Max-Planck-Institut für extraterrestrische Physik

The Asteroid Preparatory Programme for Herschel, Akari and ALMA

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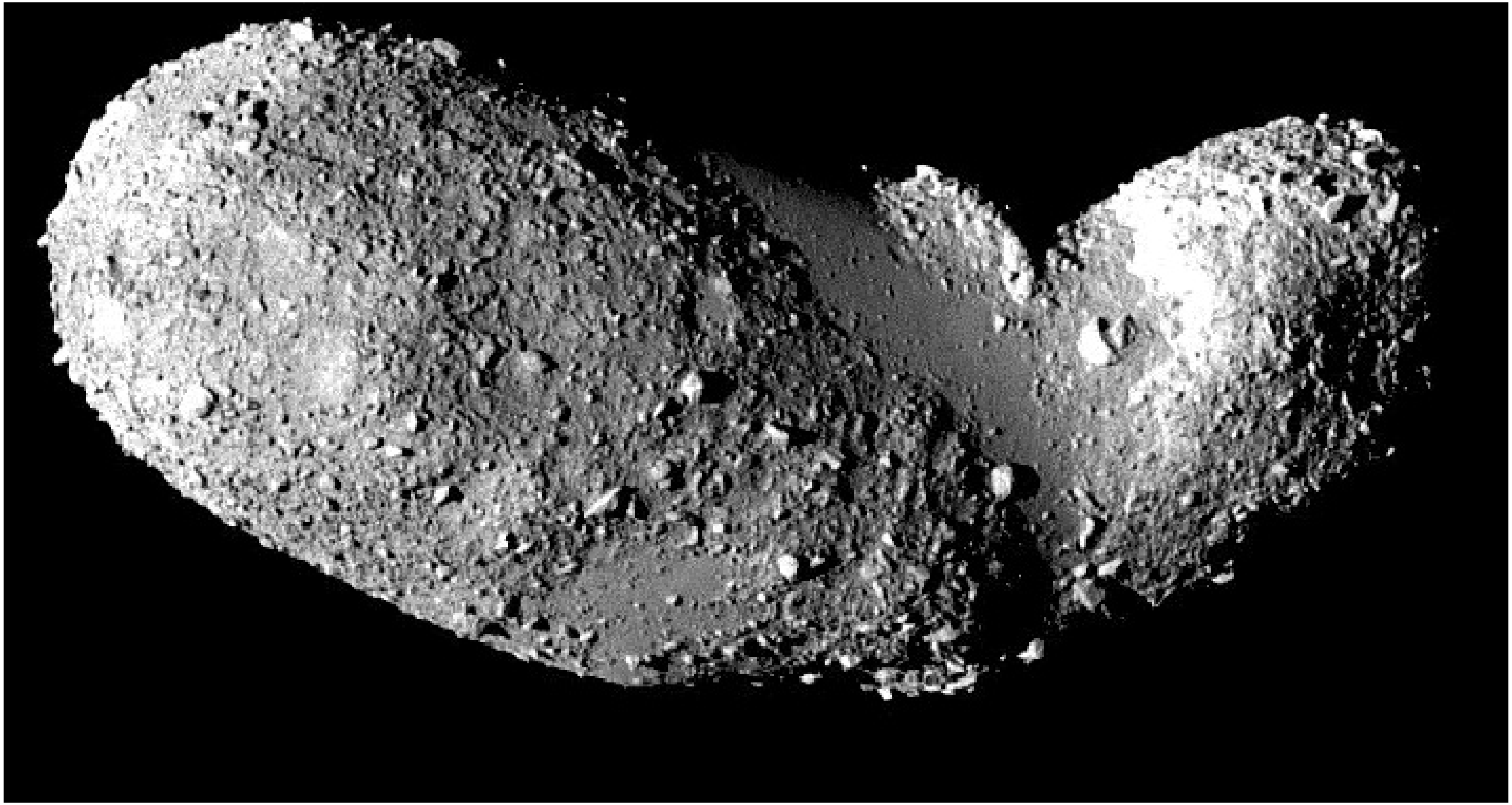
& Herschel Calibration Steering Group

& Akari calibration team

Do you really want to use asteroids as calibrators?

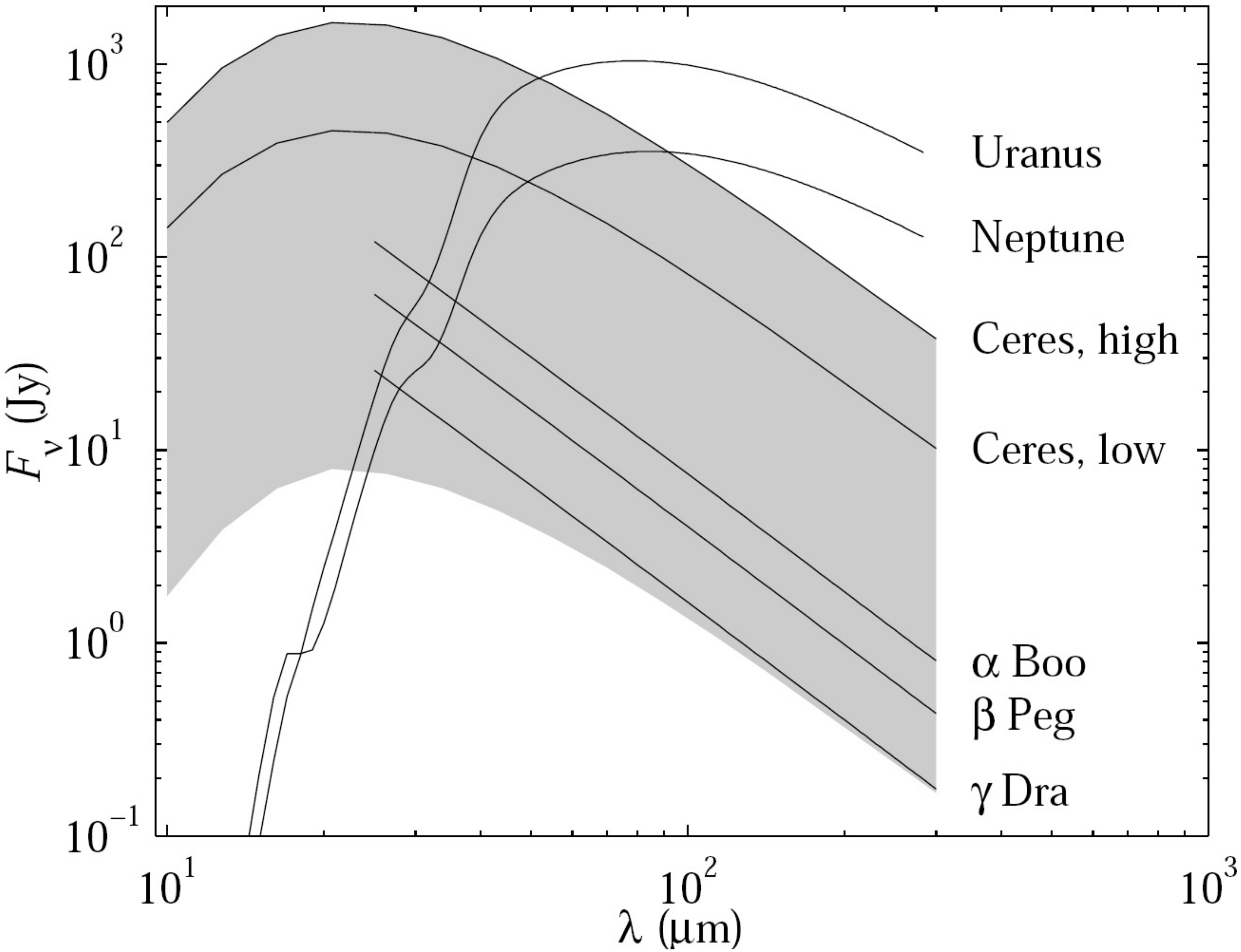


25143 Itokawa as seen by Hayabusa; Credit: ISAS, JAXA

Reports on asteroid work (HCalSG)

- HCalSG#2 presentation, Nov. 2002
- HCalSG#5 presentation, Oct. 2003
- Herschel Calibration Workshop Nr. 1, Leiden, Dec. 2004
- HCalSG#10 presentation, Nov. 2005
- HCalSG#14 presentation, Feb. 2007
- Herschel Calibration Workshop Nr. 2, Madrid, Feb. 2008

Motivation



10^3
10^2
10^1
10^0
10^{-1}
F_ν (Jy)
10^1
10^2
10^3
λ (μm)
Uranus
Neptune
Ceres, high
Ceres, low
α Boo
β Peg
γ Dra

Asteroid Selection Process

- Starting list: all known large main-belt asteroids with diameters $\geq \sim$100 km
- high quality, smooth, low amplitude lightcurves (visible)
- good quality spin vector and rotational properties (derived from multi-aspect visual lightcurves)
- availability of "Kaasalainen" shape models (lightcurve inversion complemented by radar, adaptive optics, occultations, HST, ...) or at least high-quality ellipsoidal shape models
- independent diameter and albedo information (occultation, speckle, HST, flybys, ...) → very often not available!
- multiple thermal observations (ground-based N-/Q-band & submm/mm; IRAS, ISO, MSX, Akari, Spitzer)
- exclusion of binaries, M-types, poor spin vectors, elongated objects

55 Selected Asteroids

- no extreme thermal lightcurve variations expected (up to max. 10-20 % over several hours; typically $<$ 5-10 %; many $<$ 1 %)
- thermal behaviour is dominated by the properties of the dust regolith which is expected to be present on all large main-belt asteroids (and observing and illumination geometry, albedo, ...)
- all 55 asteroids have N-/Q-band observations (31 have high quality N-/Q-band observations); 13 objects with submm/mm observations; 51 asteroids have IRAS, 14 ISO and 4 MSX observations; 54 have Akari-IRC observations (9 and 18 μm) and most of them also Akari-FIS observations at far-IR wavelengths; about 20 (tbc.) have Spitzer-MIPS (70/160 μm) observations, 6 have thermal lightcurves taken with Spitzer-IRAC
- "Kaasalainen" shape models exist for 33 asteroids; 2 shape models from HST, 19 ellipsoidal shape models, 2 spherical shape models

Nr.	Name	Quality	Observations
1	**Ceres**	A	gbNQ(IRTF,UKIRT),IRAS,gbSubmm/MM(JCMT,HHT,SCUBA,CSO), ISO(PHT,LWS,SWS),Akari-IRC
2	**Pallas**	B	gbNQ(IRTF,UKIRT),IRAS,gbSubmm/MM(JCMT,SCUBA,CSO), ISO(PHT,LWS,SWS),Akari-IRC
3	**Juno**	A	gbNQ(UKIRT),IRAS,ISO(PHT,SWS),Spitzer-MIPS,Akari-IRC
4	**Vesta**	A-B	gbNQ(UKIRT,SUBARU),IRAS,gbSubmm/MM(JCMT,ATCA,CSO), ISO(PHT,LWS,SWS),Akari-IRC
6	**Hebe**	A	IRAS,ISO(PHT),Spitzer-MIPS,Akari-IRC
7	**Iris**	D	IRAS,Spitzer-MIPS,Akari-IRC
8	**Flora**	B	IRAS,Akari-IRC
9	**Metis**	C	gbNQ(CTIO),gbSubmm/MM(ATCA),MSX,ISO(PHT),Akari-IRC
10	**Hygiea**	B-C	gbNQ(IRTF,UKIRT),IRAS,gbSubmm/MM(JCMT,SCUBA), ISO(PHT,LWS,SWS),Akari-IRC
12	**Victoria**	B	gbNQ(VISIR),IRAS,Spitzer-MIPS,Akari-IRC
17	Thetis	D	IRAS,Akari-IRC
18	Melpomene	B	IRAS,Spitzer-MIPS,Akari-IRC
19	**Fortuna**	D	Spitzer-MIPS,Akari-IRC
20	**Massalia**	B	IRAS, ISO(CAM),Spitzer-MIPS,Akari-IRC
21	**Lutetia**	B	gbNQ(TIMMI,IRTF,VISIR),IRAS,Spitzer-MIPS,Akari-FIS,Akari-IRC
23	**Thalia**	B	IRAS,MSX,Spitzer-MIPS,Akari-IRC
24	Themis	B	gbNQ(SUBARU),Akari-IRC
28	Bellona	B	gbNQ(VISIR),IRAS,MSX,Akari-IRC
29	**Amphitrite**	B	gbNQ(TIMMI),IRAS, gbSubmm/MM(CSO),Akari-IRC
31	Euphrosyne	B-C	IRAS,Akari-IRC
37	**Fides**	B-C	IRAS,Akari-IRC
40	Harmonia	B-C	gbNQ(VISIR),IRAS,Spitzer-MIPS,Akari-FIS,Akari-IRC
41	**Daphne**	B-C	IRAS,Spitzer-MIPS,Akari-IRC
42	**Isis**	B	gbNQ(TIMMI),IRAS,Spitzer-MIPS,Akari-IRC
47	Aglaja	A-B	IRAS,Akari-IRC
48	Doris	B	IRAS,Akari-IRC
52	**Europa**	A	gbNQ(TIMMI),gbSubmm/MM(CSO),IRAS,ISO(SWS),Akari-IRC
54	Alexandra	B	gbNQ(UKIRT),IRAS,ISO(PHT)
56	Melete	B-C	gbNQ(VISIR),IRAS,Akari-IRC

