Infrared Asteroid Survey with AKARI
「あかり」衛星による小惑星の赤外線サーベイ

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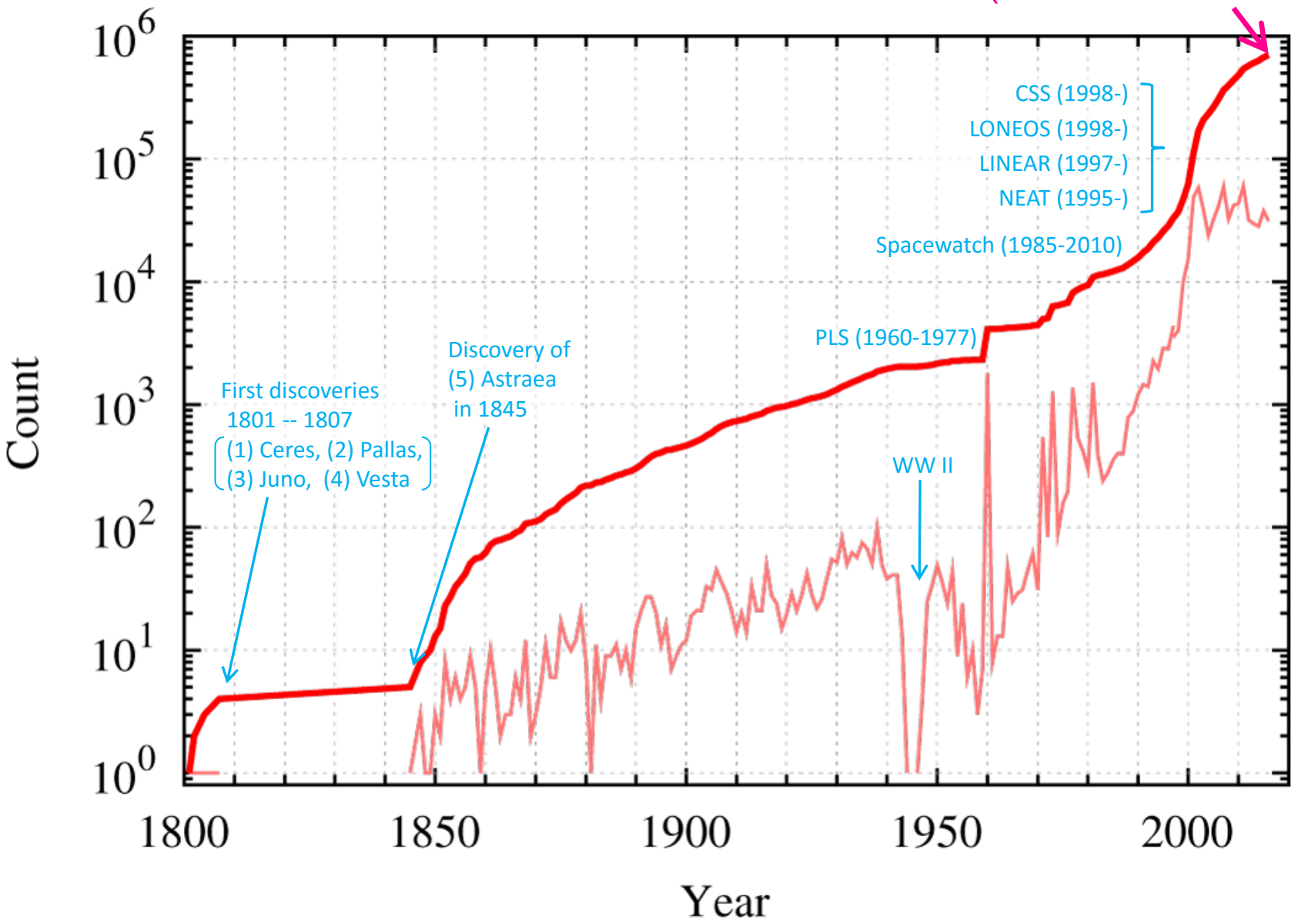
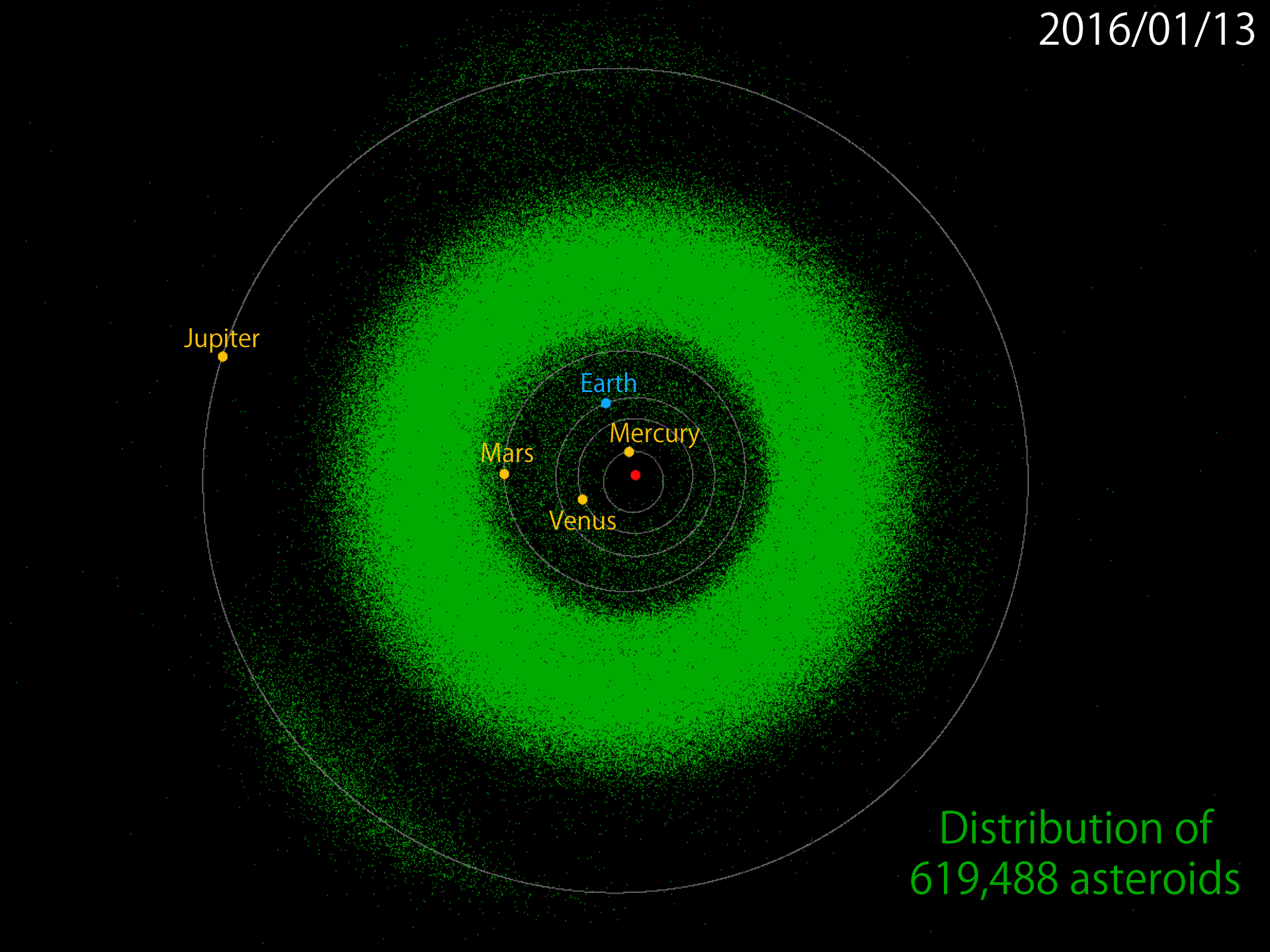
Infrared Asteroid Survey with AKARI

- AKARI mid-infrared asteroid survey
  - Asteroidal size and albedo catalog based on AKARI mid-infrared all-sky survey data

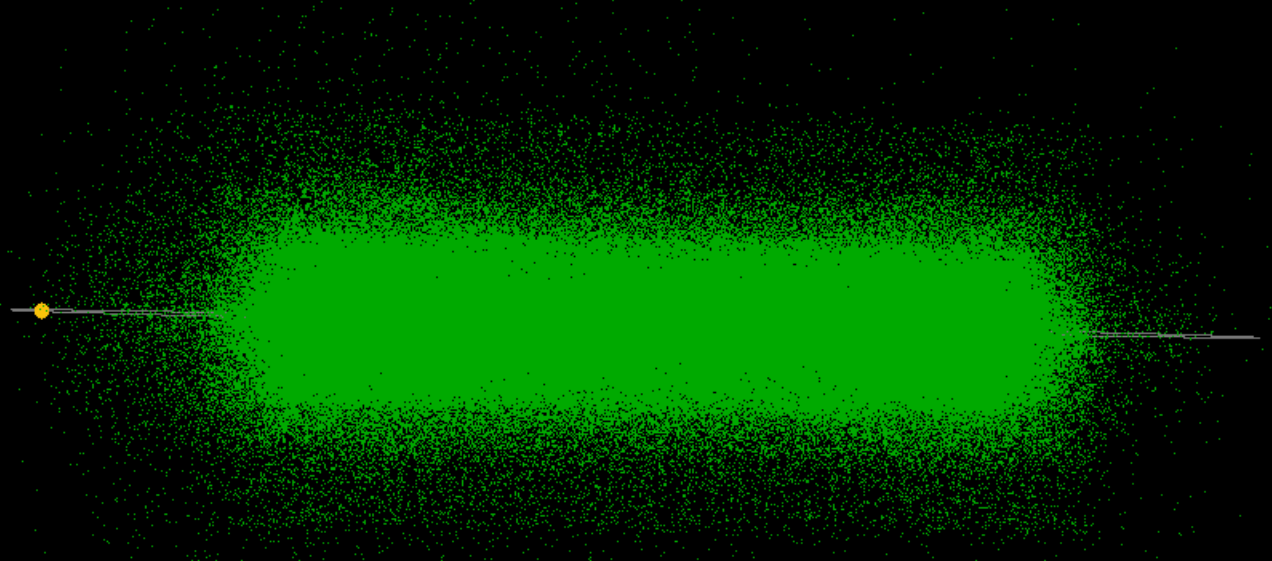
- AKARI near-infrared spectroscopic survey
  - Near-infrared spectroscopic observations with AKARI for exploring hydrated minerals on asteroids

Chronology of the number of discovered asteroids (1801--2015)



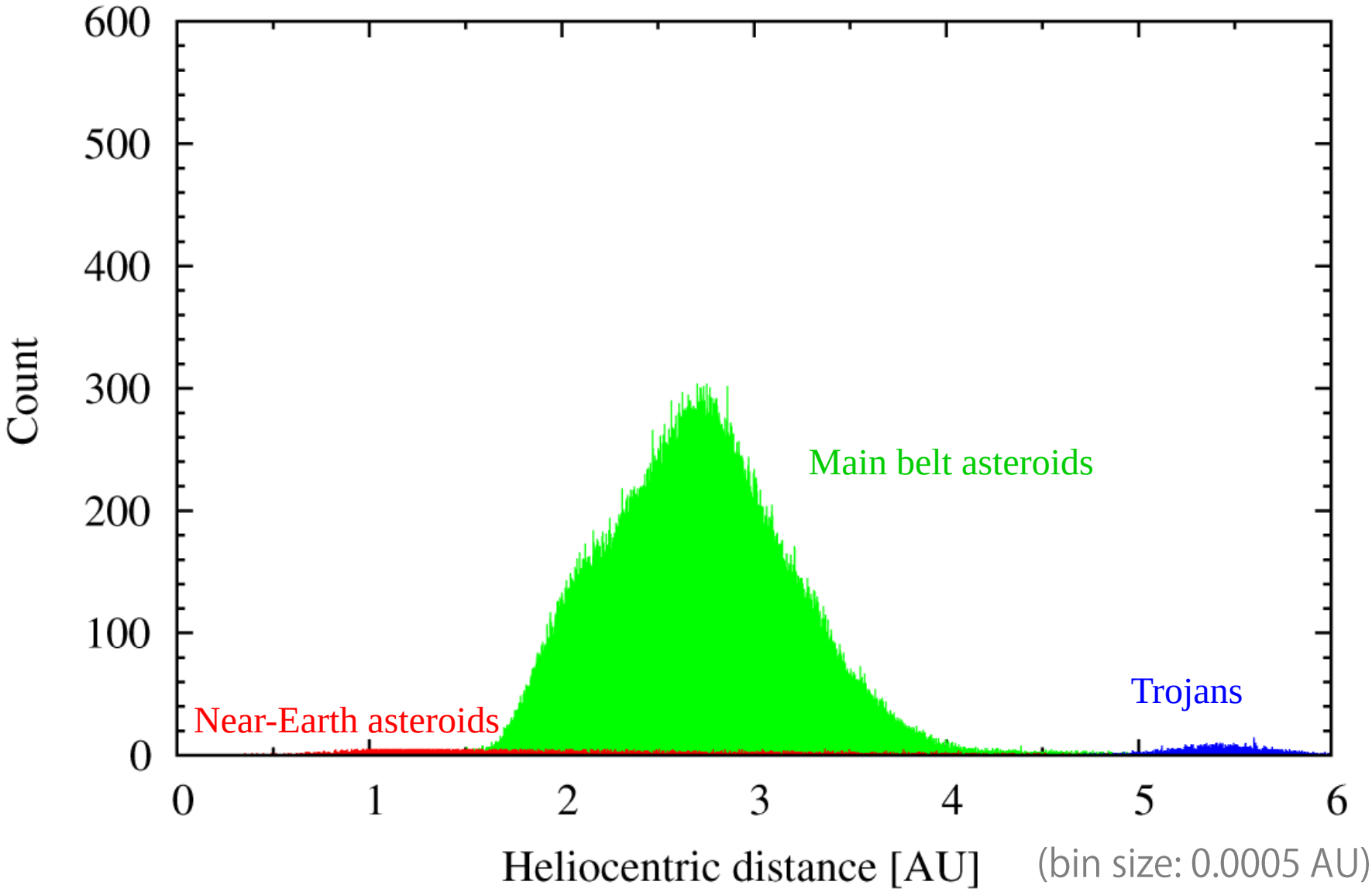

2016/01/13
Jupiter
Earth
Mercury
Mars
Venus
Distribution of
619,488 asteroids

2016/01/13

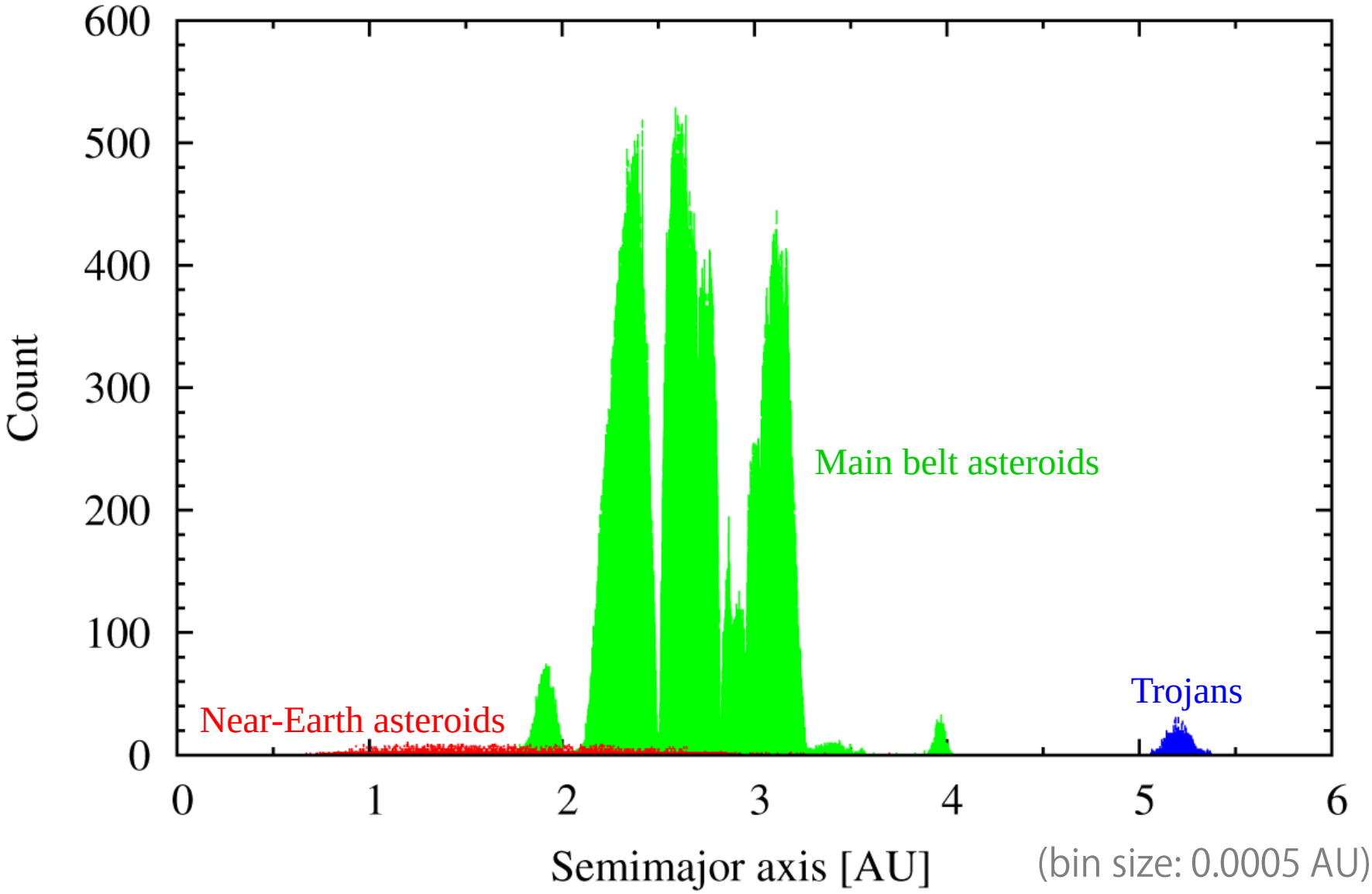


Distribution of
619,488 asteroids

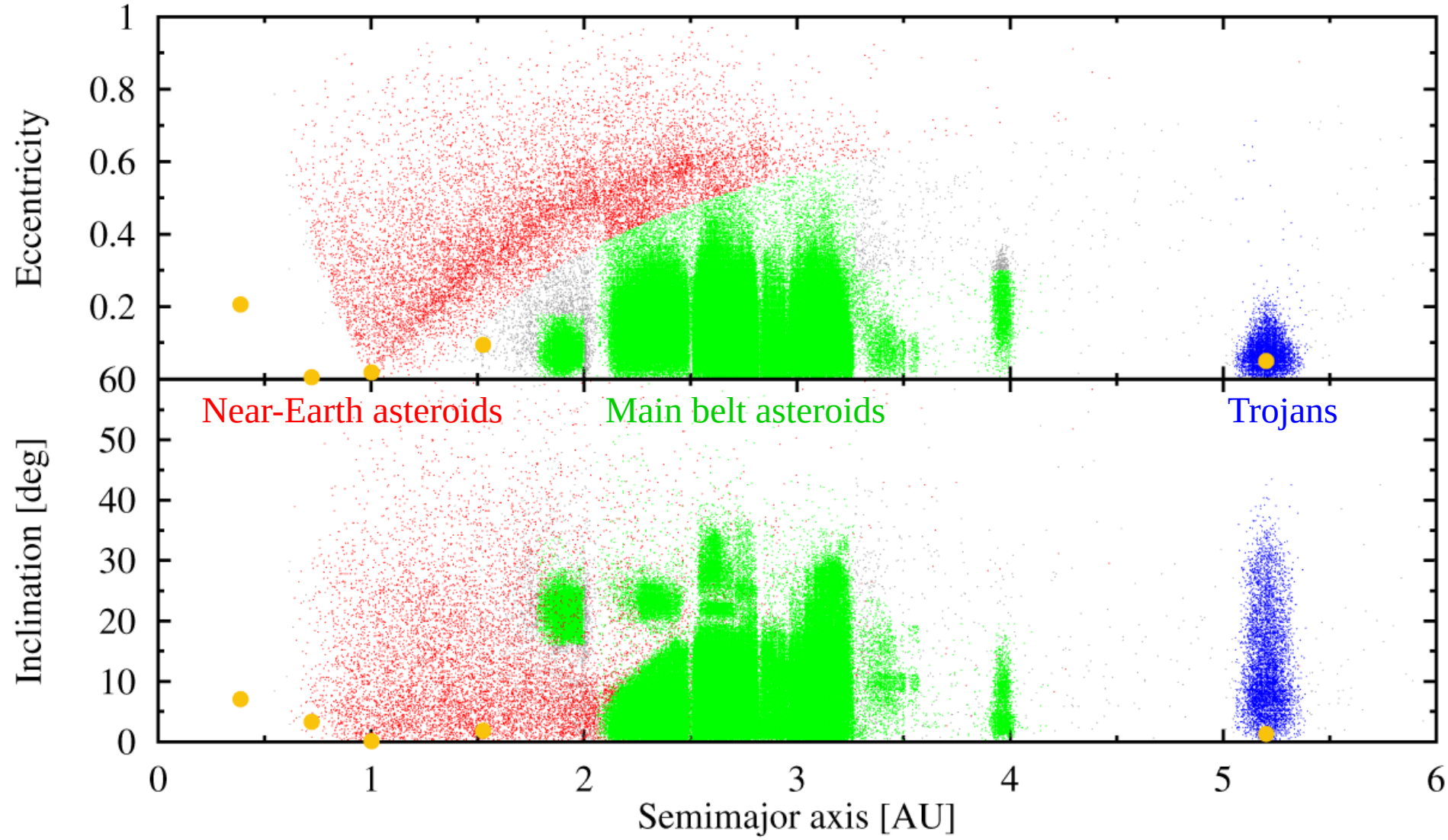
Histogram of number density of asteroids (heliocentric distance：2016/01/13)



Histogram of number density of asteroids (semimajor axis)



Distribution of orbital elements of 653,957 asteroids



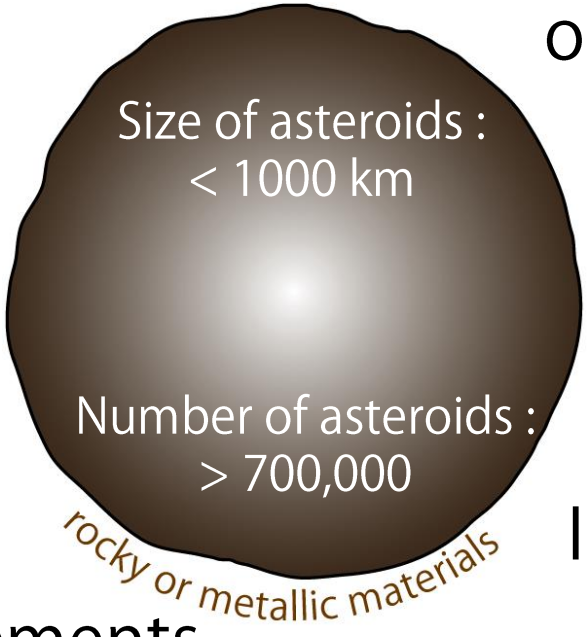
Current status of Asteroid Science

"Interdisciplinary research field"

Theoretical approach

Asteroid

Astronomical observations



Laboratory impact experiments

In-situ observations with spacecrafts

Laboratory measurements (meteorites)

Sample returns

天文観測
(地上・地球周回軌道から)

- ほとんどの場合、空間分解して見ることができない。
- 表面特性が平均化されてしまい、地域差はわからないことが多い。

- 多くの天体を網羅的に観測できる。
- 幅広い範囲の物質分布を研究する手がかりになる。

小惑星探査
(探査機)

- 1つの天体に対して、全球にわたり詳細な観測ができる。
- 表面状態の地域差や地質学的な観測を行うこともできる。
- その場で分析を行うこともできる。

- 1つ(場合によっては数個)の限られた天体にしか行くことができない。
- 詳細な軌道制御が必須で、たまたま小惑星に出会うことはない。

- 最新の計測機器は搭載できない。

天文観測と小惑星探査は
両立した相互発展が必要

- 持ち帰ったサンプルを実験室で詳細に分析することができる。

サンプルリターン

Physical characteristics of asteroids

- Orbital elements
  - Asteroid's position is determined by 6 orbital elements (and time).
  - Data source : MPCORB (Minor Planet Center), Horizons (NASA/JPL), astorb.dat (Lowell Observatory) , …
  - Asteroid family/group is defined by having common orbital elements.
- Size
  - Several techniques are developed to measure the size of asteroids.
  - Direct measurements, in-situ observations with spacecrafts, radar observations, occultations, …
  - Large amount of data are being collected from the infrared space telescopes.
- Color
  - Taxonomic classification of spectral types is established based on (mainly) ground-based telescopes at visible and near-infrared wavelengths.
  - Albedo also has information of the color and/or physical conditions of the surface material.
- And more …
  - Mass, density, rotational period, surface temperature, …

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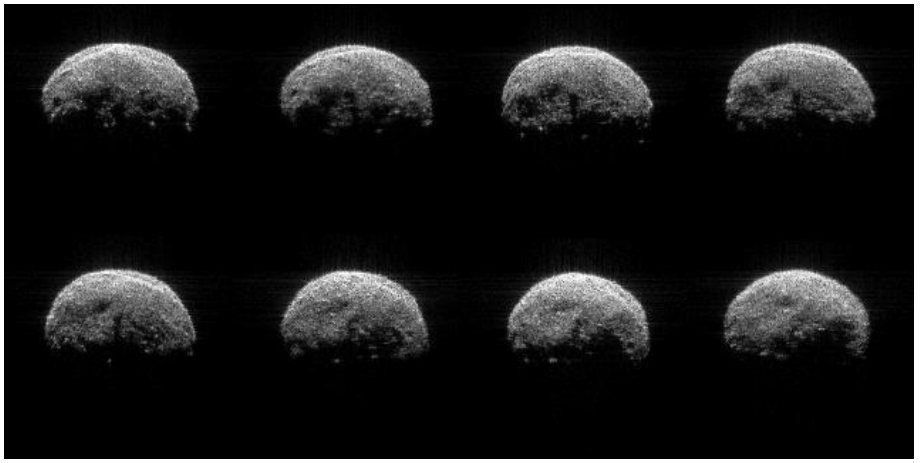
Size of asteroids

- Size (and albedo) is one of the most basic physical quantities of asteroids.
  - Combining size and mass, the bulk density can be determined.
  - Size distribution can help to understand the collisional evolution of asteroids and asteroidal families.
  - Fundamental information for the future Rendezvous / sample return missions.
- Several techniques are developed to measure size of asteroids.
  - Since the beginning of asteroid science in 19th century, measuring size of asteroids is one of the essential tasks.
  - Polarimetric observations, speckle interferometry, radar observations, stellar occultations, direct imaging with HST / ground-based telescopes with AO, in-situ measurements with spacecrafts, etc...
- Radiometric measurements with thermal infrared observations
  - A combination of the thermal infrared flux and the reflected optical flux provide unique solutions for size and albedo.
  - Large amount of data are being collected by infrared space telescopes.

