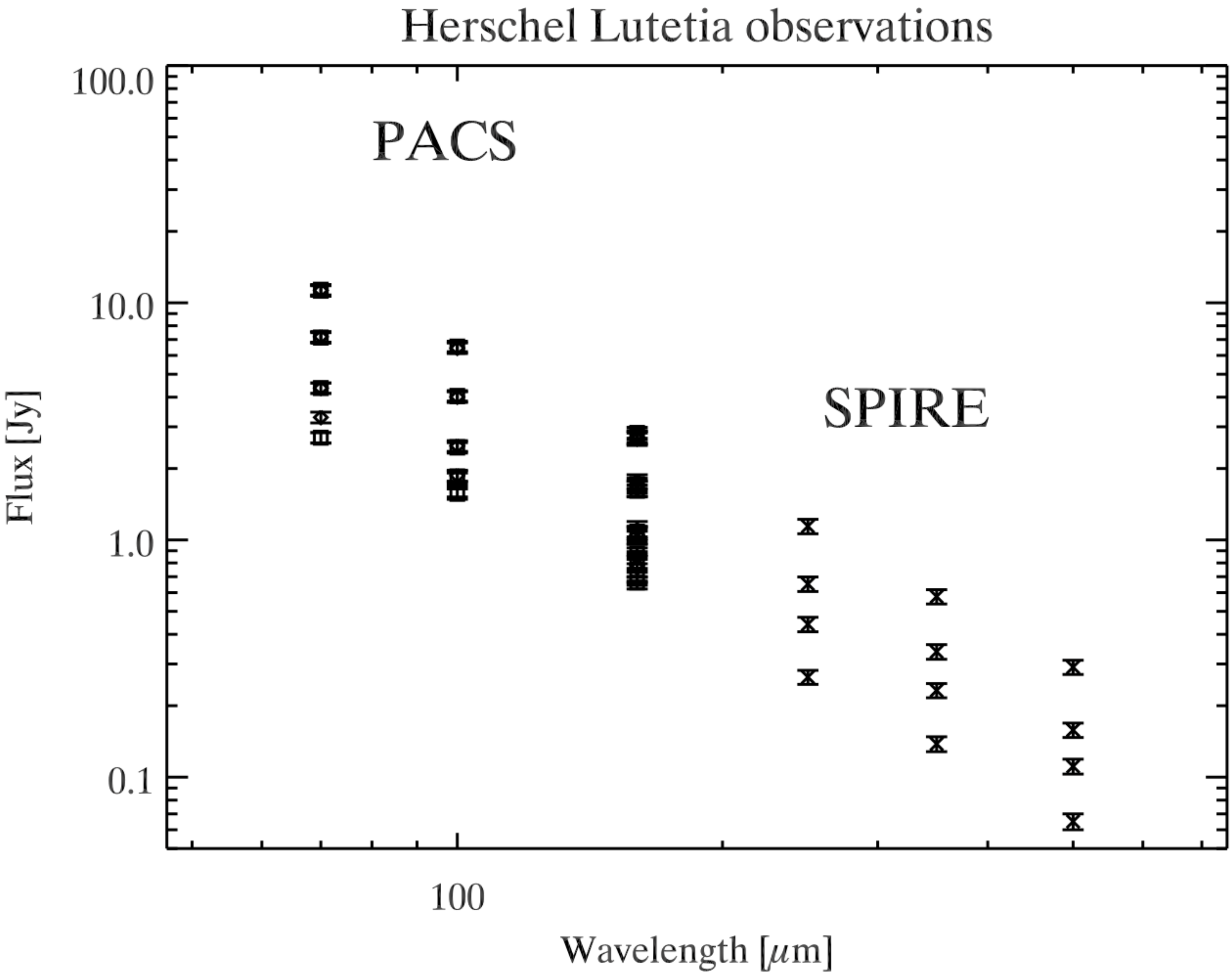
21 Lutetia

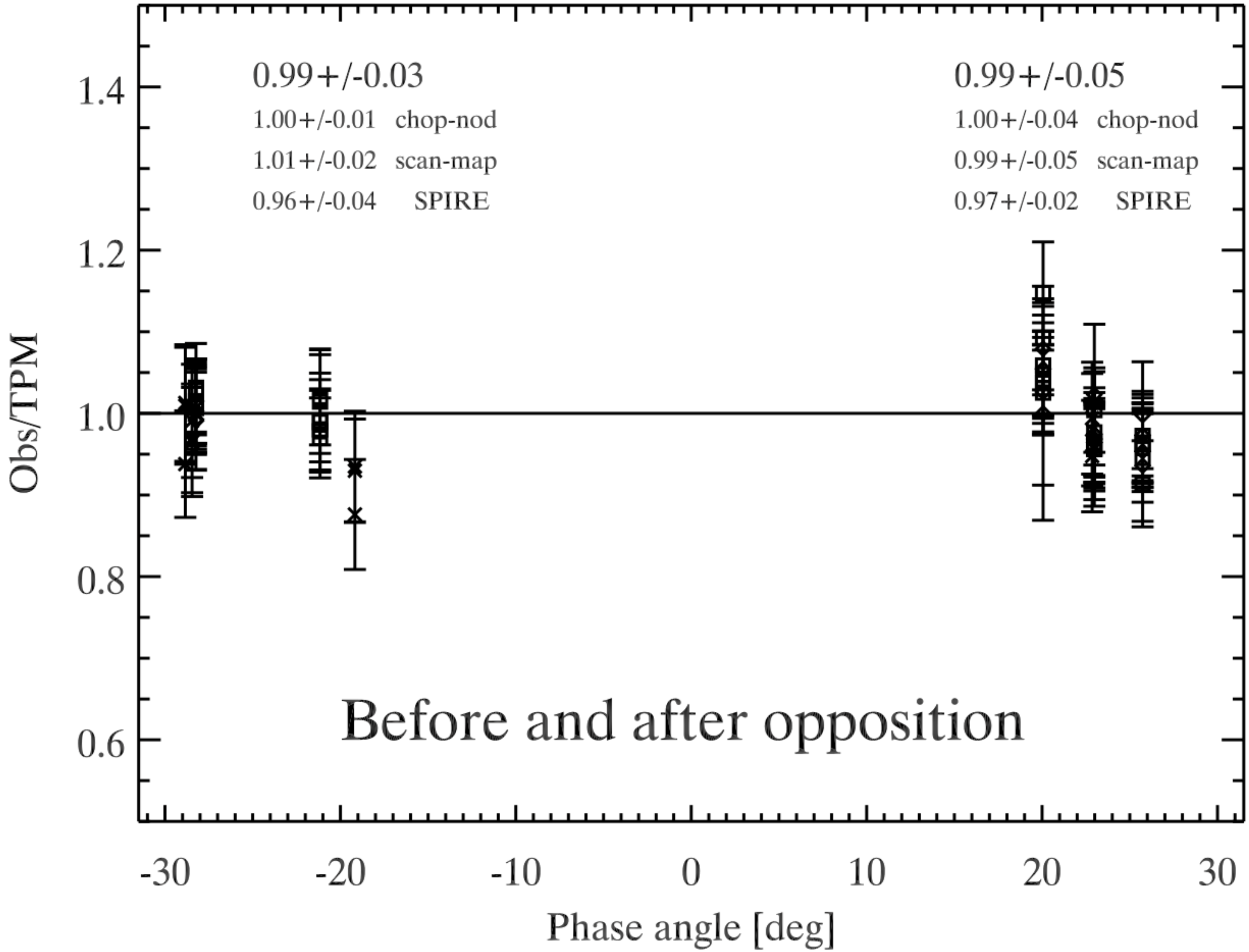


O’Rourke, Müller et al. 2012

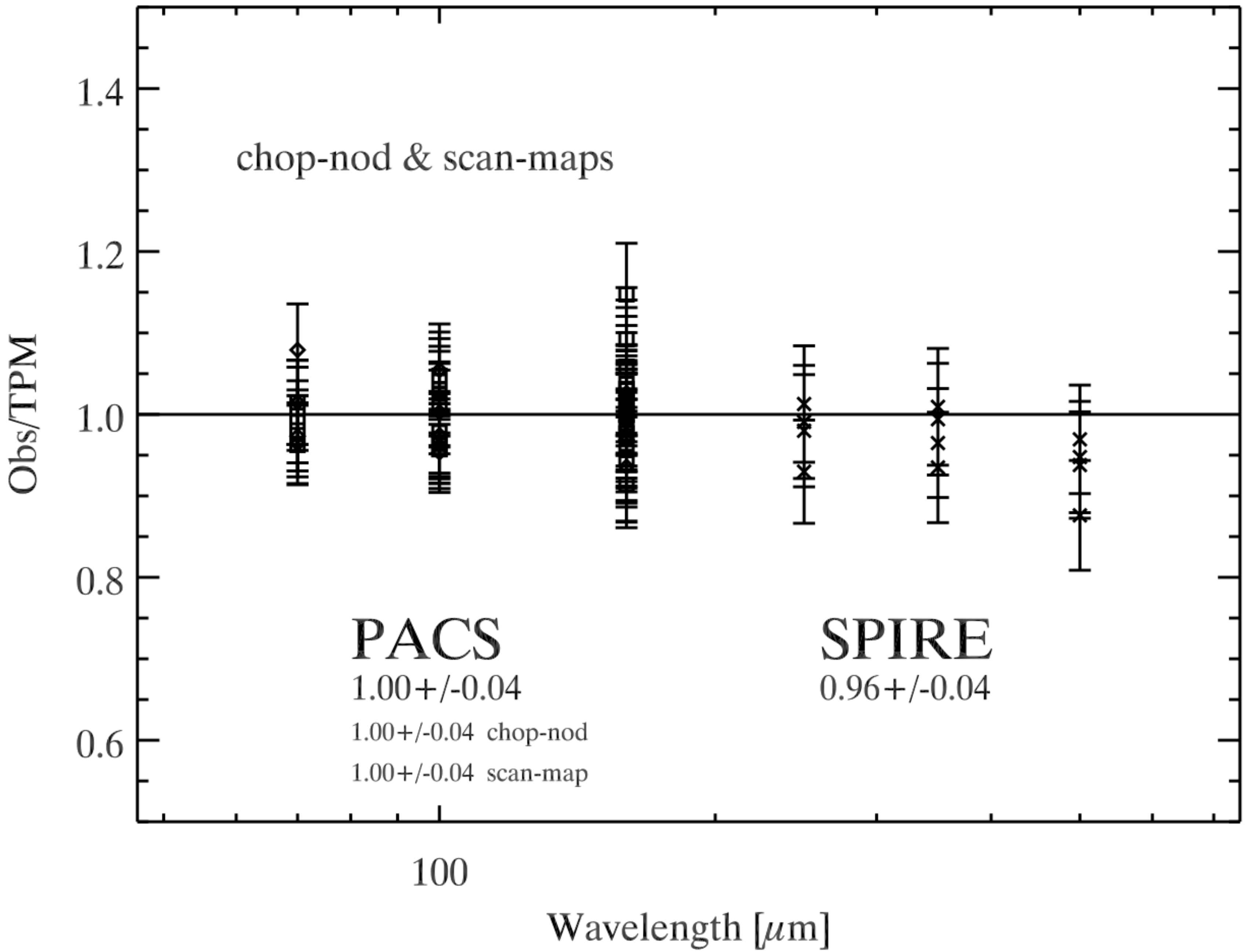


21 Lutetia
with
thermal inertia
without
thermal inertia
70 micron [Jy]
12.5
12
11.5
11
10.5
10
9.5
12
13
14
15
16
17
18
19
20
21
19-Sep-2011 (UT)

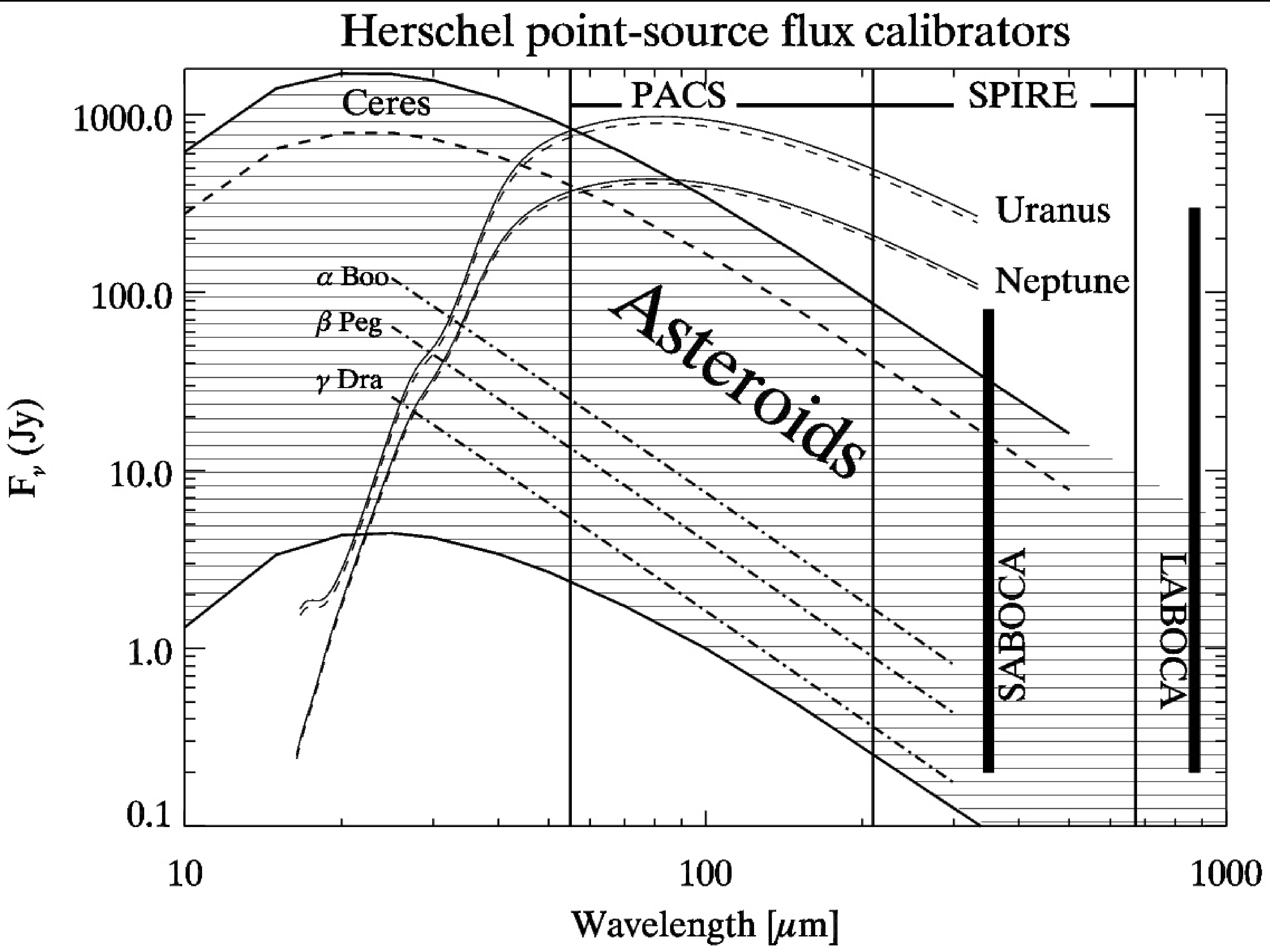

Herschel Lutetia observations
PACS
SPIRE
Flux [Jy]
100.0
10.0
1.0
0.1
100
Wavelength [μm]