Nr.	Name	Quality	Observations
65	Cybele	A	gbNQ(UKIRT,TIMMI,UCL,IRTF),IRAS,ISO(PHT,CAM), gbSubmm/MM(CSO),Akari-IRC
69	**Hesperia**	B	gbNQ(TIMMI,VISIR),IRAS,Akari-FIS,Akari-IRC
85	**Io**	B	gbNQ(TIMMI,VISIR),gbSubmm/MM(CSO),IRAS,Spitzer-MIPS, Akari-FIS,Akari-IRC
88	**Thisbe**	A-B	IRAS,Akari-IRC
93	Minerva	A-B	IRAS,MSX,Akari-IRC
94	Aurora	B	gbNQ(VISIR),IRAS,Akari-FIS,Akari-IRC
106	Dione	C	gbNQ(UKIRT),IRAS,ISO(PHT),gbSubmm/MM(JCMT),Akari-IRC
165	**Loreley**	B-C	IRAS,Akari-IRC
173	**Ino**	B-C	IRAS,Akari-IRC
196	**Philomela**	B-C	gbNQ(VISIR),IRAS,Akari-FIS,Akari-IRC
230	**Athamantis**	A-B	gbNQ(VISIR),IRAS,Akari-FIS,Akari-IRC
241	Germania	B-C	IRAS,Akari-IRC
283	**Emma**	B-C	gbNQ(VISIR),IRAS,Akari-FIS,Akari-IRC
313	Chaldaea	B	gbNQ(UKIRT),IRAS,ISO(PHT),gbSubmm/MM(JCMT), Spitzer-MIPS,Akari-IRC
334	Chicago	C	gbNQ(VISIR),IRAS,Akari-IRC
360	Carlova	D	IRAS,Akari-IRC
372	**Palma**	B-C	IRAS,Akari-IRC
423	**Diotima**	A	gbNQ(VISIR),IRAS,gbSubmm/MM(CSO),Akari-FIS,Akari-IRC
451	**Patientia**	C	IRAS,Akari-IRC
471	Papagena	B	IRAS,Spitzer-MIPS,Akari-IRC
505	Cava	B	gbNQ(SUBARU,VISIR),Spitzer-MIPS,Akari-FIS,Akari-IRC
511	**Davida**	B	gbNQ(TIMMI,VISIR),IRAS,Akari-FIS,Akari-IRC
532	**Herculina**	C	gbNQ(UKIRT),IRAS,gbSubmm/MM(JCMT),ISO(PHT),Akari-IRC
690	**Wratislavia**	B	IRAS,Akari-IRC
704	Interamnia	B	IRAS,Akari-IRC
776	**Berbericia**	B	gbNQ(VISIR),IRAS,Akari-IRC

⋆ Asteroids with "Kaasalainen shape models" are in bold face;

⋆ Recent CSO data (D. Dowell, 2008/Feb/02) are still missing.

Thermophysical Modelling (TPM)

- Based on a model code by J. Lagerros, Uppsala
- Energy balance between solar insolation, reflected light and thermal emission: $sS_{\odot}r^{-2} = F_r + F_e$
- Modelling of surface (regolith, craters, roughness, multiple scattering, ...): beaming model with hemispherical segment craters (f: fraction of the surface covered by craters; ρ: r.m.s. of surface slopes)
- Thermal behaviour (1-dim heat conduction, thermal inertia, diurnal temperature variation; wavelength dependent emissivity $\epsilon(\lambda)$)
- Observing and illumination geometry (distances and angles)
- Size (D_{eff}) and shape
- Spin vector and rotational behaviour (+ abs. timing and positioning)
- Geometric albedo p_V
- TPM techniques have been successfully applied to NEOs, MBAs, TNOs, cometary nuclei or planetary satellites

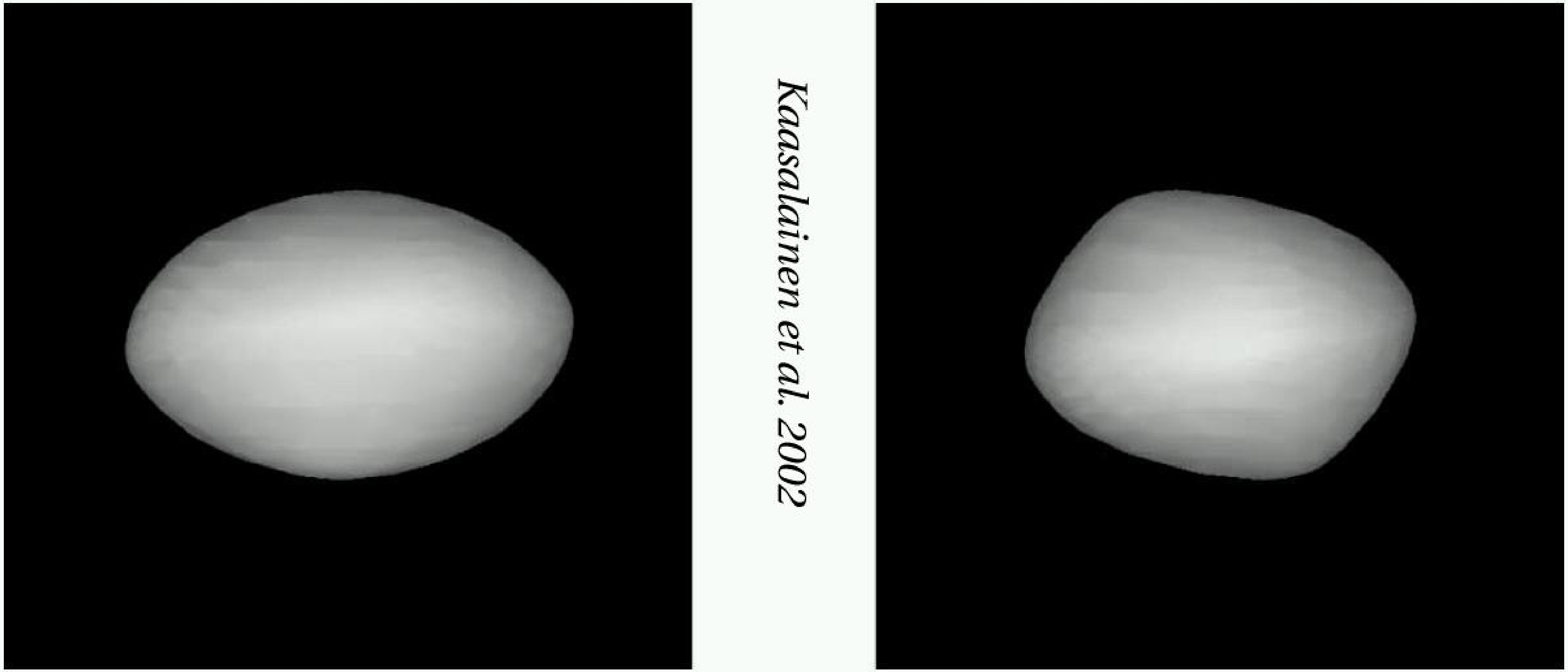


FIG. 1. The shape model of 3 Juno, shown at equatorial viewing/illuminaton geometry, with rotational phases 90° apart.

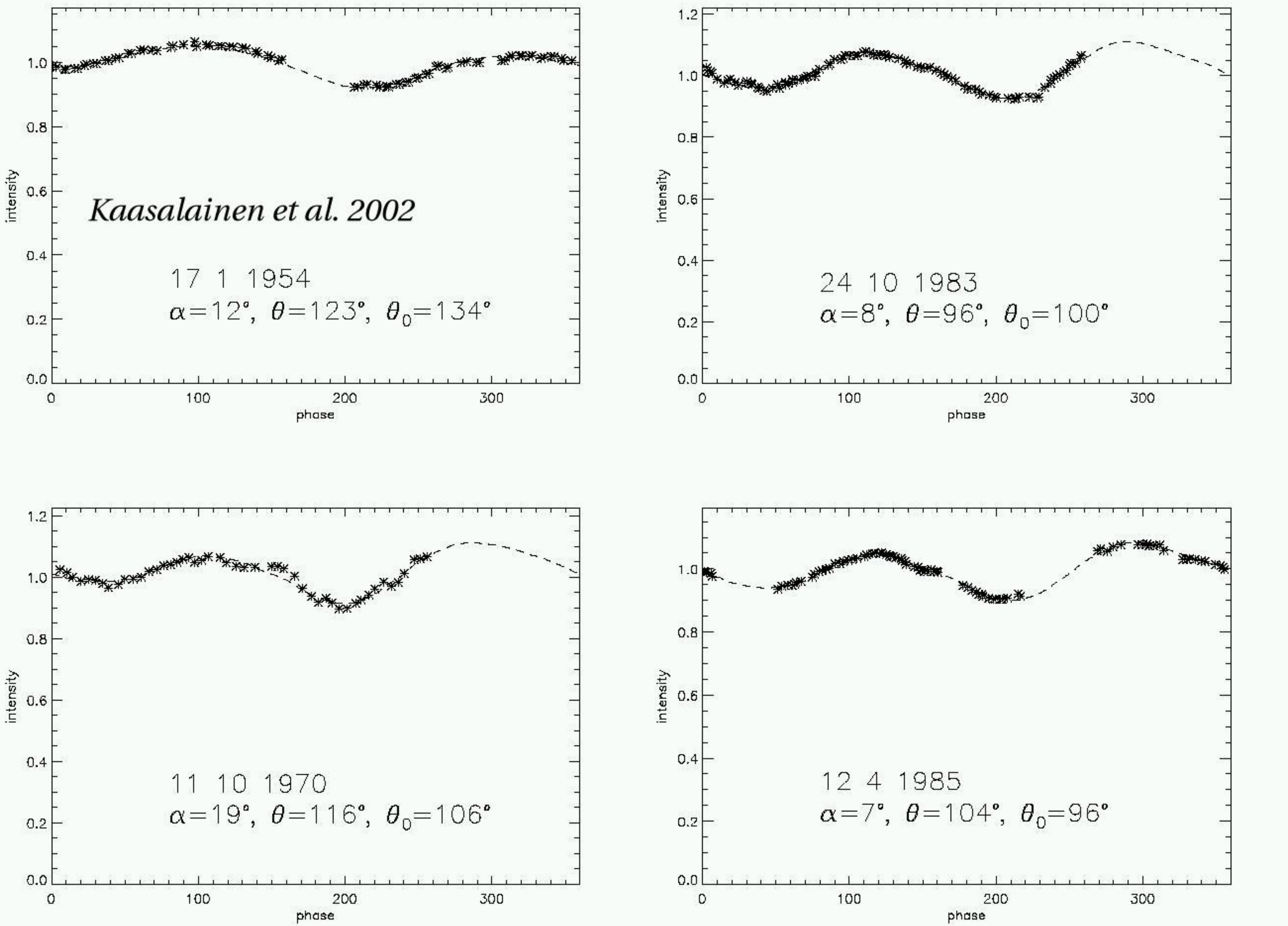
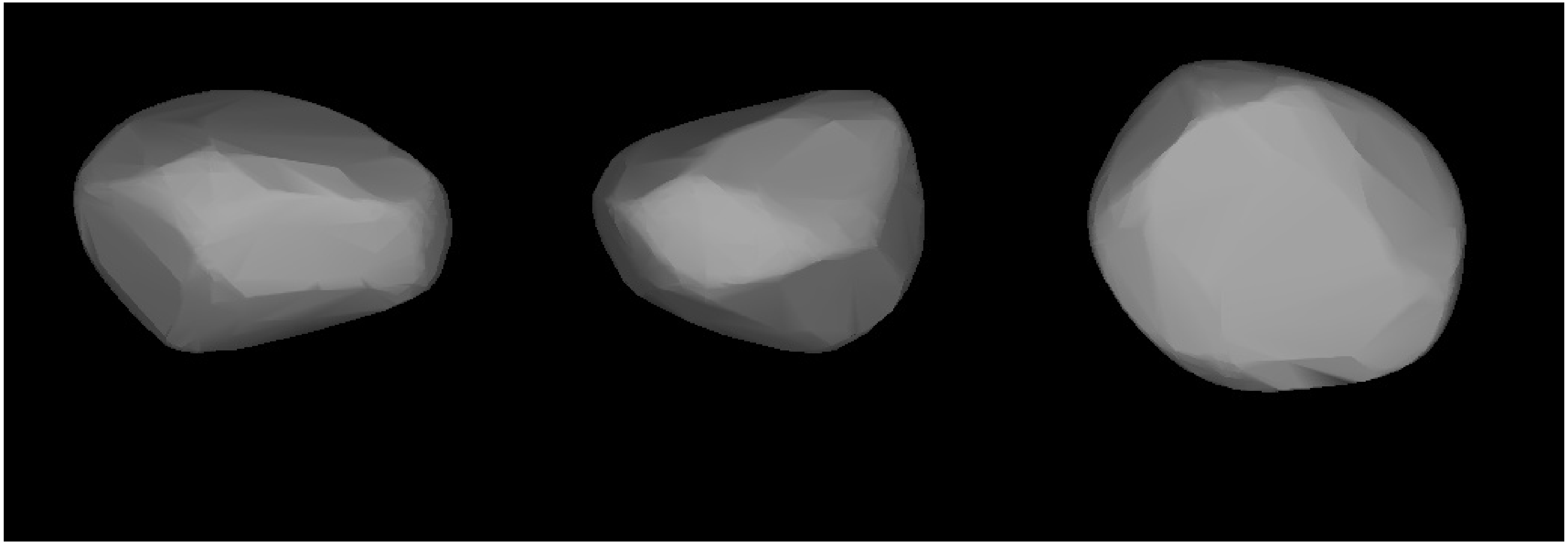
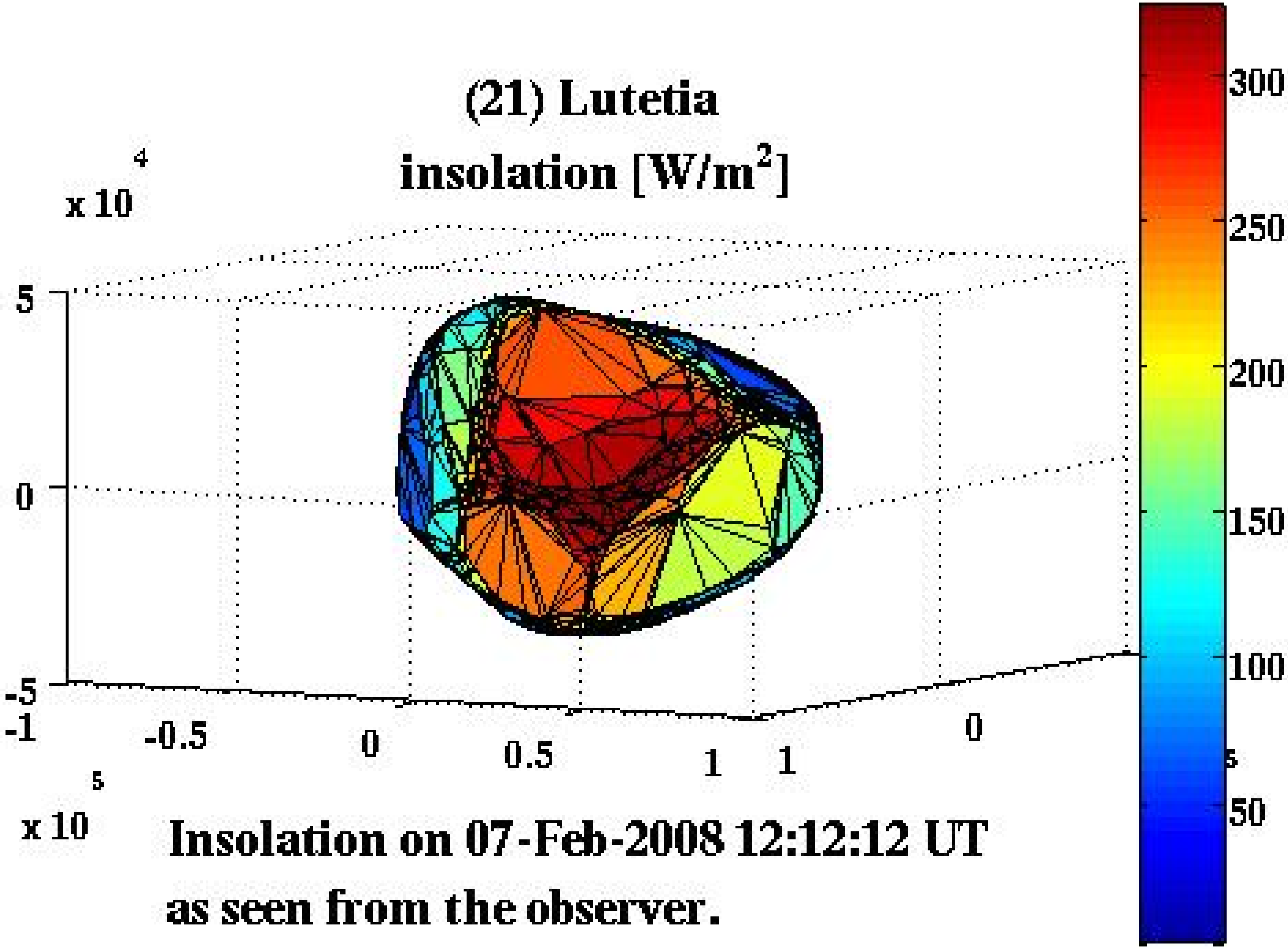