Methods to measure the size of asteroids

- (Direct measurements in 19th century)
- Polarimetric observations
- Speckle interferometry
- Radar observations

2005 YU55 (Goldstone Radar Observations)
2011/11/09

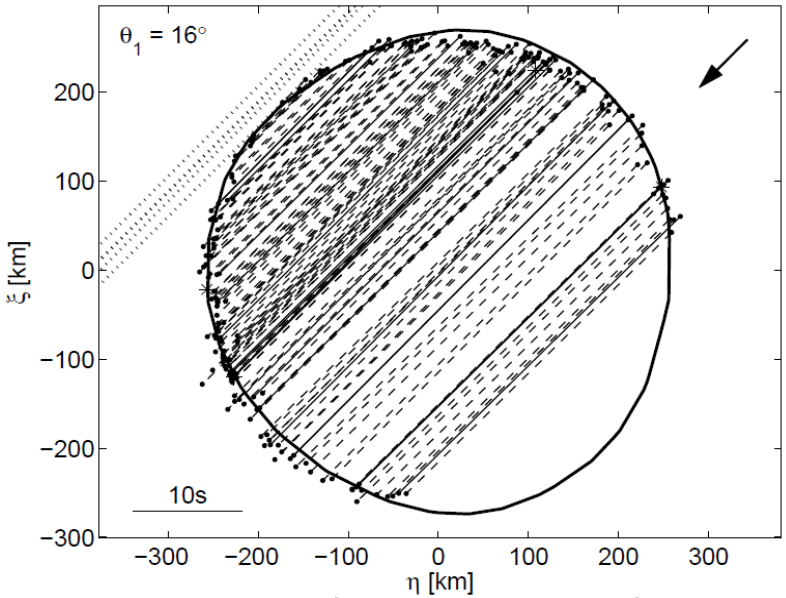


http://echo.jpl.nasa.gov/asteroids/2005YU55/

Methods to measure the size of asteroids

- (Direct measurements in 19th century)
- Polarimetric observations
- Speckle interferometry
- Radar observations
- Stellar occultations

(2) Pallas (with 121 observers)
1983/05/29



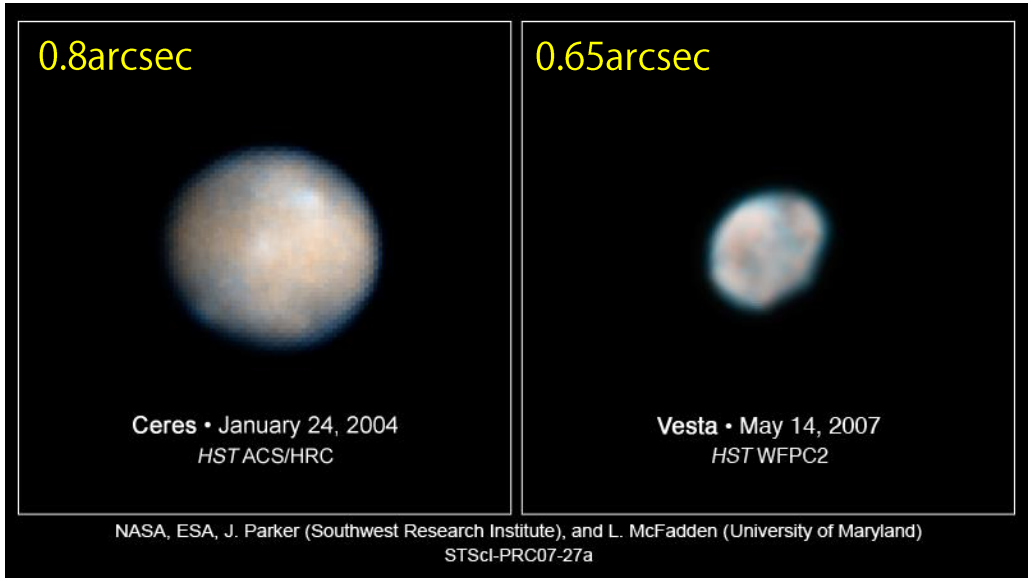
Dunham+1988; Durech+2011

Methods to measure the size of asteroids

- (Direct measurements in 19th century)
- Polarimetric observations
- Speckle interferometry
- Radar observations
- Stellar occultations
- Direct imaging
  - HST

(1) Ceres, (4) Vesta (HST images)

2003/12--2004/01 2007/05



http://hubblesite.org/newscenter/archive/releases/2007/27/

Methods to measure the size of asteroids

- (Direct measurements in 19th century)
- Polarimetric observations
- Speckle interferometry
- Radar observations
- Stellar occultations
- Direct imaging
  - HST
  - Ground-based telescopes with AO
- In-situ measurements with spacecrafts

These methods need :
- large targets with trajectories approaching the Earth
- narrow observational windows
- technically challenging
- a huge amount of cost

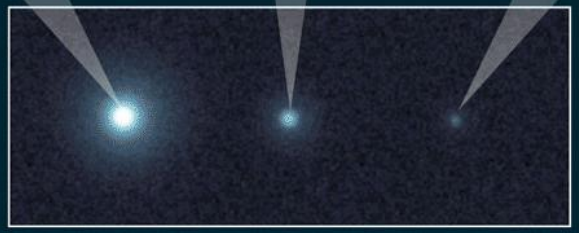
Methods to measure the size of asteroids

- (Direct measurements in 19th century)
- Polarimetric observations
- Speckle interferometry
- Radar observations
- Stellar occultations
- Direct imaging
  - HST
  - Ground-based telescopes with AO
- In-situ measurements with spacecrafts
- Thermal infrared observations with space telescopes

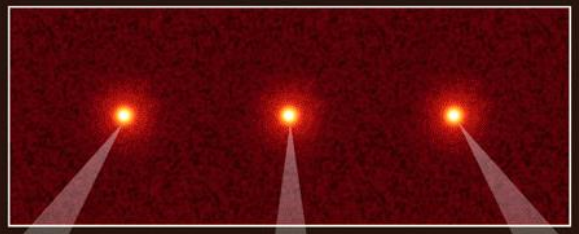
http://wise.ssl.berkeley.edu/gallery_asteroid_albedos.html

Optical brightness depends on the size and albedo of objects.

In optical wavelengths

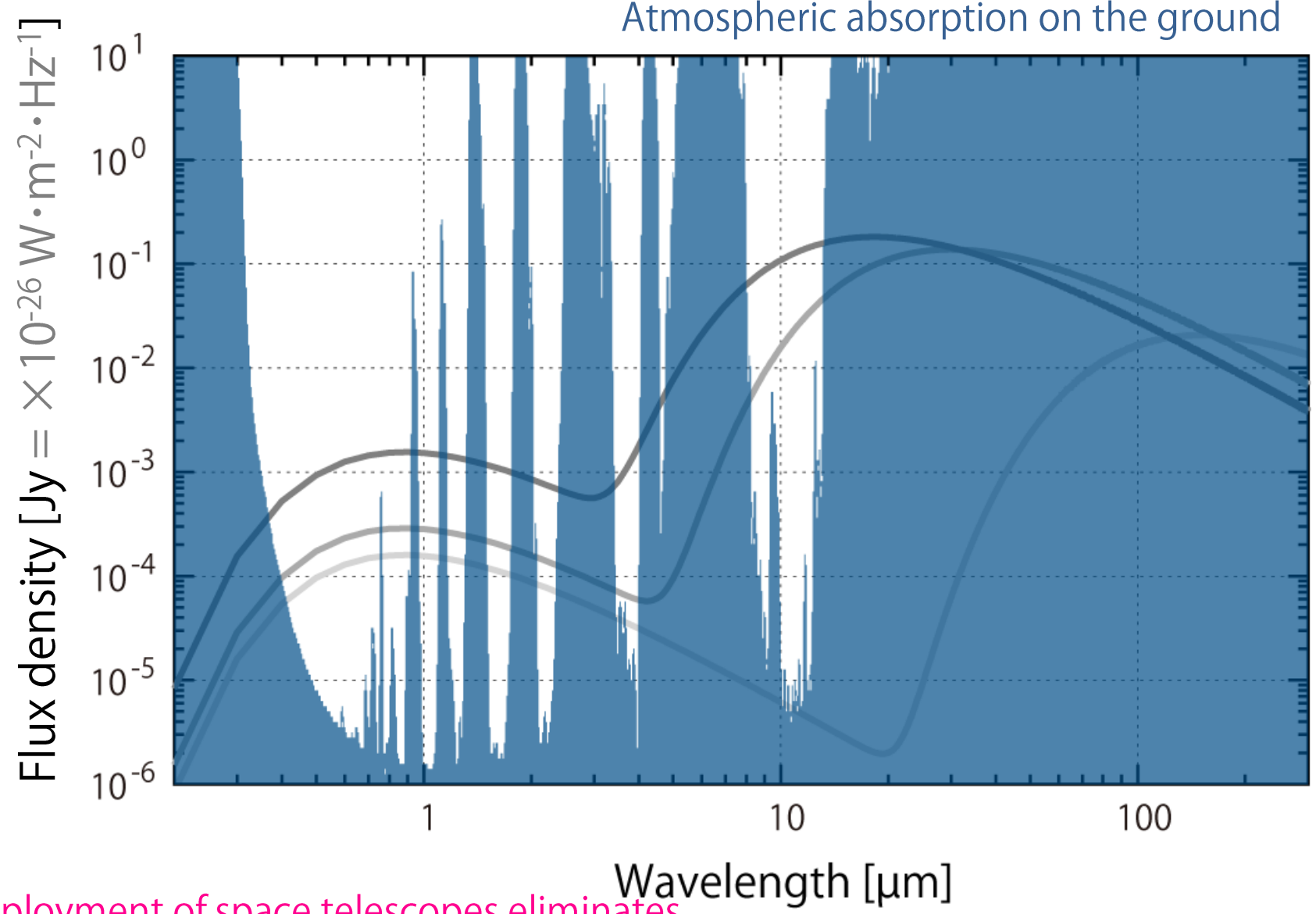


In infrared wavelengths



Infrared brightness depends on their size and temperature (i.e., distance from the sun).

Model spectra of asteroids



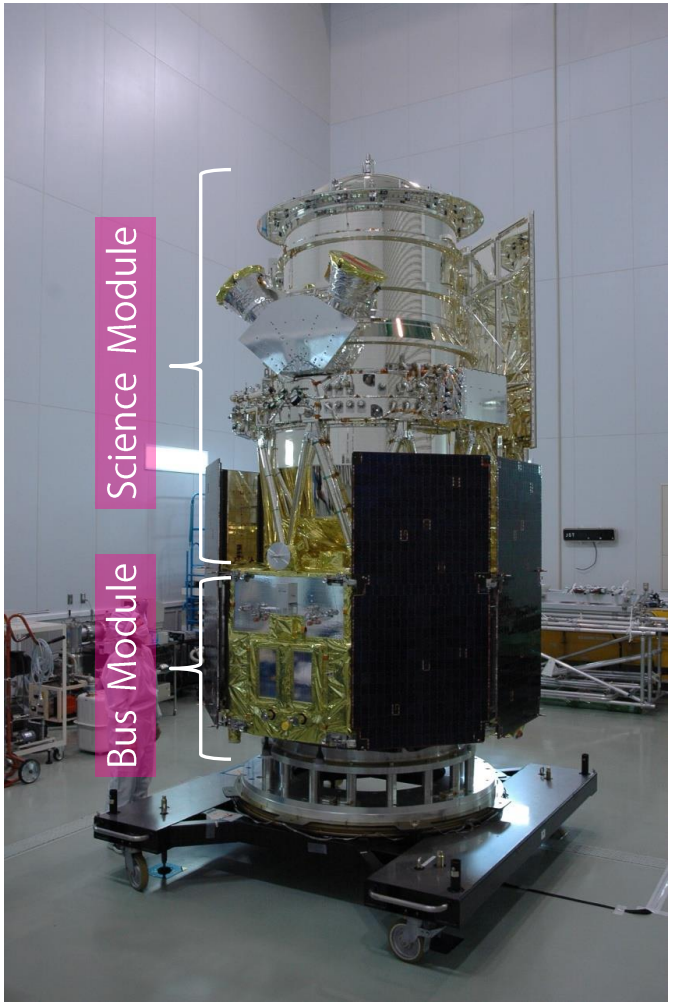
Deployment of space telescopes eliminates the problem of atmospheric absorption !

Infrared astronomical satellite AKARI

Infrared astronomical satellite “AKARI”

(pre-launch name : ASTRO-F)

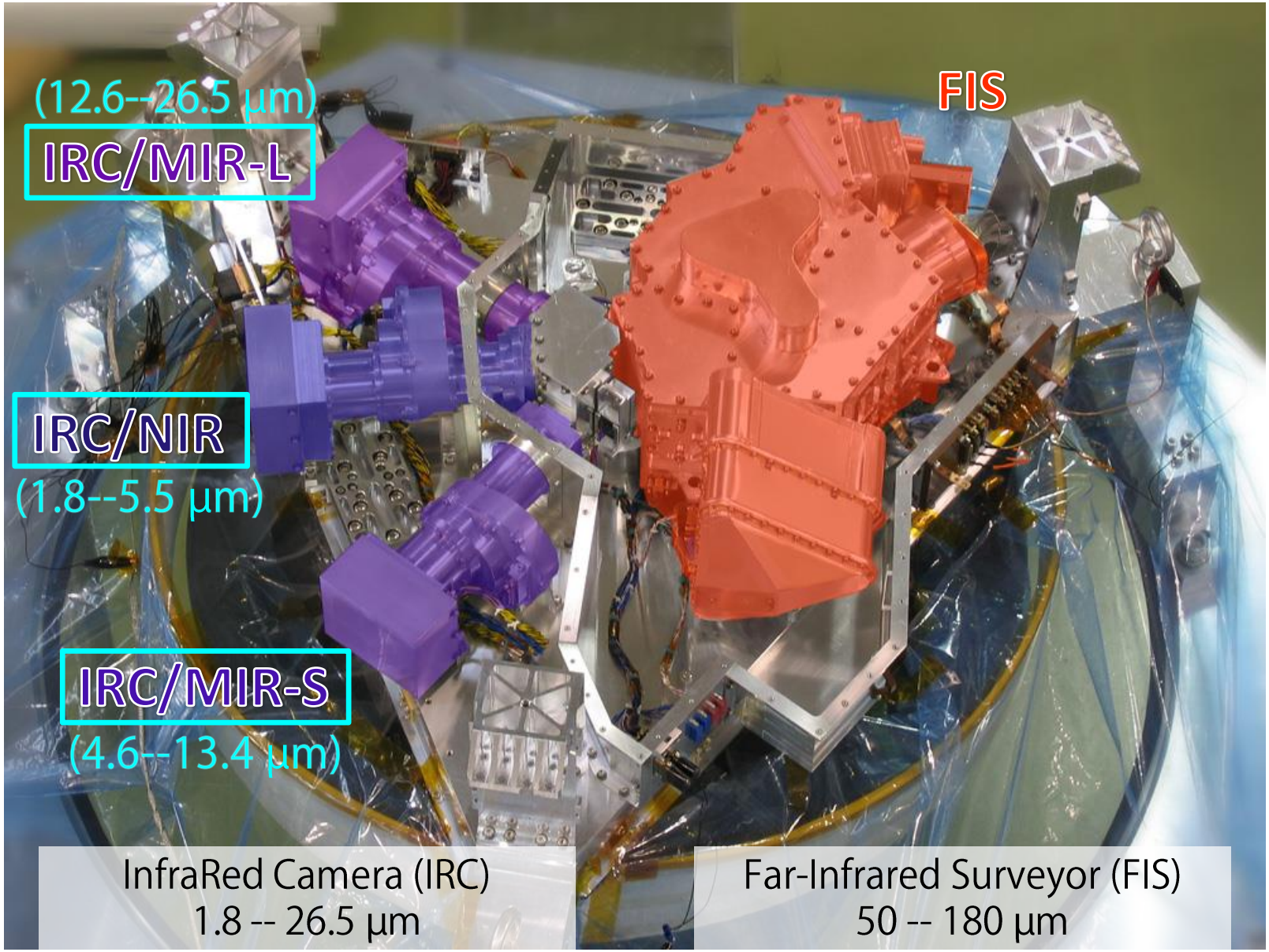
- The first Japanese infrared satellite dedicated to all-sky survey
  - Orbit：altitude=700km, sun-synchronous
  - Size ：5.5×1.9×3.7m (in orbit)
  - Mass：952kg (at launch)
  - Telescope： Ritchey-Chrétien, f/6 (68.5cm SiC)
  - Cryogenics: liquid helium＋mechanical coolers (< 6K)




Telescope


Cryostat

AKARI Focal plane instruments



AKARI All-Sky Survey

- Mission phase：2006/05/08 -- 2007/08/26 (16 months)
  (liquid helium cooled phase)
- Orbit：altitude = 700km sun-synchronous polar orbit
  (day-night boundary)

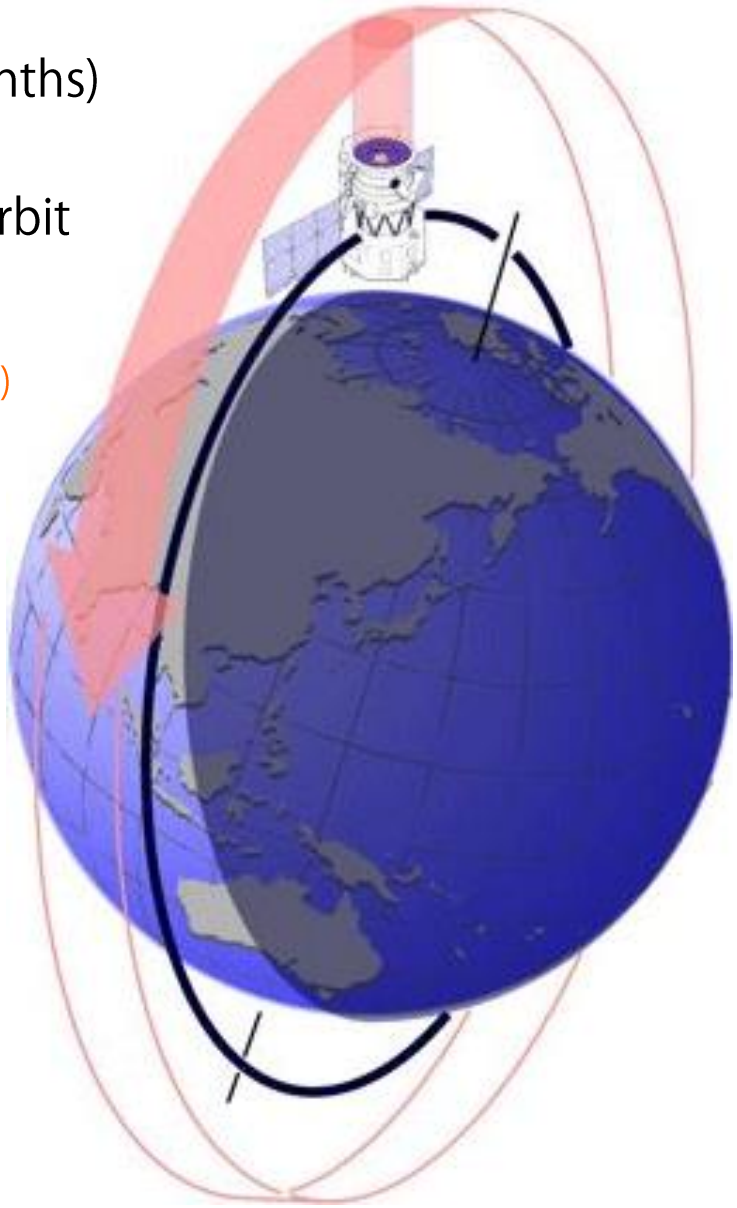
(~direction of ecliptic latitude)

- Orbital period：~100min → scan rate = 3.6′/sec
- Observing in solar elongation of 90±1deg

(~direction of ecliptic longitude)

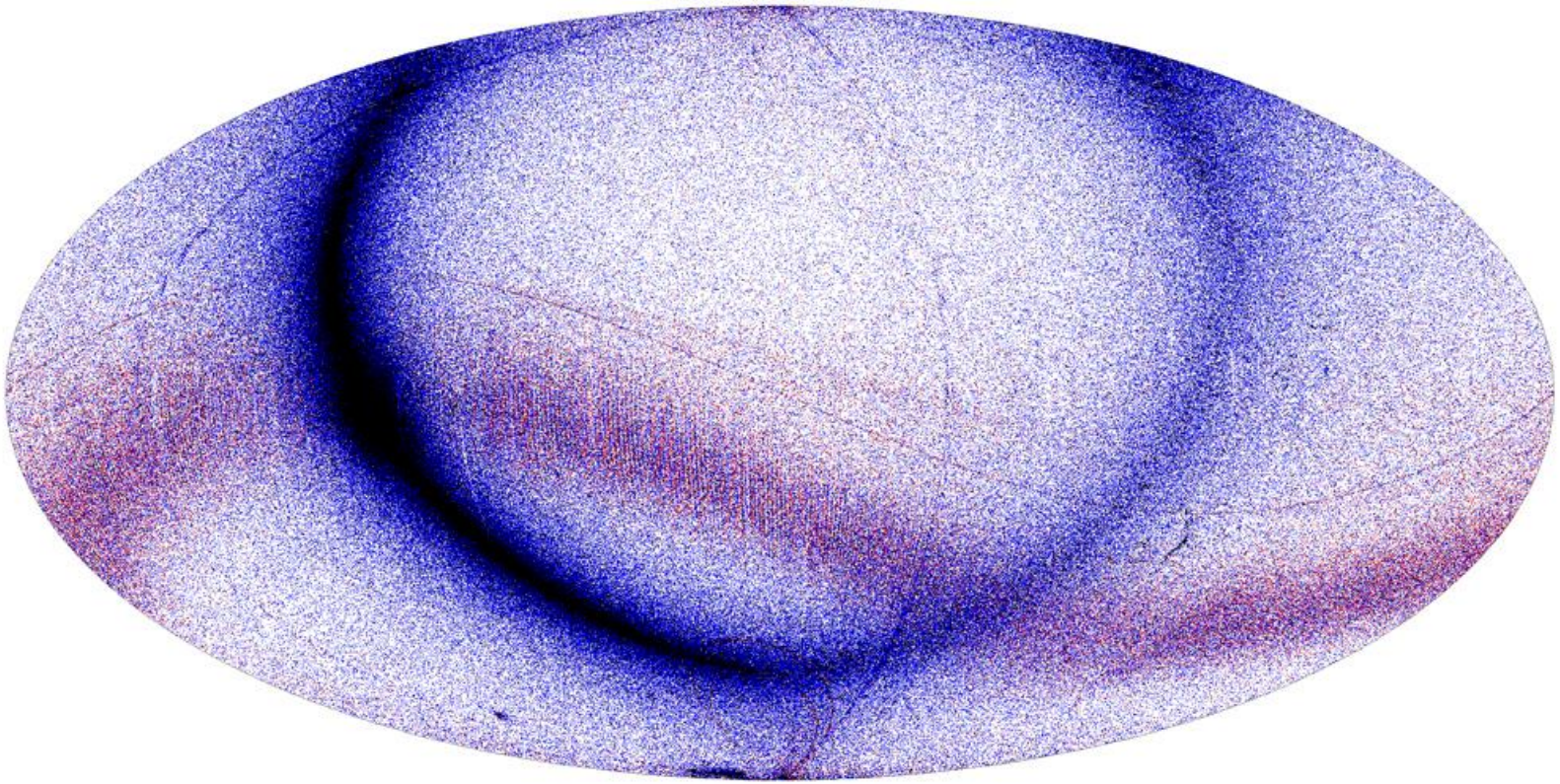
- Scan direction shifted ~4′ every orbital revolution
  → whole sky can be covered in half a year

- Observing wavelength bands
  - IRC：9, 18 μm
  - FIS：65, 90, 140, 160 μm



Distribution of the detected point sources in Ecliptic coordinate

Point sources are extracted by pipeline processing from the mid-infrared part of the all-sky survey image data.