0.99+/-0.03
1.00+/-0.01 chop-nod
1.01+/-0.02 scan-map
0.96+/-0.04 SPIRE
0.99+/-0.05
1.00+/-0.04 chop-nod
0.99+/-0.05 scan-map
0.97+/-0.02 SPIRE
Before and after opposition
Obs/TPM
1.4
1.2
1.0
0.8
0.6
-30
-20
-10
0
10
20
30
Phase angle [deg]



chop-nod & scan-maps
Obs/TPM
1.4
1.2
1.0
0.8
0.6
PACS
1.00+/-0.04
1.00+/-0.04 chop-nod
1.00+/-0.04 scan-map
SPIRE
0.96+/-0.04
100
Wavelength [μm]

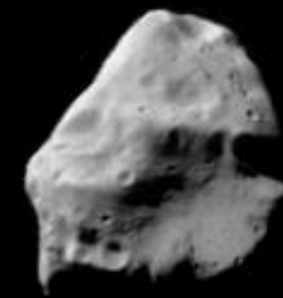


Herschel point-source flux calibrators
Ceres
PACS
SPIRE
Uranus
Neptune
Asteroids
α Boo
β Peg
γ Dra
SABOCA
LABOCA
1000.0
100.0
10.0
1.0
0.1
10
100
1000
F_ν (Jy)
Wavelength [μm]

Asteroids/TNOs in the thermal infrared

Relevant:

- Observing & illumination geometry
- Size & geometric albedo
- Shape & spin properties
- Surface thermal & roughness properties



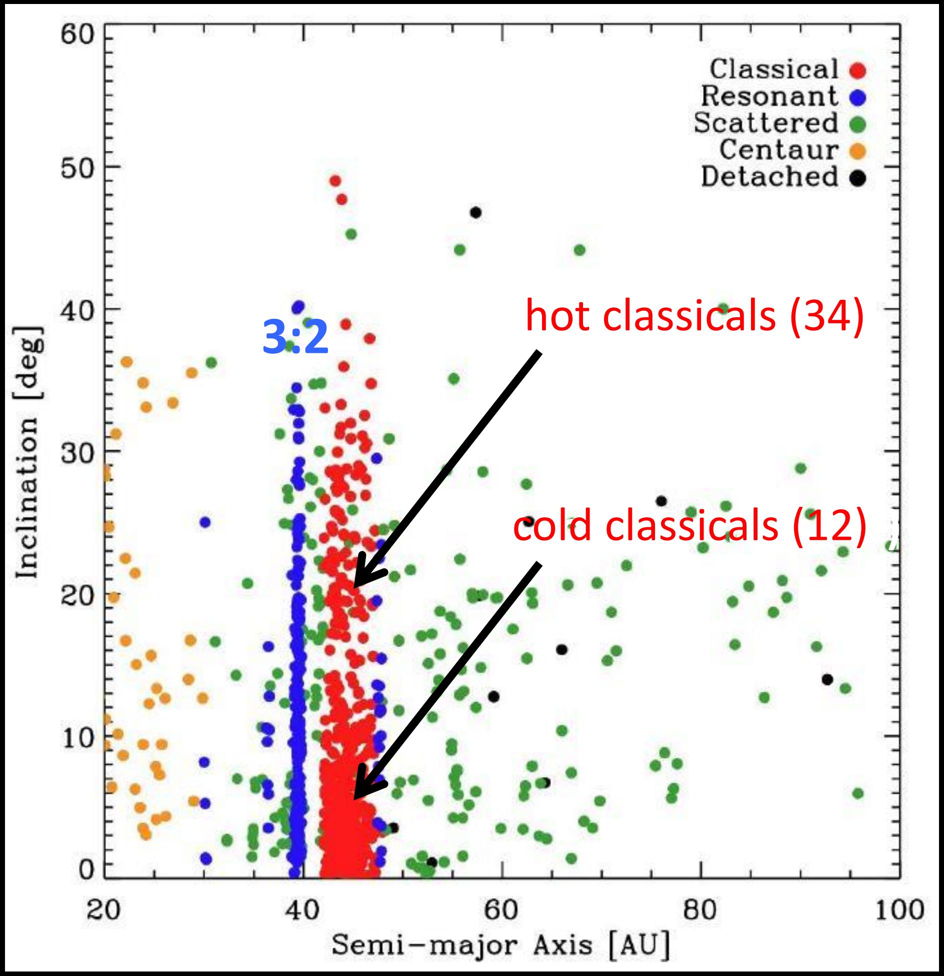
Less relevant:

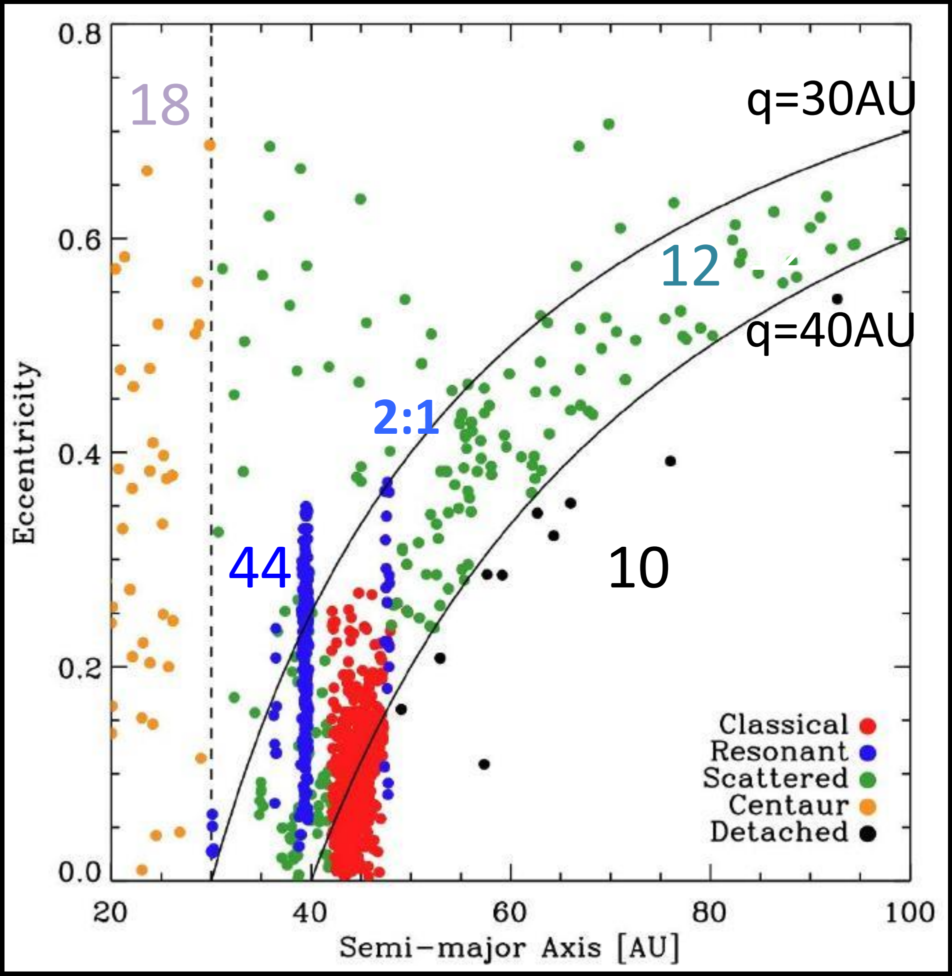
- Colour, albedo variations, mineralogy, small surface features or shape

“TNOs are Cool” A survey of the transneptunian region with Herschel

- Infrared Space Observatory (ESA): 2009 – 2013
- 3.5 m telescope, L2 Orbit
- Photometry and spectroscopy (55 to 672 µm), cooled instruments PACS, SPIRE, HIFI
- Observed about 1/10 of the sky (individual targets, small fields)
- Galaxy formation & evolution, star/planet formation, ISM, solar system
- OT Key Project (PI: T. Müller) targeted photometry of about 130 TNOs/Centaurs

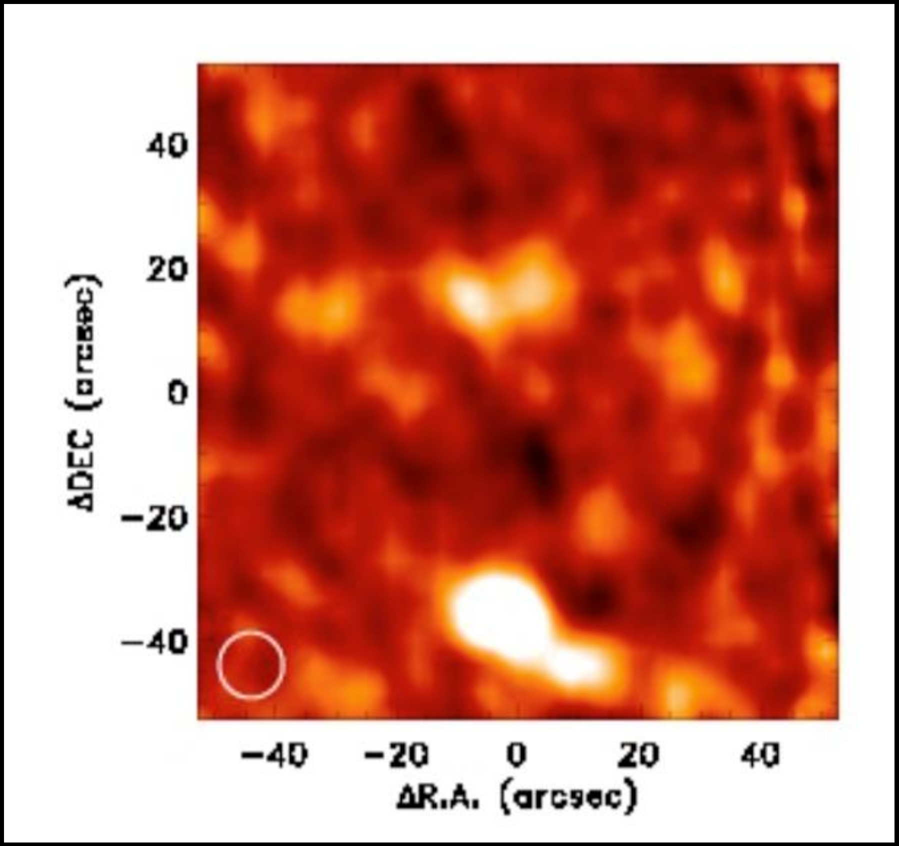
The trans-Neptunian Region & "TNOs are Cool" Sample



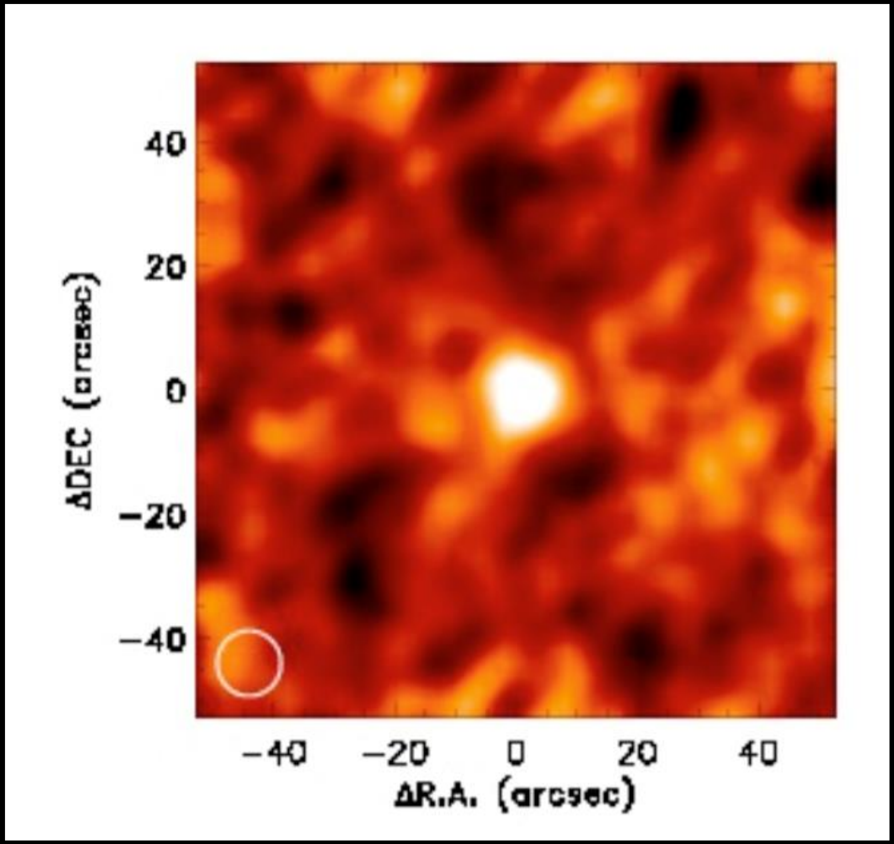


Jewitt et al. 2008, Müller et al. 2009

Standard map
(scan + cross-scan)



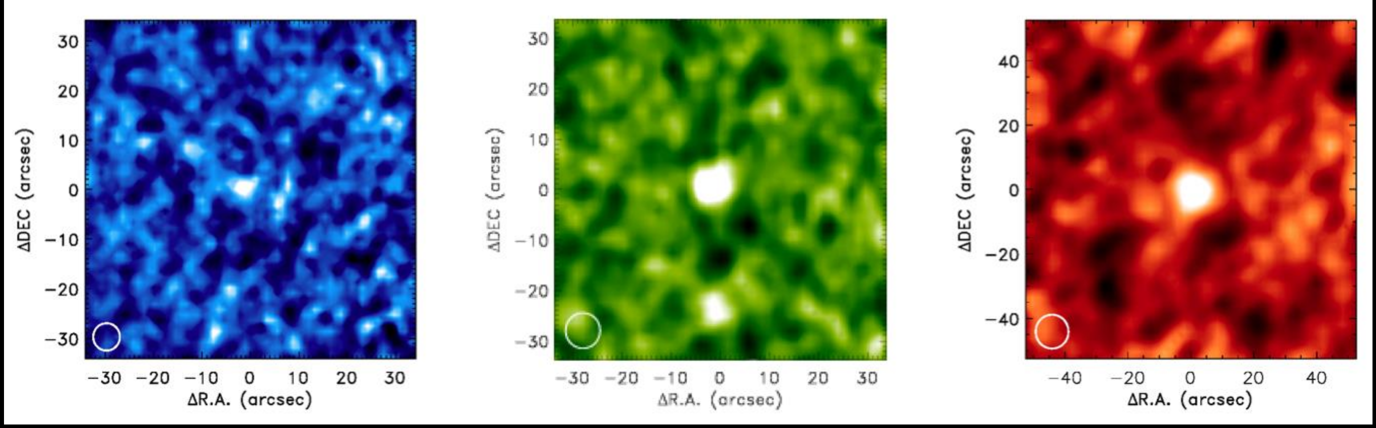
Double-differential map
(after background subtraction)