FIG. 2. Four lightcurves (asterisks) and the corresponding fits (dashed lines) for 3 Juno. The rotational phase is given in degrees, and the brightness in units of relative intensity. The aspect angle of the Earth (measured from the North pole) is given by θ, and that of the Sun by θ_0. The solar phase angle is given by α.

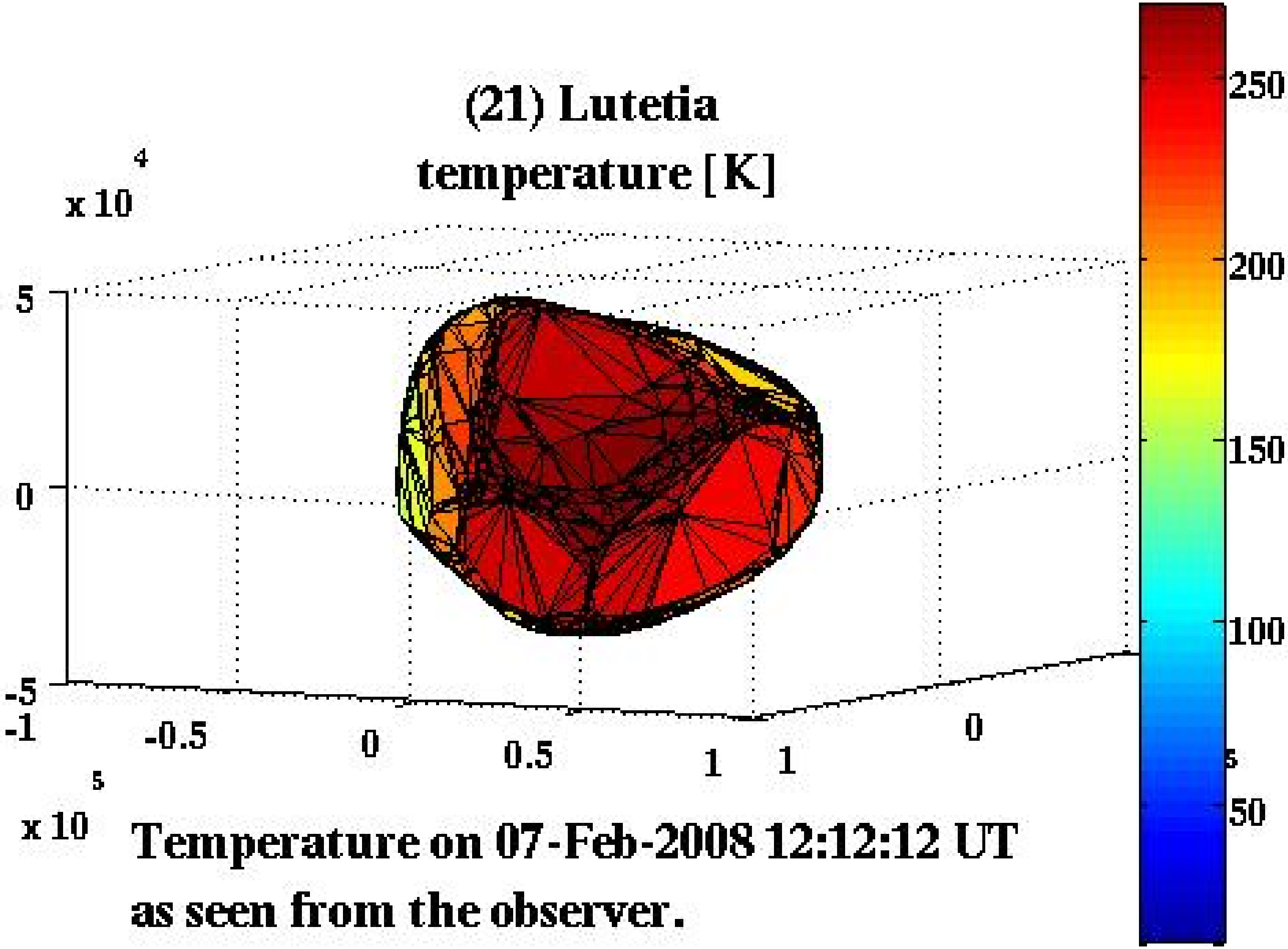
21 Lutetia

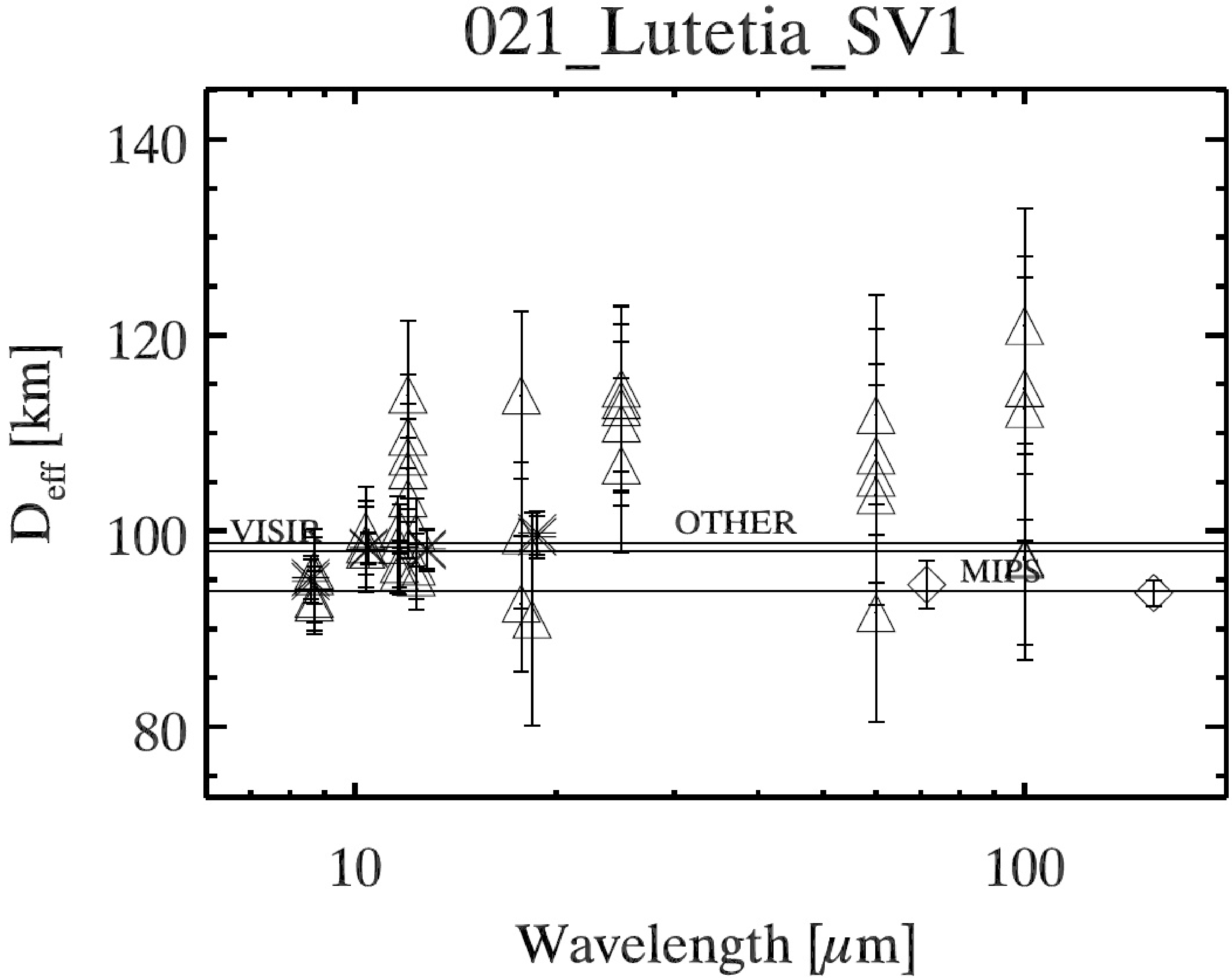
(model by Torppa, Kaasalainen et al. 2003;
fly by target of the Rosetta mission)