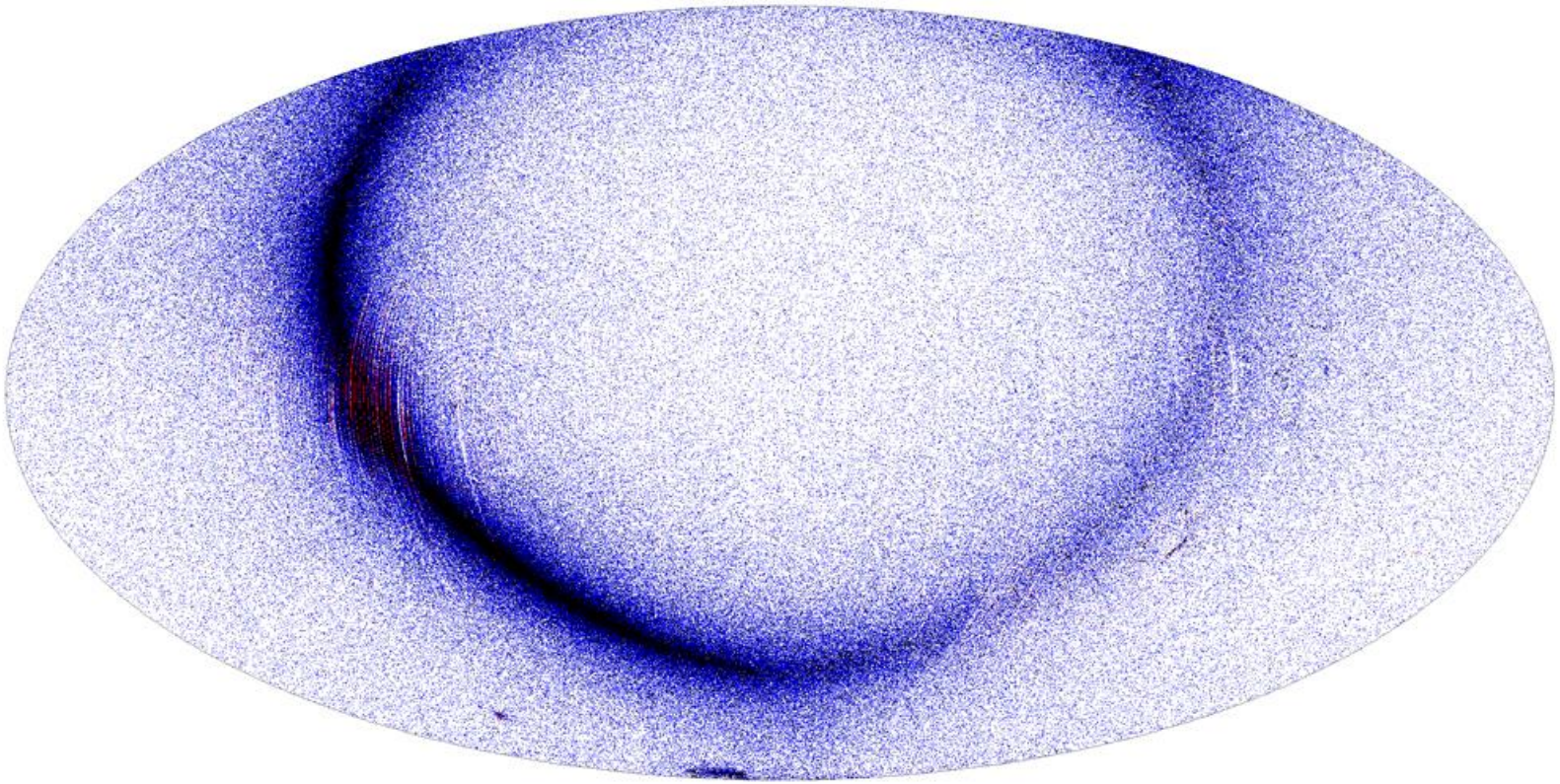
Detected events

MIR-L (18 μm) = 1,244,249

MIR-S (9 μm) = 4,762,074

Distribution of the detected point sources in Ecliptic coordinate

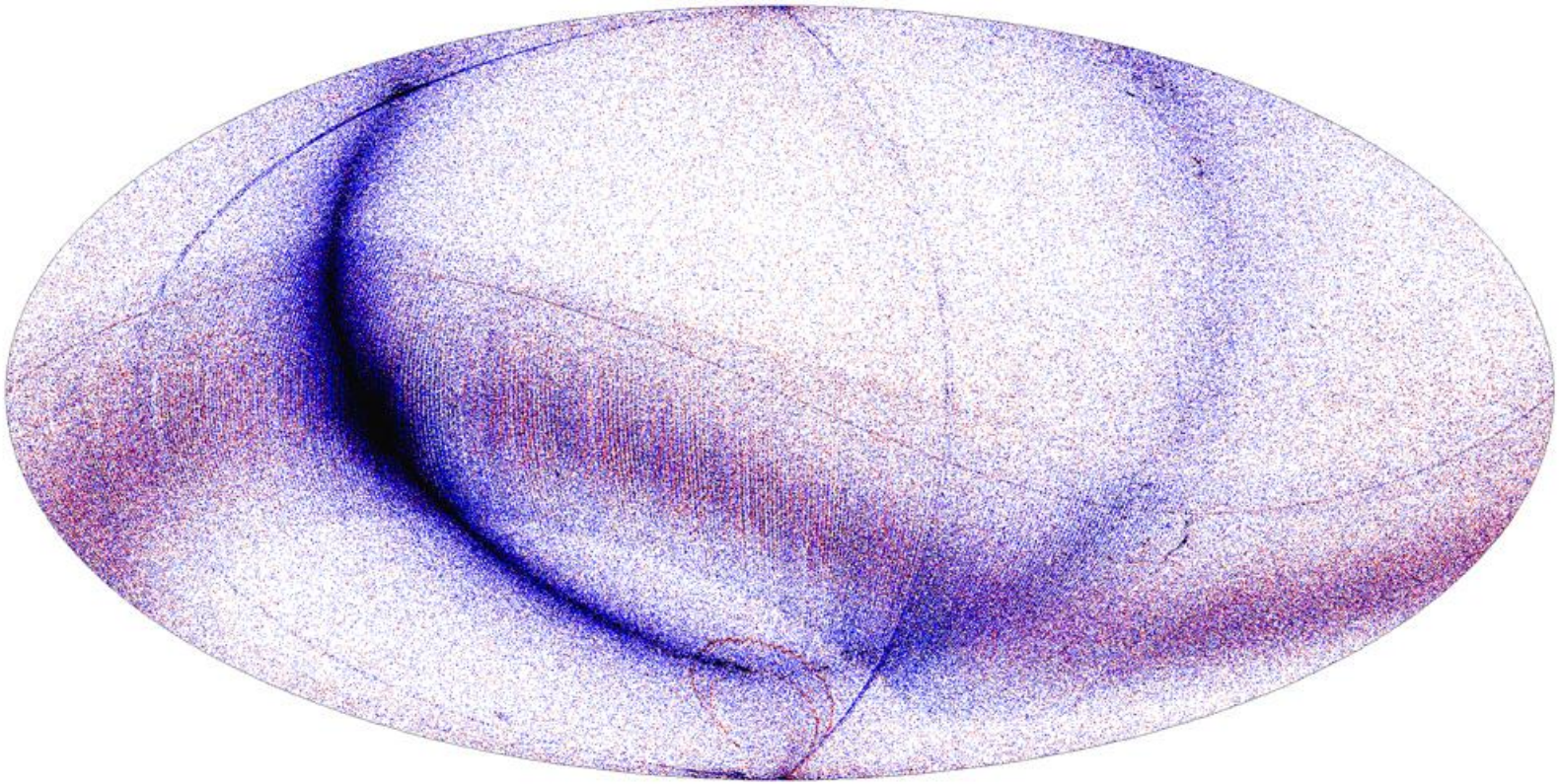
The sources detected twice or more at the same position of the sky are cataloged in the Point Source Catalog (PSC).



	Detected events	Point Source Catalog
MIR-L (18 μm)	1,244,249	936,231
MIR-S (9 μm)	4,762,074	3,882,122

Distribution of the detected point sources in Ecliptic coordinate

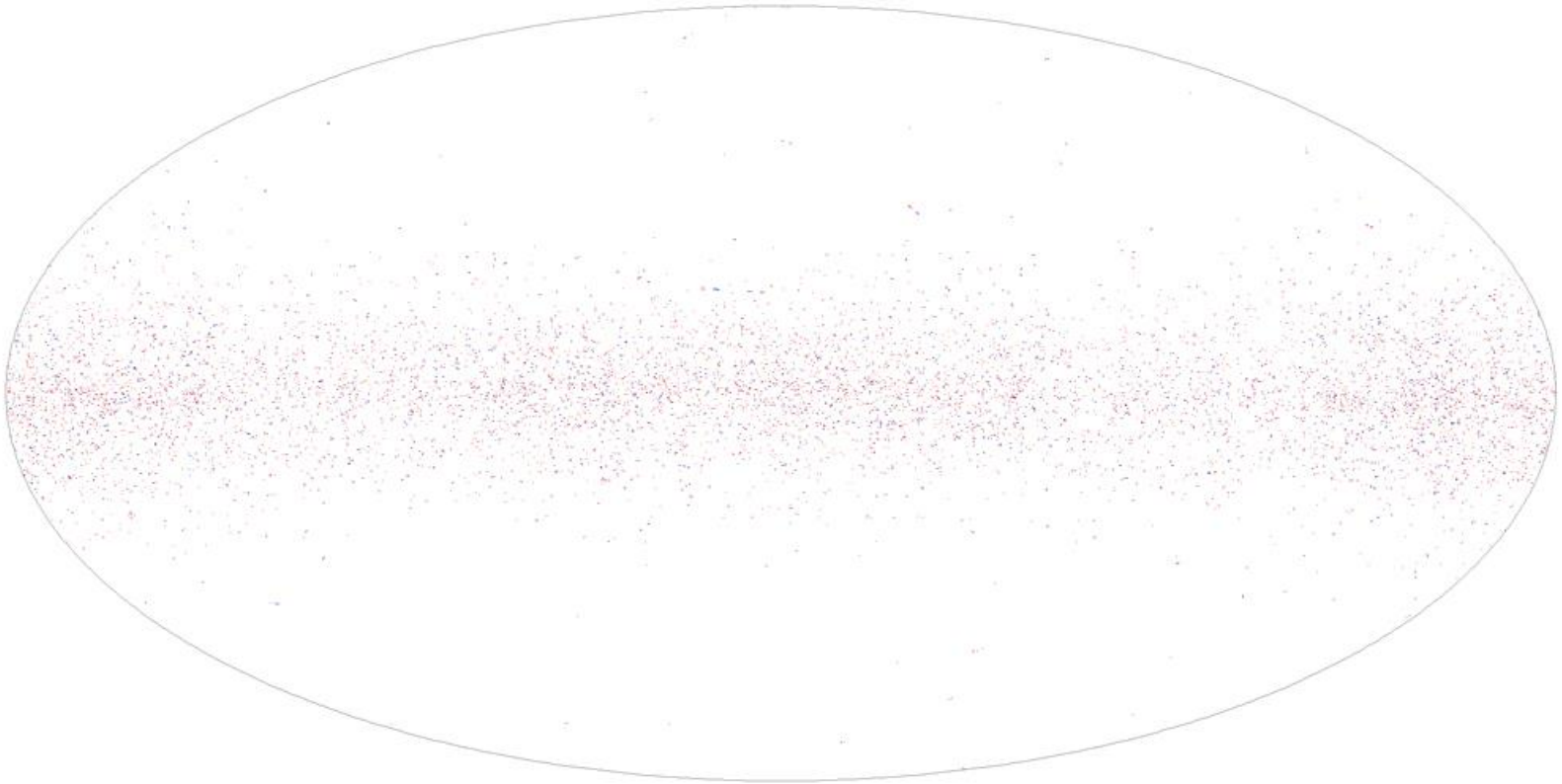
The residuals consist of extended sources, signals due to cosmic rays, geostationary satellites and space debris, and the solar system objects.



	Detected events	Point Source Catalog	Residuals
MIR-L (18 μm) =	1,244,249	936,231	308,018
MIR-S (9 μm) =	4,762,074	3,882,122	879,952

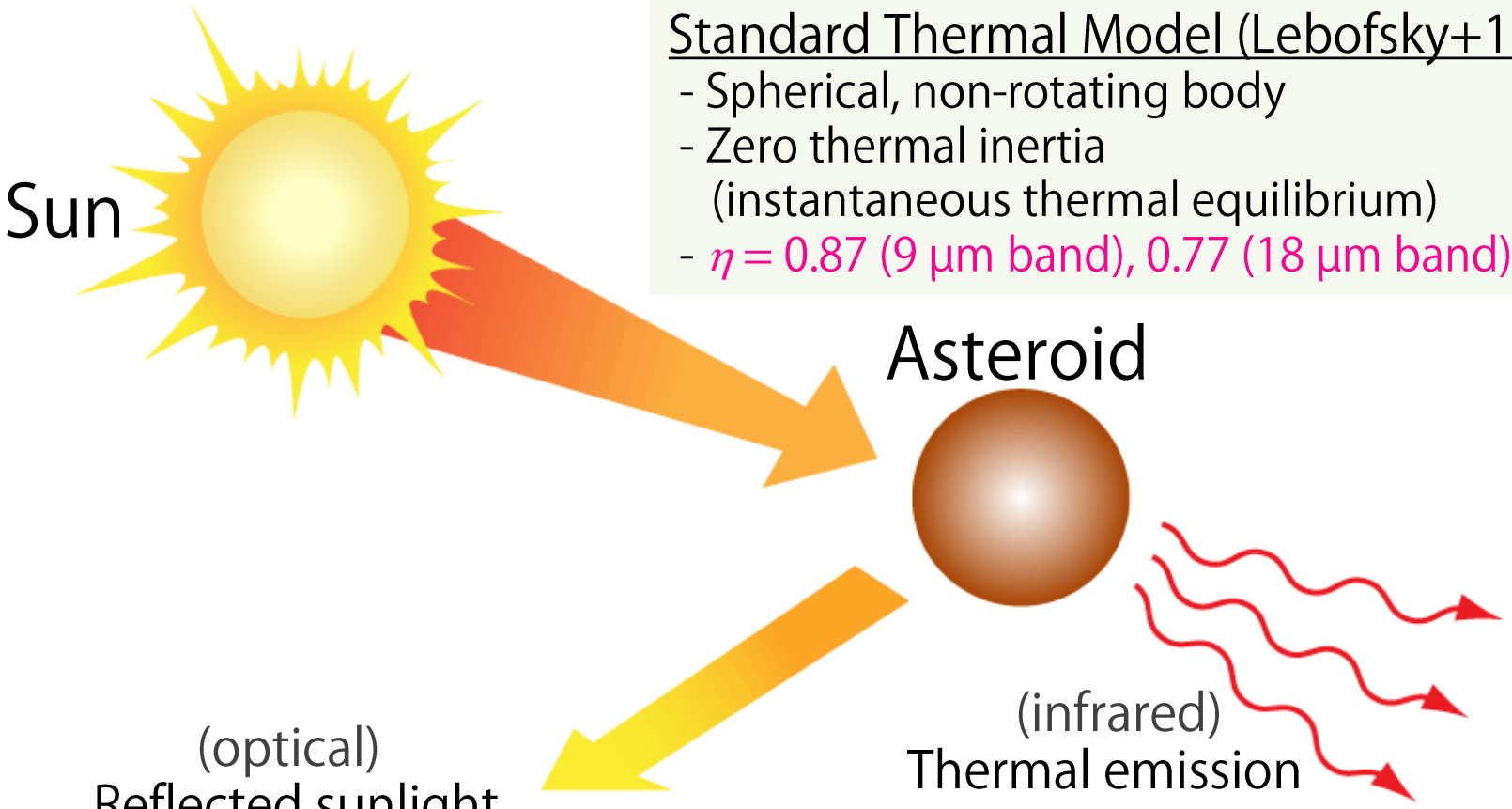
Distribution of the detected point sources in Ecliptic coordinate

Asteroids are identified with detected point sources based on the predicted positions of the asteroids with known orbital elements.



Detected events	Point Source Catalog	Residuals	Asteroid Catalog
MIR-L (18 μm) = 1,244,249	936,231	308,018	13,760
MIR-S (9 μm) = 4,762,074	3,882,122	879,952	6,924
			objects = 5,010 / 3,540 (total 5,120)

Thermal Model Calculations



Standard Thermal Model (Lebofsky+1986)

- Spherical, non-rotating body
- Zero thermal inertia
  (instantaneous thermal equilibrium)
- $\eta = 0.87$ (9 μm band), 0.77 (18 μm band)

$$D = \frac{1329}{\sqrt{p_v}} \cdot 10^{-H^{mag}/5}$$

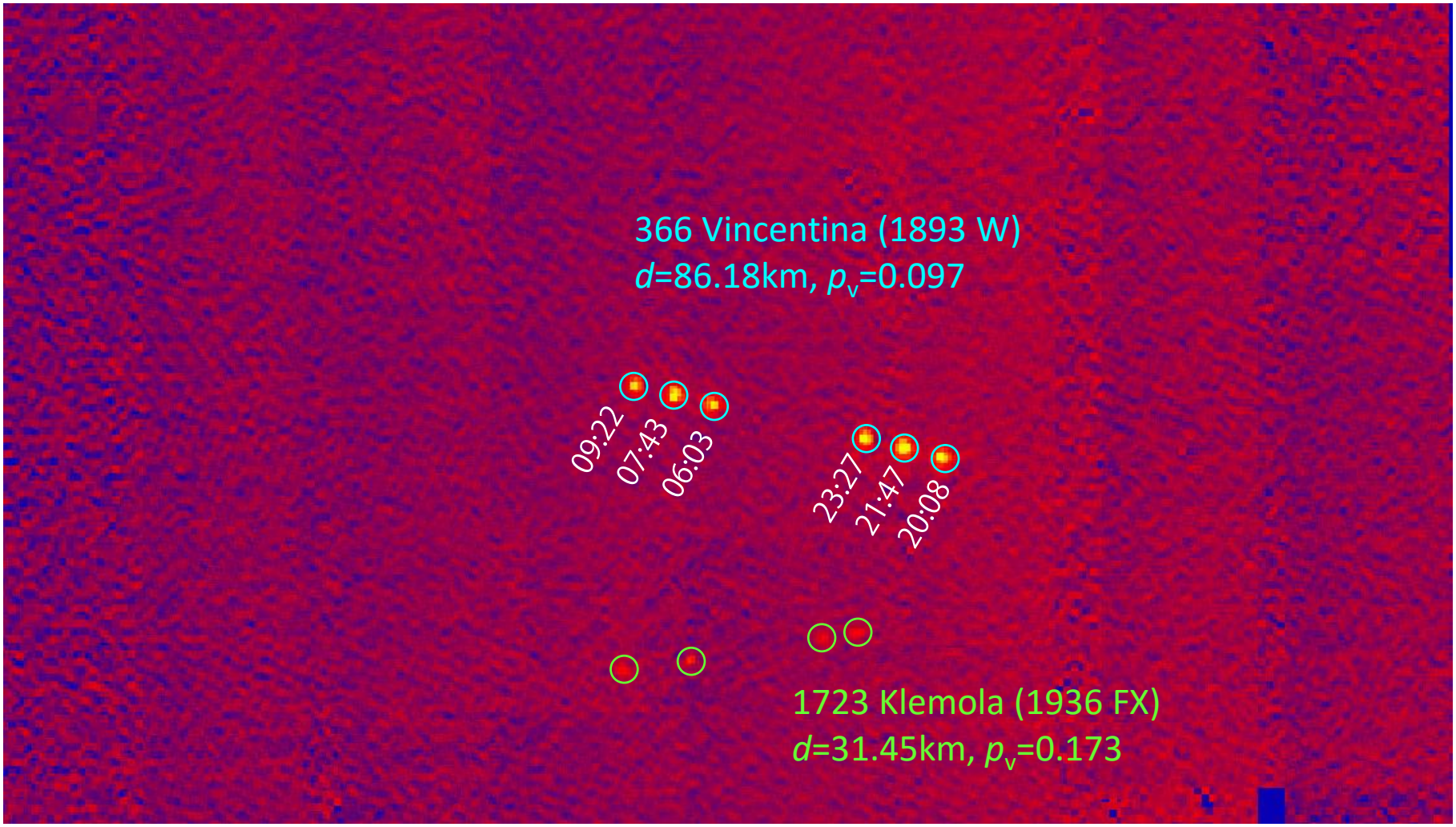
absorption

thermal emission

$$\pi\left(\frac{D}{2}\right)^2 \cdot (1 - A_b)\frac{S_s}{R_h{}^2} = \eta\varepsilon\sigma\left(\frac{D}{2}\right)^2 \cdot \iint T^4(\theta,\varphi)\,d\theta\,d\varphi$$

D: diameter [km], p_v: geometric albedo, H^{mag}: absolute magnitude
A_b: Bond albedo ($A_b = q\,p_v$, $q = 0.290 + 0.684\,G$), G: slope parameter
S_s: incident solar flux, R_h: heliocentric distance, η: beaming parameter, ε: emissivity, σ: Stefan-Boltzmann const.
θ,φ: spherical coordinate of object

Example of All-Sky Survey data (2006/11/12—13)



AKARI asteroid catalog (AcuA)