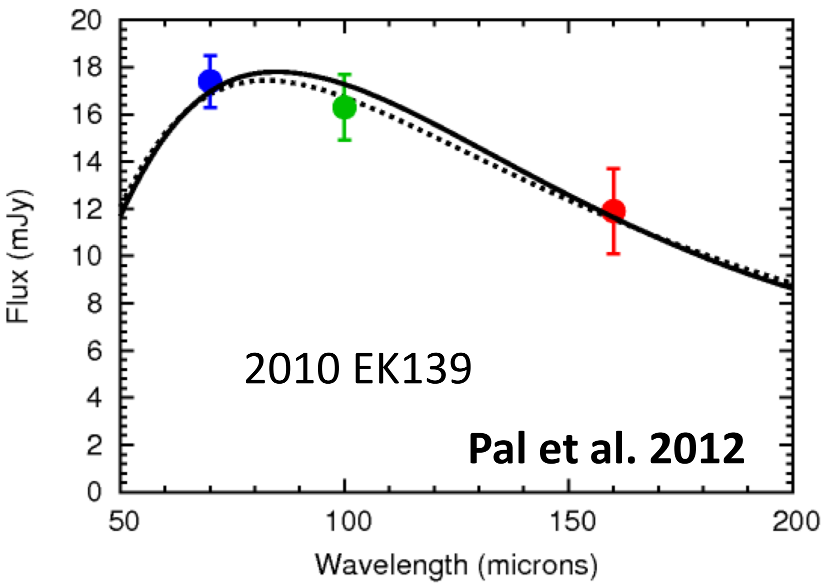


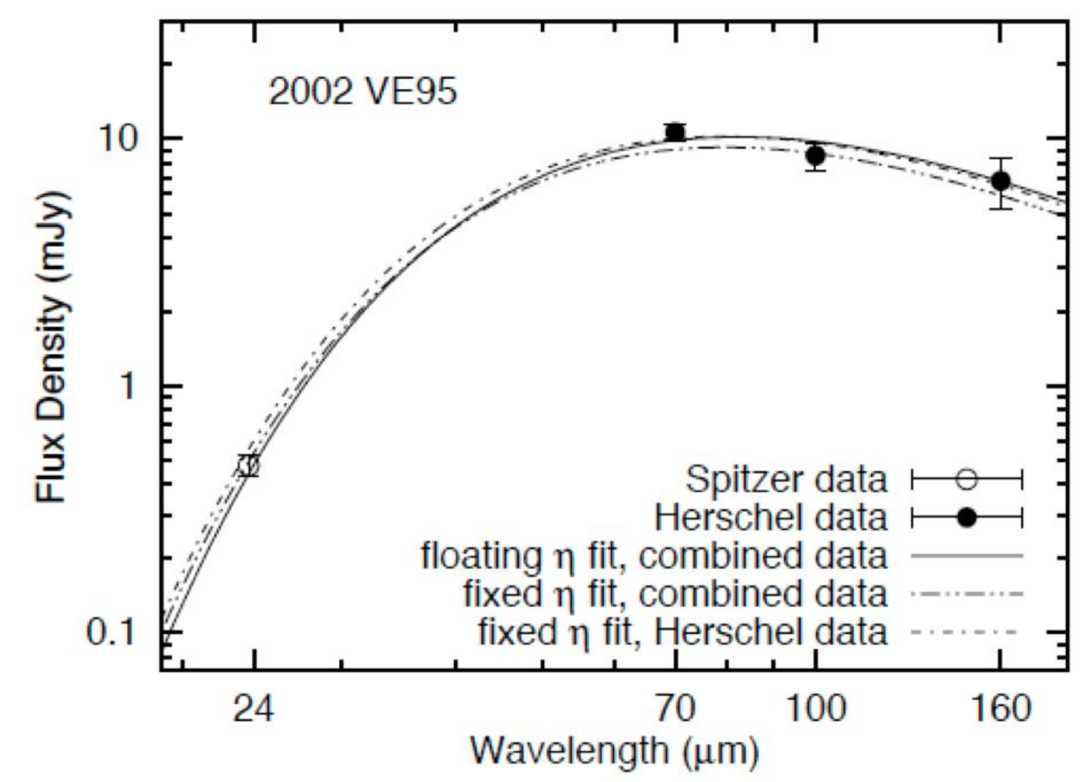
Eris at 160 μm

Fundamental Properties: Size & Albedos

130 TNO/Centaurs
>90% detections with Herschel, partially detected by Spitzer



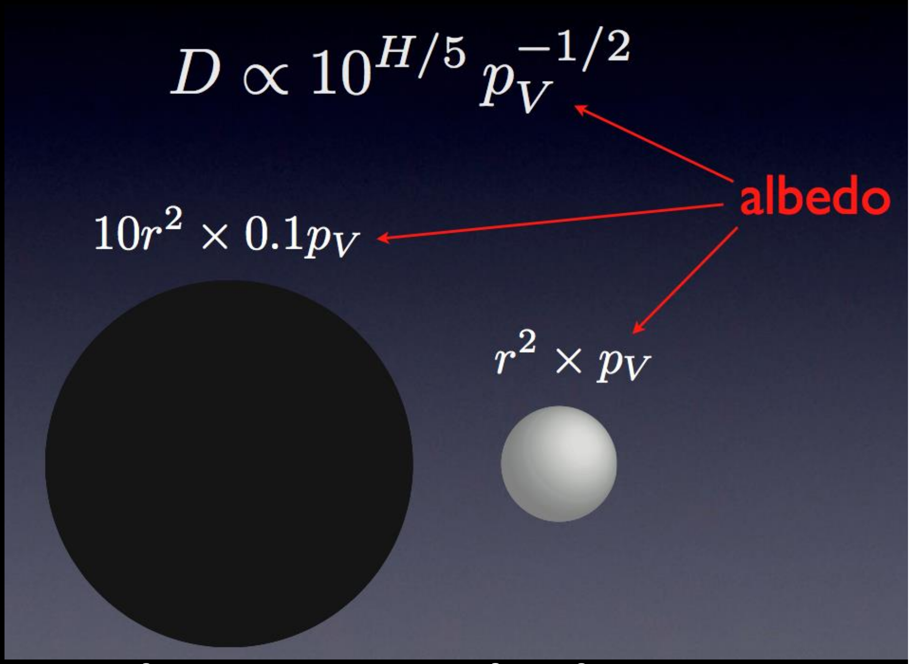


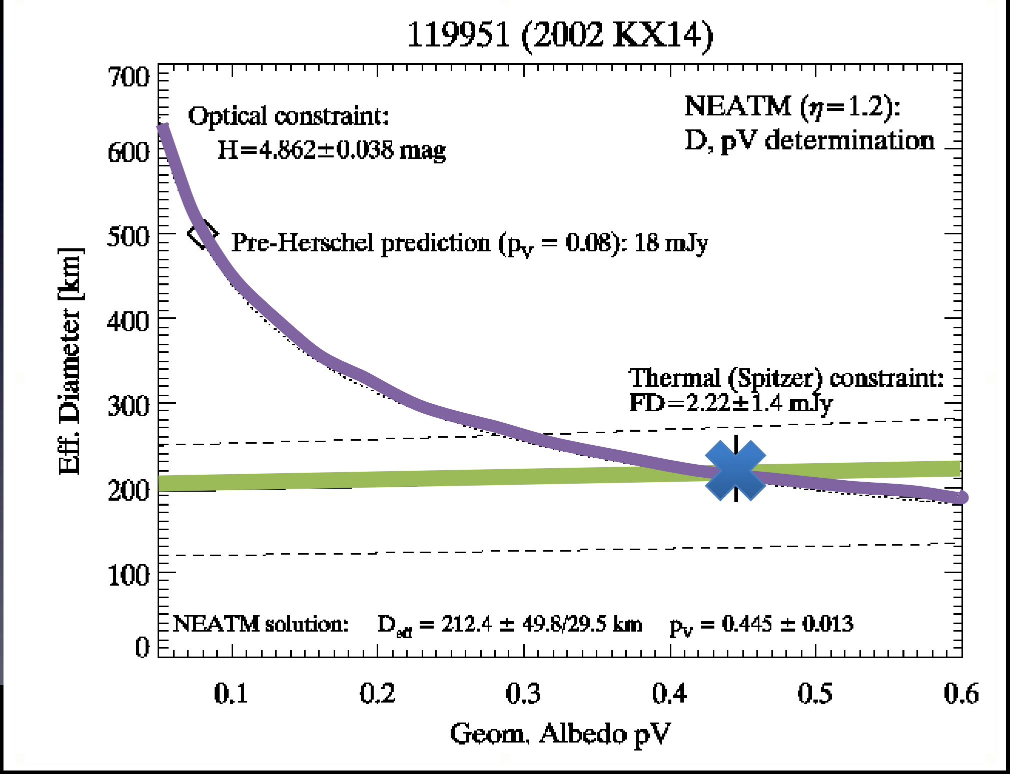


Different thermal models

Fundamental Properties: Size & Albedos

- groundbased support to characterize the reflected light
- careful determination of error bars
- well-established (and calibrated) model setups

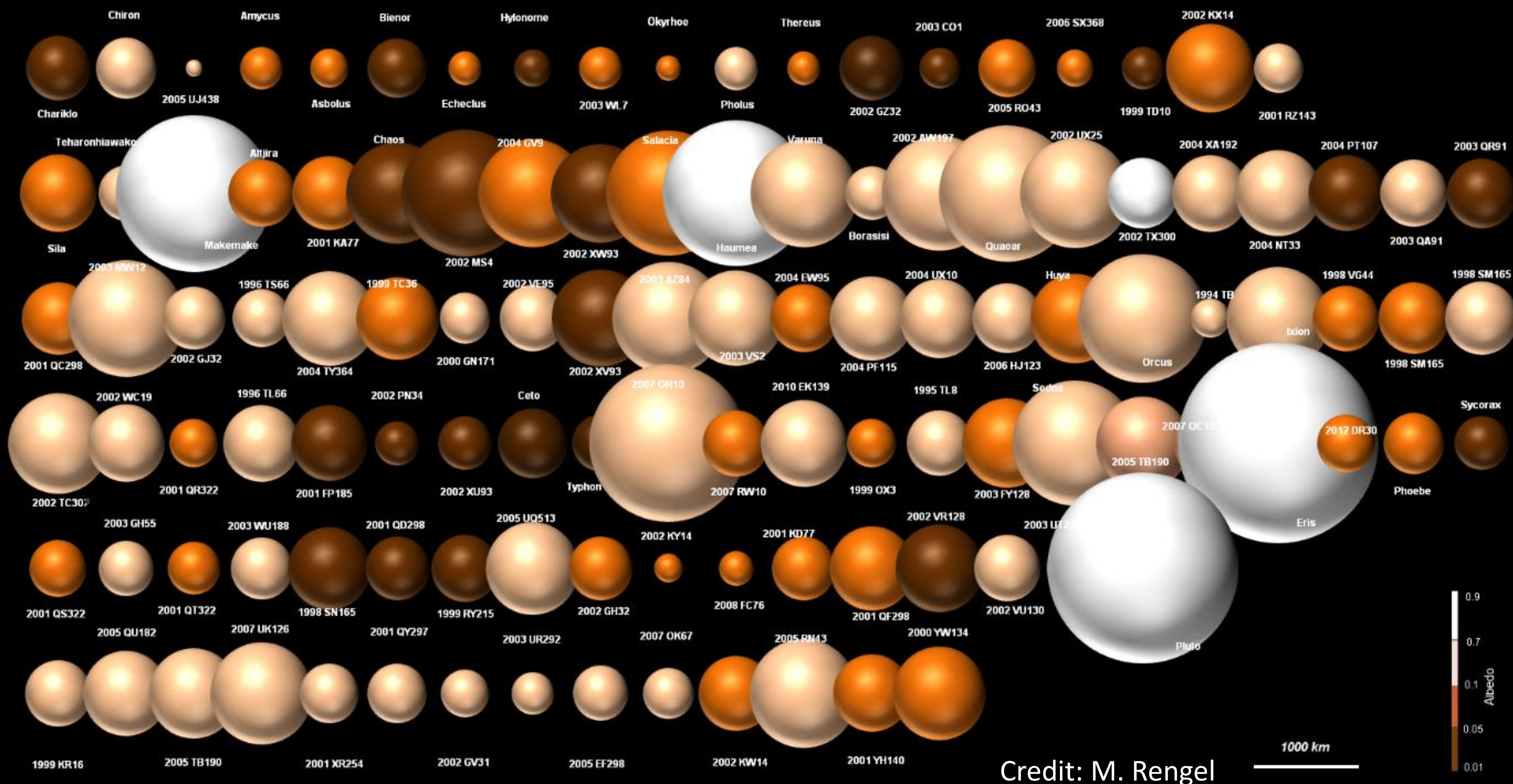




Radiometric method:

- solving for size & albedo
- reflected light: absolute magnitude H
- thermal emission: as measured by (Spitzer)/Herschel