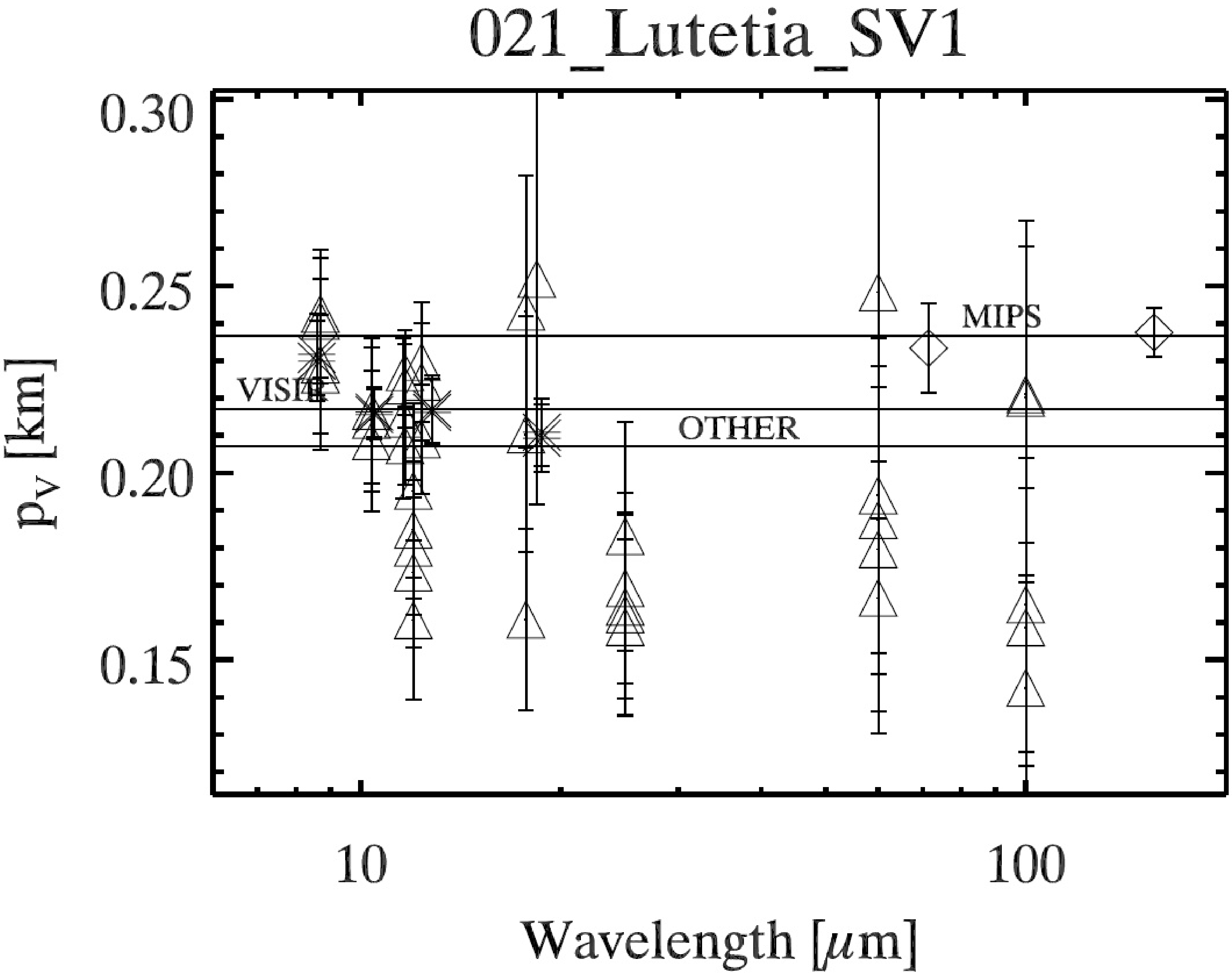


Insolation on 07-Feb-2008 12:12:12 UT
as seen from the observer.


(21) Lutetia
temperature [K]
x 10^4
5
0
-5
-1
-0.5
0
0.5
1
1
0
x 10^5
250
200
150
100
50
Temperature on 07-Feb-2008 12:12:12 UT
as seen from the observer.



021_Lutetia_SV1
140
120
100
80
VISIR
OTHER
MIPS
10
100
D_eff [km]
Wavelength [μm]


021_Lutetia_SV1
0.30
0.25
0.20
0.15
p_V [km]
VISIR
MIPS
OTHER
10
100
Wavelength [μm]

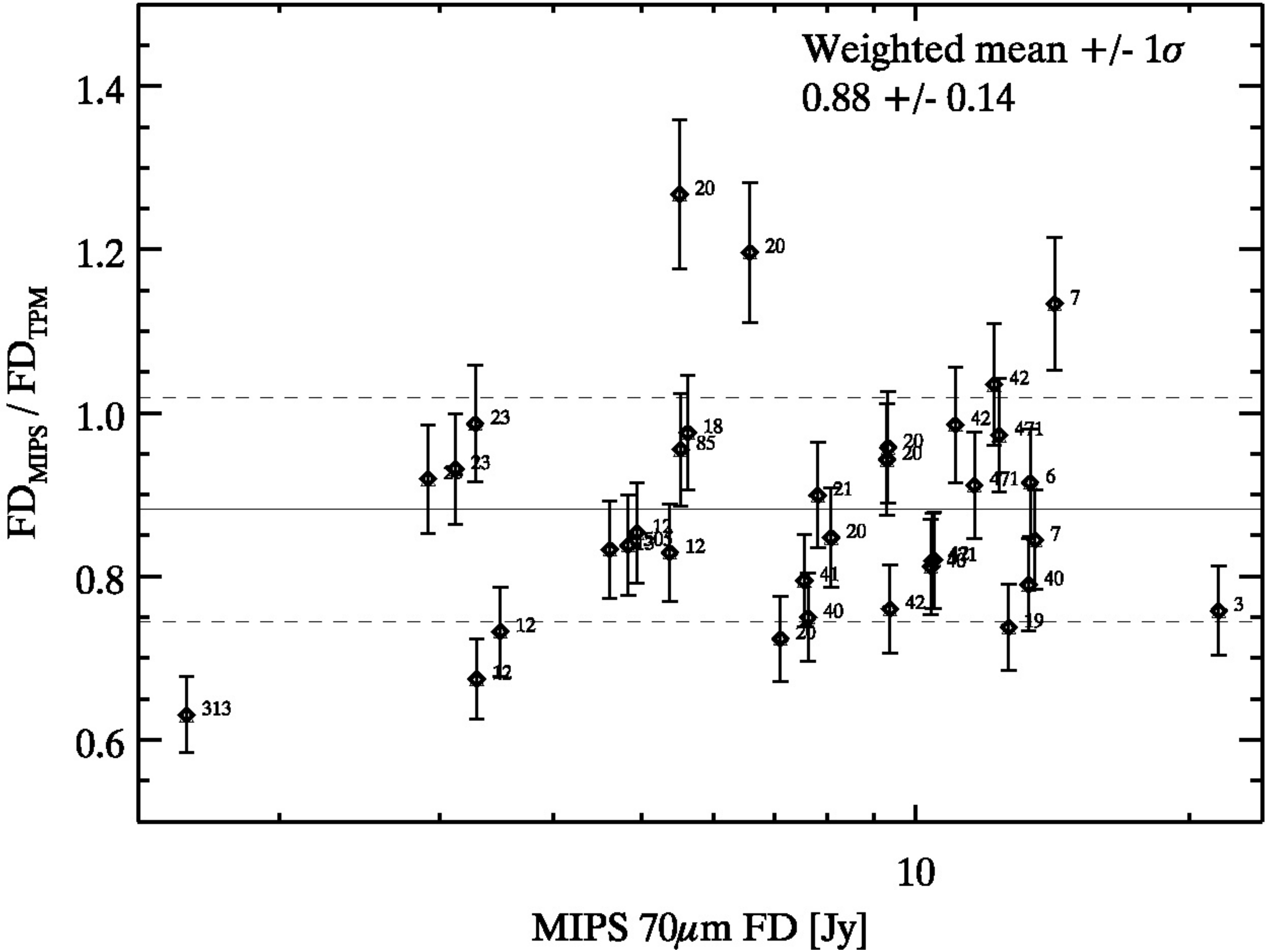
Thermal Observations & Results for Lutetia

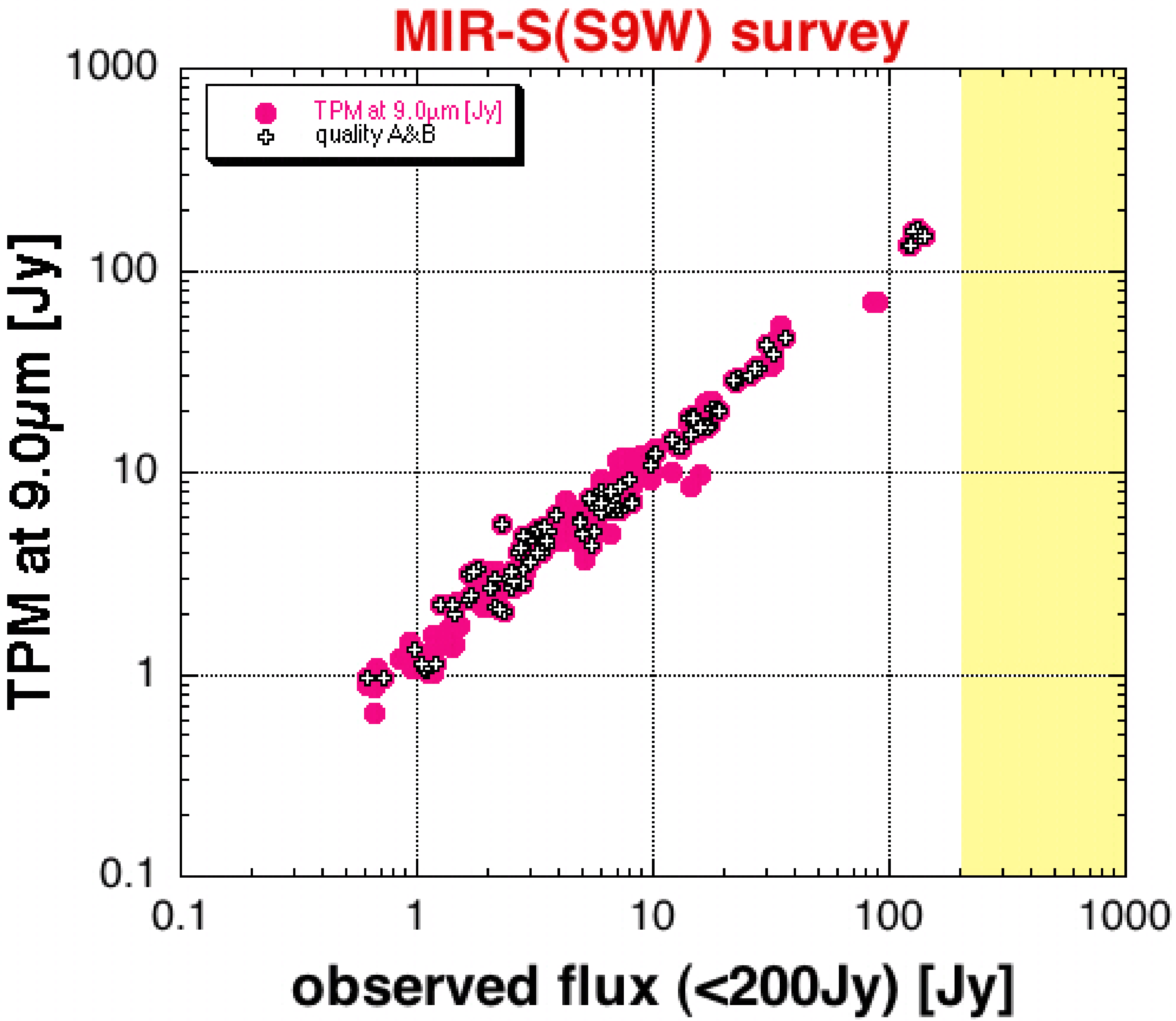
- Based on 38 published observations (IRAS, ESO-TIMMI, IRTF): D_{eff}=98.8±8.0 km & p_V=0.21±0.03
- Based on 8 very recent VISIR observations: D_{eff}=97.9±1.7 km & p_V=0.22±0.01 (8 observations)
- Based on 2 MIPS observations (Stansberry et al. 2007): D_{eff}=93.8±0.4 km & p_V=0.24±0.01 (2 observations)
- Müller, M. et al. 2006: 98.3±5.9 km & p_V=0.208±0.025
- **Lutetia is currently classified as quality B: enough thermal data existing, absolute flux predictions are accurate on 5-10%-level**

Thermal Observations & Results for the 55 asteroids

- Total number of thermal observations for the 55 asteroids in the database: 2282
  + 124 VISIR (16): 8.59, 10.49, 12.81, 18.72 μm (Müller et al.)
  + 553 Akari-IRC (54): 9, 18 μm (Hasegawa et al.)
  + 70 Spitzer-MIPS (~20): 70, 160 μm (Stansberry et al. 2007)
  + 495 CSO-SHARCII (14): 350 μm (Dowell, Sandell, Teyssier)
- **6** asteroids are currently A quality (enough data; accuracy 5%);
  5 have A-B (enough data; accuracy 5-10%);
  22 have B (accuracy 5-10%);
  12 have B-C (accuracy 5-15%);
  6 have "C" (accuracy 10-15%);
  4 have D (rest).
- Quality label based on: robustness of D_{eff} and p_V, quality of shape model and spin-vector solution, availability of thermal data.