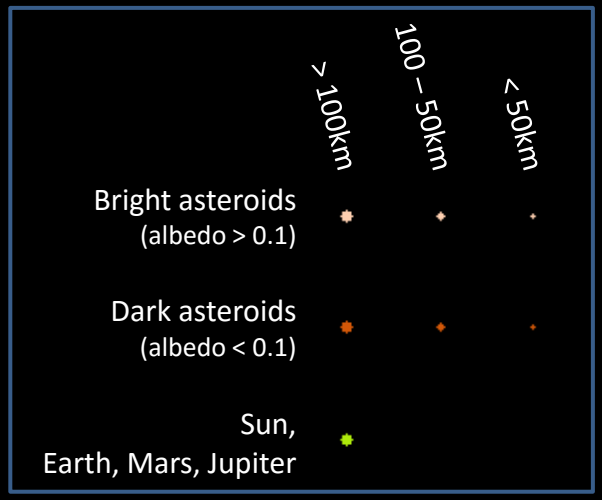
Asteroids: total 5120 detected

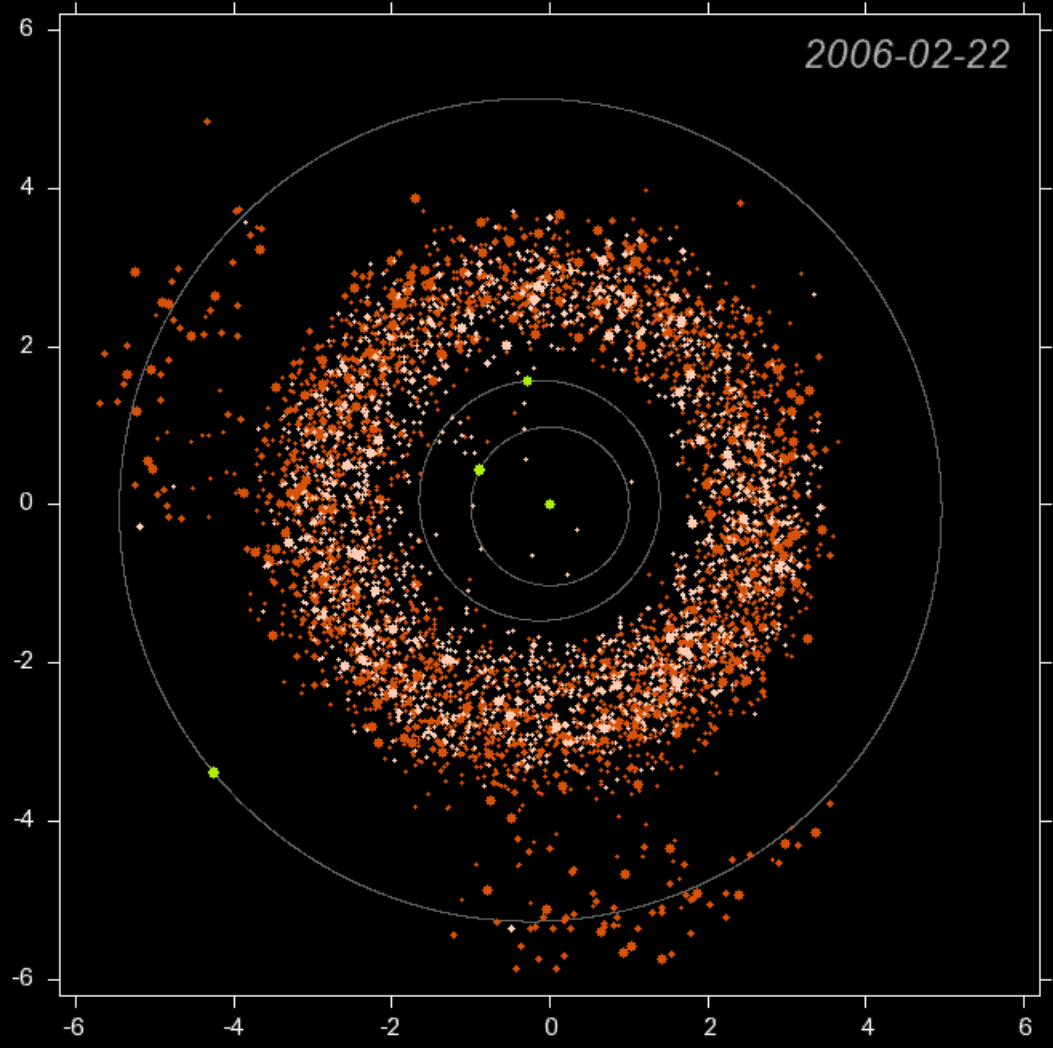
- Main belt asteroids: 4572
- Near-Earth asteroids: 58
- Jovian Trojans: 109
- Others (Hildas, Cybeles, ...): 381

Animation:

2006/02/22 – 2007/08/27

- Obs. start: 2006/04/23 (05/08)
- LHe boiled off: 2007/08/26



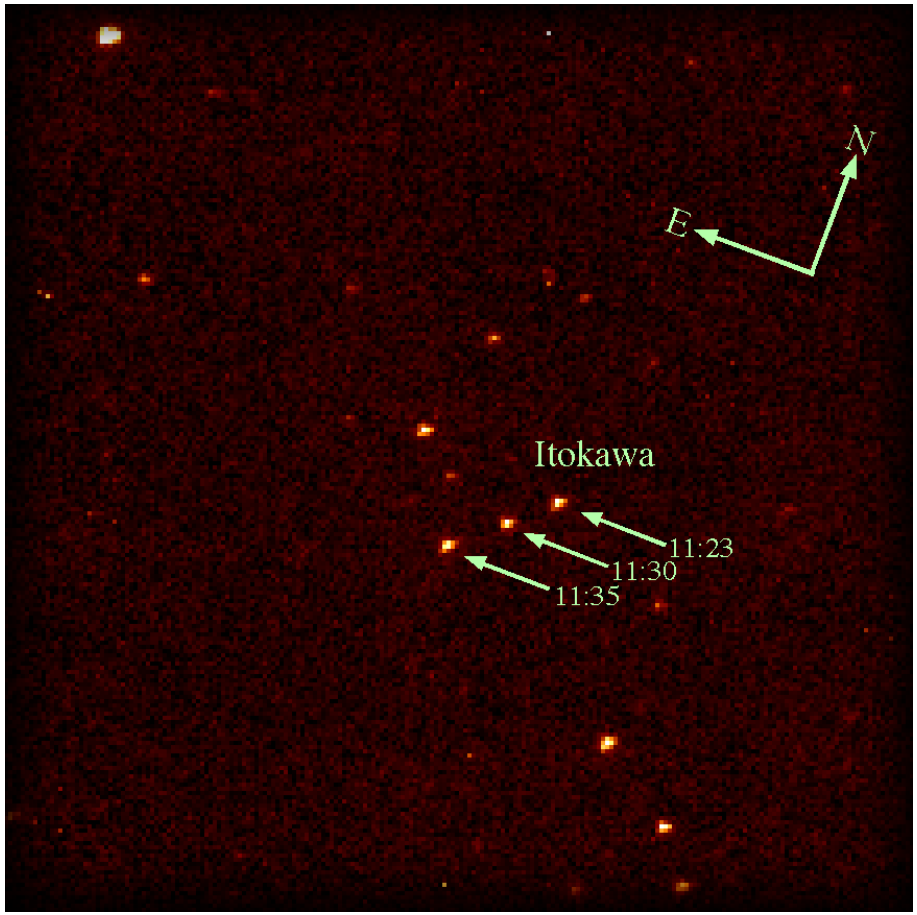


Asteroid catalog using AKARI (AcuA)

- AKARI asteroid survey was conducted from the mid-IR survey data of AKARI/IRC.
  - Unbiased asteroid survey in the mid-infrared wavelengths including sizes and albedos of 5120 asteroids
  - Duration of survey observation： 2006/05 -- 2007/08 (16 months)
  - Wavelengths : 9 μm (MIR-S), 18 μm (MIR-L)
  - Catalog data is open to the public : http://darts.jaxa.jp/ir/akari/catalogue/AcuA.html
  - Note that the flux data of individual asteroids observed with AKARI will also be released in the near future.

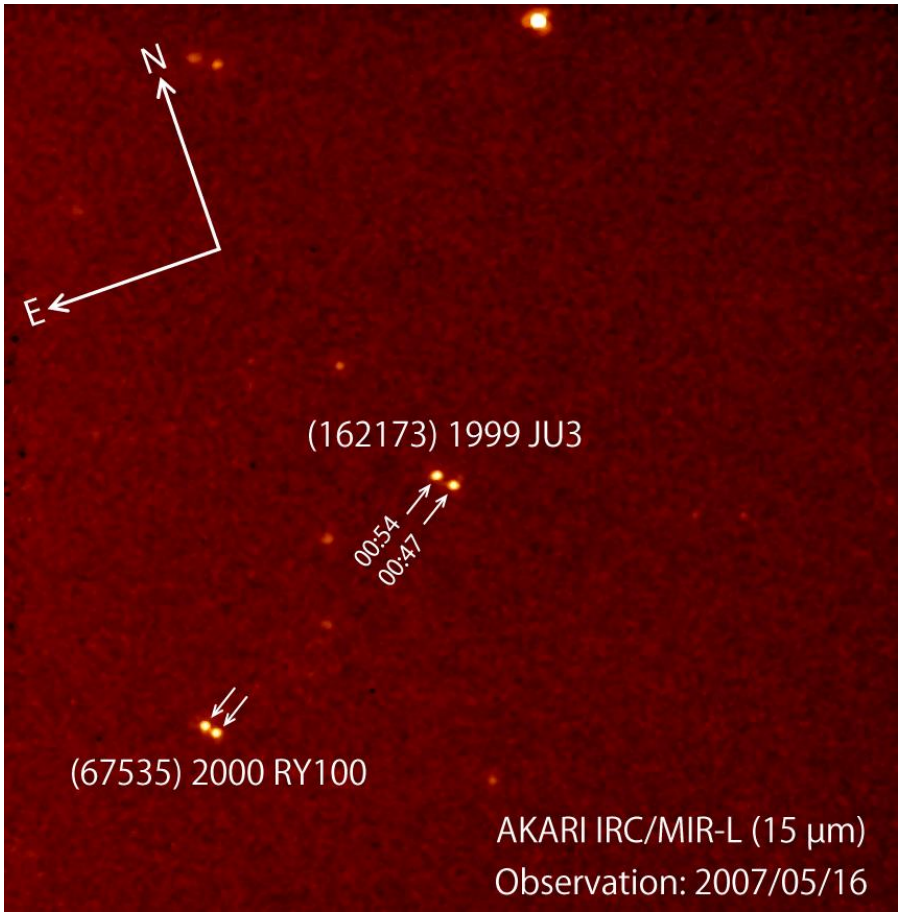
Itokawa and Ryugu

(25143) Itokawa



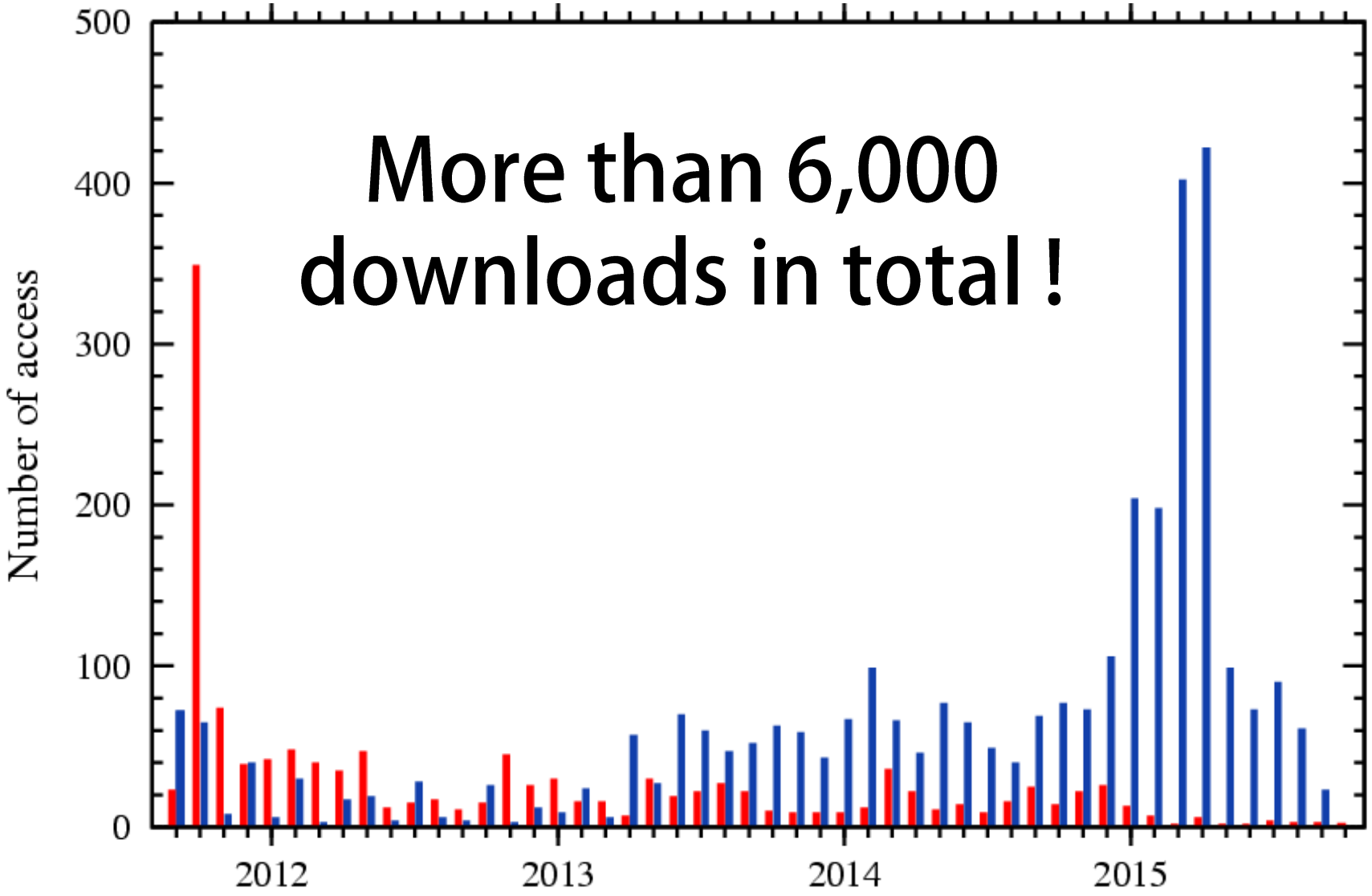
(2007/07/26)

(162173) Ryugu



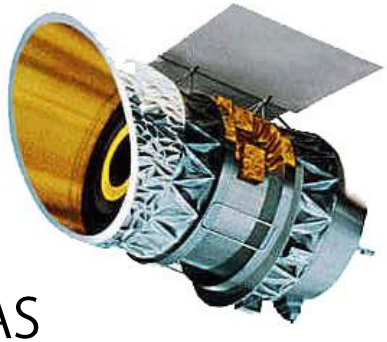
(2007/05/16)

Number of data access to the catalog file
(2011/09--2015/09)



- DARTS/ISAS (http://darts.jaxa.jp/ir/akari/catalogue/AcuA.html)
- CDS/Strasbourg (http://cdsarc.u-strasbg.fr/cgi-bin/VizieR?-source=J/PASJ/63/1117)

Infrared all-sky surveyors



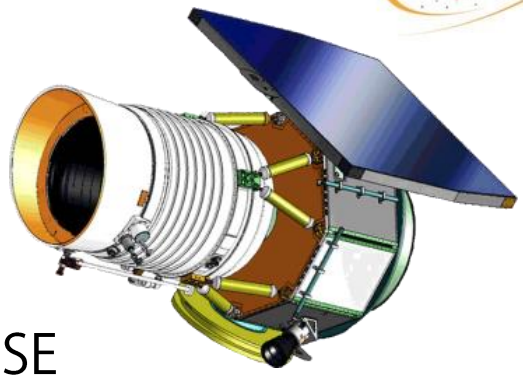
IRAS

Infrared Astronomical Satellite
(USA, Netherlands, UK)

Launched in 1983, altitude = 900km

All-sky survey：9.5 months

A pioneering systematic survey
with space-borne telescope



WISE

Wide-field Infrared Survey Explorer
(USA)

Launched in 2009, altitude = 525km

All-sky survey：9 months

On-boarding higher sensitivity
infrared detectors

AKARI

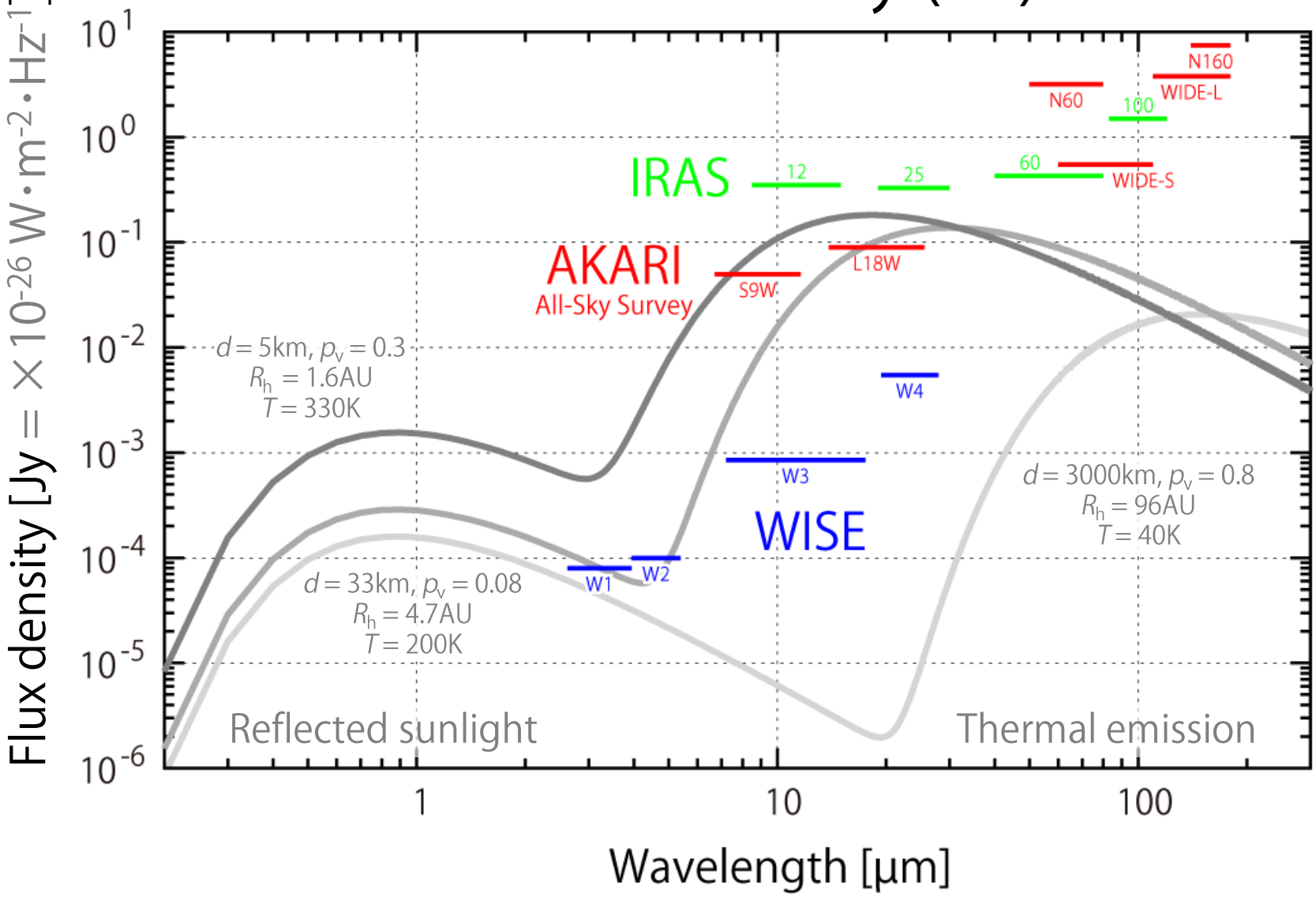
(Japan + ESA)

Launched in 2006, altitude = 750km

All-sky survey：16 months

Conducting a 16-month continuous survey

Model spectra of asteroids and detector sensitivity (5σ)



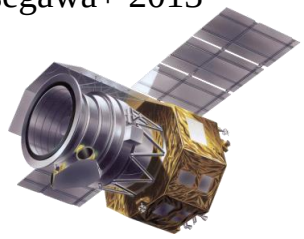
Neugebauer+1984; Ishihara+2010, Yamamura+2010; Wright+2010, Mainzer+2011

Asteroid catalog from three infrared surveyors

- IRAS (Supplemental IRAS Minor Planet Survey: SIMPS)
  - Tedesco+2004
  - Catalog data: opened at NASA/Planetary Data System
    http://sbn.psi.edu/pds/resource/imps.html (last modified: 2006/02)
- AKARI (Asteroid catalog using AKARI: AcuA)
  - Usui+2011
  - Catalog data: opened at ISAS/DARTS (Data ARchives and Transmission System)
    http://darts.jaxa.jp/ir/akari/catalogue/AcuA.html (2011/09)
- WISE/NEOWISE
  - Catalog data is published as the online table of journal
    - Main belt asteroids : Masiero+2011, Masiero+2012, Masiero+2014
    - Jovian Trojans : Grav+2011, Grav+2012
    - Near Earth objects : Mainzer+2011, Mainzer+2012, Mainzer+2014
    - Hilda group : Grav+2012
  - Final version will be opened at NASA/Planetary Data System.

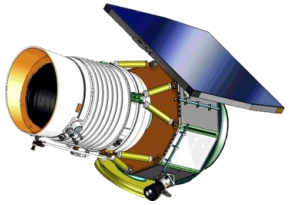
Number of asteroids detected by IRAS, AKARI, and WISE

Usui+ 2011
Hasegawa+ 2013

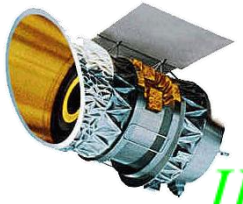


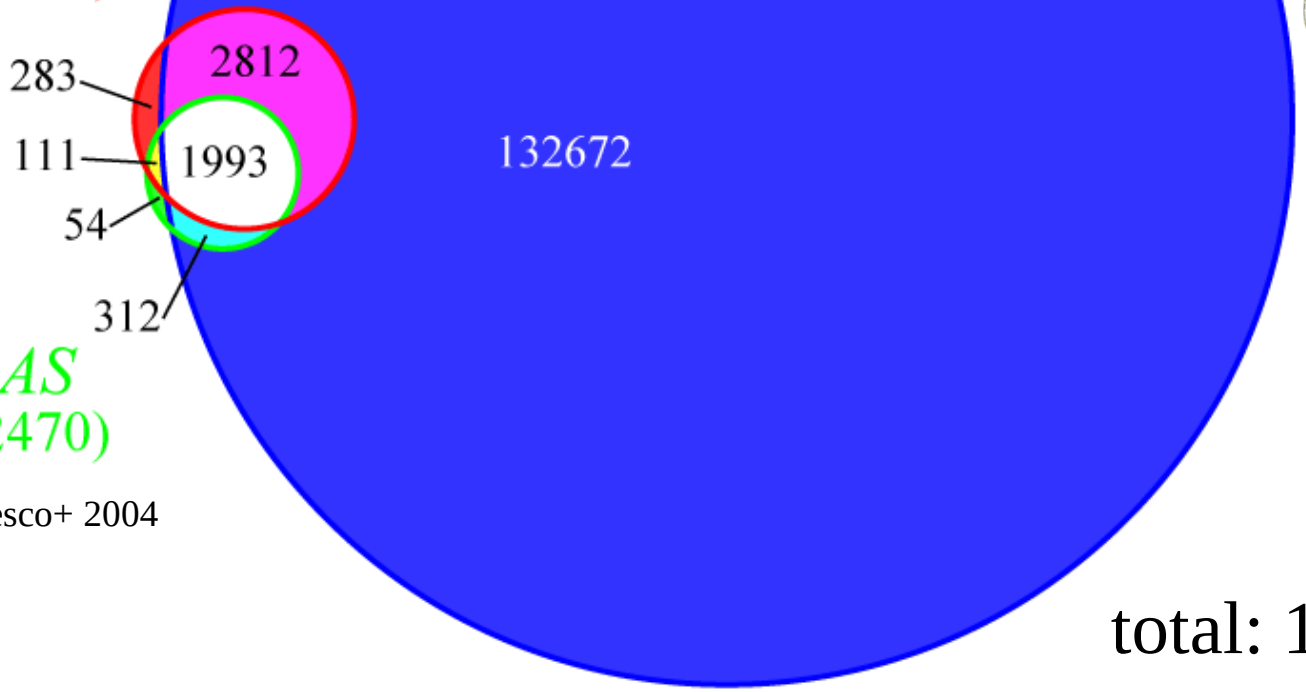
WISE
(137789)

Mainzer+ 2011, 2012
Masiero+ 2011, 2012
Grav+ 2011, 2012a, b



AKARI
(5199)





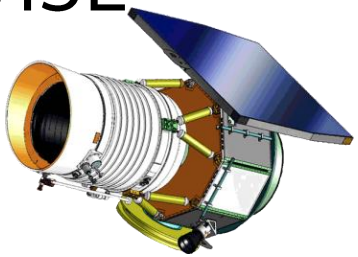
IRAS
(2470)