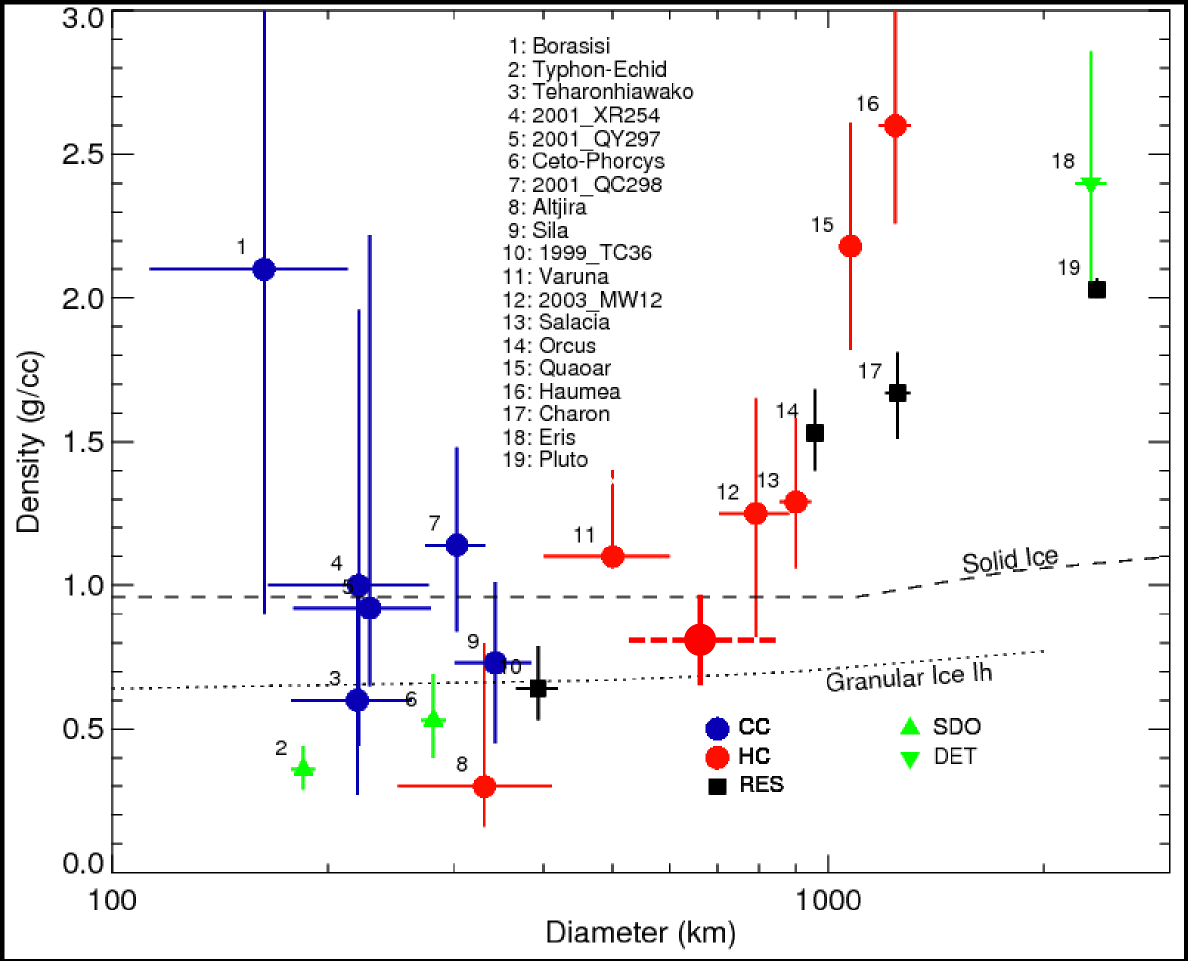
TNO Fundamental Properties: Size & Albedos



Credit: M. Rengel

Müller et al. 2010, Lellouch et al. 2010, Lim et al. 2010, Mommert et al. 2012, Vilenius et al. 2012, Santos-Sanz et al. 2012, Fornasier et al. 2013, Duffard et al. 2013, Kiss et al. 2013, Vilenius et al. 2013

TNO Densities: derived from binary systems



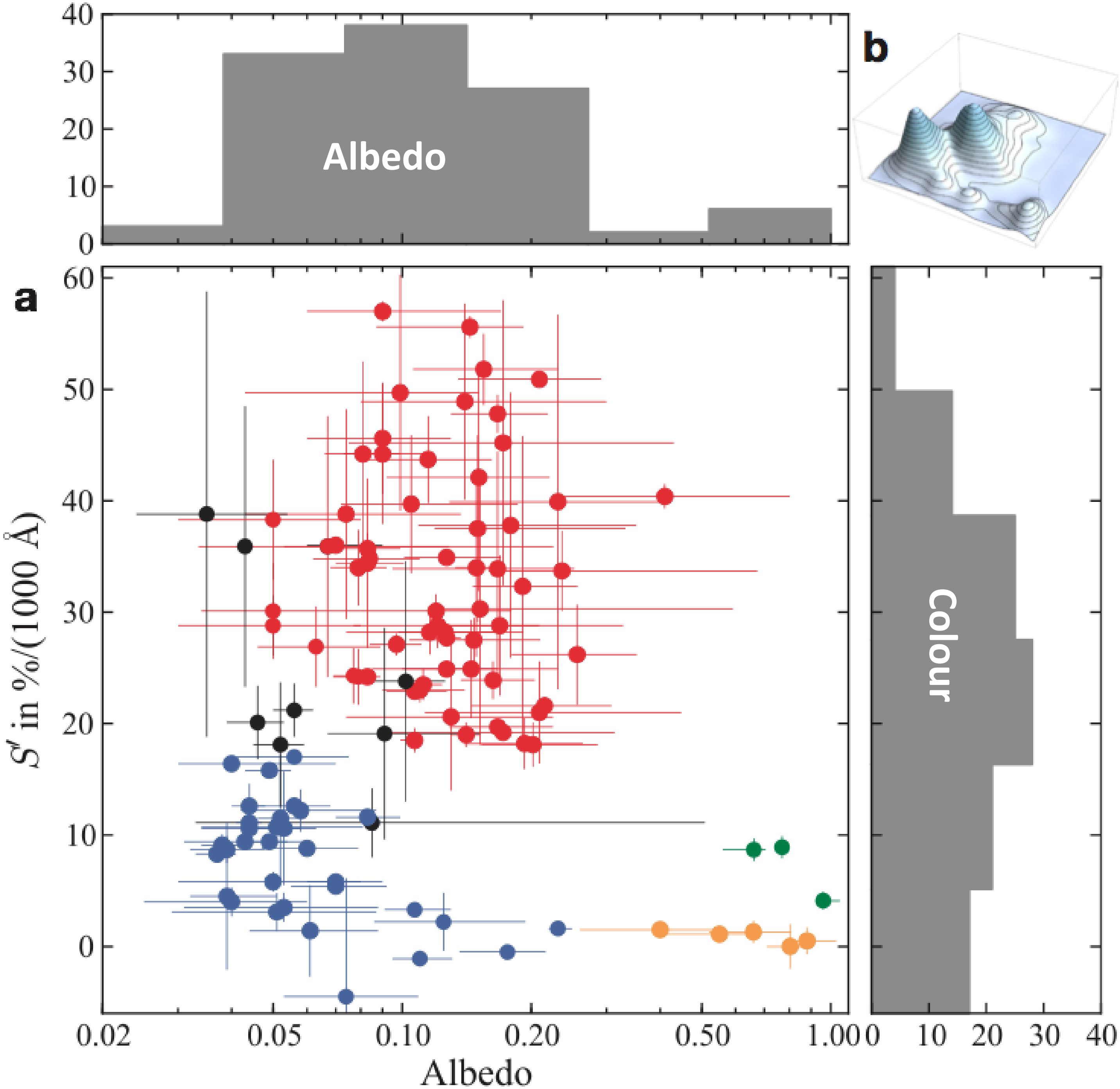
objects > ≈500 km all have densities above ≈1 g/cm^3
→ requires inclusion of rocks

Pluto 2 g/cm^3
→ 50-70% rock, 30-50% ice
Eris 2.5 g/cm^3,
Haumea ≈ 2.6-3.3 g/cm$_3$

most of the objects <≈350 km have densities <≈1 g/cm^3
(methane ice 0.5 g/cm^3
pure H_2O < ≈1 g/cm^3)
→ macro-porosity?
→ very high ice/rock ratios?
→ fluffy ice?

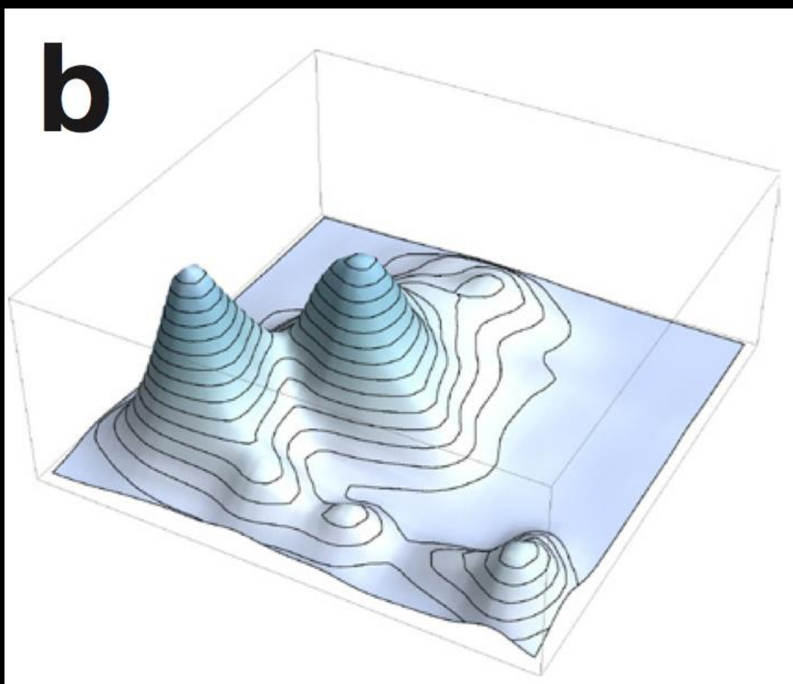
Different formation scenarios for large and small TNOs?:
→ dwarf planets: direct collapse from over dense regions of the disk?
→ smaller TNOs: standard pairwise accretion?

Brown 2013, Vilenius et al. 2013

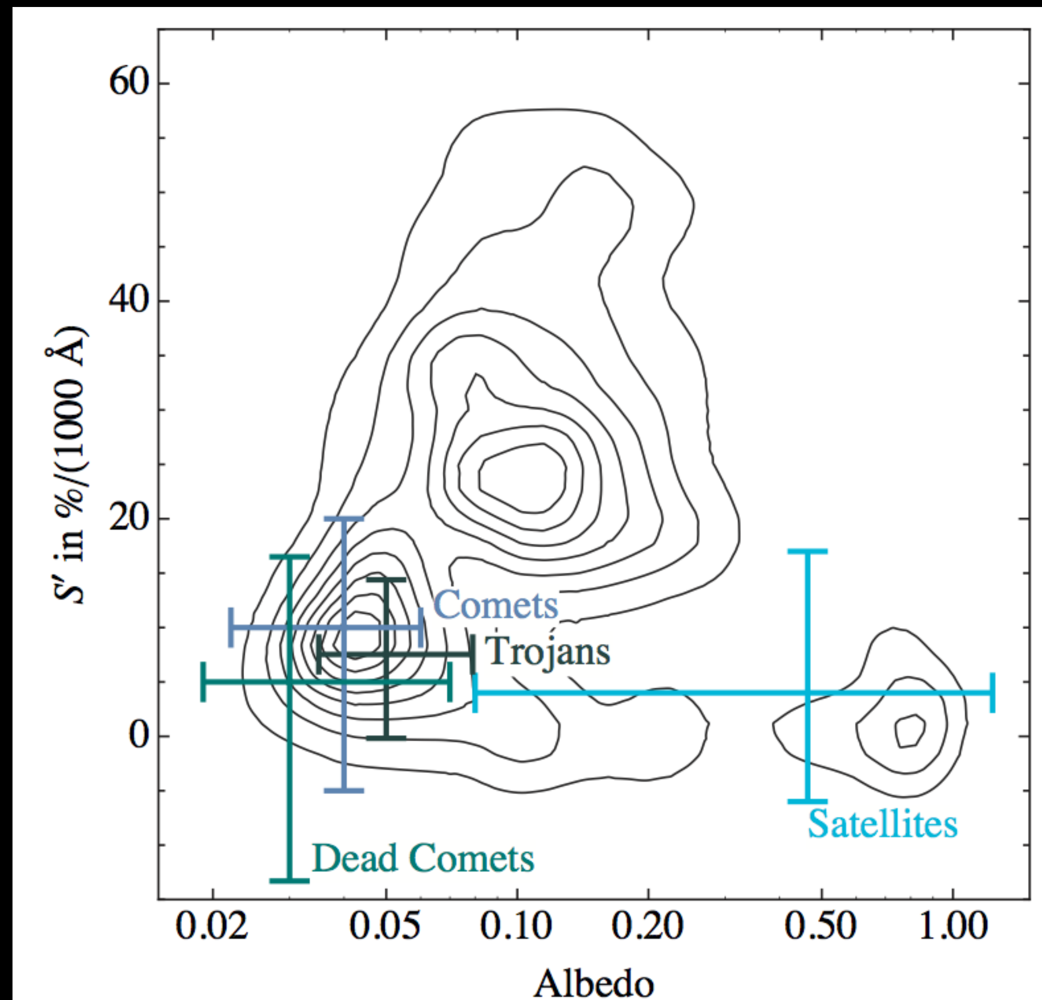


Lacerda et al. 2014

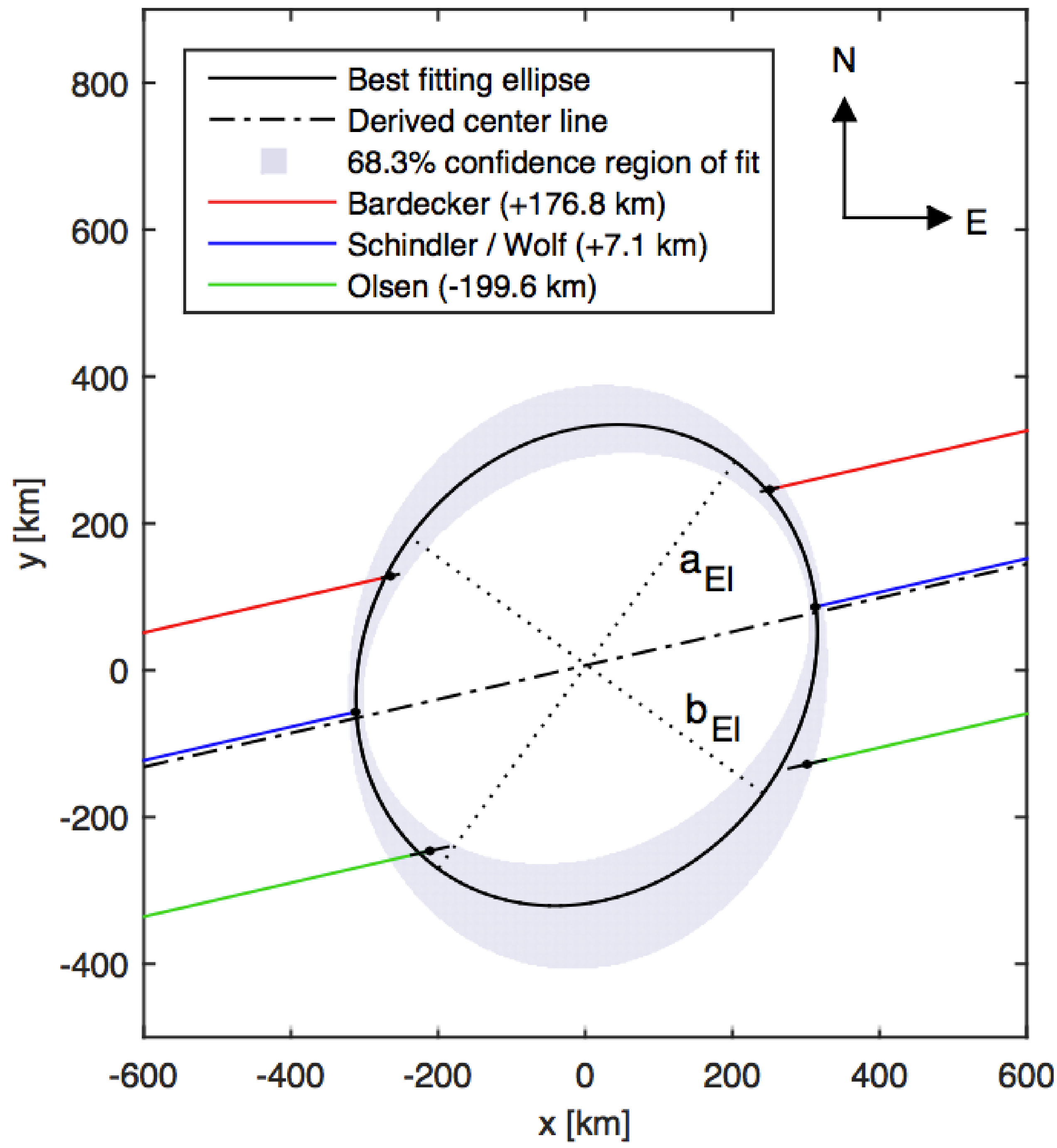
Colour-albedo information reveals the location of formation: red, high-albedo objects (cold classicals, detached, resonant) formed at larger distances; dark, neutral-colour objects (Centaurs, hot classicals) formed further in. This color-albedo separation is evidence for a compositional discontinuity in the young solar system.