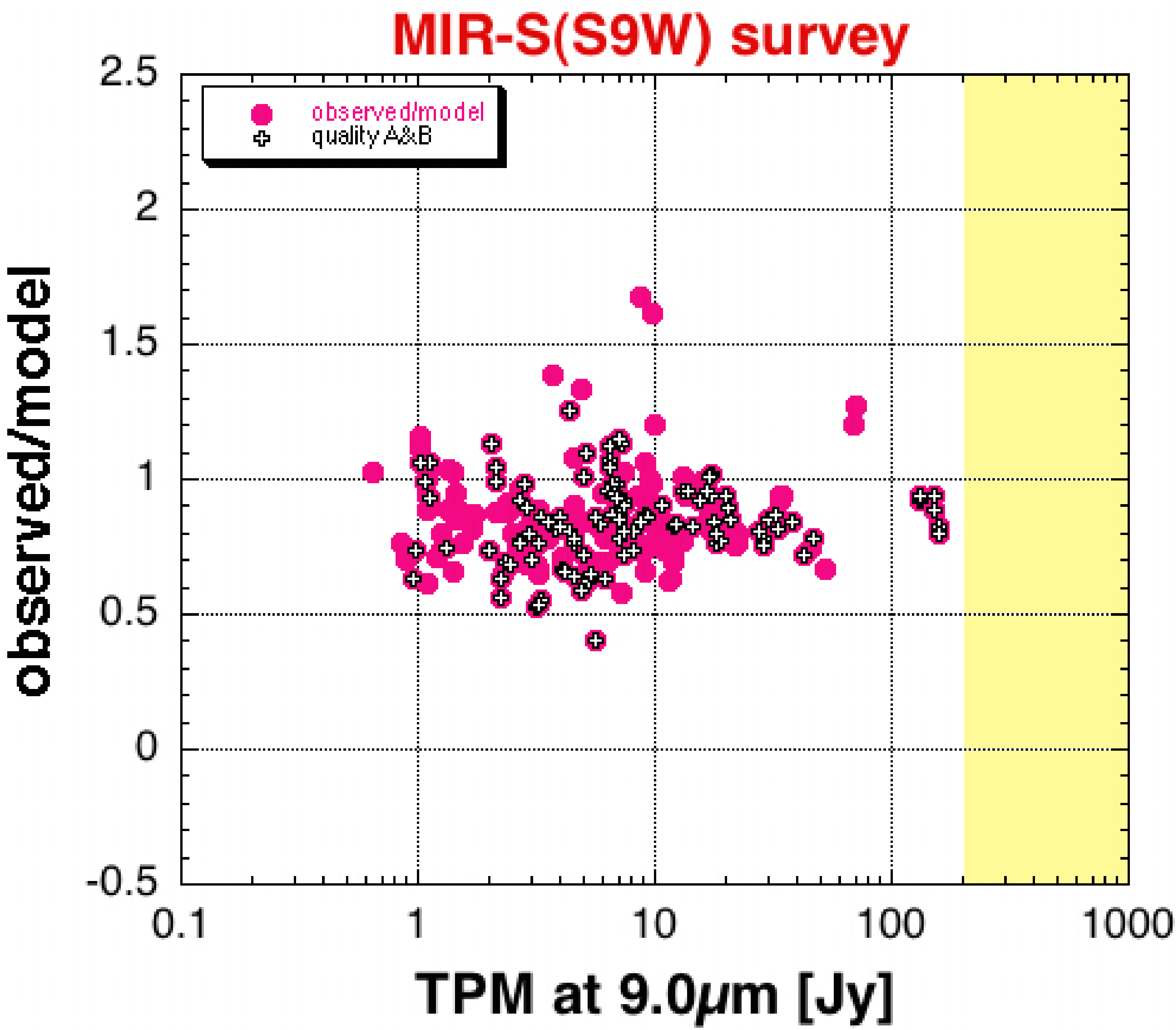
Asteroid calibrators: MIPS 70μm check





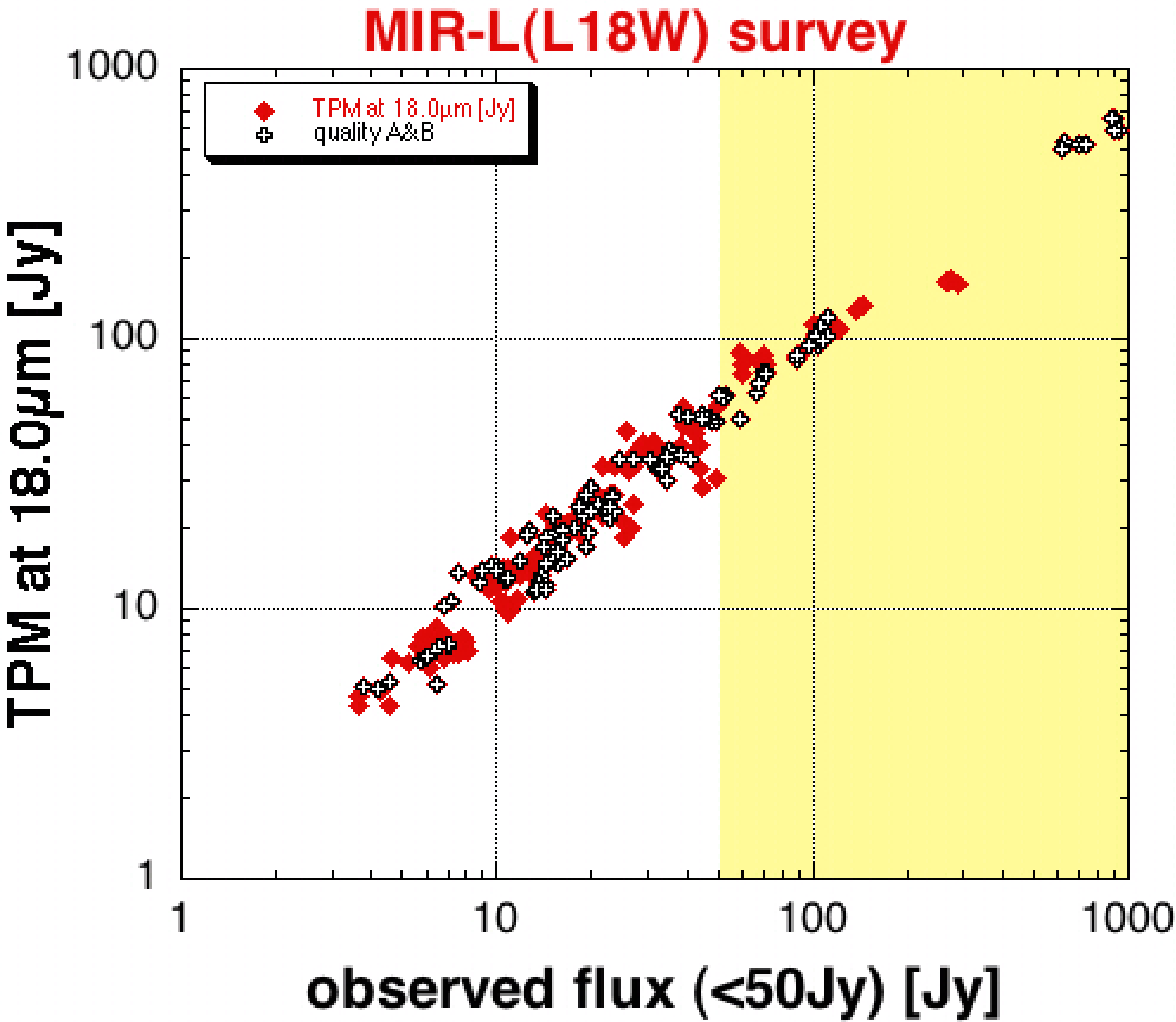
Note: not yet colour-corrected!

Credit: S. Hasegawa & Akari calibration team



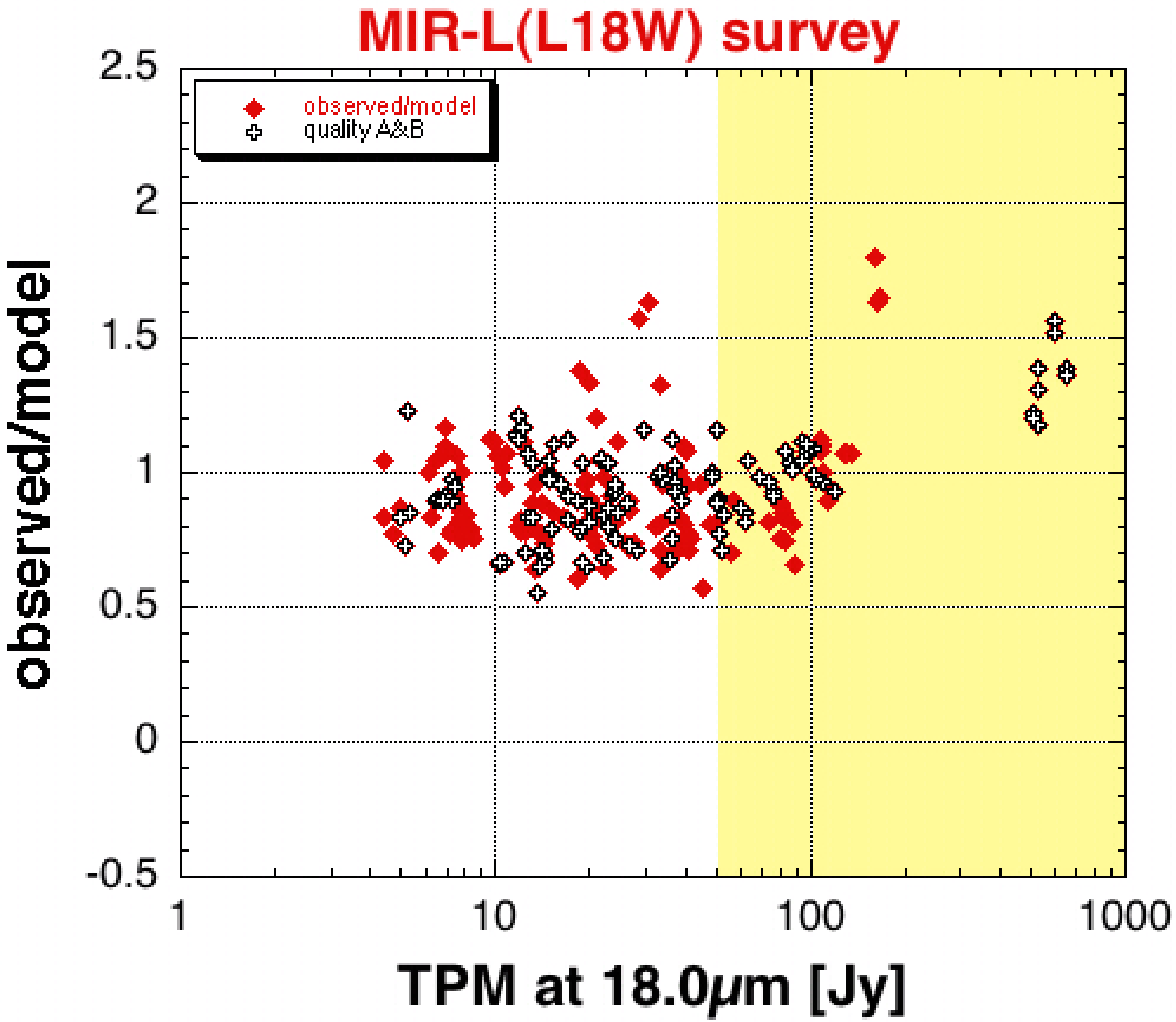
Note: not yet colour-corrected!

Credit: S. Hasegawa & Akari calibration team



Note: not yet colour-corrected!

Credit: S. Hasegawa & Akari calibration team



Note: not yet colour-corrected!

Credit: S. Hasegawa & Akari calibration team

Flux statistics: 55 asteroid calibrators

Asteroids above threshold (only during visibility periods):

	threshold	70	100	160	250	350	500	3000 μm
max above	100 Jy:	3	3	1	0	0	0	0
max above	10 Jy:	49	29	16	3	3	1	0
max above	1 Jy:	all	all	all	51	31	17	0
max above	0.1 Jy:	all	all	all	all	all	all	3

Statistics:

- min and max flux of one asteroid can change by up to a factor of 10 during visibility regions
- 3 asteroids reach fluxes of above 100 Jy at 70 micron
- 49 asteroids reach fluxes of above 10 Jy at 70 micron
- all 55 asteroids reach fluxes of above 1 Jy at 70 micron
- 16 asteroids are above 10 Jy at 160 micron
- 17 asteroids are above 1 Jy at 500 micron