Tedesco+ 2004

total: 138237

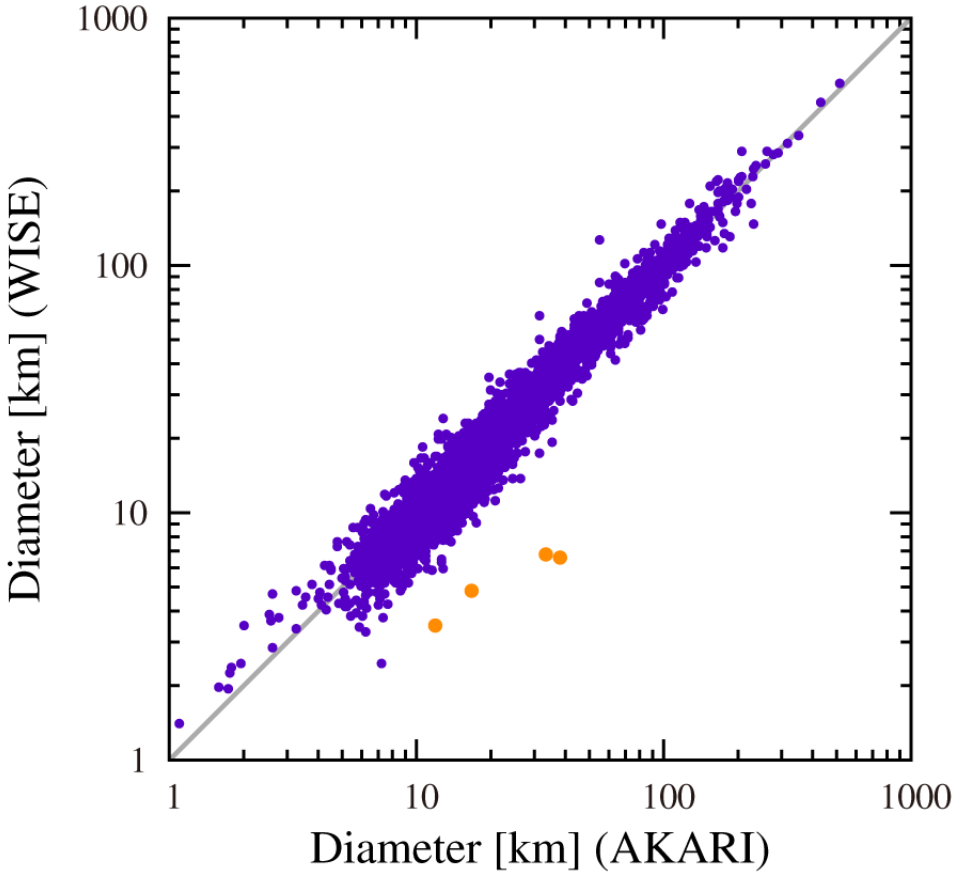
Comparison between AKARI and WISE
(4805 asteroids)

AKARI

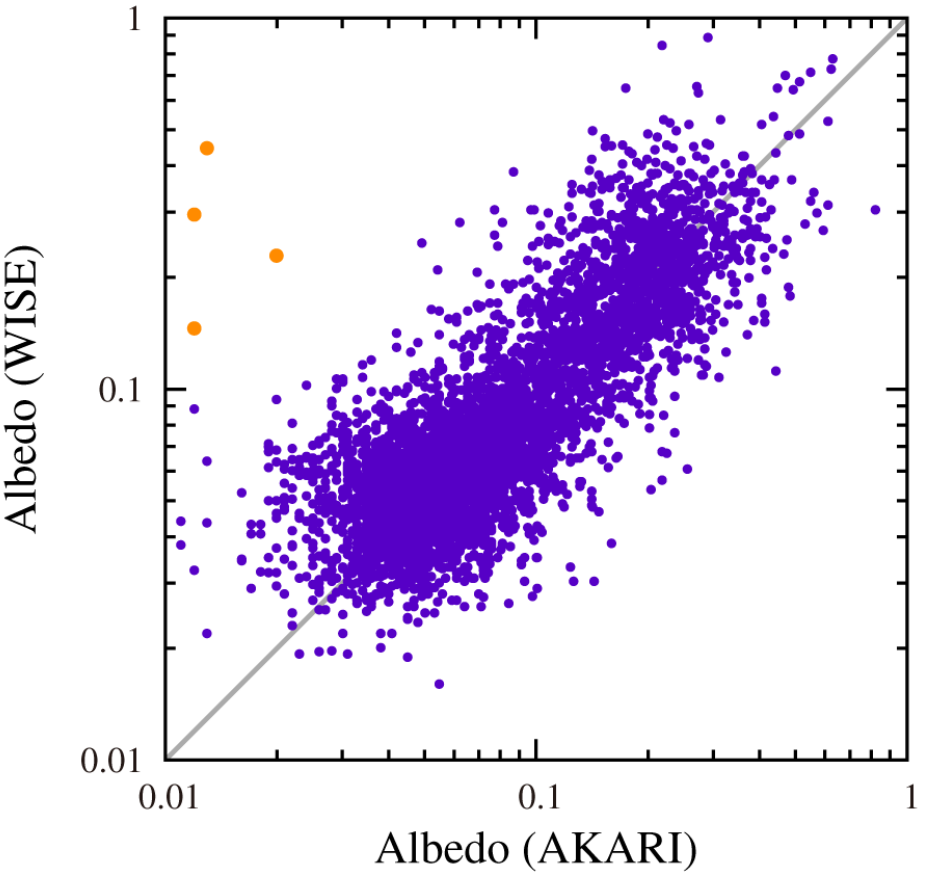


WISE

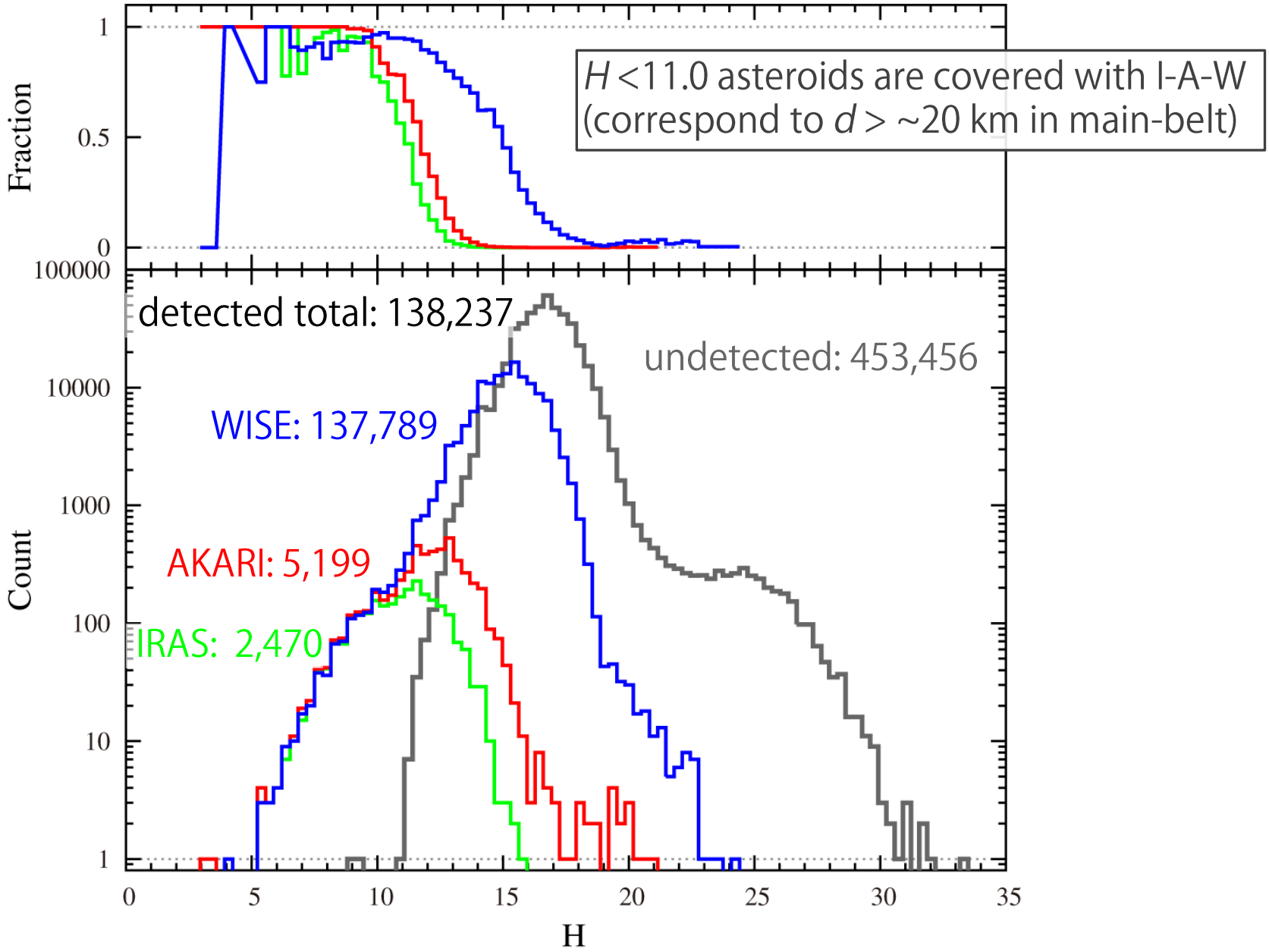
correl.coeff = 0.9865



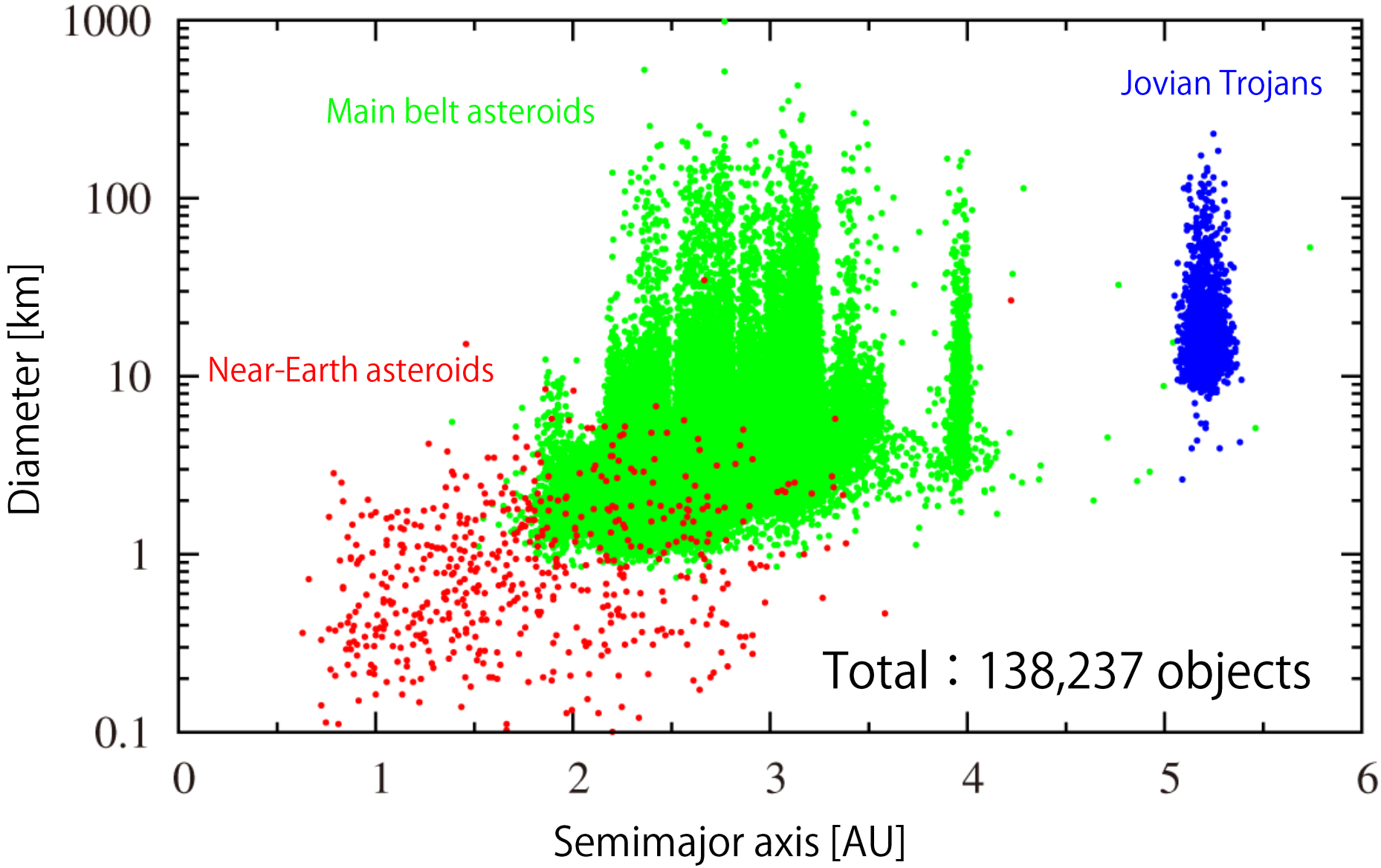
correl.coeff = 0.7957



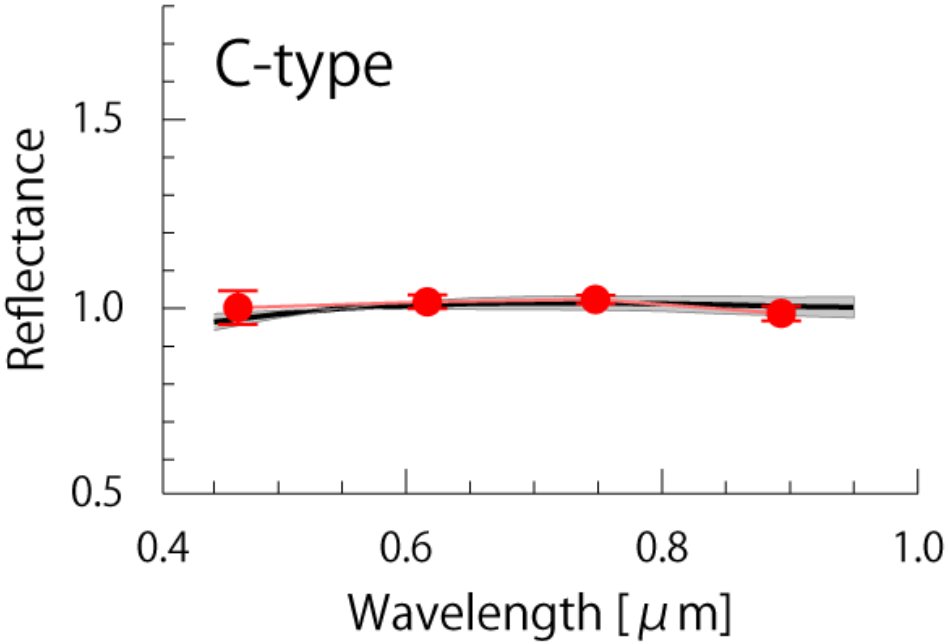
Distribution of absolute magnitude of asteroids in data set of IRAS, AKARI, and WISE (I-A-W)

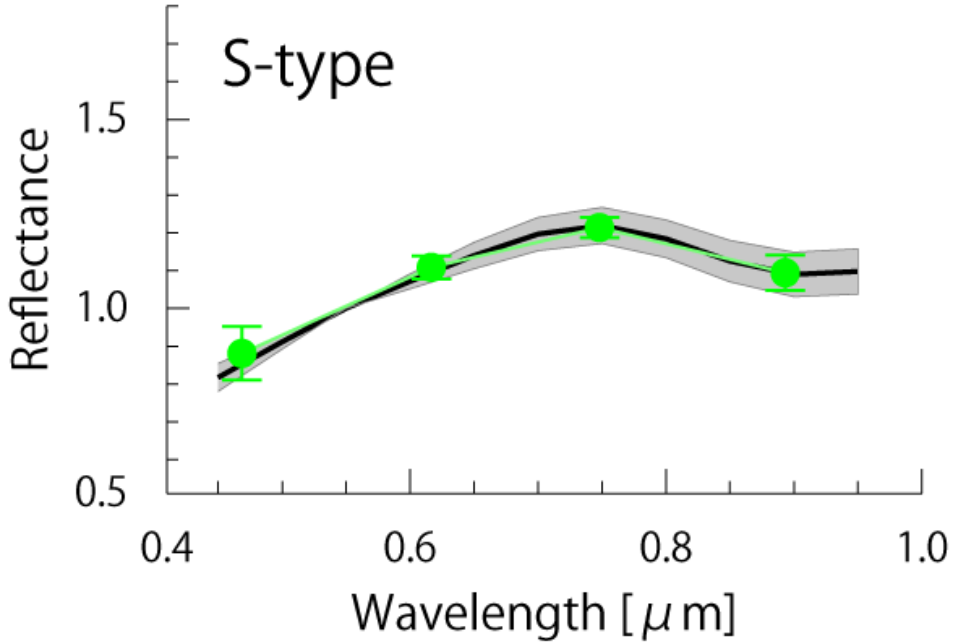


Size distribution of asteroids detected with infrared all-sky surveyors (IRAS-AKARI-WISE)



Taxonomic classification of asteroids
(spectral features in optical to near-infrared wavelengths)





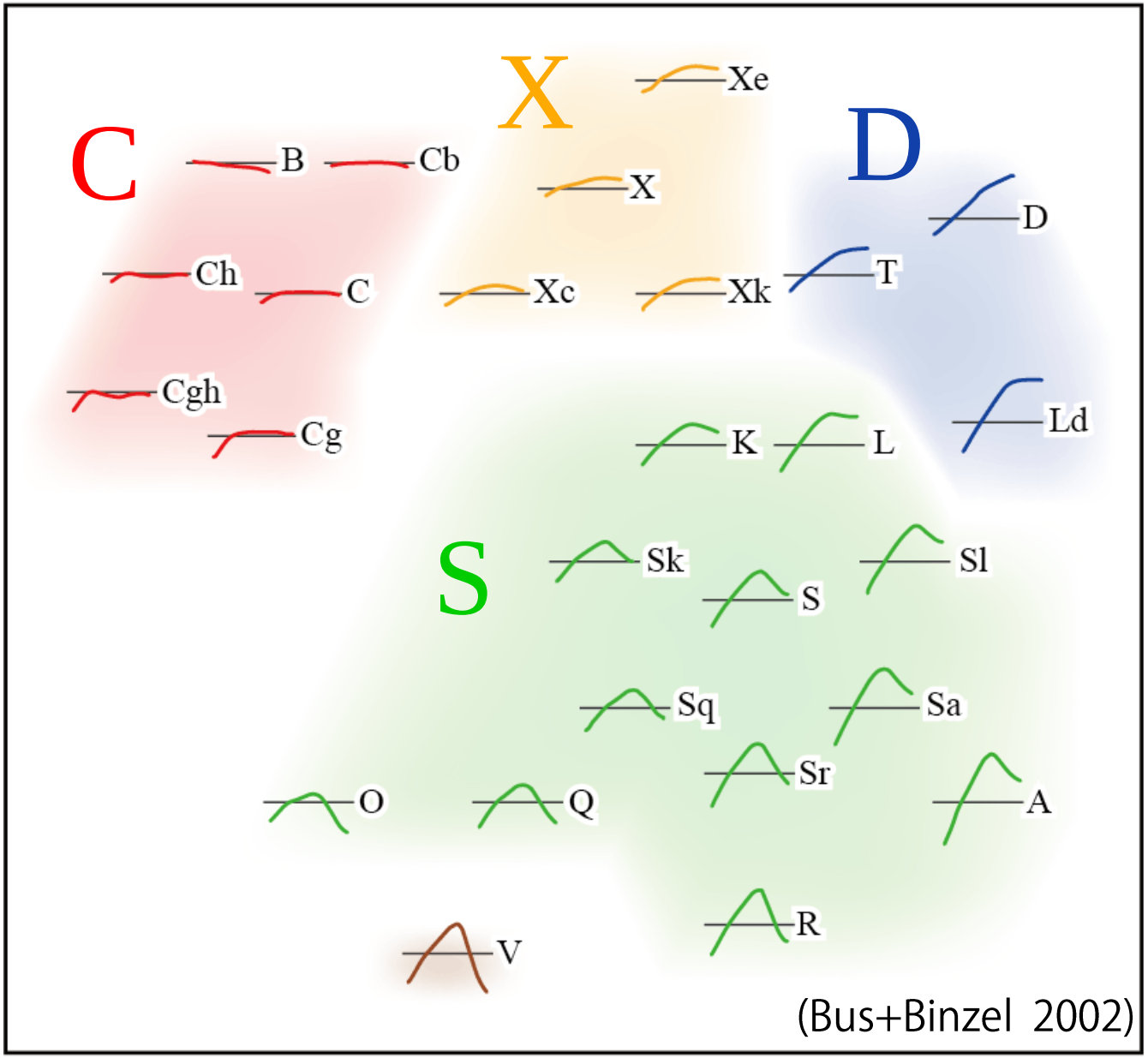
- Relatively flat and featureless spectra
- Dark ($0.01 < p_v < 0.1$)

- Significant absorption feature around 1μm associated with silicates
- Moderately bright ($0.1 < p_v < 0.3$)

Taxonomic classification of asteroids

- Eight-Color Asteroid Survey (ECAS)
  - 0.3--1.1 μm (8-band) spectrophotometric data
  - 589 asteroids are classified into 14 types.
    (Tholen 1984; Tholen 1989; Tholen+Barucci 1989)
- Small Main-Belt Asteroid Spectroscopic Survey II (SMASSII)
  - 0.44--0.92 μm spectroscopic survey
  - 1447 asteroids are classified into 24 types.
    (Bus 1999; Bus+Binzel 2002)
- Small Solar System Objects Spectroscopic Survey (S^3OS^2)
  - 0.49--0.92 μm spectroscopic survey
  - 820 asteroids are classified based on Tholen and Bus schemes.
    (Lazzaro+2004)
- Sloan Digital Sky Survey Moving Object Catalog (SDSS-MOC)
  - 0.354--0.913 μm (5-band) photometric data
  - 63,468 asteroids are classified into 9 types.
    (Carvano+2010)

Reflectance spectra of asteroids : taxonomic classification (0.4--0.9 μm)