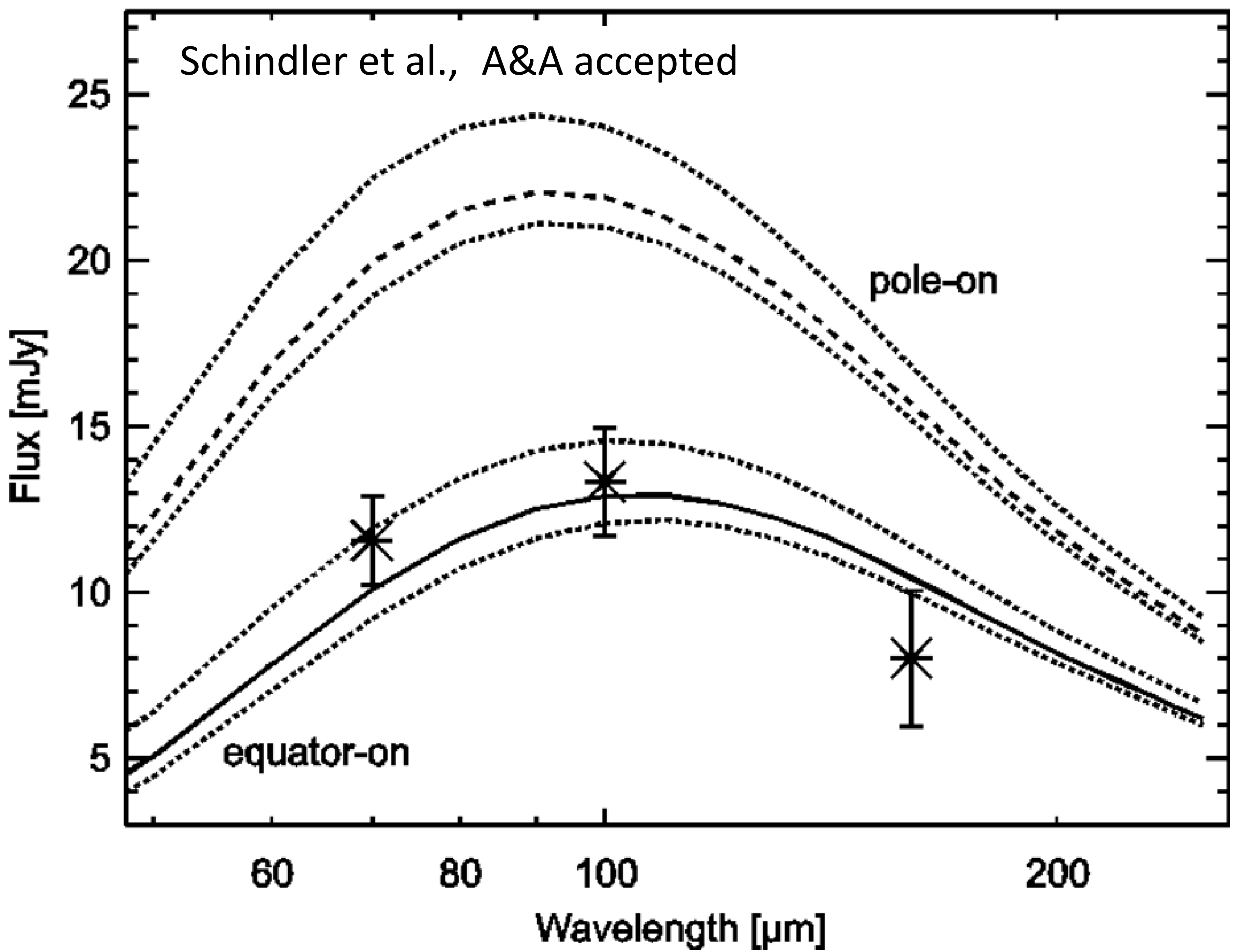


Lacerda et al. 2014

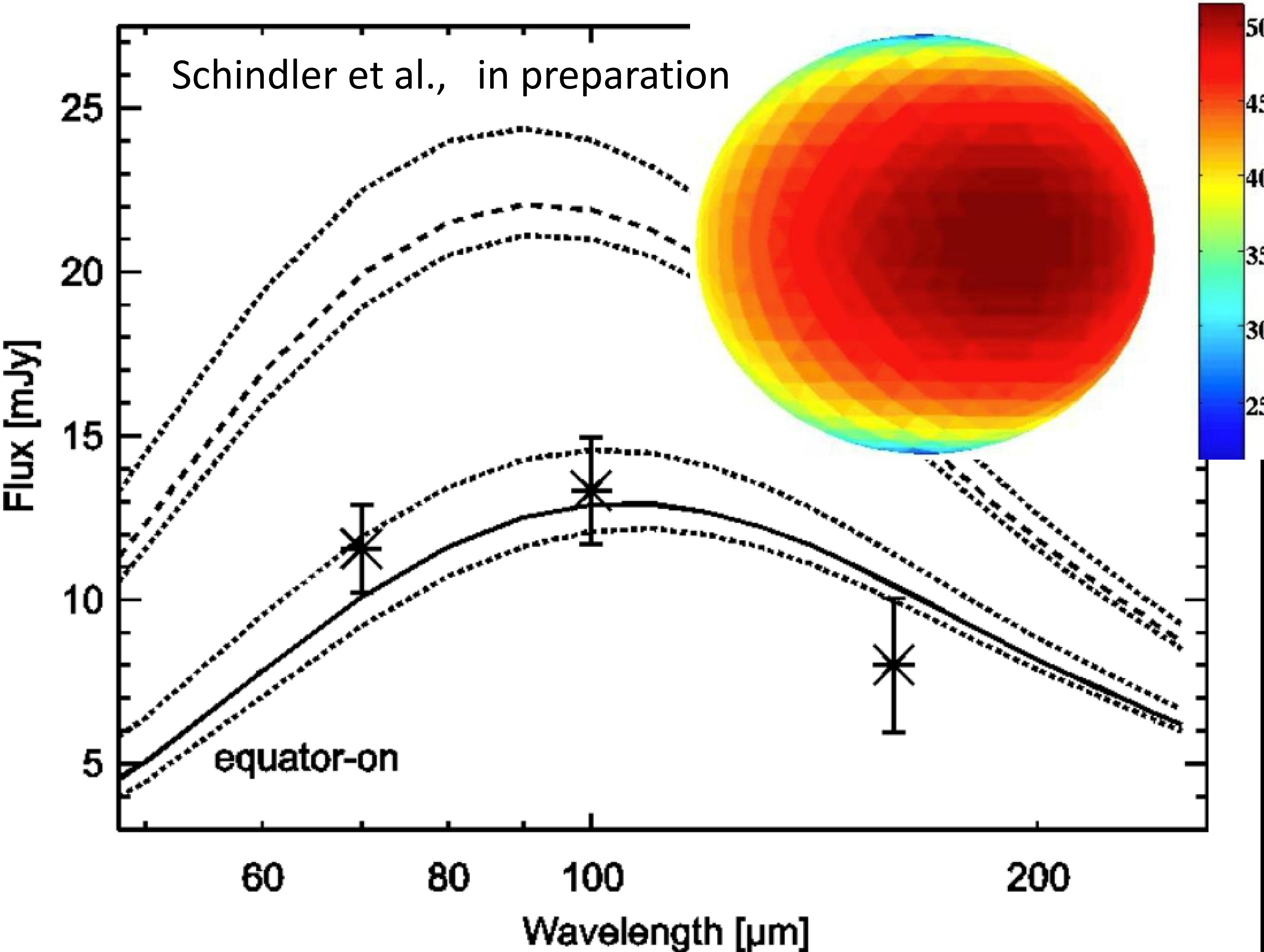


- occultation of TNO 2007 UK126 in Nov 2014
- lightcurve ampl. 0.03 mag
- Herschel 3-band photometric obs.
- Schindler et al., A&A accepted





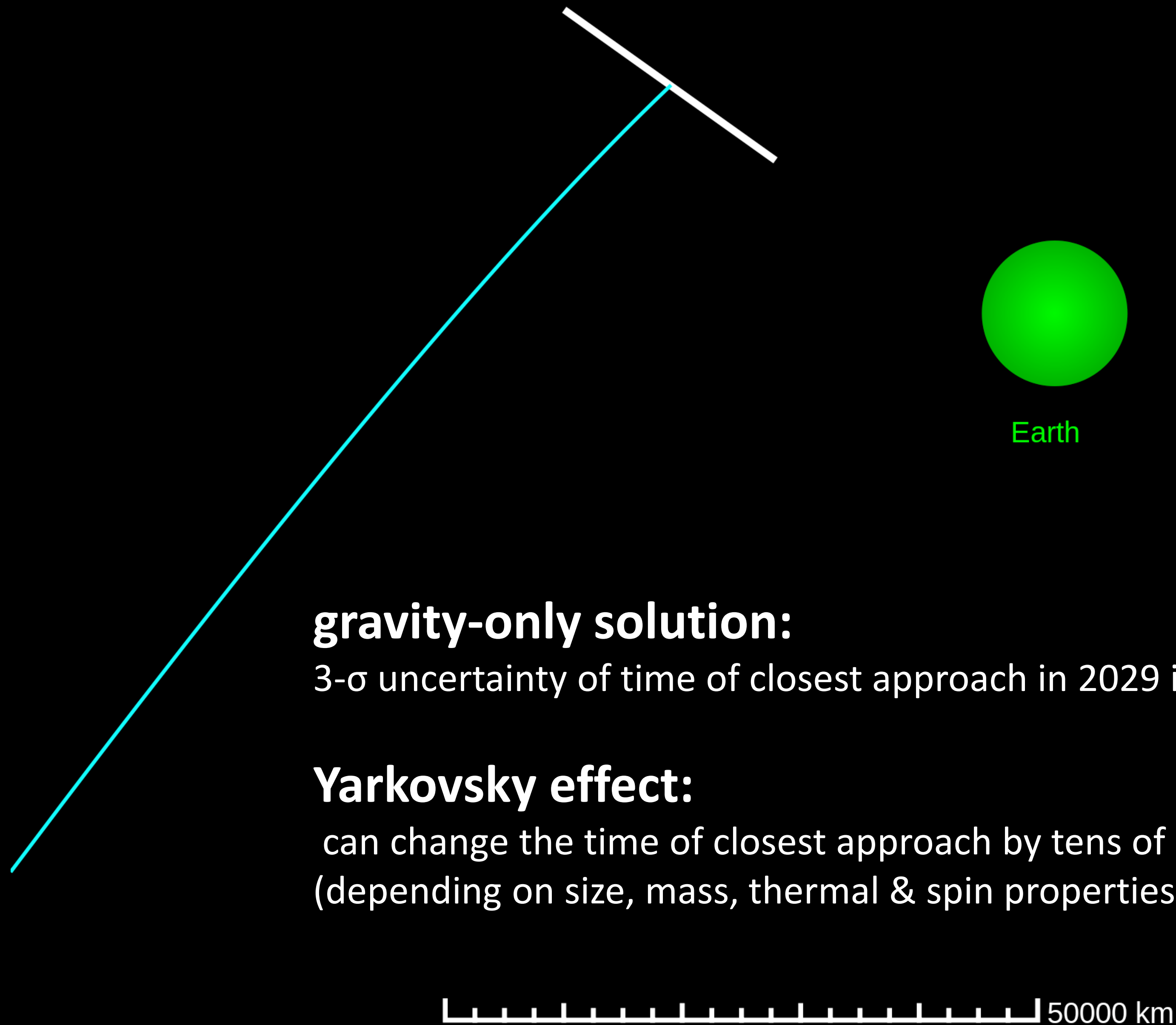
Schindler et al., A&A accepted
pole-on
equator-on
Flux [mJy]
Wavelength [µm]
25
20
15
10
5
60
80
100
200


Schindler et al., in preparation
Flux [mJy]
25
20
15
10
5
equator-on
60
80
100
200
Wavelength [µm]
50
45
40
35
30
25

Near-Earth asteroids

- Size & albedo
- thermal properties
- Yarkovsky (& YORP)
- long-term orbit calculations & impact risks
- interplanetary mission support
- ground truth from in-situ measurements

Near-Earth asteroid 99942 Apophis:
Friday Apr. 13, 2029



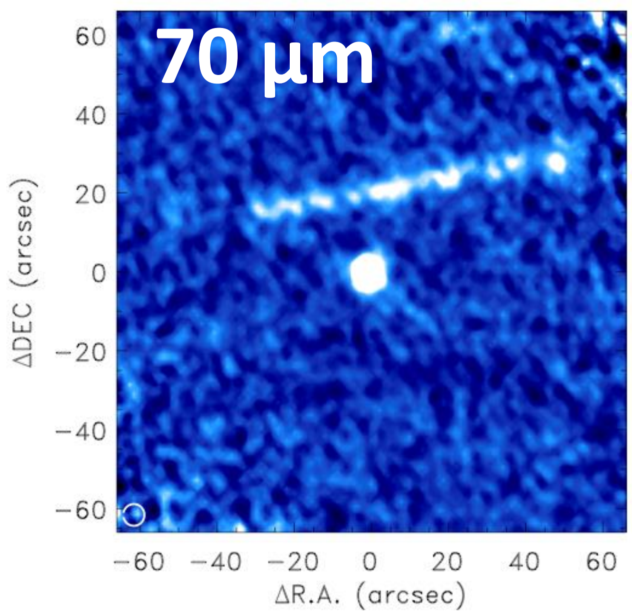
gravity-only solution:

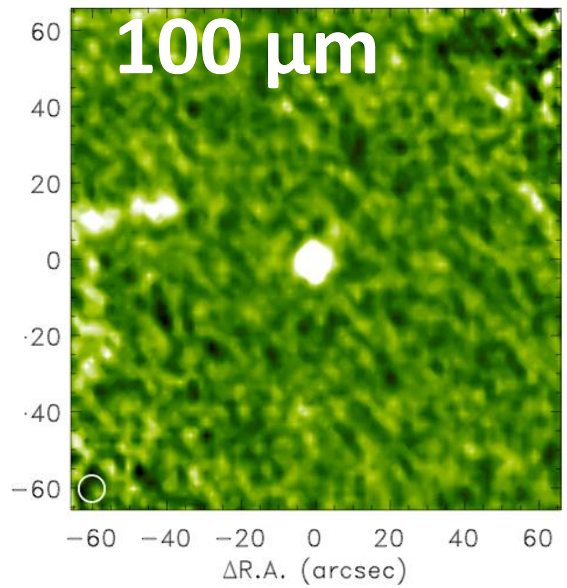
3-σ uncertainty of time of closest approach in 2029 is about 1 sec

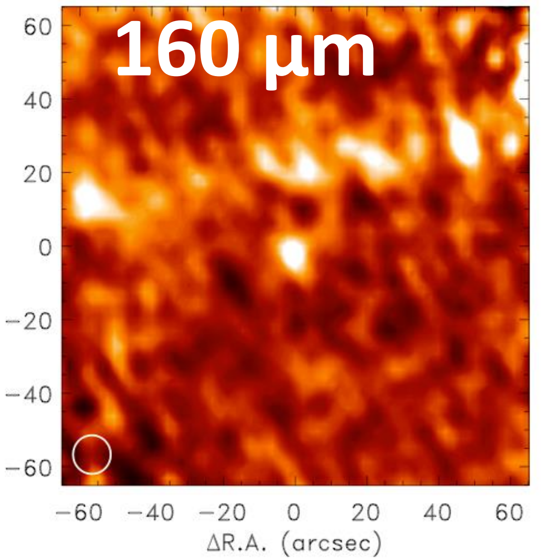
Yarkovsky effect:

can change the time of closest approach by tens of seconds!
(depending on size, mass, thermal & spin properties)

Observations:

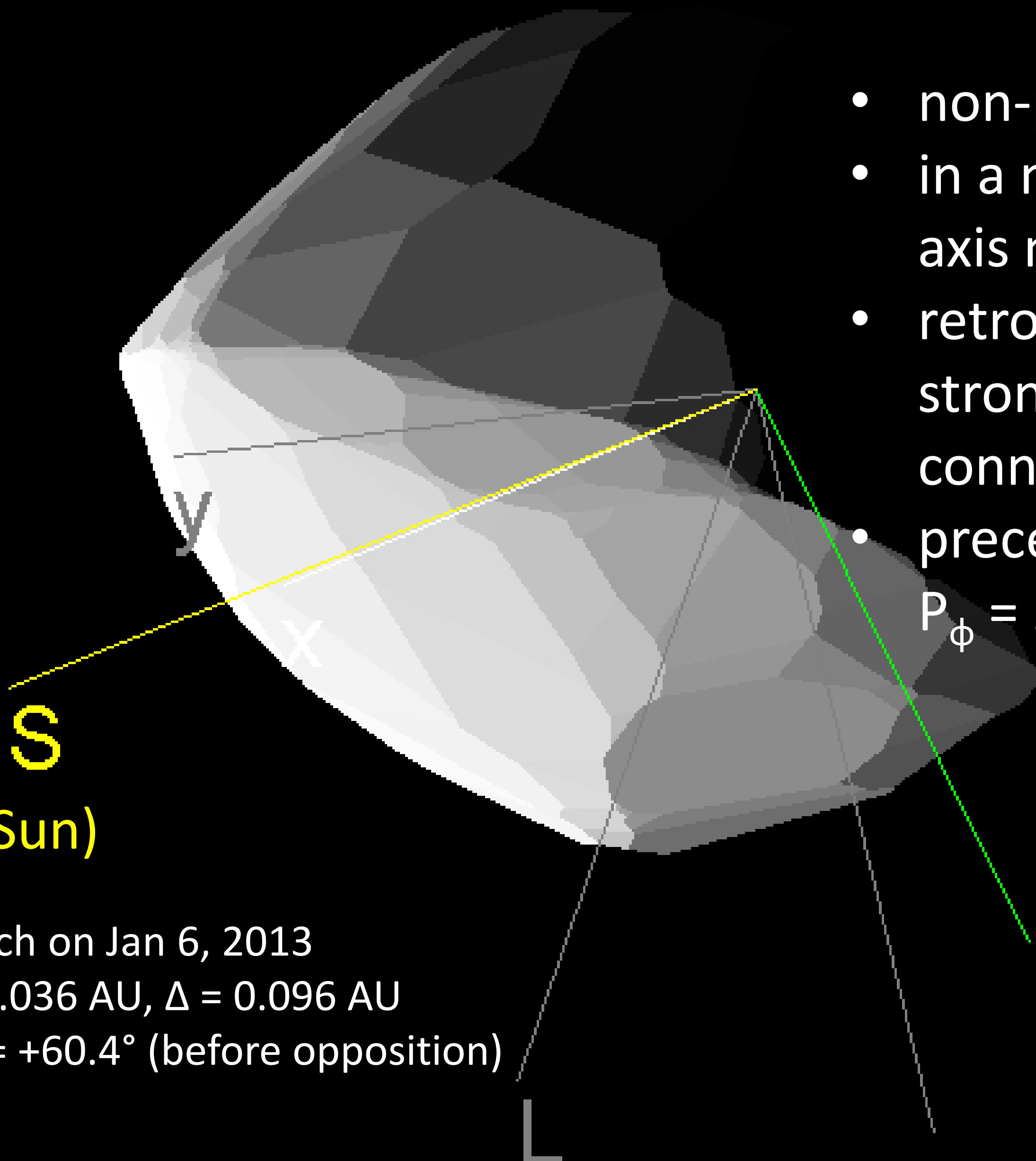






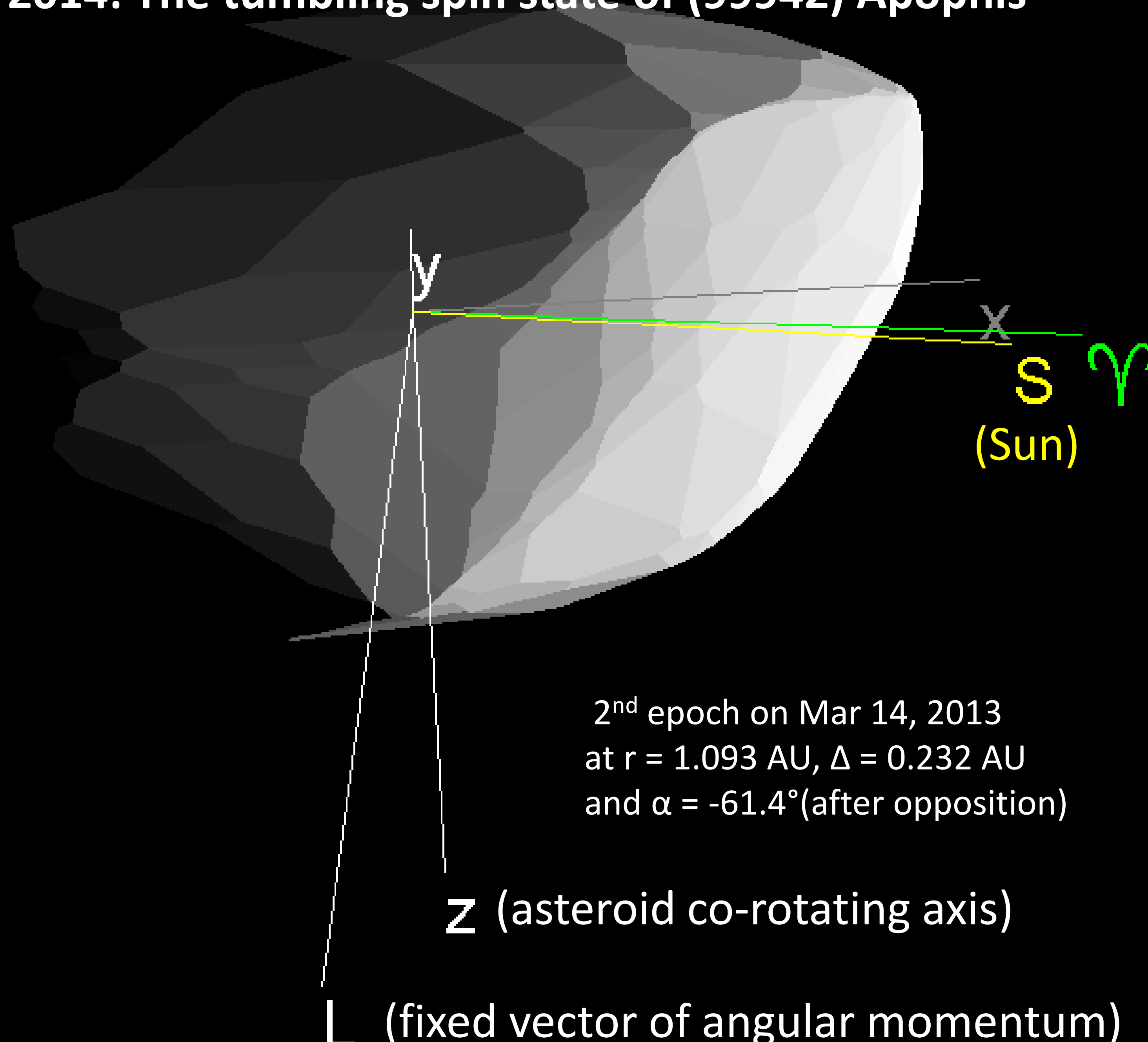
Pravec et al. 2014: The tumbling spin state of (99942) Apophis

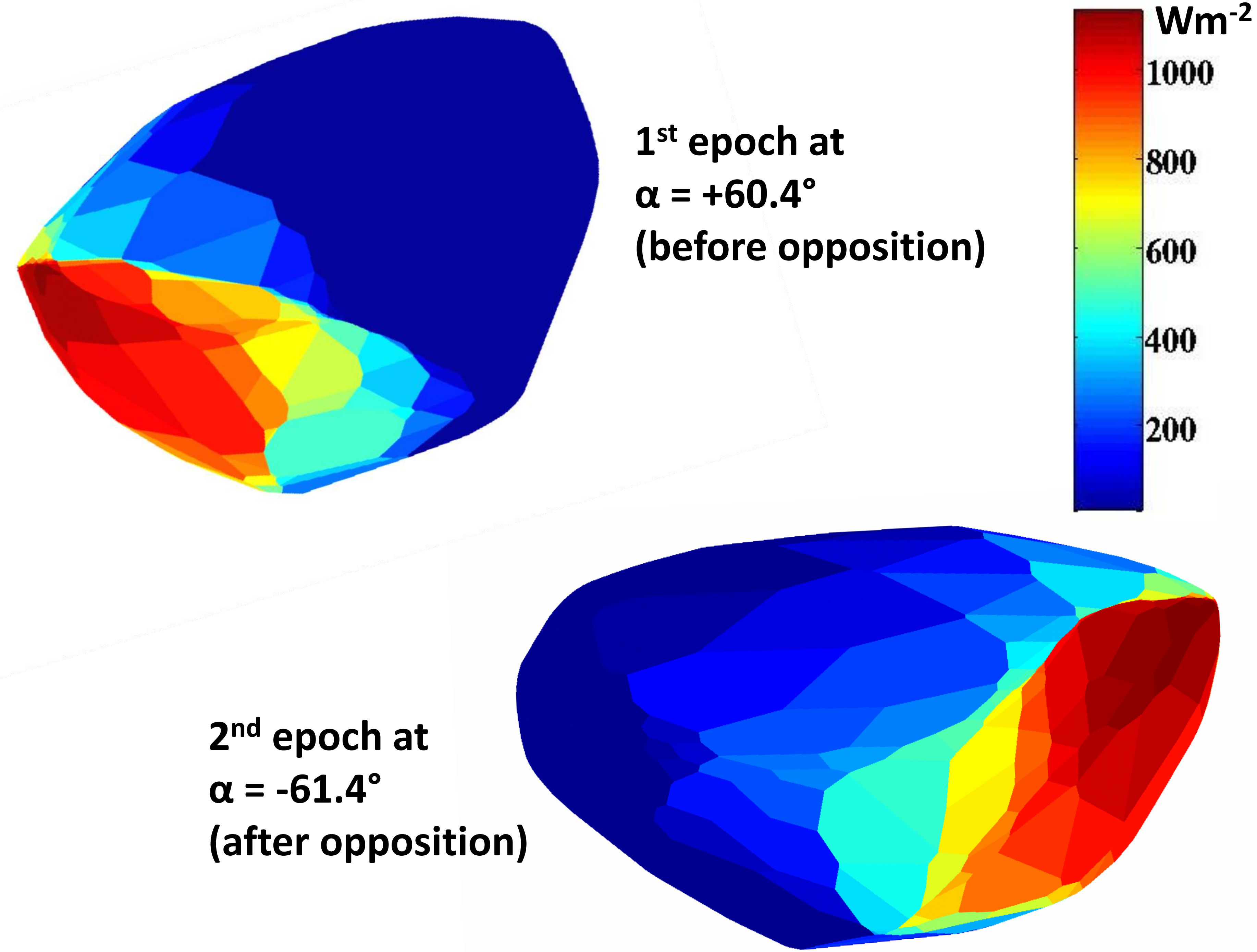
- non-principle axis rotation
- in a moderately excited sho
  axis mode
- retrograde rotation with strongest observed lightcurve connected to P1 = 30.56 h
- precession and rotation periods P_ϕ = 27.38 h & P_ψ = 263 ± 6 h