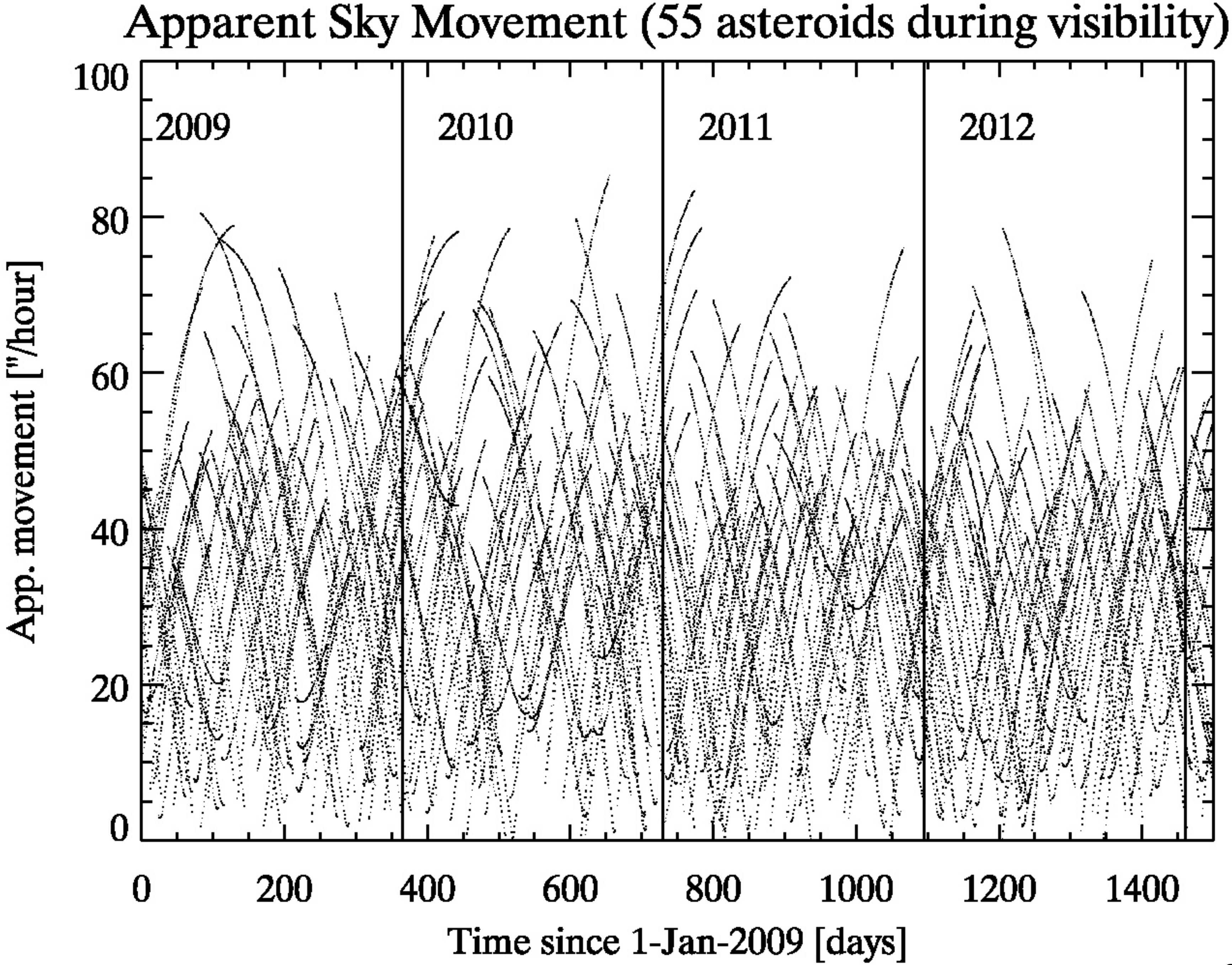
Flux statistics: 721 asteroids

Asteroids above threshold (only during visibility periods):

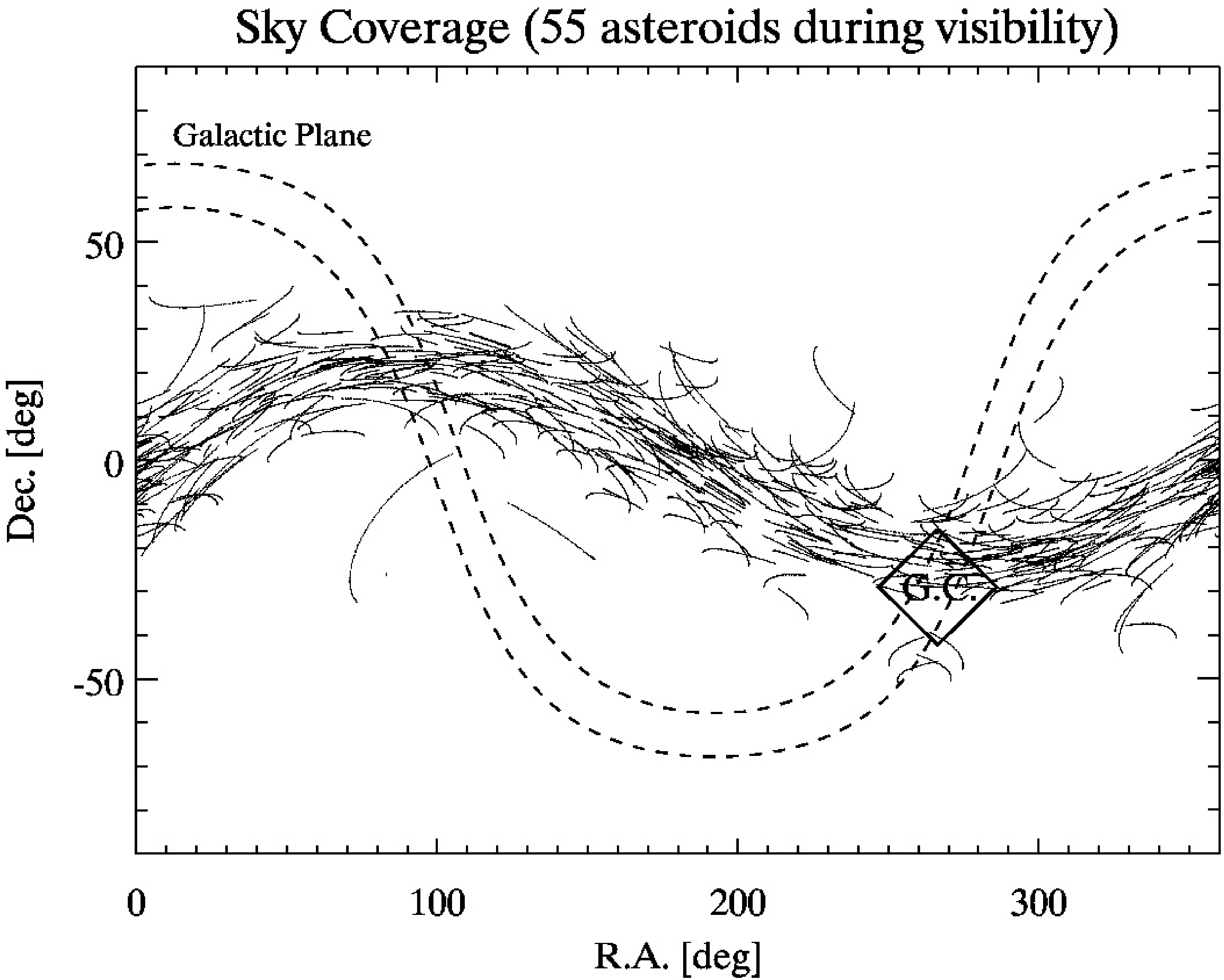
threshold	70	100	160	250	350	500	3000 μm
max above 100 Jy:	4	3	1	0	0	0	0
max above 10 Jy:	151	69	18	4	3	1	0
max above 1 Jy:	679	542	321	168	72	23	0
max above 0.1 Jy:	720	719	719	693	570	383	4

Statistics:

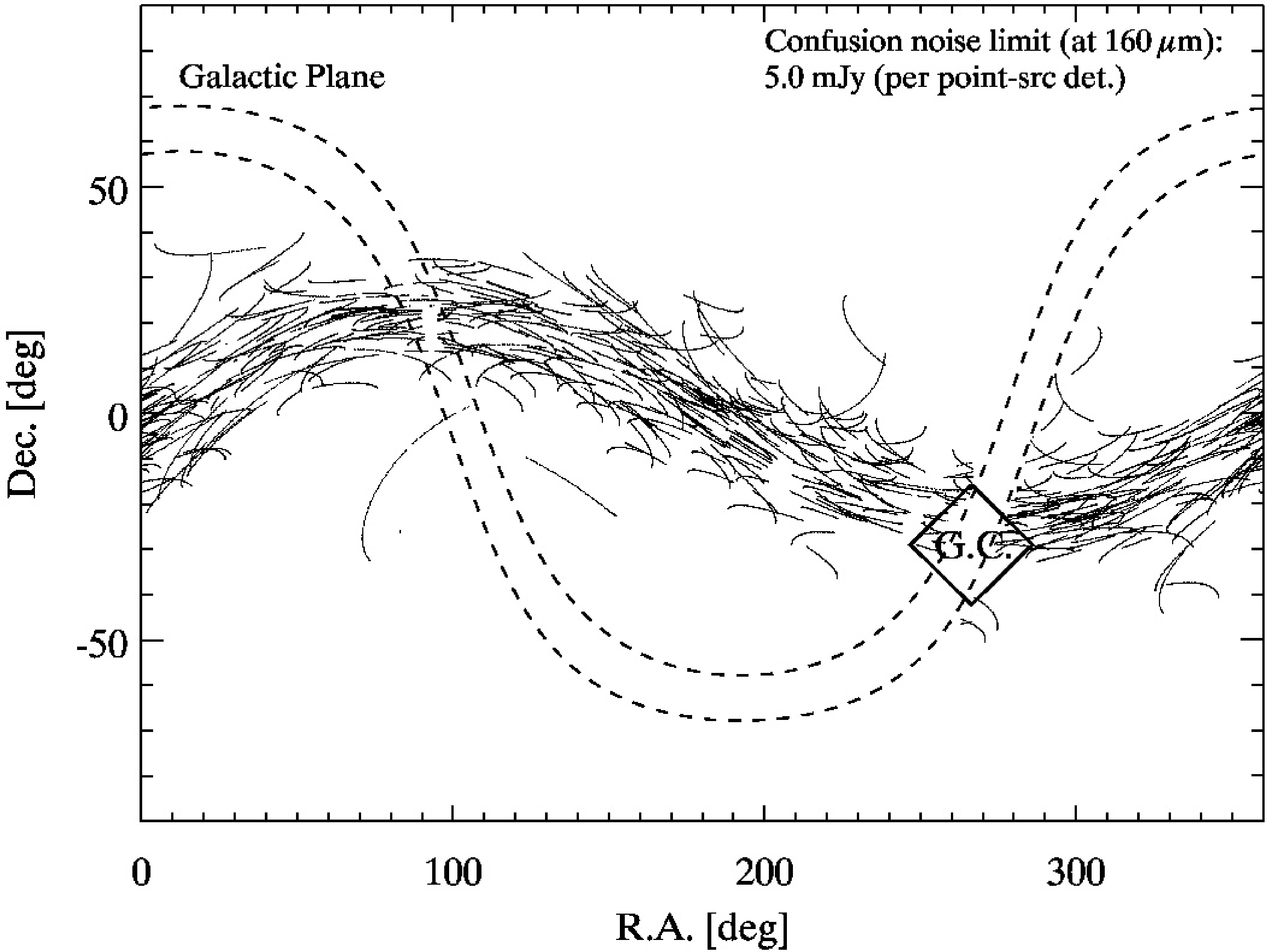
- min and max flux of one asteroid can change by up to a factor of 20 during visibility regions!
- 4 asteroids reach fluxes of above 100 Jy at 70 μm (1,2,4,324)
- 151 asteroids reach fluxes of above 10 Jy at 70 μm
- 679 asteroids reach fluxes of above 1 Jy at 70 μm
- 18 asteroids are above 10 Jy at 160 μm
- 23 asteroids are above 1 Jy at 500 μm



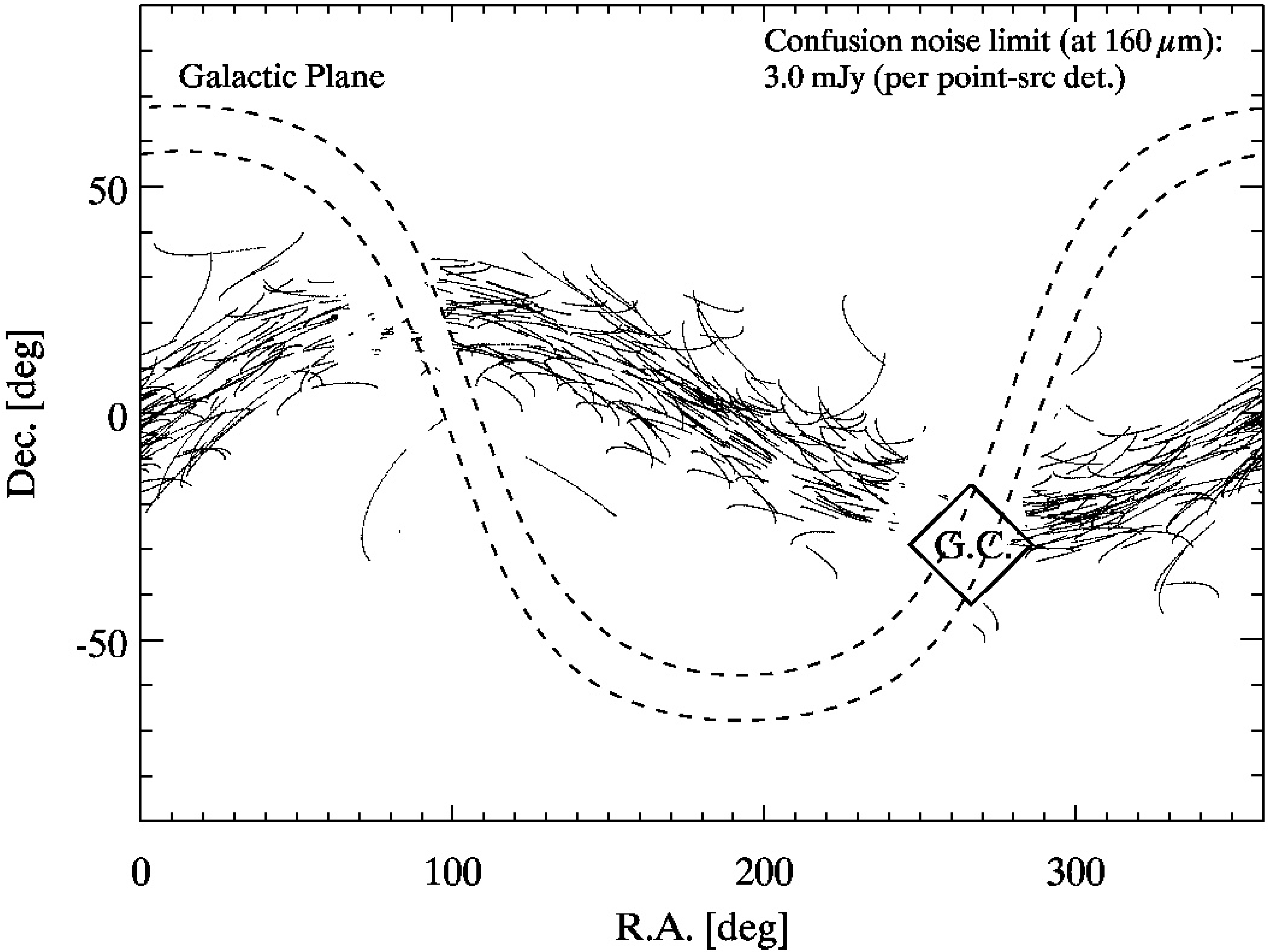
Apparent Sky Movement (55 asteroids during visibility)
2009
2010
2011
2012
App. movement ["/hour]
0
20
40
60
80
100
0
200
400
600
800
1000
1200
1400
Time since 1-Jan-2009 [days]