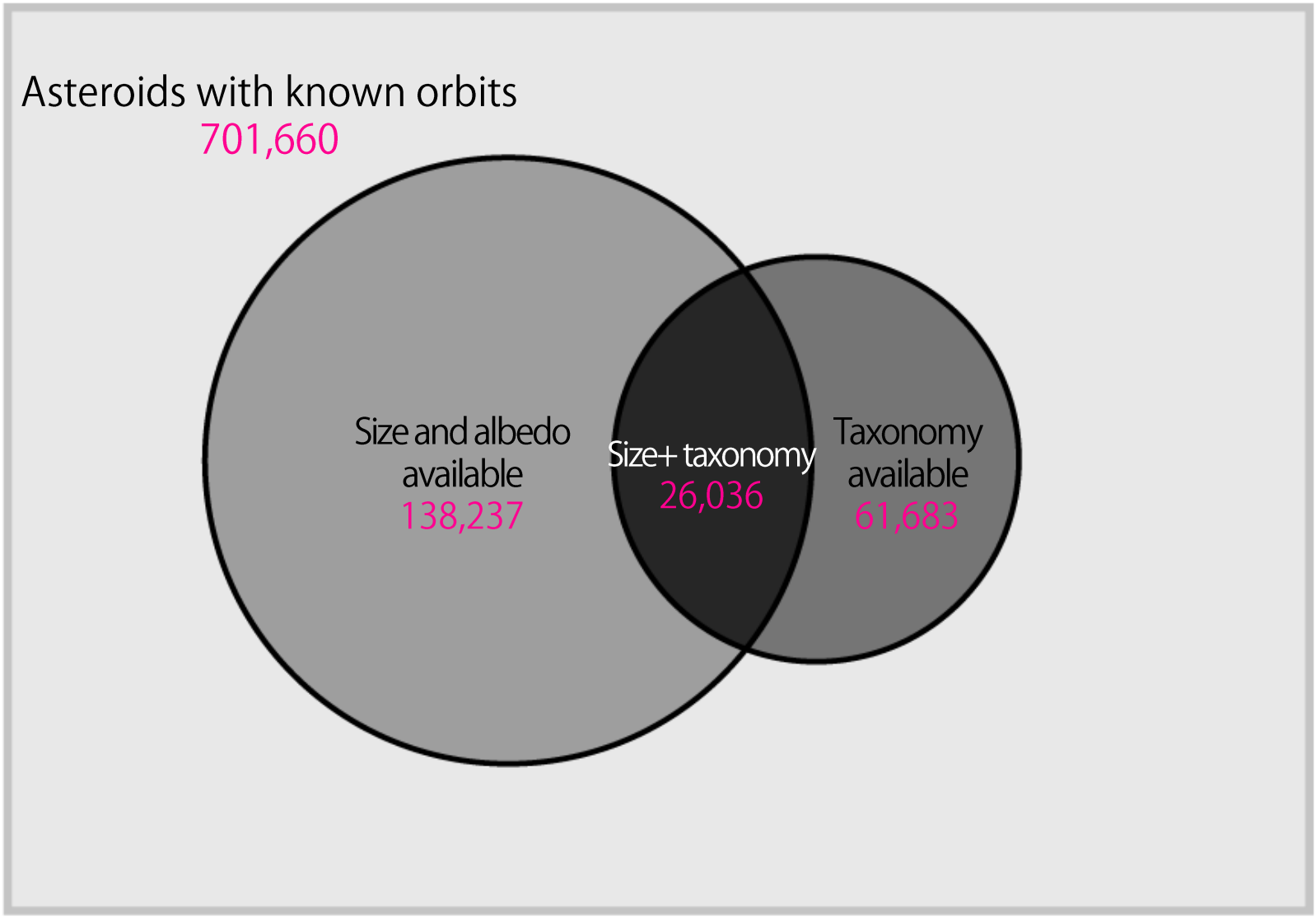


Taxonomic classification of asteroids

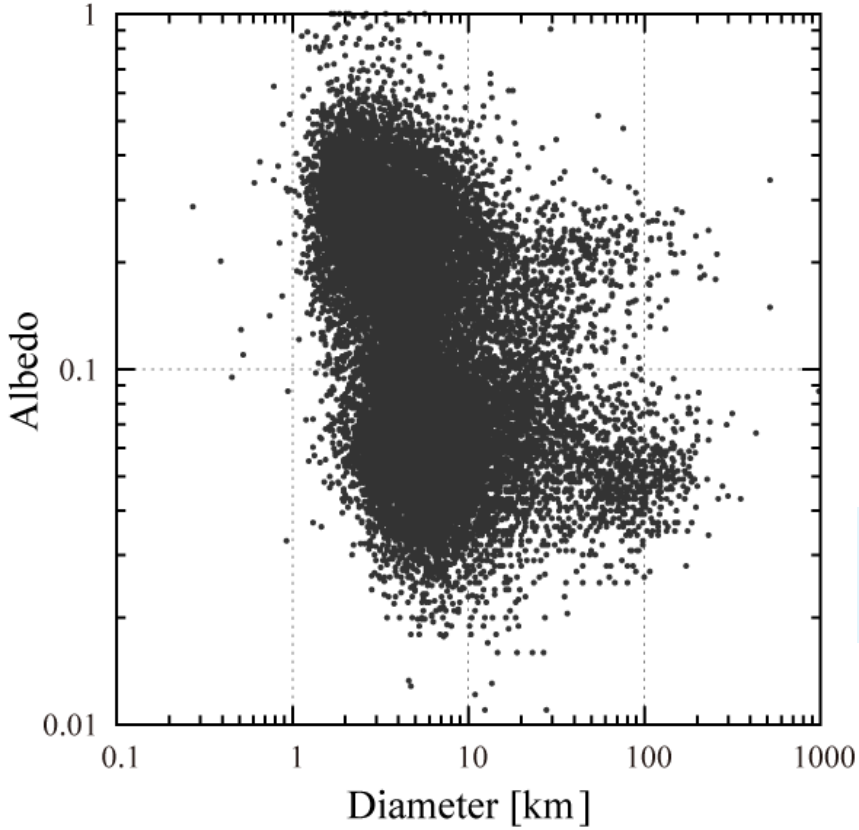
	Tholen 1984 Lazzaro+ 2004	Bus 1999 Lazzaro+ 2004	Carvano+ 2010
S-type	S, O, Q, K, A, R	A, K, L, Ld, O, Q, R, S, Sa, Sk, Sl, Sq, Sr	A, AQ, L, LA, LQ, LS, O, Q, QO, S, SA, SO, SQ
C-type	C, B, F, G	B, C, Cb, Cg, Cgh, Ch	C
X-type	X, M, E, P	X, Xc, Xe, Xk	X
D-type	D, T	D, T	D
V-type	V, J	V	V

Taxonomy available :
61683 objects

Number of asteroids with orbital elements, size and albedo data, and taxonomic information



Size and albedo distribution



138,237 asteroids
with size and albedo

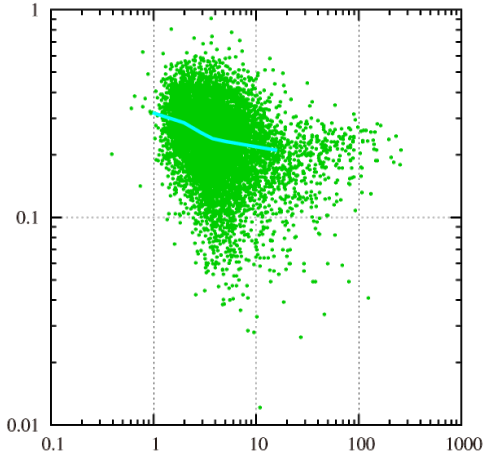
↓

26,036 asteroids
with taxonomy

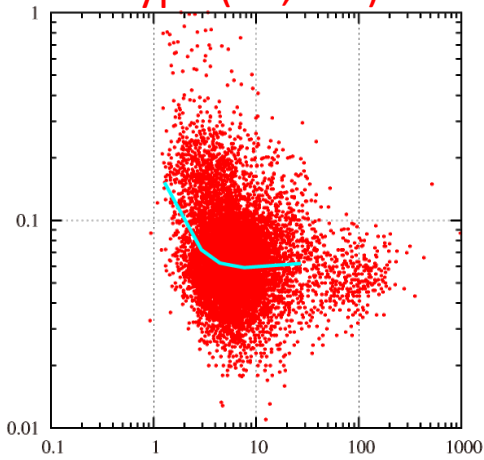
↓

12,593 asteroids
with $d > 5$ km

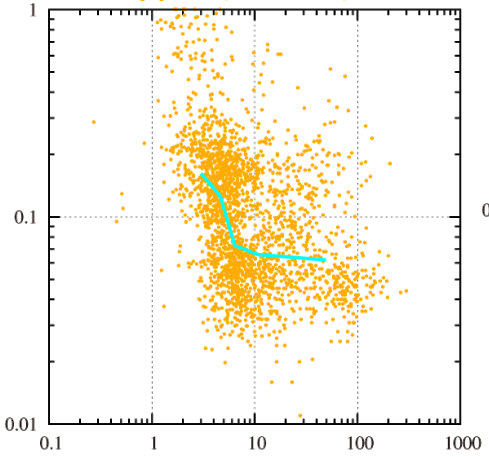
S-type (10,548)



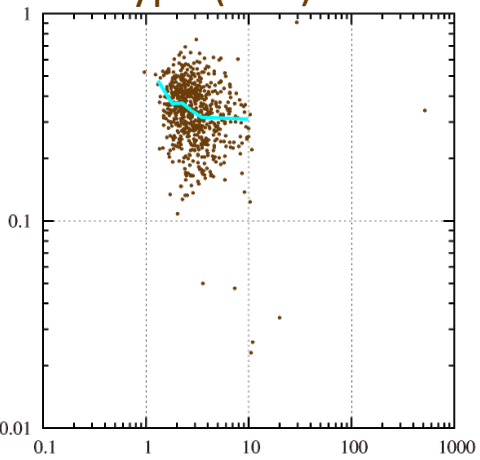
C-type (10,939)



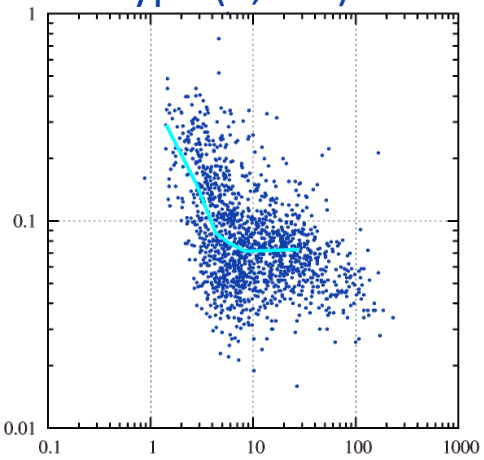
X-type (2,377)



V-type (711)



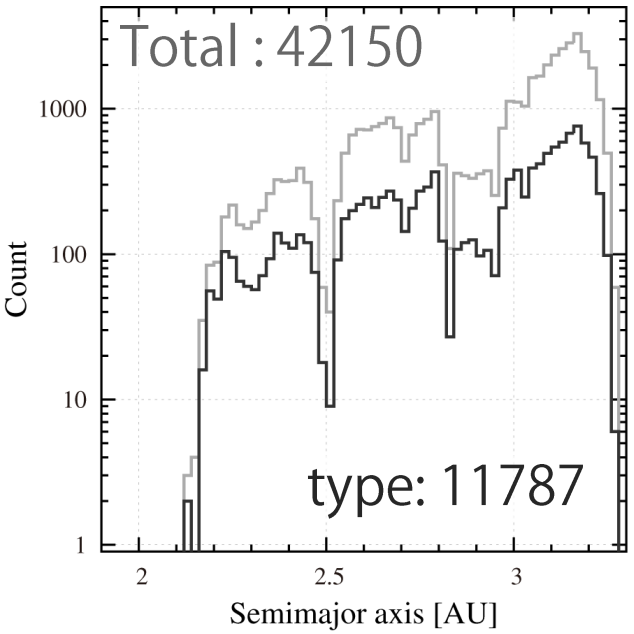
D-type (1,461)

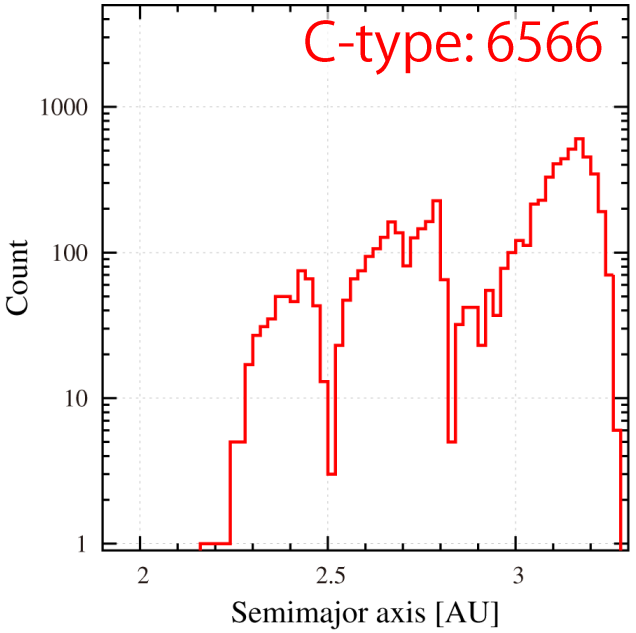


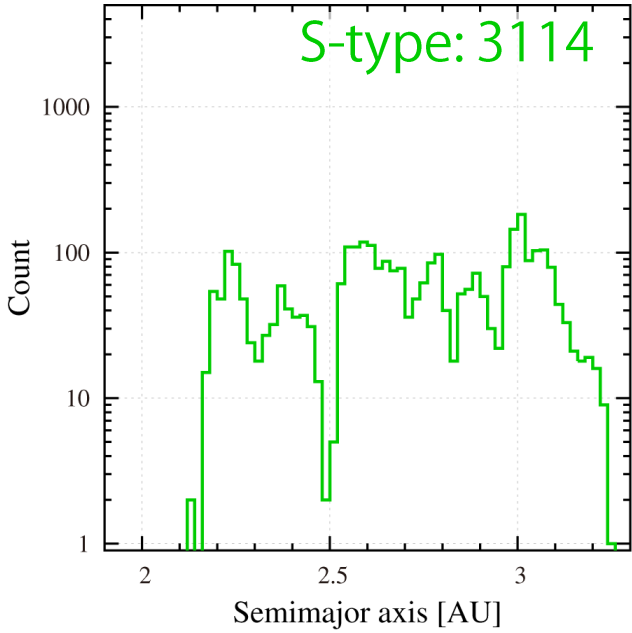
cyan lines：median of albedo

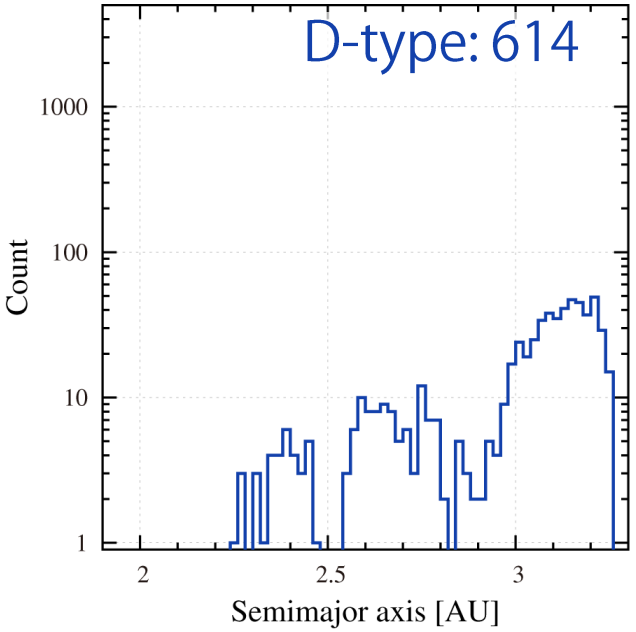
Distribution of the main belt asteroids

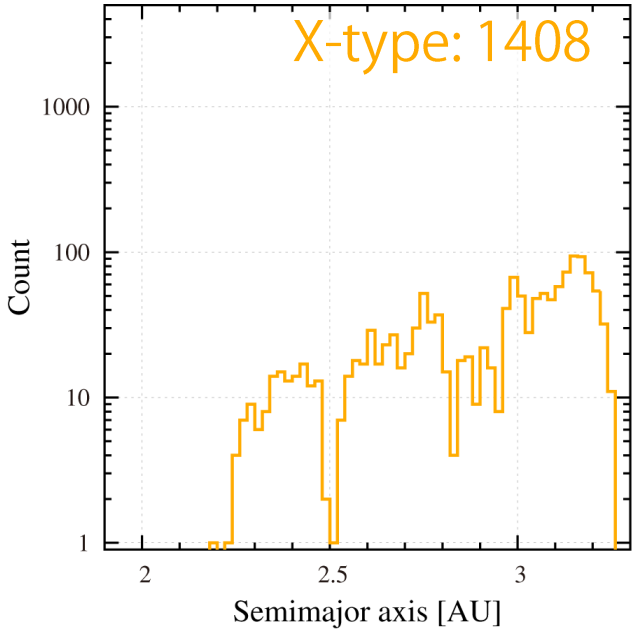
Number of objects







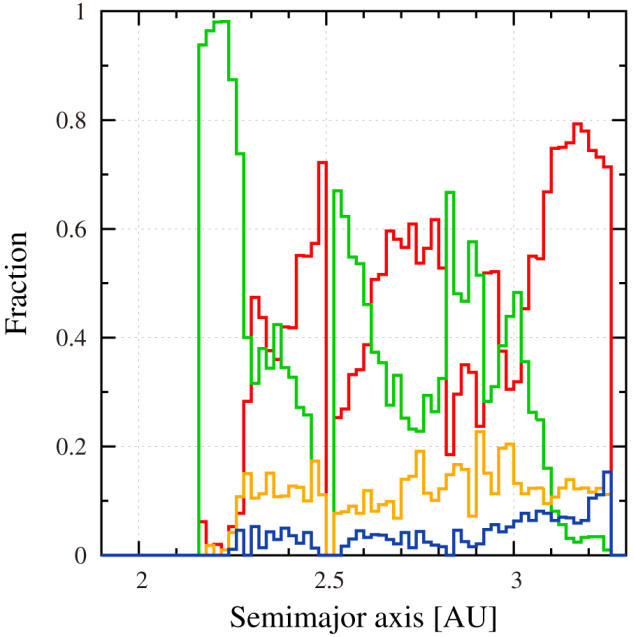


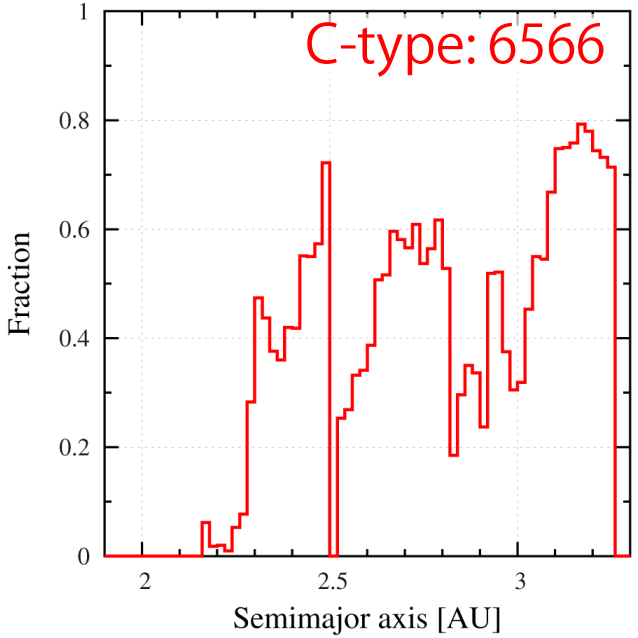


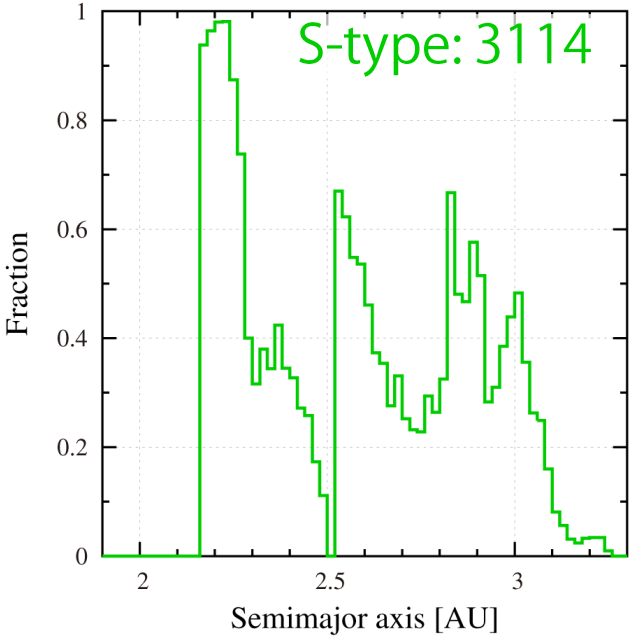
($d > 5$km; 0.02AU bin)

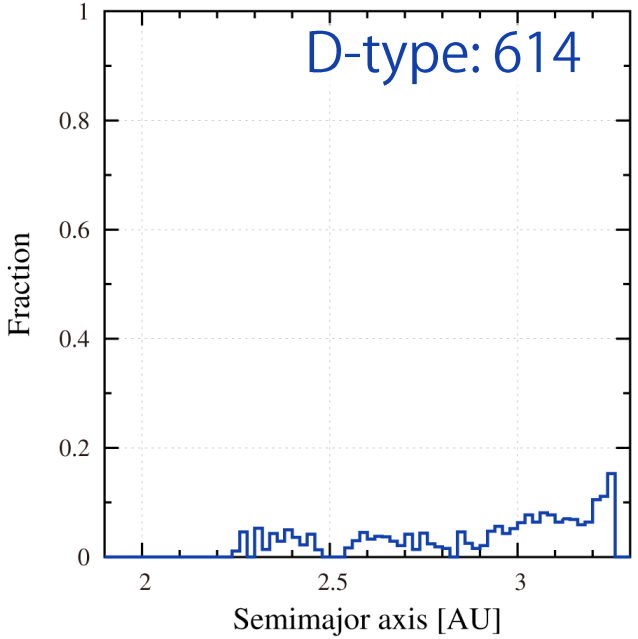
Distribution of the main belt asteroids

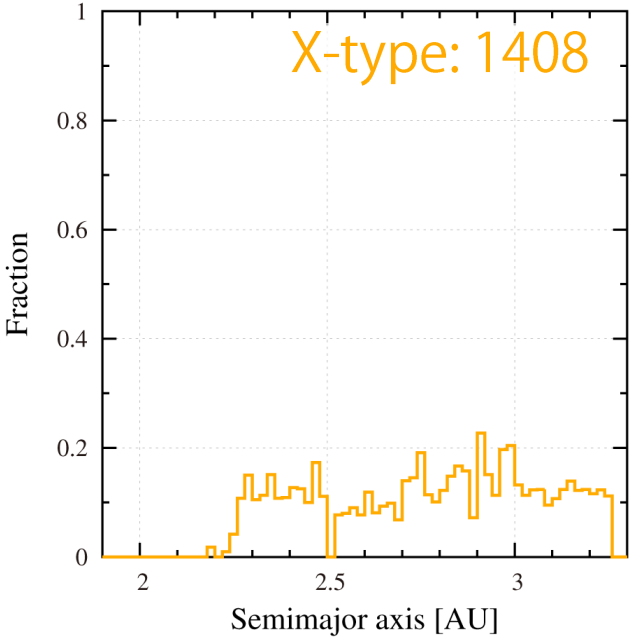
Ratio of taxonomy







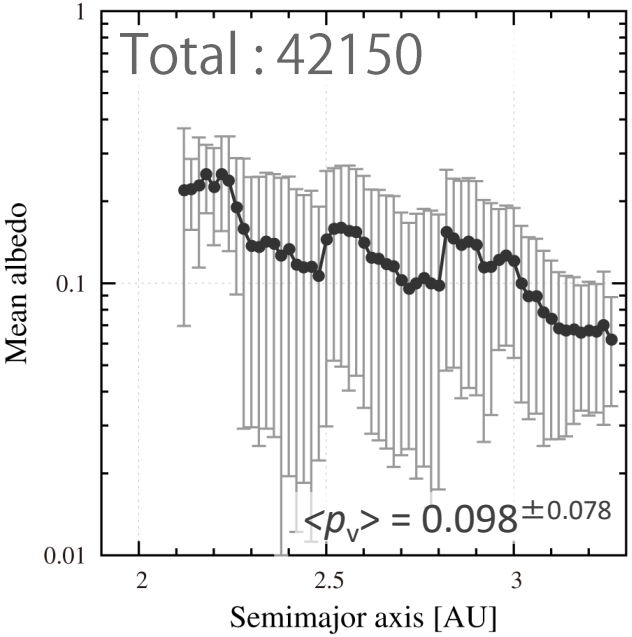


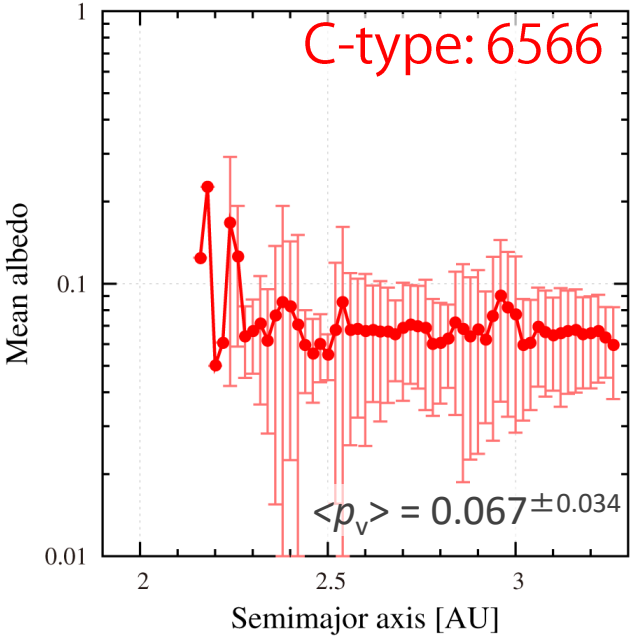


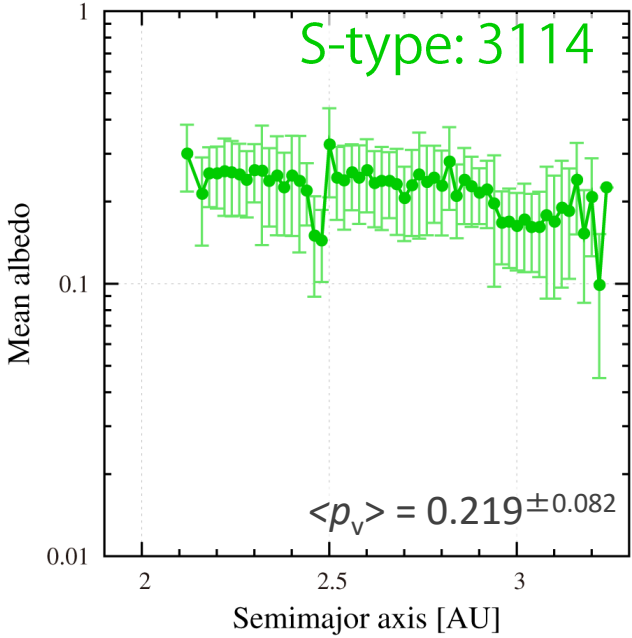
($d > 5$km; 0.02AU bin)

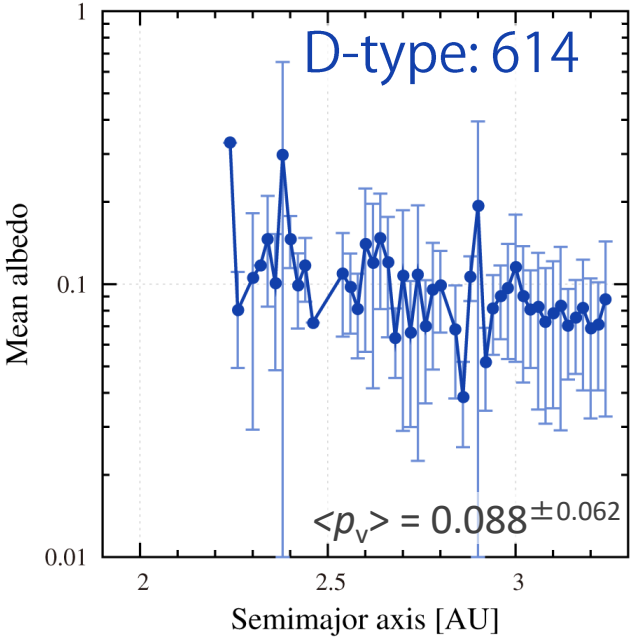
Distribution of the main belt asteroids

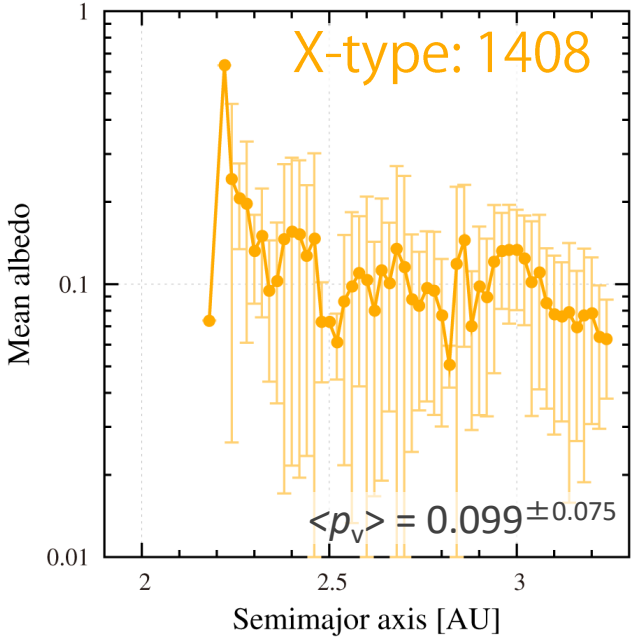
Albedo distribution











(d > 5km; 0.02AU bin)

Asteroid catalog using AKARI (AcuA)

- AKARI asteroid survey was conducted from the mid-IR survey data of AKARI/IRC.
  - Unbiased asteroid survey in the mid-infrared wavelengths including sizes and albedos of 5120 asteroids
  - Duration of survey observation： 2006/05 -- 2007/08 (16 months)
  - Wavelengths : 9 μm (MIR-S), 18 μm (MIR-L)
  - Catalog data is open to the public : http://darts.jaxa.jp/ir/akari/catalogue/AcuA.html
  - Note that the flux data of individual asteroids observed with AKARI will also be released in the near future.