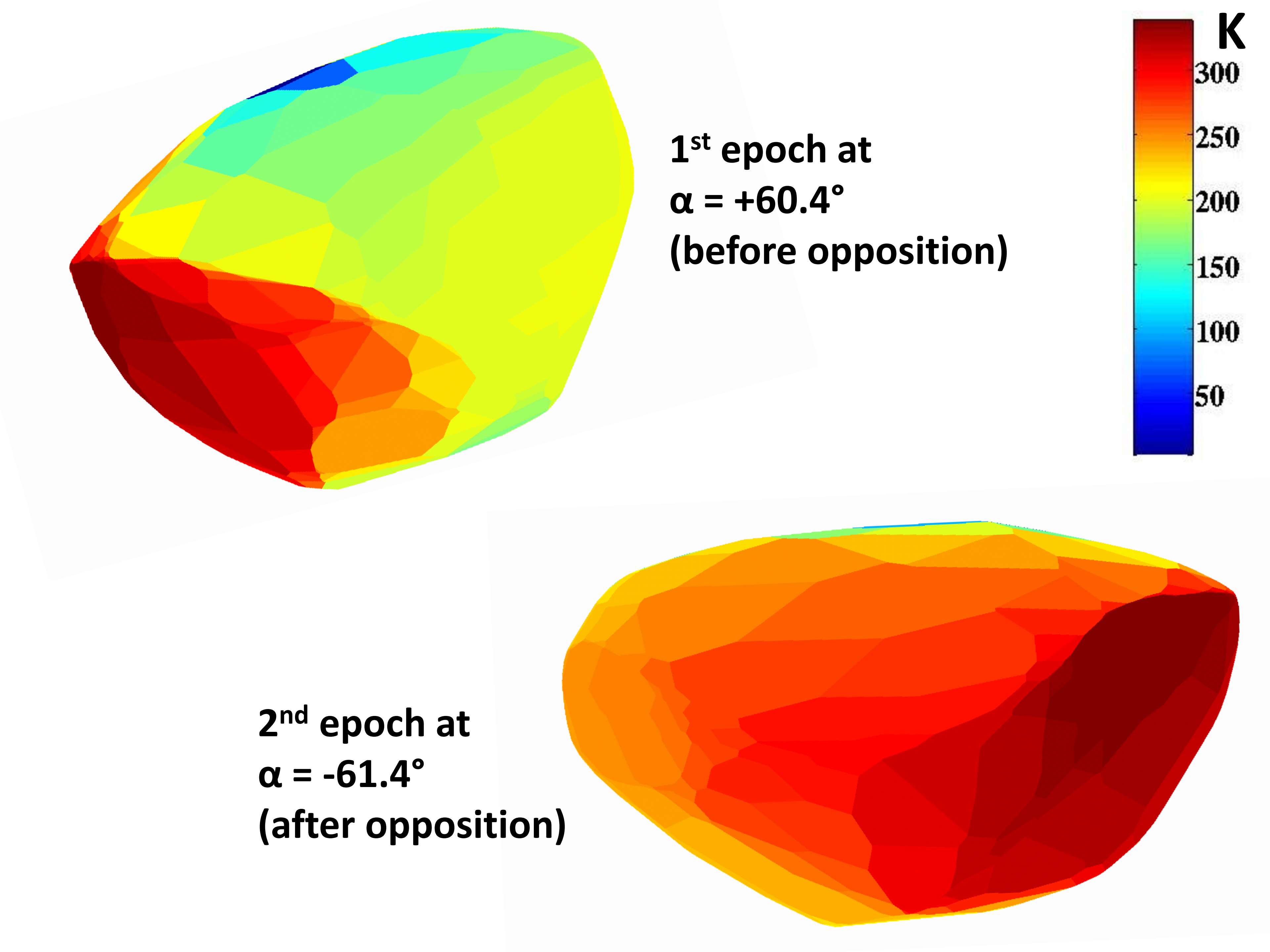


1st epoch on Jan 6, 2013
at r = 1.036 AU, Δ = 0.096 AU
and α = +60.4° (before opposition)

Pravec et al. 2014: The tumbling spin state of (99942) Apophis




Wm-2
1000
800
600
400
200
1st epoch at
α = +60.4°
(before opposition)
2nd epoch at
α = -61.4°
(after opposition)

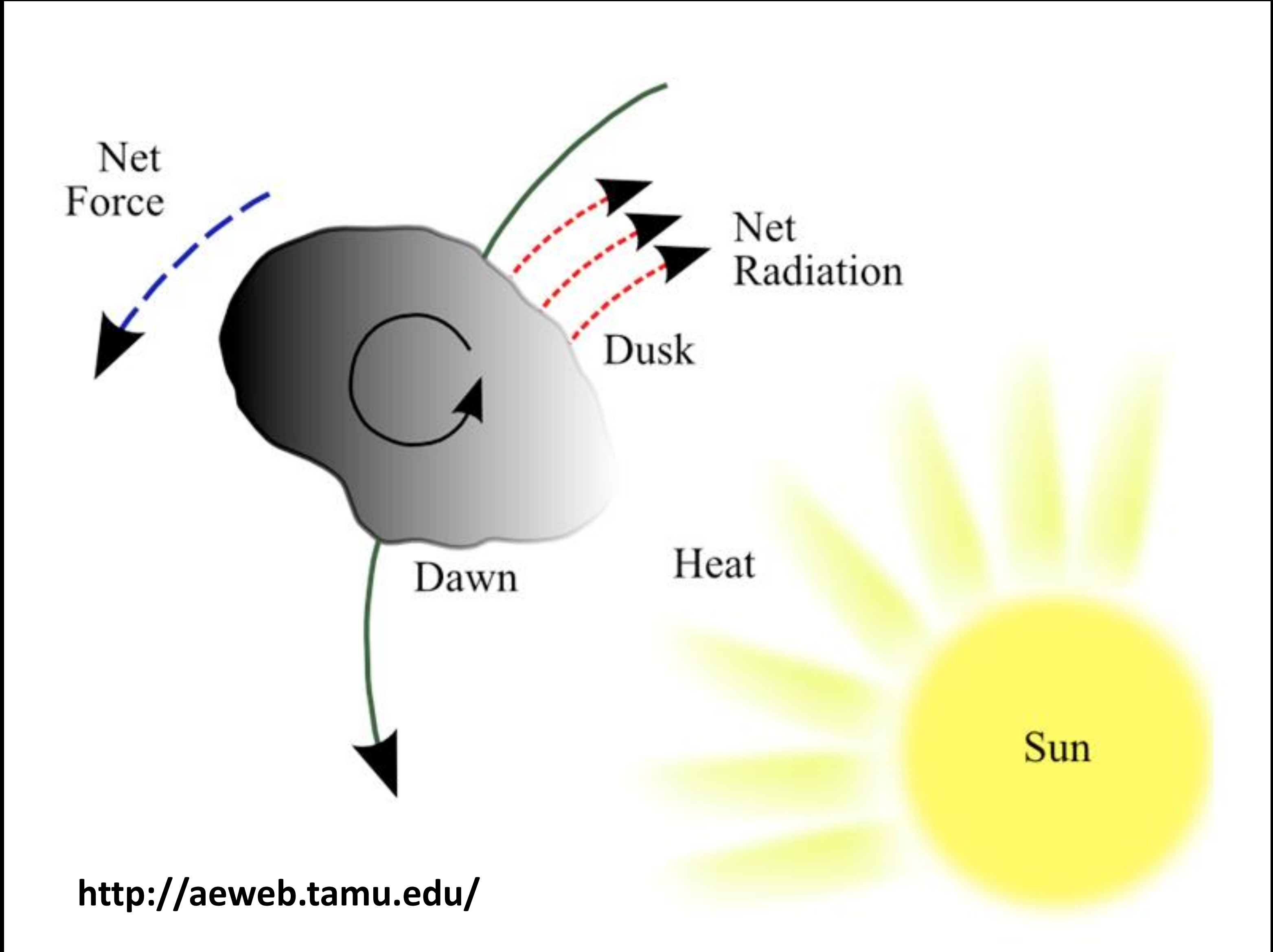


K
300
250
200
150
100
50
1st epoch at
α = +60.4°
(before opposition)
2nd epoch at
α = -61.4°
(after opposition)

Apophis Summary (Müller et al. 2014, A&A)

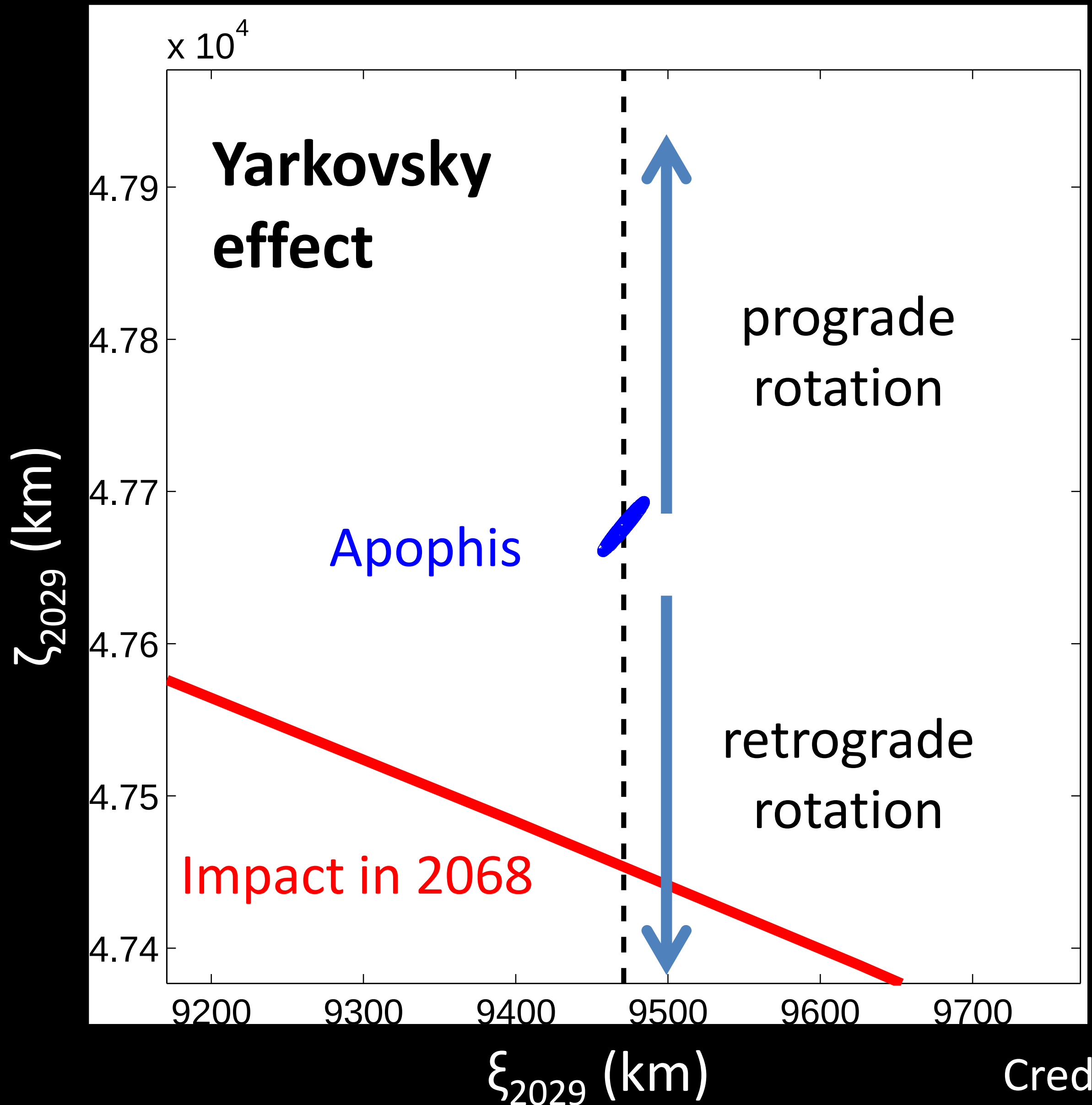
- radiometric (volume-equivalent) effective diameter of 375^{+14}_{-10} m
- geometric V-band albedo $p_V = 0.30^{+0.05}_{-0.06}$ Bond albedo $A = 0.14^{+0.03}_{-0.04}$
- thermal inertia $\Gamma = 600^{+200}_{-350}$ $Jm^{-2}s^{-0.5}K^{-1}$
- mass $(5.3 \pm 0.9) \times 10^{10}$ kg (2-3 times higher than previous estimates)
- cohesionless structure is very likely (rubble pile)
- properties influence the calculations of the Yarkovsky effect and the impact probabilities

The Yarkovsky effect is dominating the final accuracy of orbit predictions of small bodies



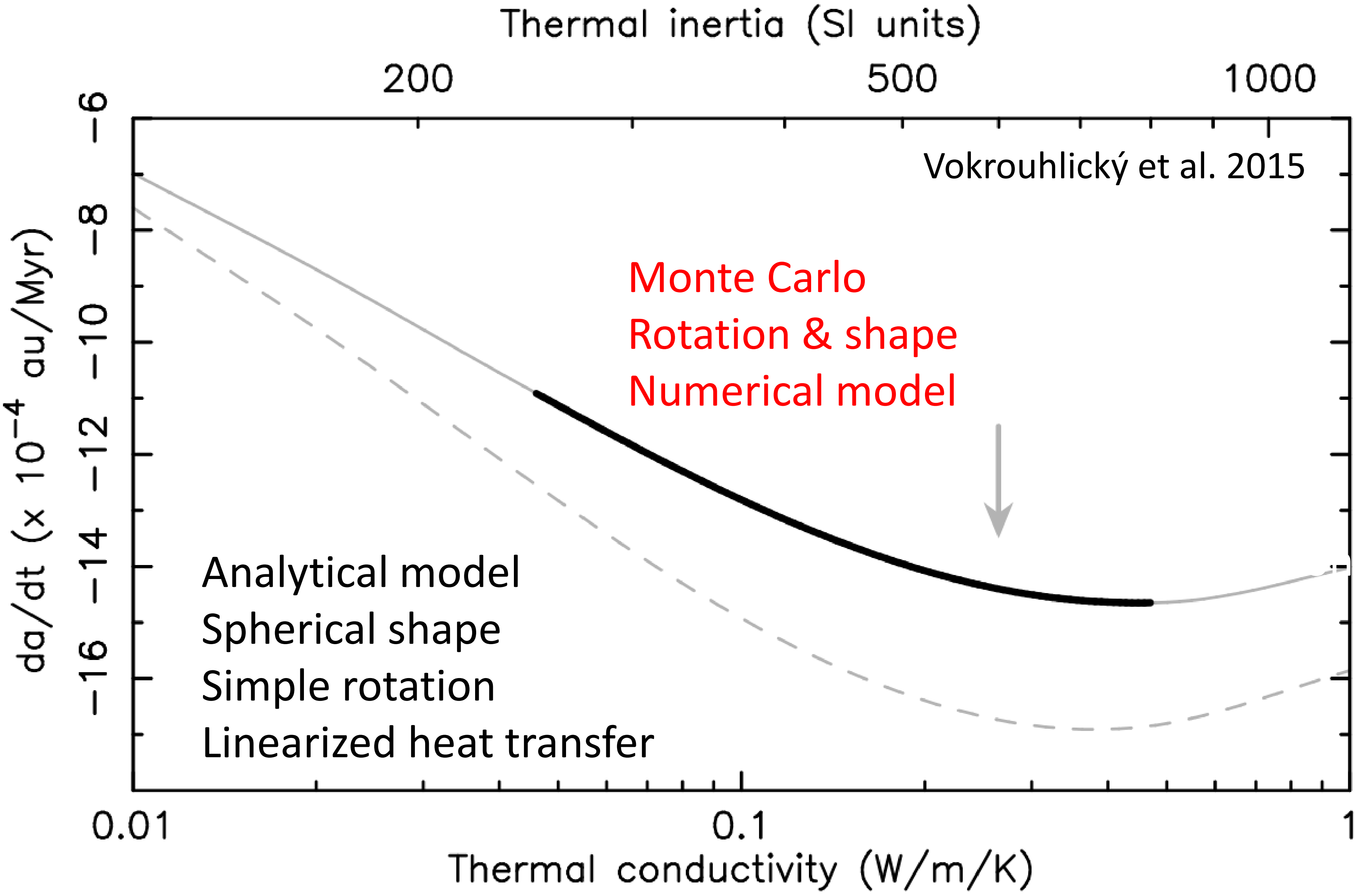
http://aeweb.tamu.edu/

Impact in 2068?