Sky Coverage (55 asteroids during visibility)
Galactic Plane
G.C.
50
0
-50
Dec. [deg]
0
100
200
300
R.A. [deg]

Sky Coverage (visible & low confusion)

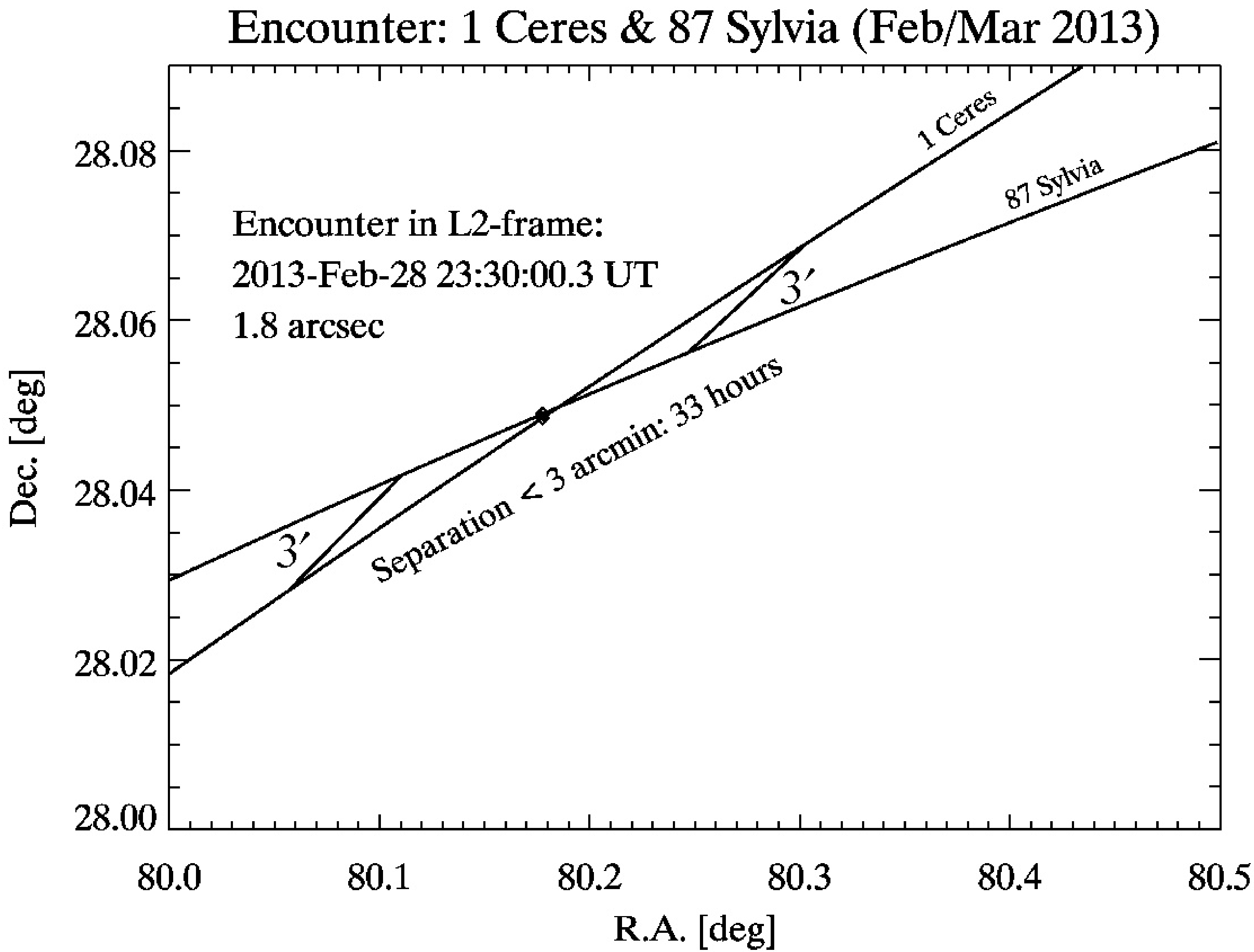


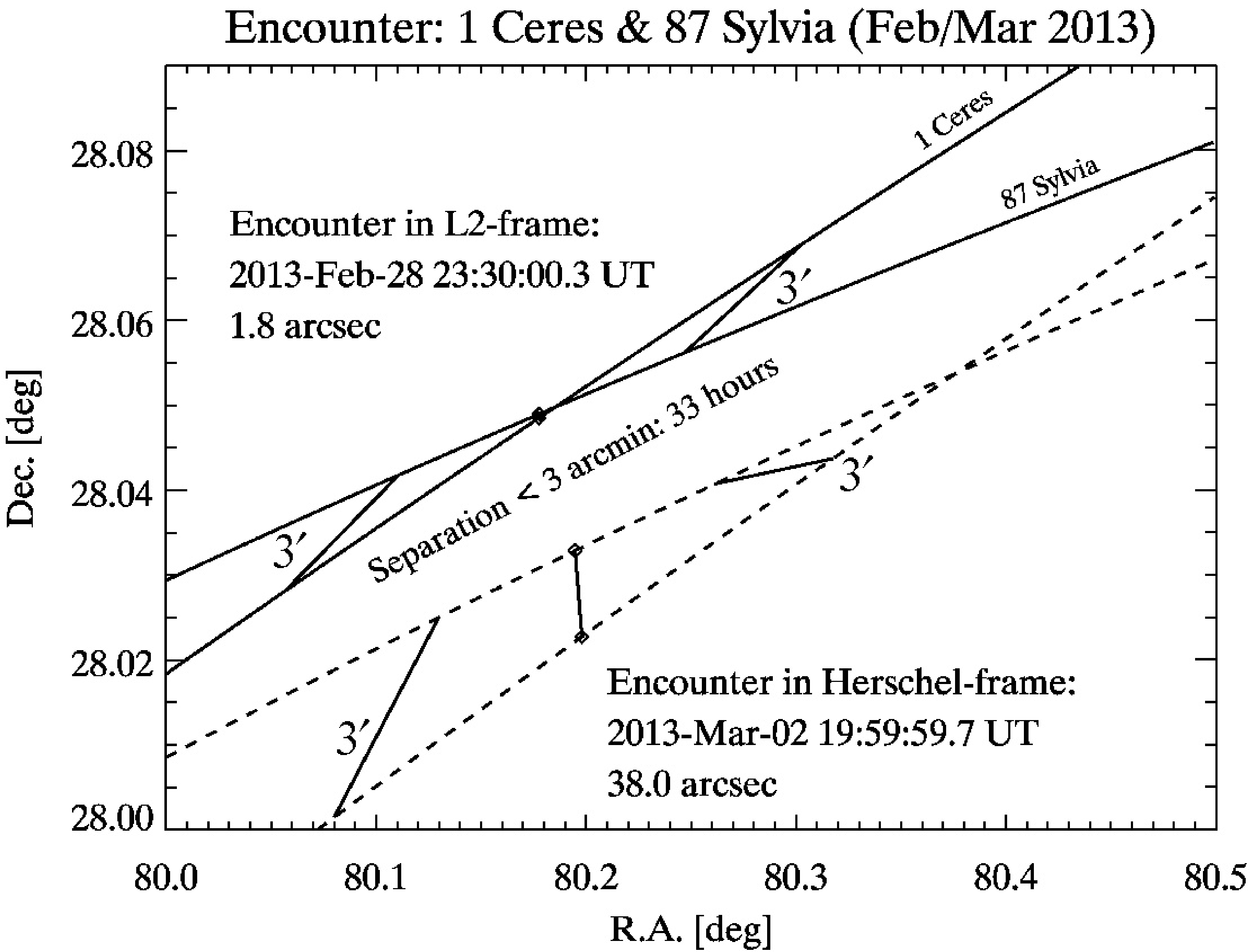
Sky Coverage (visible & low confusion)



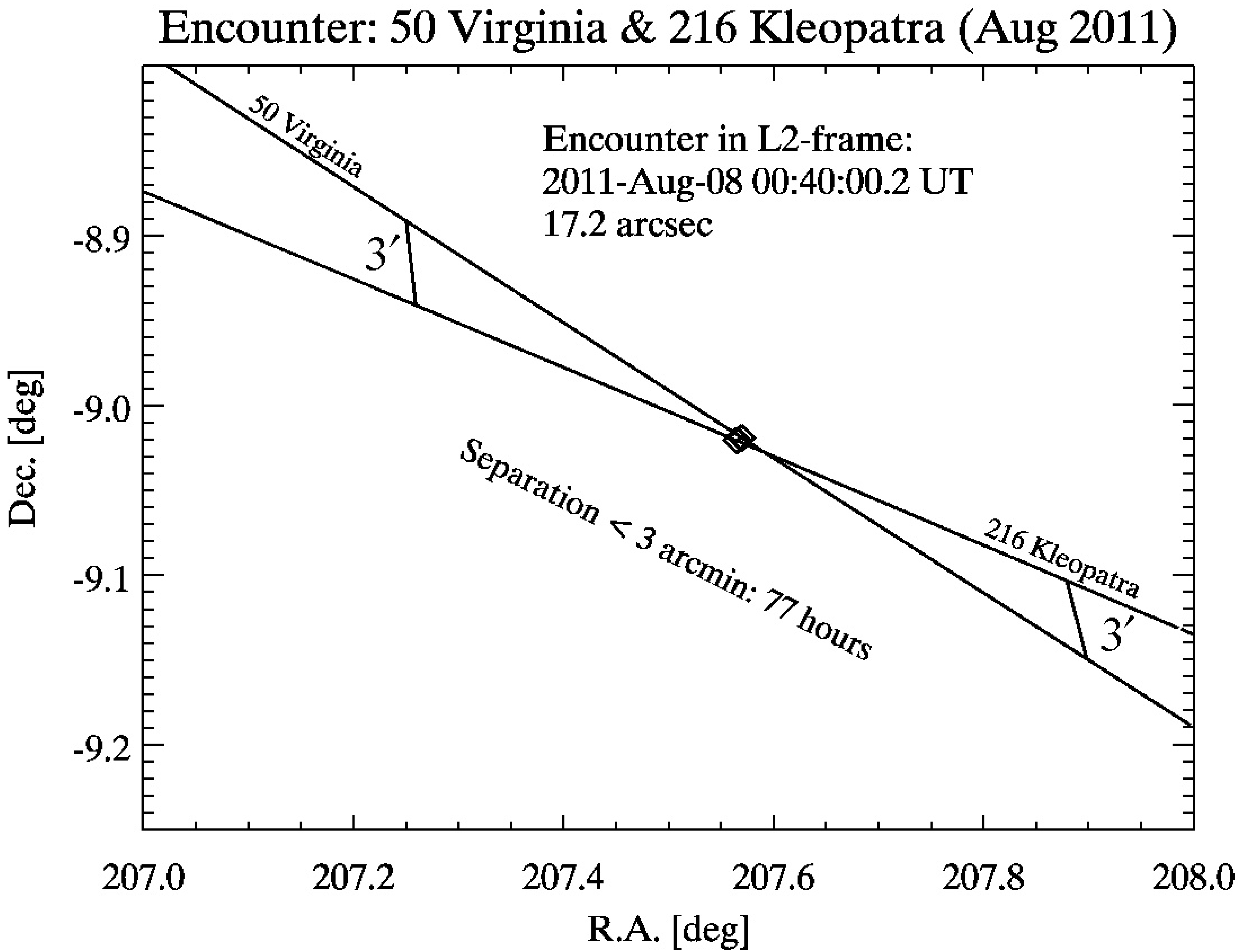
SSO Encounters in Herschel Mission

- The 55 asteroid calibrators have 30 encounters with less than 1 deg separation between 2009 and 2013 (during visibility).
- The 55 asteroid calibrators have 9 encounters with less than 1 deg with the planets (M,J,S,U,N).
- The extended asteroid list with 721 asteroids (IRAS 60 μm flux $>$ 1 Jy): $\star$ 2826 encounters within 1 deg $\star$ 80 encounters within 3 arcmin $\star$ smallest separation (L2-centric): 1.8 arcsec $\star$ smallest separation (Herschel-centric): 7.2 arcsec
- The 721 asteroids have 3592 encounters with less than 1 deg with the planets (M,J,S,U,N) (some are within a few arcmin with Jupiter or Saturn!)