- Asteroid catalogs from other infrared all-sky surveyors
  - IRAS (2,470), AKARI (5,199), and WISE (137,789), as well as other infrared telescopes (MSX, ISO, Spitzer, Herschel)
  - These three data sets complement one another and provide a comprehensive catalog for characterizing the physical properties of asteroids.

Infrared Asteroid Survey with AKARI

- AKARI mid-infrared asteroid survey
  - Asteroidal size and albedo catalog based on AKARI mid-infrared all-sky survey data

- AKARI near-infrared spectroscopic survey
  - Near-infrared spectroscopic observations with AKARI for exploring hydrated minerals on asteroids

Existence of “water” in the solar system

- Existence of plenty of liquid water (as oceans)
  - Earth !
- Small deposits of water ice in craters
  - Mercury, Moon, etc
- Liquid water once covered large areas of surface
  - Venus, Mars
- Water droplets may form in certain gas layers
  - Jupiter, Uranus, Neptune
- Surface partially composed of ice (and liquid water may exist beneath surface)
  - Jovian satellites (Europa・Ganymede・Callisto) ,
    Saturnian satellites (Titan・Enceladus) ,
    Neptunian Satellite (Titania) , Uranian Satellite (Triton) , etc
  - Pluto (?)

Existence of “water” in the solar system

- Existence of “water” on asteroids
  - (1) Ceres：hydrated minerals (Rivkin+ 2002)、water vapor (Küppers+2014)、etc
  - (4) Vesta： hydrated minerals (Hasegawa+2003, Rivkin+2006, Russel+2015)
  - (24) Themis, (65) Cybele： water ice (Campins+ 2010; Rivkin+ 2010; Licandro+ 2011)
  - etc
- Hydrated minerals：
  - Any minerals containing OH or H_2O, which are formed in environments where anhydrous rock and liquid water are together (aqueous alteration).
  - They are found within chondrite matrix of meteorites.
  - Hydrated minerals are stable above the sublimation temperature of water ice.
  - Knowledge of the hydrated mineral is important for deducing the origin of Earth's water, and unraveling the processes in the earliest times of the solar system.
  - Diagnostic absorption features in 3 μm band ：
    - ✓ Hydroxyl associated with hydrated mineral (2.7--2.8 μm)
    - ✓ H_2O ice (3.07 μm), etc
    - ✓ Other species (CO, CH_4, NH_3) are not stable on surfaces of asteroids.

Reflectance spectra of asteroids and meteorite (Hiroi+1996)

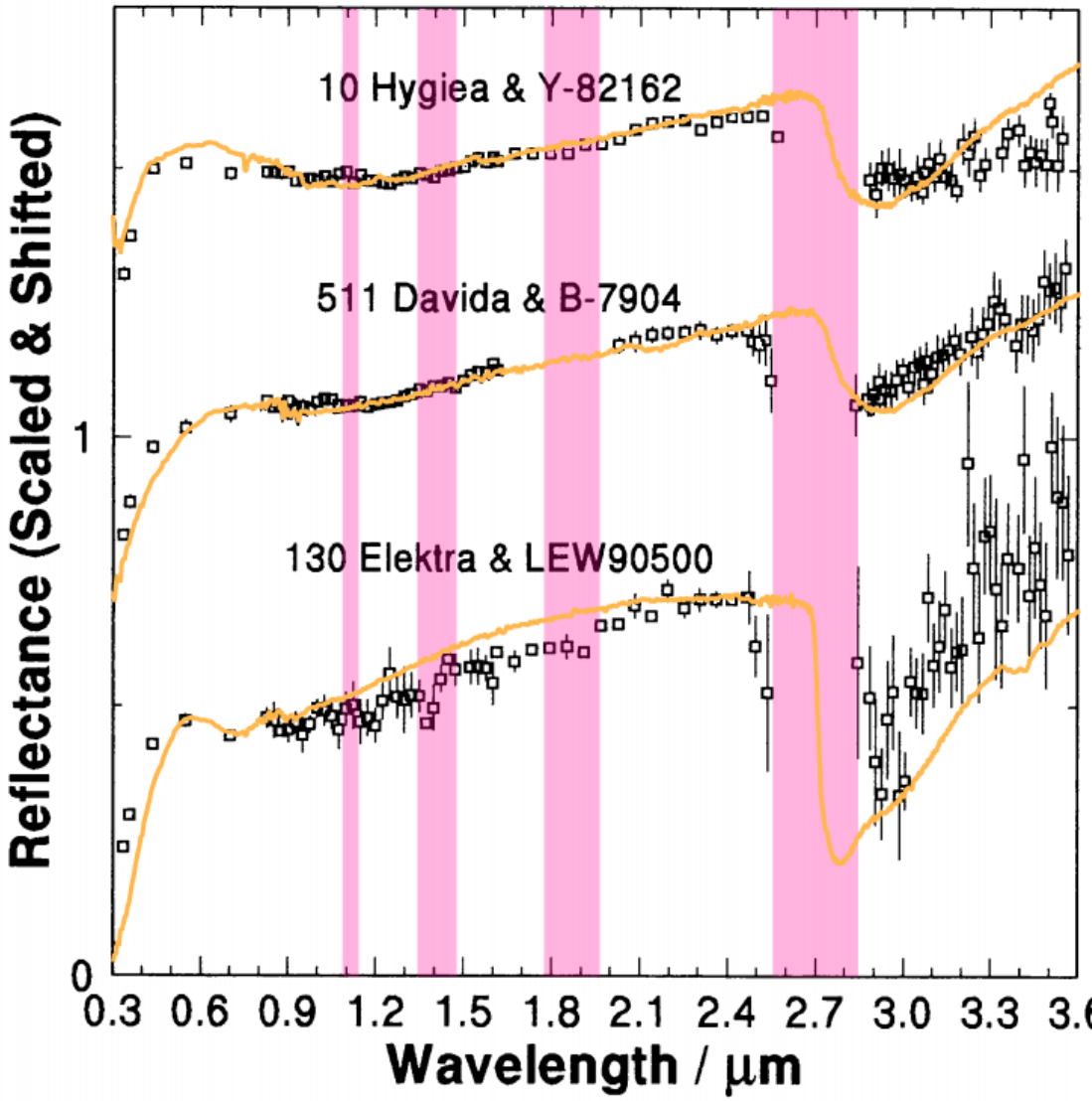


FIG. 3. Three sets of asteroid-meteorite counterparts that have similar overall reflectance spectra. All spectra are scaled to 1.0 at 2.37 μm and offset for clarity.

Observations (**dots**):
- Zellner+1985 (1.54m Catalina, 2.29m Steward)
- Bell+1988 (NASA/IRTF)
- Jones+1990 (NASA/IRTF)

Meteorite measurements (lines):
- Carbonaceous chondrites (RELAB, Brown University)

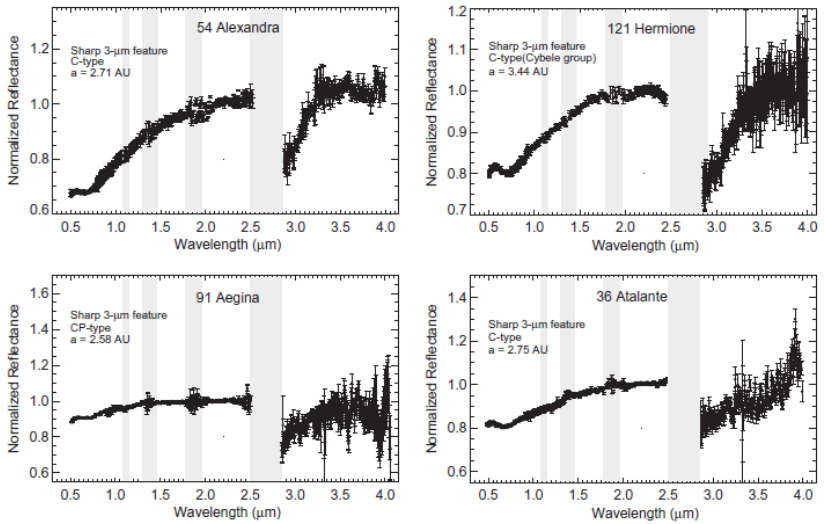
Infrared observations with ground-based telescopes are limited by atmospheric absorption and thermal emission.

⇩

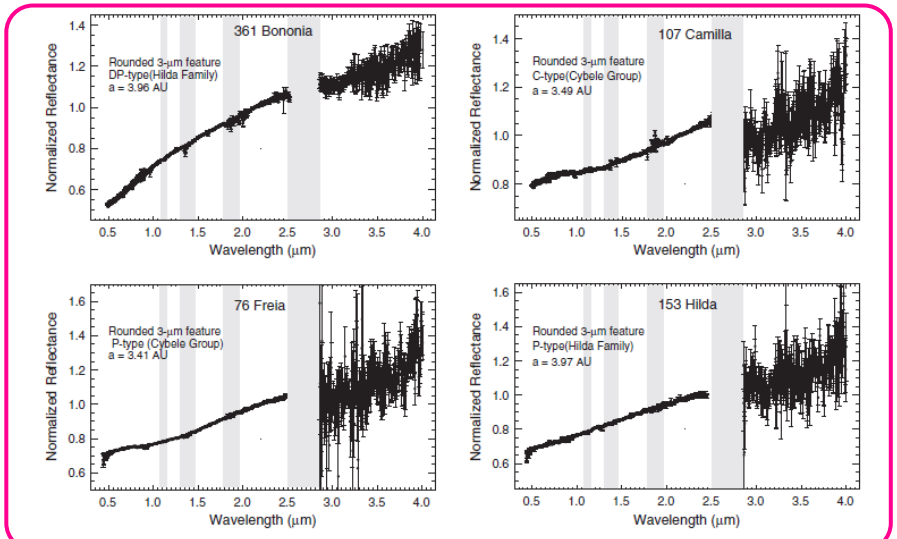
Need to send telescopes into space!

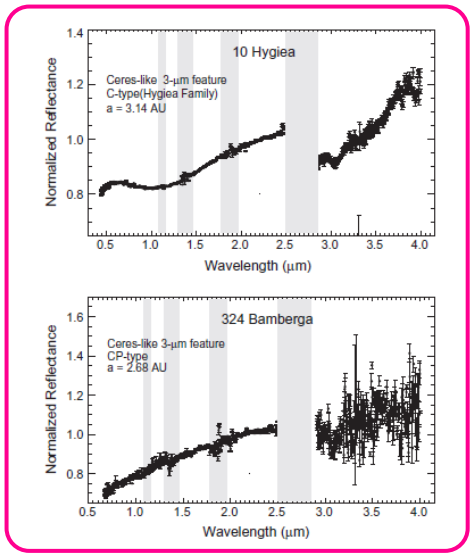
Vis to near-infrared spectra of C-type asteroids (Takir+2012, 2013)

sharp (15)

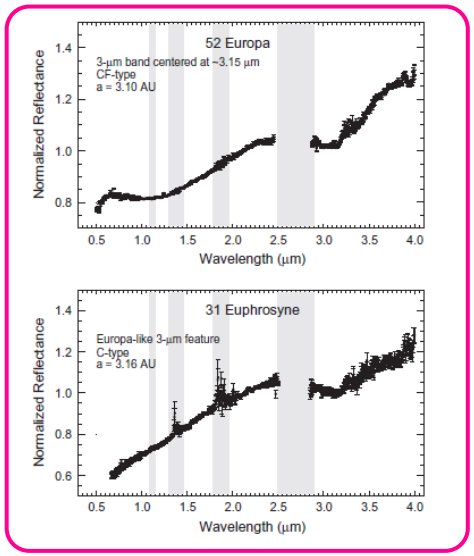


rounded (8)





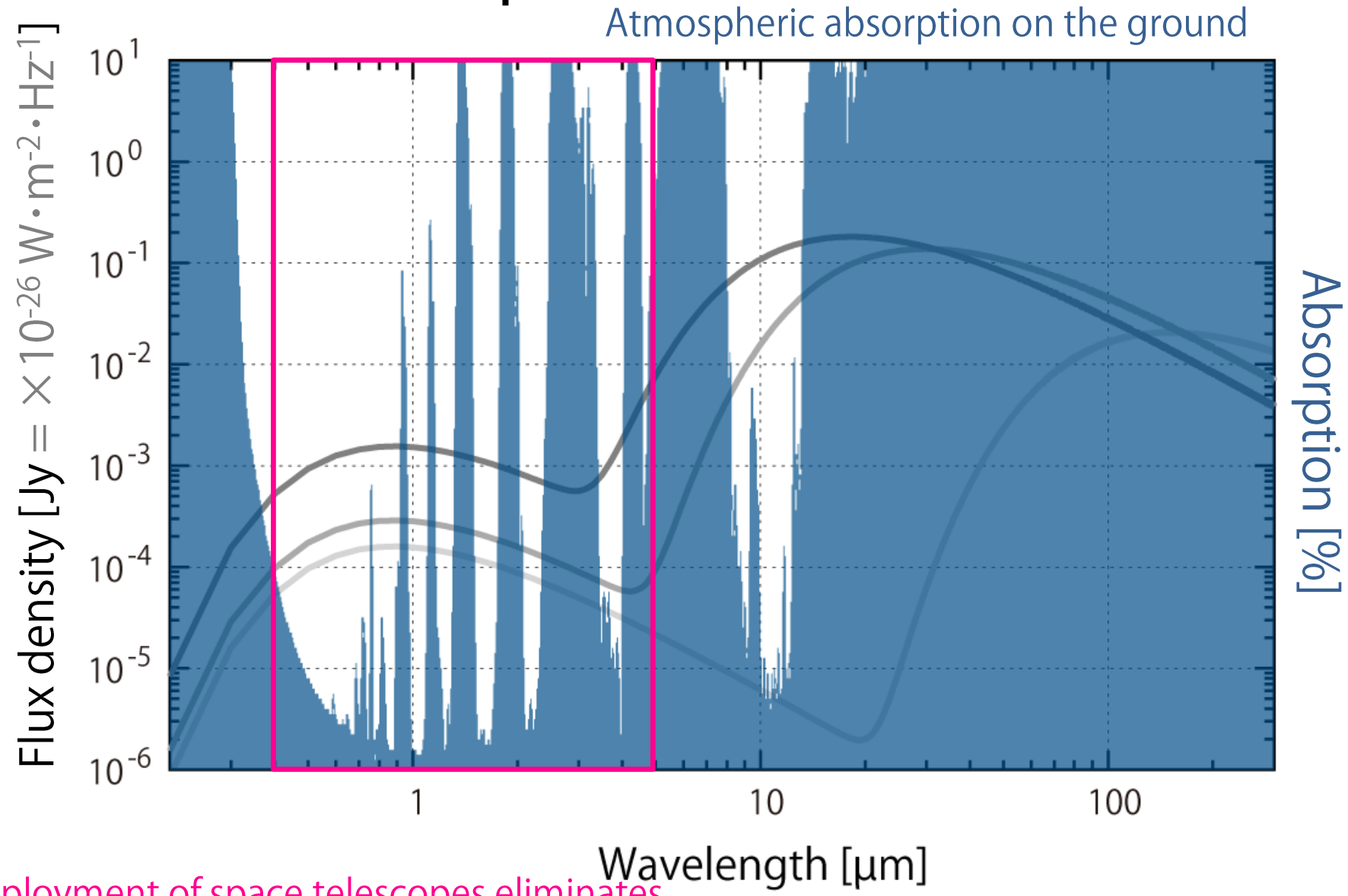
Ceres-like (2)



Europa-like (3)

Classifying 3μm-band feature based on observations of 28 asteroids (IRTF/SpeX)

Model spectra of asteroids

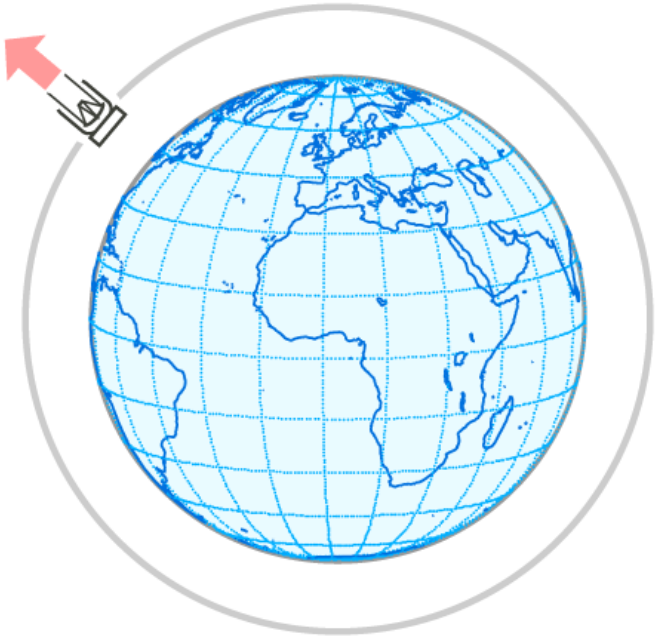


Deployment of space telescopes eliminates the problem of atmospheric absorption !

2 observational modes of AKARI

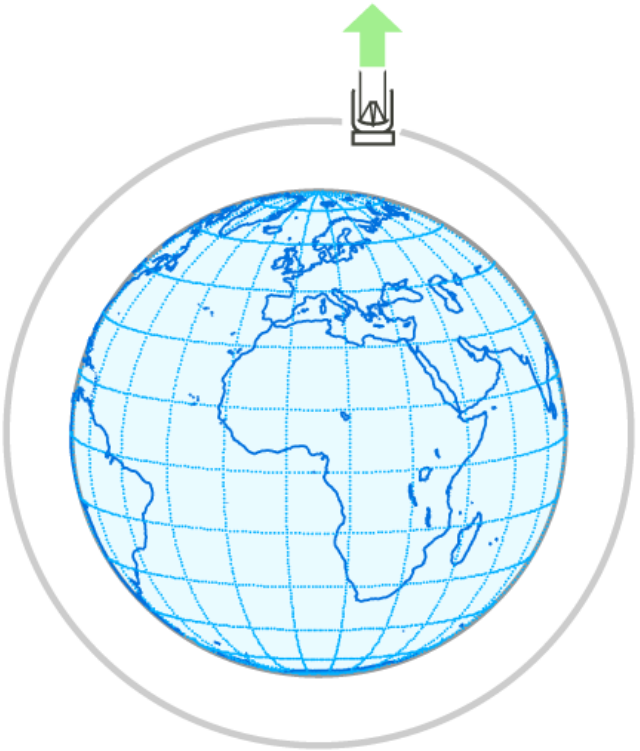
All-sky survey

Continuous survey mode
(scan rate = 3.6′/sec)

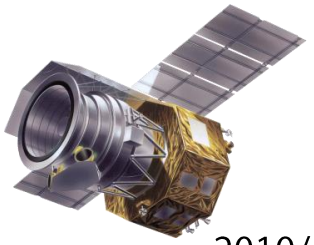


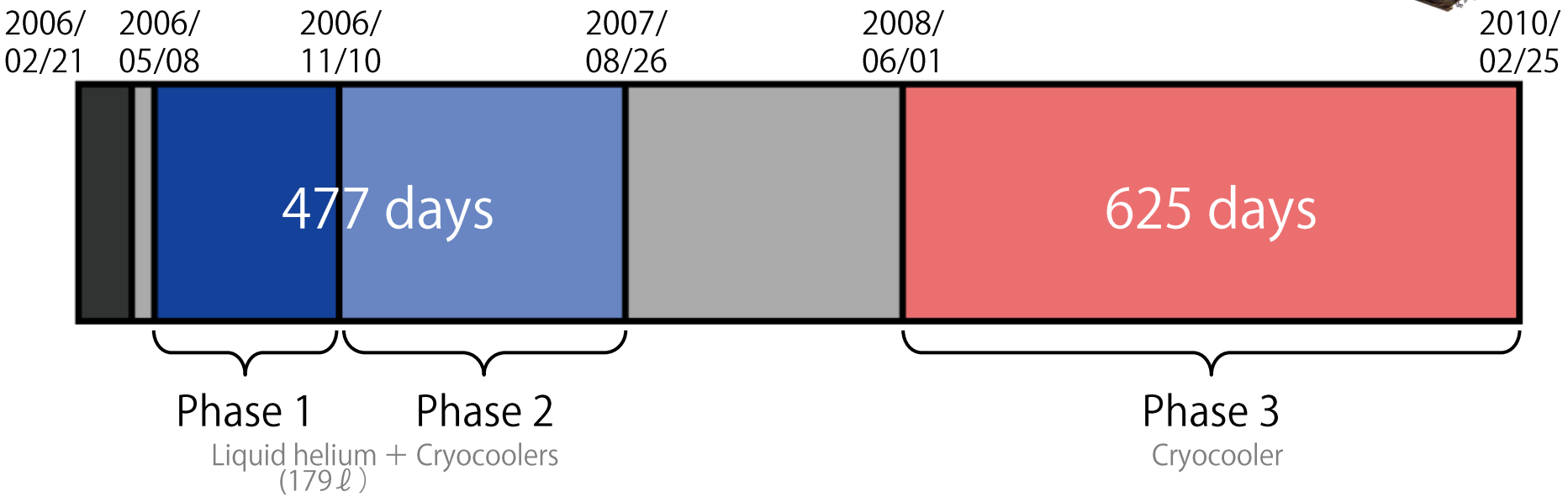
Pointed observations

Targeted observing mode
(about 10 minutes)
for deep imaging and spectroscopy



AKARI observations





All-Sky Survey
+
5088 pointed observations
(IRC + FIS)