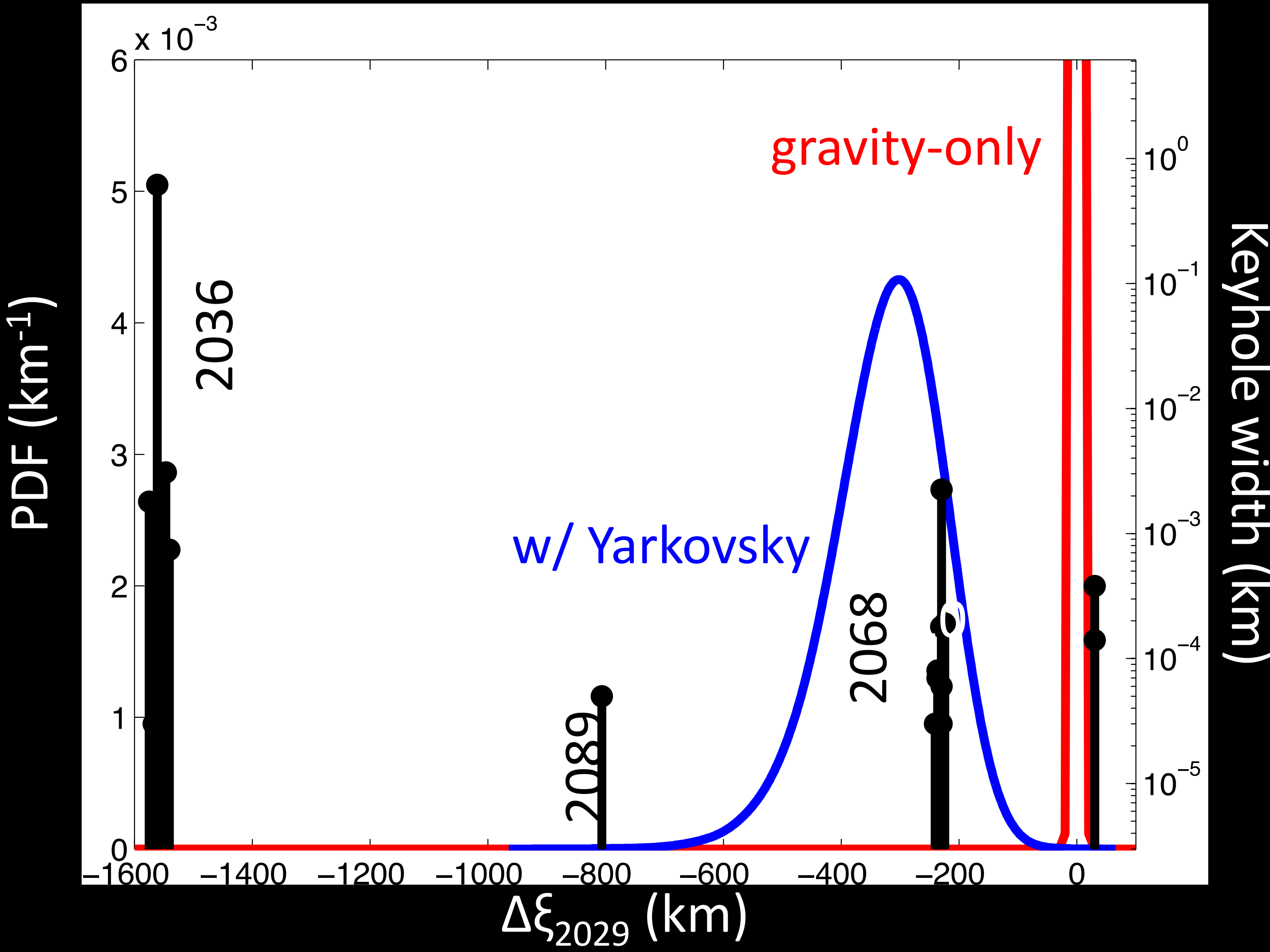


Credit: D. Farnocchia

secular drift of semimajor axis (TI)



Hazard assessment



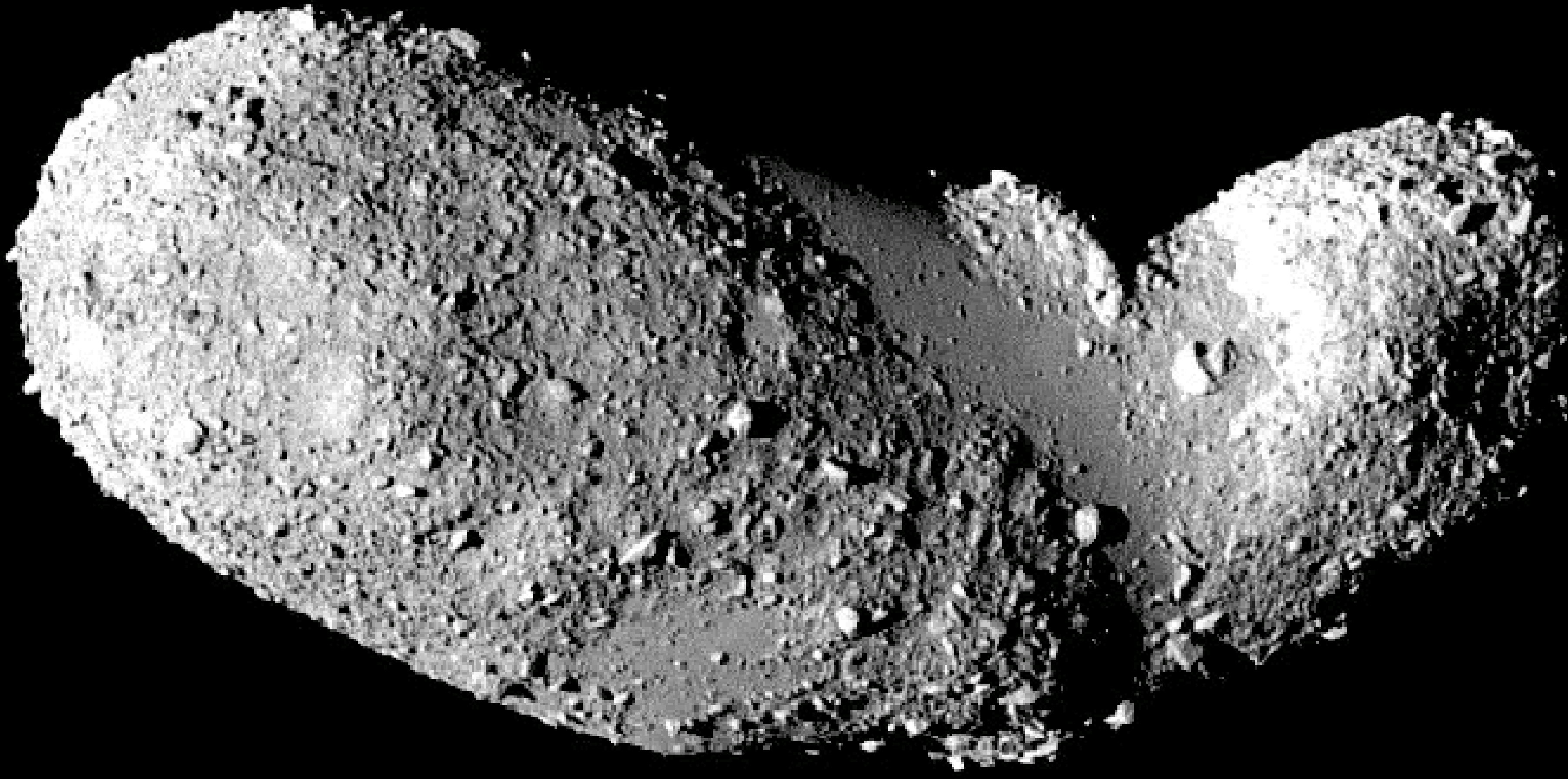
Year	IP × 10^6
2060	0.1
2065	0.3
2068	6.7
2076	0.5
2077	0.2
2078	0.2
2091	0.2
2103	0.5

Credit: D. Farnocchia

Collision with Earth before 2060 is ruled out, impacts are still possible after 2060 with probabilities up to a few parts in a million!

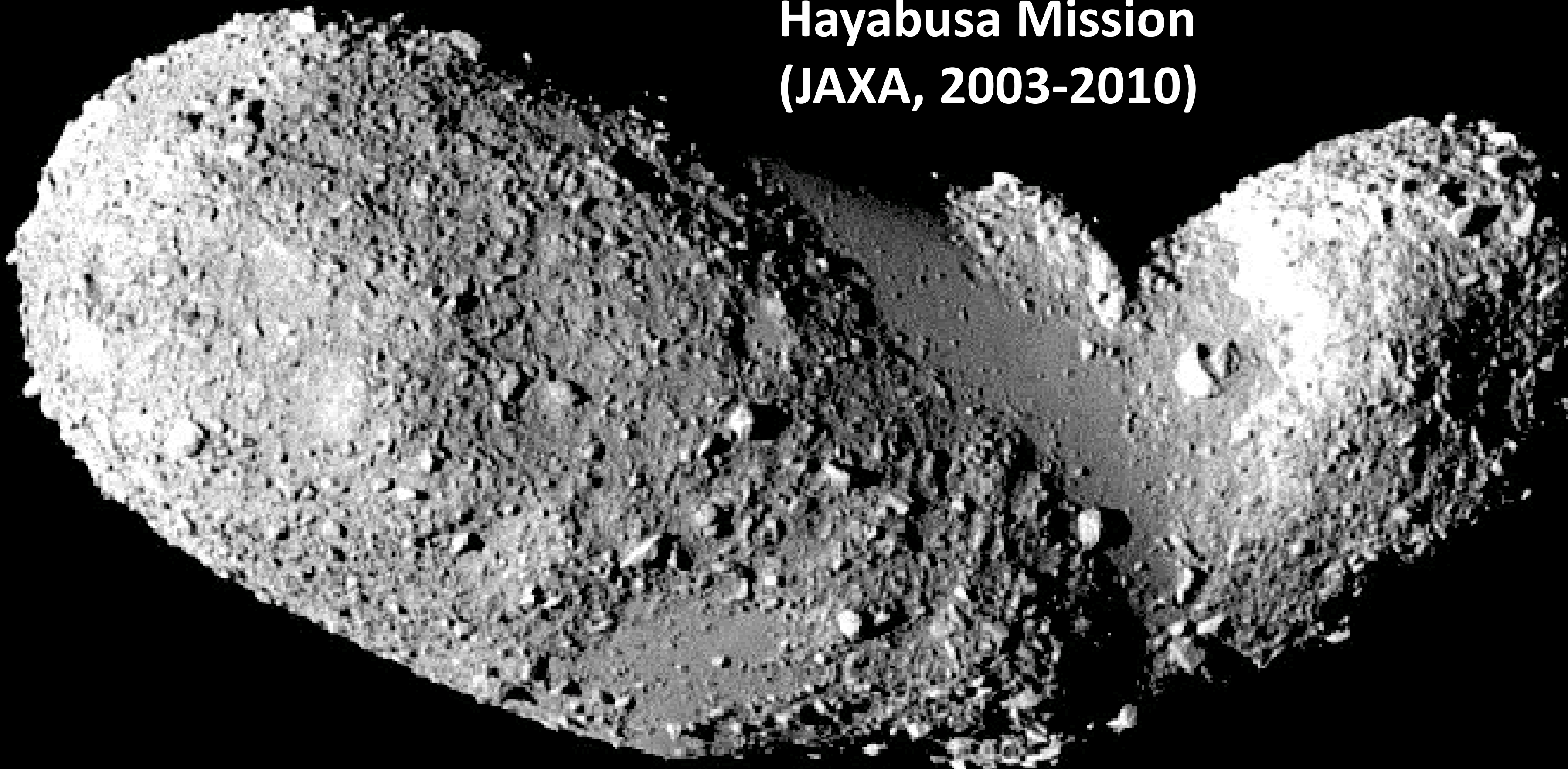
(Vokrouhlický et al. 2015)

Near-Earth asteroid 25143 Itokawa: rubble-pile structure, $\rho = 1.9\ gcm^{-3}$



Hayabusa Mission
(JAXA, 2003-2010)

Hayabusa Mission
(JAXA, 2003-2010)



Radar eff. size (Ostro et al. 2001, 2004, 2005): 364 m (±10%)

Radiometric eff. size (Müller et al. 2005): 320 ± 30 m

In-situ eff. size (Demura et al. 2006): 327.5 ± 5.5 m

(25143) Itokawa: The power of radiometric techniques for the interpretation of remote thermal observations in the light of the Hayabusa rendezvous results: Müller, Hasegawa, Usui, PASJ 66 (2014)

Small Bodies Near And Far

Small Bodies Near And Far

EU Project 2016-2019
1.6 M€, PI: T. Müller
Team:
- **AMU, Poznan, PL**
- **Konkoly, Budapest, HU**
- **IAA, Granada, ES**
- **MPE, Garching, DE**
- **supported by AKARI and Hayabusa-2 teams**

A benchmark study for selected NEAs, MBAs, Trojans/Centaurs/TNOs

Summary
Small body thermophysical modeling

- asteroid thermal measurements started in the early 70th
  - big IR surveys: IRAS, AKARI, (NEO)WISE
  - IR space observatories: ISO, AKARI, Spitzer, Herschel
  - ground-based data (N-/Q-band, submm/mm/cm)
- information about size, shape, spin properties, albedo, thermal inertia, surface roughness, grain sizes
- thermal model techniques can be tested against ground-truth from spacecraft visits, direct measurements (HST, occultations, adaptive optics), or against radar signals
- thermal properties influence the non-gravitational effects: Yarkovsky orbit drifts, YORP spin changes
- radiative heating produces space weathering effects (thermal cracking, thermal metamorphism, subsurface ice sublimation)