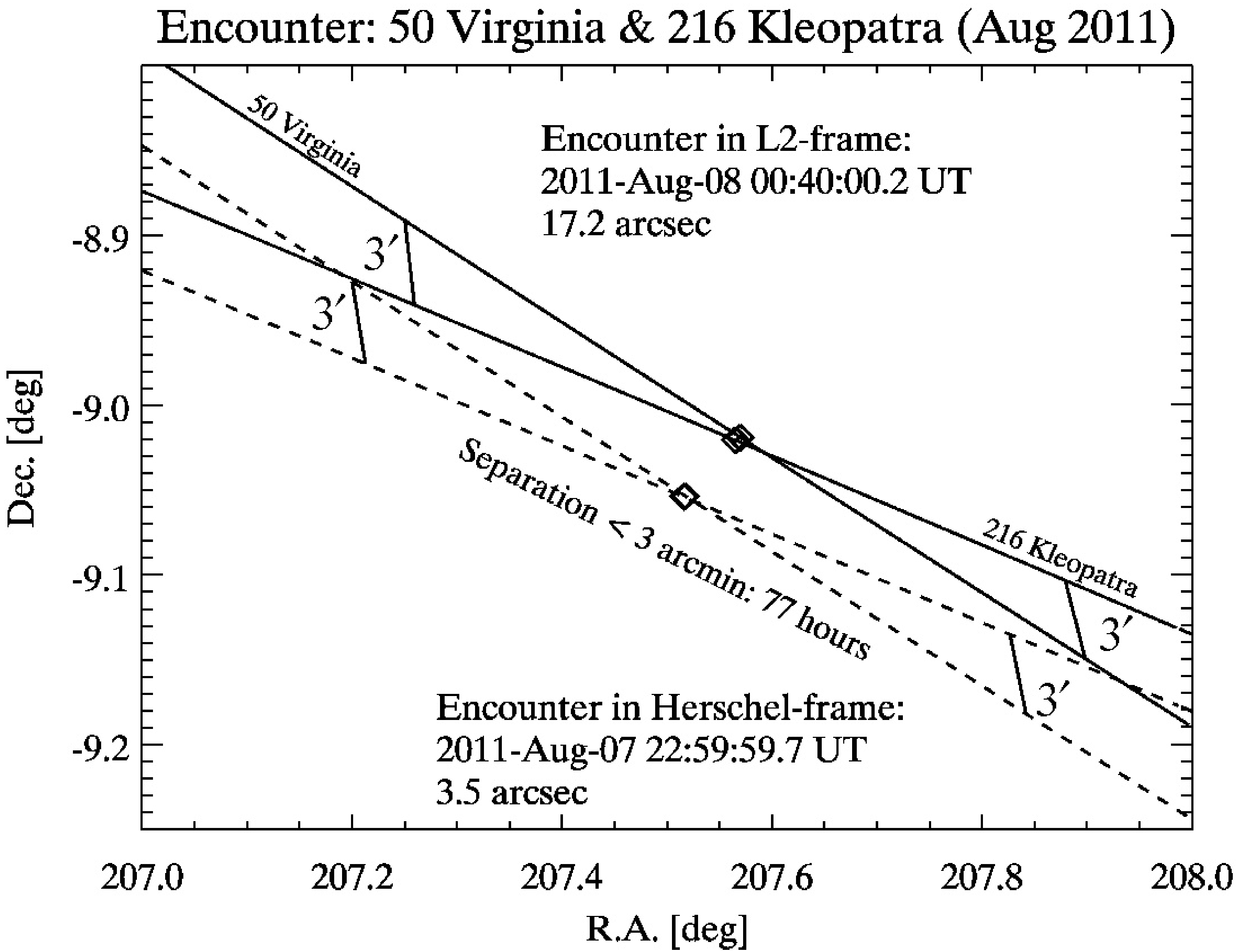

Encounter: 1 Ceres & 87 Sylvia (Feb/Mar 2013)
Encounter in L2-frame:
2013-Feb-28 23:30:00.3 UT
1.8 arcsec
1 Ceres
87 Sylvia
3′
3′
Separation < 3 arcmin: 33 hours
28.00
28.02
28.04
28.06
28.08
Dec. [deg]
80.0
80.1
80.2
80.3
80.4
80.5
R.A. [deg]



Encounter: 1 Ceres & 87 Sylvia (Feb/Mar 2013)
1 Ceres
87 Sylvia
Encounter in L2-frame:
2013-Feb-28 23:30:00.3 UT
1.8 arcsec
3′
3′
Separation < 3 arcmin: 33 hours
3′
3′
Encounter in Herschel-frame:
2013-Mar-02 19:59:59.7 UT
38.0 arcsec
Dec. [deg]
28.08
28.06
28.04
28.02
28.00
80.0
80.1
80.2
80.3
80.4
80.5
R.A. [deg]



Encounter: 50 Virginia & 216 Kleopatra (Aug 2011)
50 Virginia
Encounter in L2-frame:
2011-Aug-08 00:40:00.2 UT
17.2 arcsec
3′
Separation < 3 arcmin: 77 hours
216 Kleopatra
3′
-8.9
-9.0
-9.1
-9.2
Dec. [deg]
207.0
207.2
207.4
207.6
207.8
208.0
R.A. [deg]


Encounter: 50 Virginia & 216 Kleopatra (Aug 2011)
50 Virginia
216 Kleopatra
Encounter in L2-frame:
2011-Aug-08 00:40:00.2 UT
17.2 arcsec
Separation < 3 arcmin: 77 hours
Encounter in Herschel-frame:
2011-Aug-07 22:59:59.7 UT
3.5 arcsec
3′
3′
3′
3′
-8.9
-9.0
-9.1
-9.2
Dec. [deg]
207.0
207.2
207.4
207.6
207.8
208.0
R.A. [deg]

Past Applications

- transport of flux calibration from 60 to 100 μm (IRAS) and from 70 to 160 μm (Spitzer-MIPS)
- absolute photometric calibration of ISOPHOT in the far-IR
- flux calibration check for ISOSWS and ISOLWS
- validation of relative spectral response functions for the spectrometers onboard ISO
- colour correction and filter leak tests (IRAS, ISO, Spitzer, Akari)
- absolute photometric calibration of Akari-FIS
- validation and improvement of the photometric system for ISOCAM Parallel Mode and ISOPHOT Serendipity Mode
- cross-calibration between instruments, satellites, projects

Expected Herschel Applications

- absolute photometric calibration of PACS/SPIRE
- validation of relative spectral response functions for the PACS spectrometer
- point-source characterisation (PSF measurements): all 55 asteroids are point-like ($< 1''$), bright (1 ... 500 Jy) and have at certain times slow apparent movements below $10''$/hour (9 objects even drop below $1''$/hour during visibility windows)
- spatial characterisation through close encounters
- colour correction and filter leak tests (PACS/SPIRE)
- cross-calibration between instruments, satellites, projects
- satellite tracking modes (fastest apparent motion: 12 Victoria with $85.37''$/hour)

Products for the 55 asteroids

For planning purposes (via web-page):

- simple flux predictions (modified STM) for all 55 asteroids at 70, 100, 160, 250, 350, 500 and 3000 μm for the full Herschel mission lifetime (L2-centric frame, time resolution 1 day)
- confusion noise calculation at 100 and 160 μm along the apparent sky pathes
- apparent motion (L2-centric), close encounters between asteroids and with planets + software tools
- ecliptic, galactic, R.A./Dec. and sun-centric coordinates

For the final calibration (on request):

⋆ SED prediction for a given epoch (TPM)

⋆ thermal lightcurve prediction for a given wavelength ($> 5\,\mu$m)

⋆ quality assessment for individual products

⋆ products are delivered as standard FITS-files or ASCII-tables

References: Asteroids as far-IR/submm calibrators

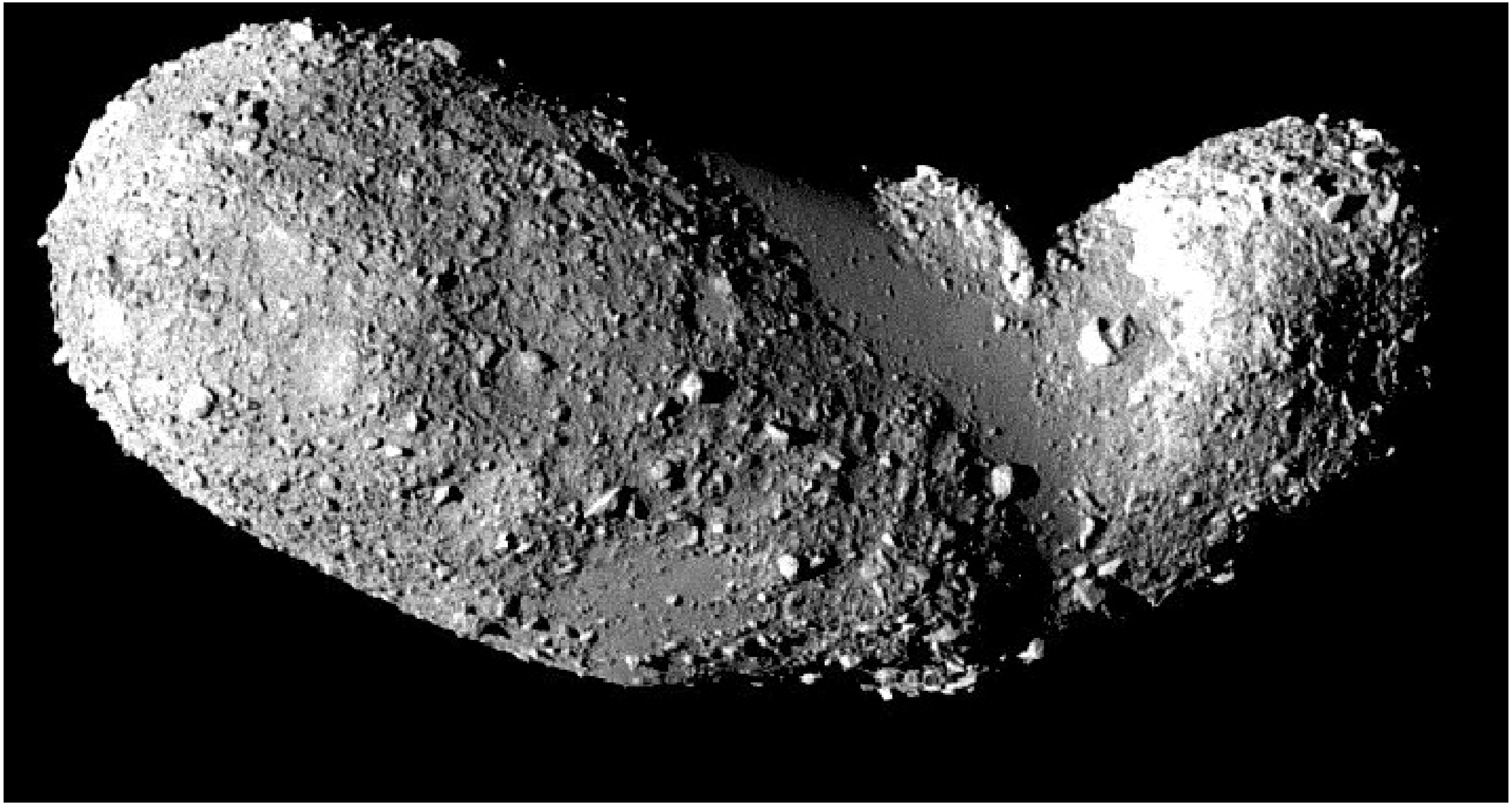
- Lagerros, J. S. V. 1996, A&A 310, 1011; 1997 A&A 325, 1226; 1998 A&A 332, 1123
- Müller & Lagerros 1998, A&A 338, 340
- Müller & Lagerros 2002, A&A 381, 324
- Müller & Lagerros 2003, ESA SP-481, 157
- Müller et al. 2008, A&A, in preparation

- Müller 2002, M&PS 37, 1919: TPM & observations
- Müller & Blommaert 2004, A&A 418, 347: STM vs. TPM
- Müller et al. 2005, A&A 418, 347: Itokawa, thermal lightcurves
- Müller & Barnes 2007, A&A 467, 737: mm-emission
- Kiss et al. 2008, A&A 478, 605: confusion aspects

Ongoing Projects & Open Points

- Filling and maintance of the observation data base: Analysis of recent observations, search for published data, recalibration of old data, identification of missing and/or critical observational data
- Implementation of Kaasalainen shape models and extensive tests with available observations
- Determination of radiometric solutions for size and albedo
- Documentation of the TPM input parameters
- Proposal writing for mid-IR/submm/mm observations + analysis
- Iterations on the asteroid list, establishment of individual TPMs for the selected calibrators
- Support of Spitzer-MIPS calibration, Akari-IRC/FIS calibration
- Submm (CSO) and mm-projects (ATCA)
- groundbased N-/Q-band observations (VISIR)

Although well studied: Itokawa is not a far-IR calibrator



25143 Itokawa as seen by Hayabusa; Credit: ISAS, JAXA

Yes, some asteroids are useful far-IR calibrators