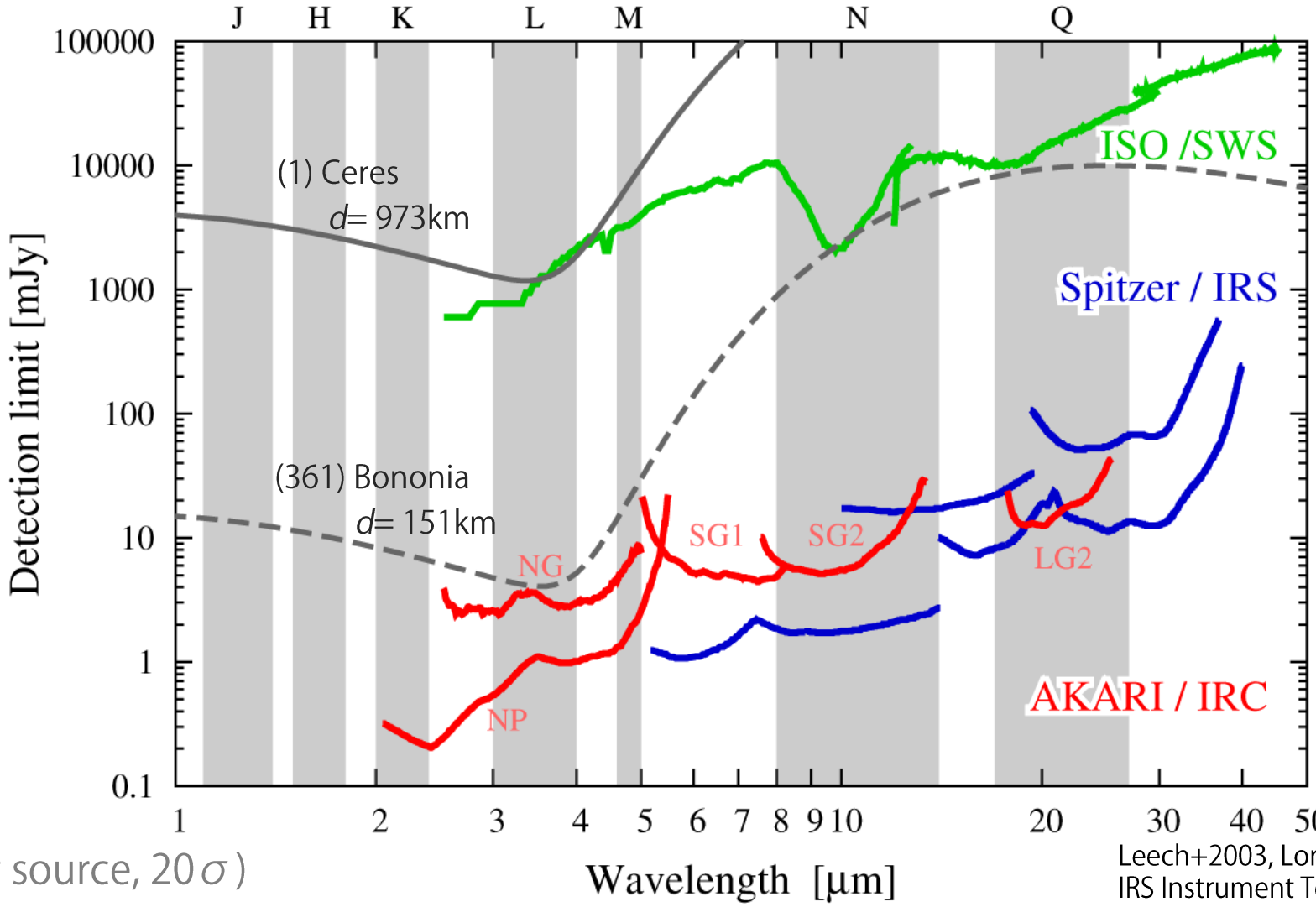
Asteroid catalog using AKARI (AcuA)

12802 pointed observations
(IRC only)

157 asteroid spectroscopy
(Np aperture; 147: NG, 10: NP)

AKARI/IRC spectroscopic observations

- AKARI provides valuable spectroscopic data because of its high sensitivity and unique wavelength coverage (in 2.5--5 μm).

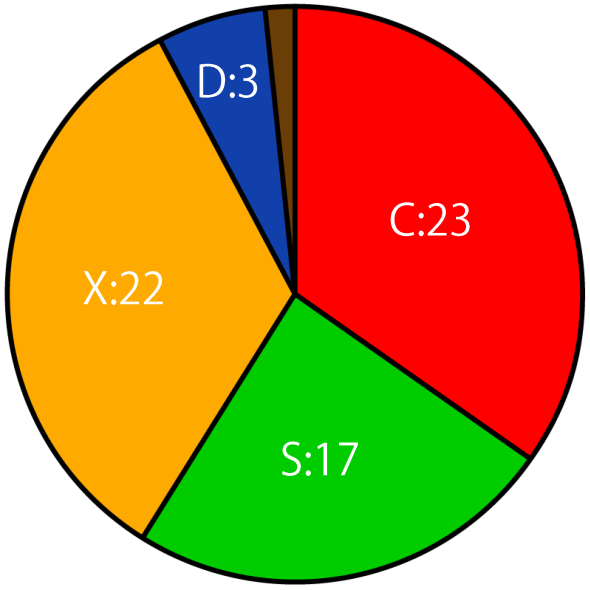


(Point source, 20σ)

Leech+2003, Lorente+2008, IRS Instrument Team+2011

Near-infrared spectroscopy for asteroids with AKARI

- Observations for 66 asteroids (total 147 times) with IRC/NIR
  - Wavelength coverage： 2.5--5 μm
    Spectral resolution ： R=120@3.6μm
  - Targets: main-belt to Hildas (d > 40 km)
  - Determination of taxonomy：
    - ✓ ECAS (Tholen 1984; Tholen 1989; Tholen+Barucci 1989)
    - ✓ SMASSII (Bus 1999; Bus+Binzel 2002)
    - ✓ S^3OS^2 (Lazzaro+2004)
    - ✓ SDSS-MOC (Carvano+2010)



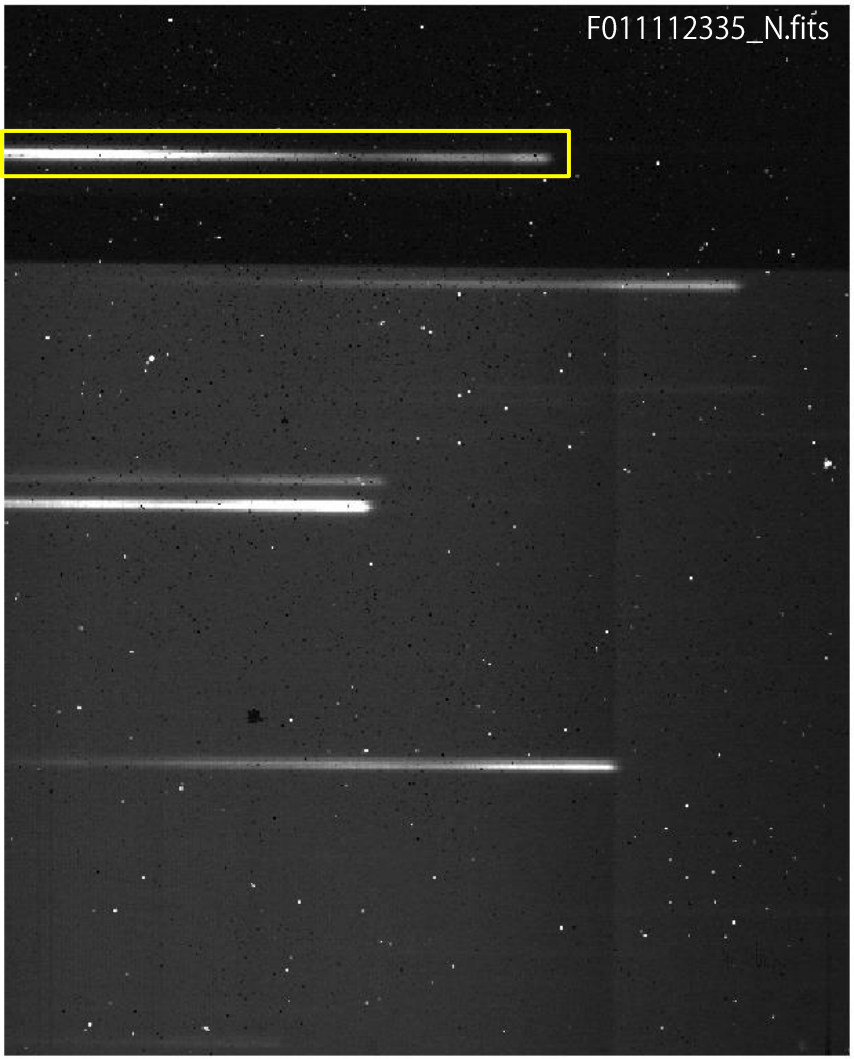
Taxonomy of asteroids for AKARI observations

- Data reduction
  - IRC Spectroscopy Toolkit for Phase 3 Version 20150331
    (http://www.ir.isas.jaxa.jp/ASTRO-F/Observation)
  - Frame shift-and-add for moving objects (Ootsubo+2012)
  - Object positions ： obtained from JPL/Horizons
  - Computed solar spectrum： corrected Kurucz model (Berk+1999)

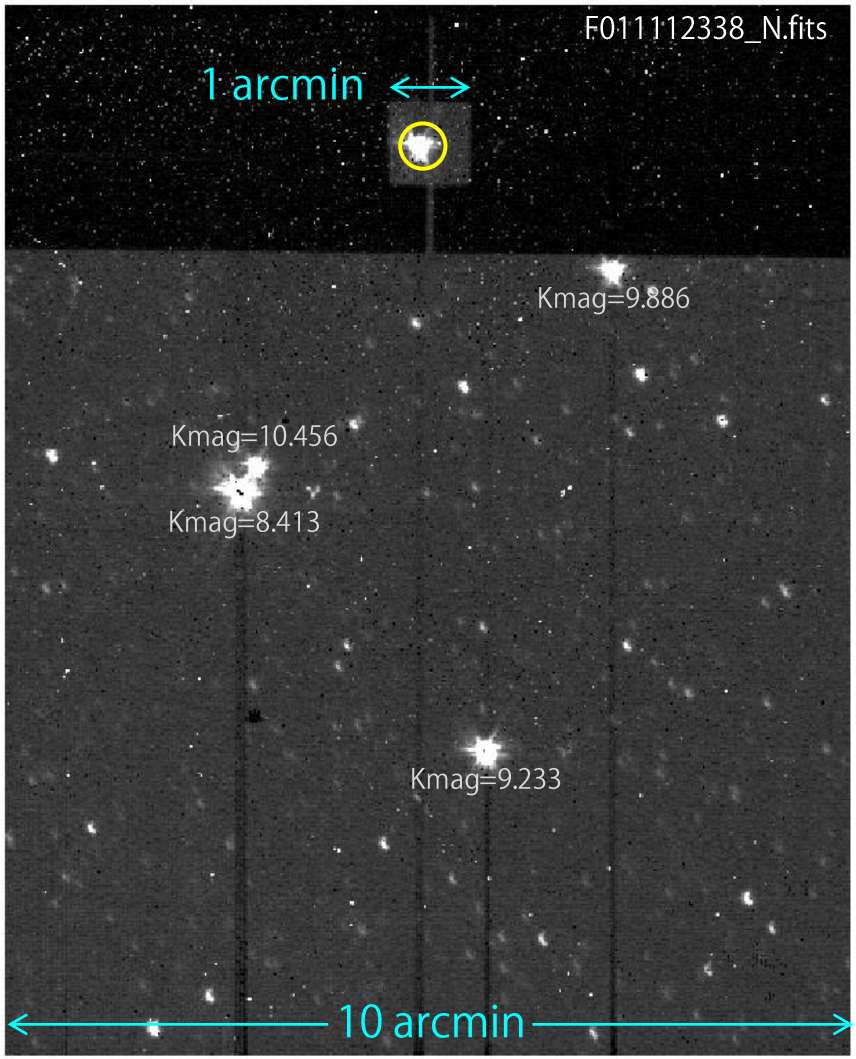
Example of data reduction：(511) Davida

ID=1520065-001, IRCZ4, b;Np, 2008/11/16_11:26:34

spec data (NG; 1/9)

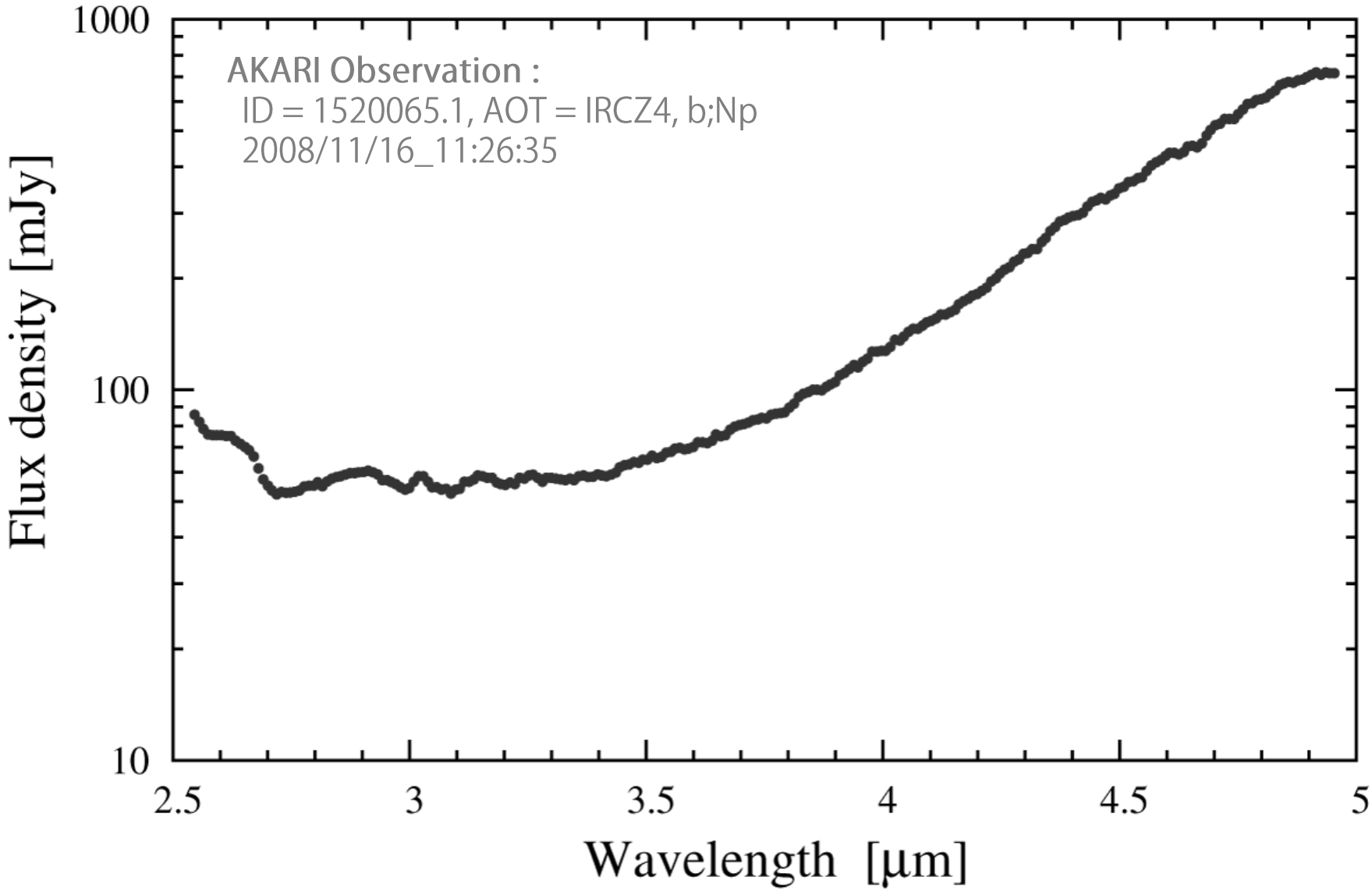


reference image (N3; 1/1)



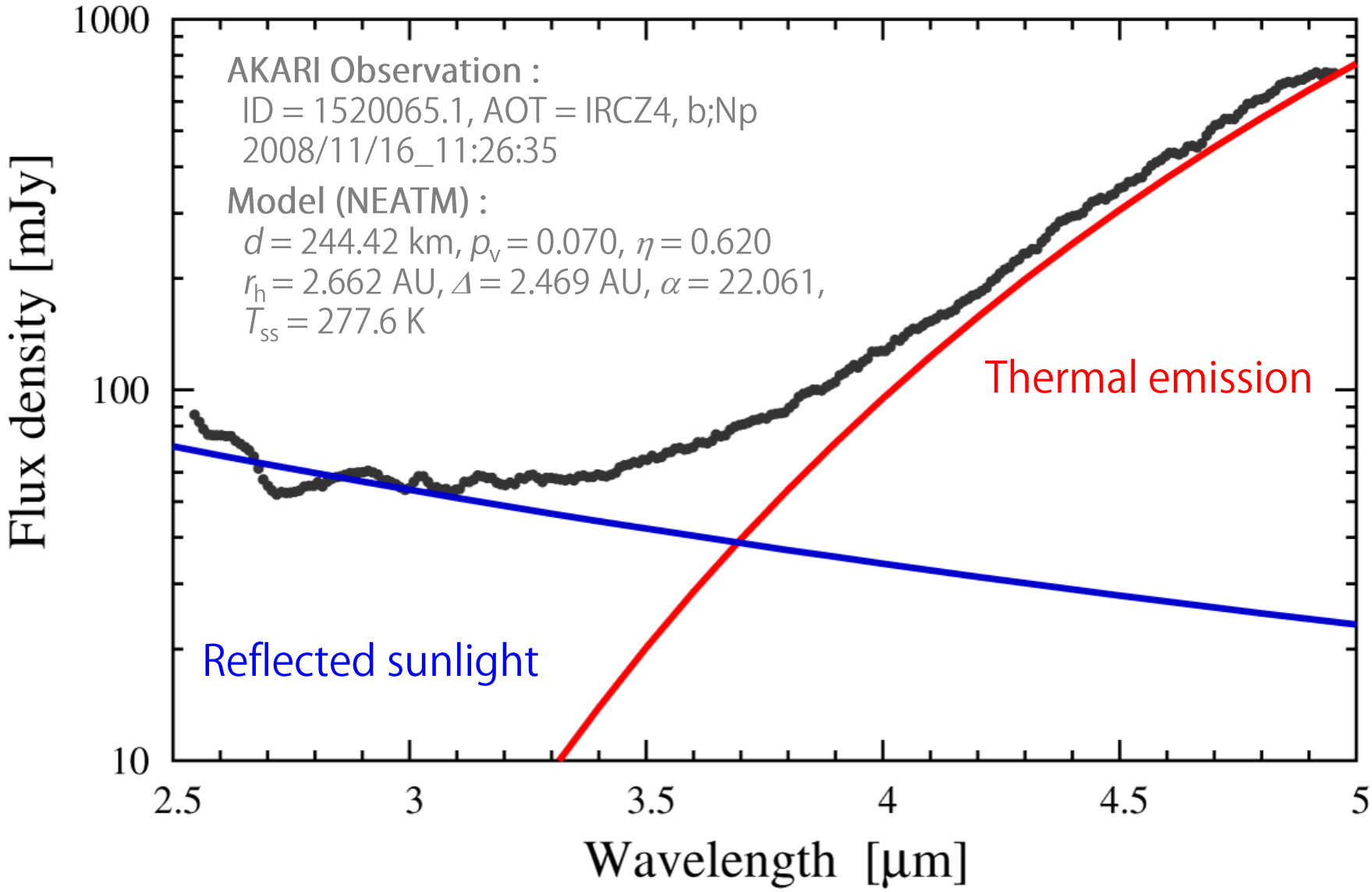
Example of data reduction：(511) Davida

Near-infrared spectrum



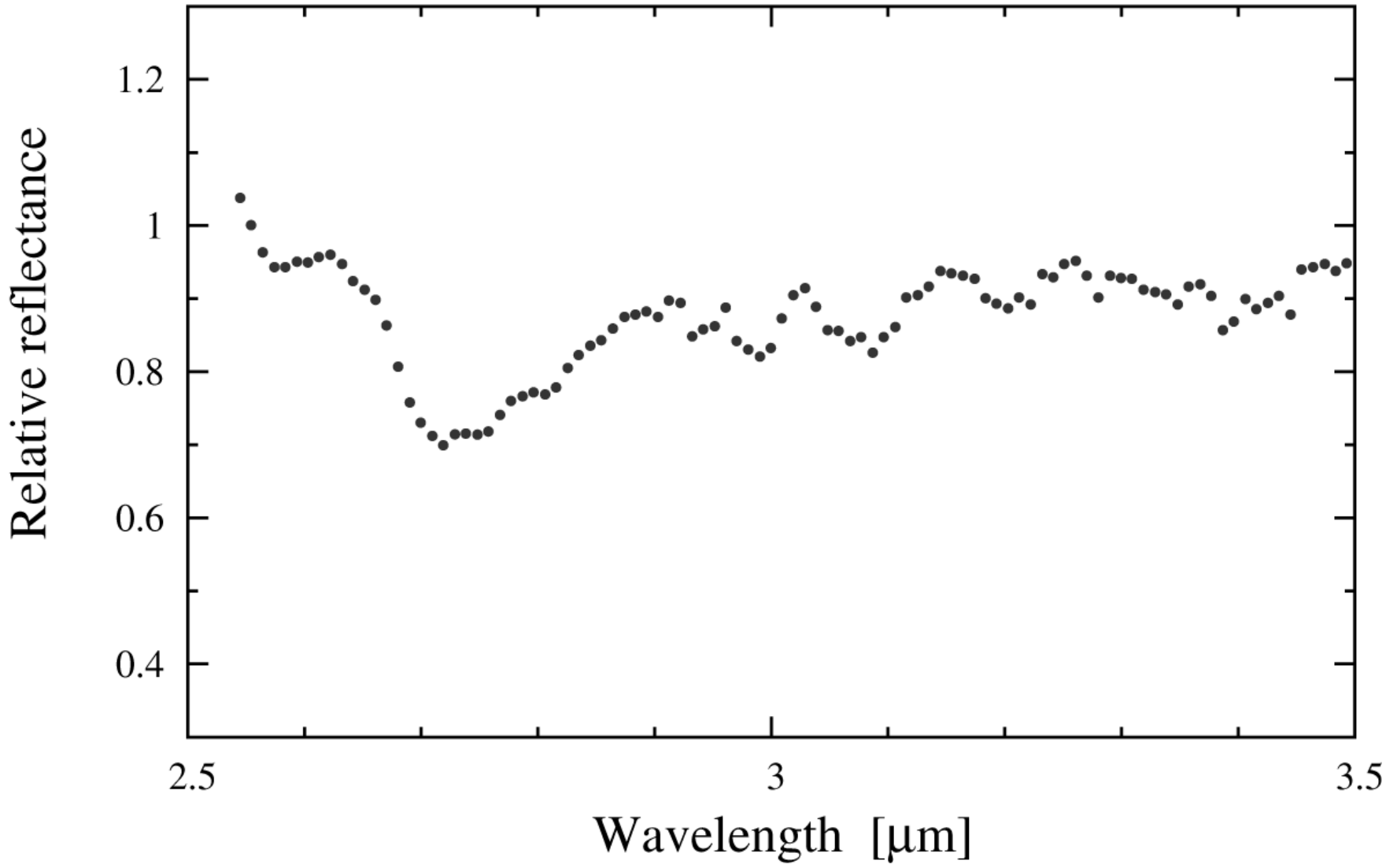
Example of data reduction：(511) Davida

Near-infrared spectrum



Example of data reduction：(511) Davida

Reflectance spectrum



Summary

Near-infrared spectroscopy for asteroids with AKARI

- Spectroscopic observations for 66 asteroids (total 147 times) with IRC/NIR in warm mission phase of AKARI
  - Wavelength coverage：2.5--5 μm , spectral resolution：R=120

- From reduced spectra (in 2.5--3.5 μm range),
  - Most C-types (16/23) have clear absorption feature in 2.7--2.8 μm band. (which is considered to be associated with hydrated minerals).
  - All S-types (17) have flat spectra, no obvious absorption feature in 2.7--2.8 μm band.
  - Some X-types (4/22) and D-types (2/3) have absorption feature like C-types.

Infrared Asteroid Survey with AKARI

- AKARI mid-infrared asteroid survey
  - Asteroidal size and albedo catalog based on AKARI mid-infrared all-sky survey data

    Usui et al. 2011, PASJ, 63, 1117; Usui et al. 2013, ApJ, 762, 56; Usui et al. 2014, PASJ, 66, 56; Usui et al. 2016, PKAS, in press

- AKARI near-infrared spectroscopic survey
  - Near-infrared spectroscopic observations with AKARI for exploring hydrated minerals on asteroids

    Usui et al. 2016, in preparation