TNO's are Cool!

Trans-Neptunian objects as seen with the Herschel Space Observatory

(Celebrating the 20^{th} birthday of the Kuiper belt)

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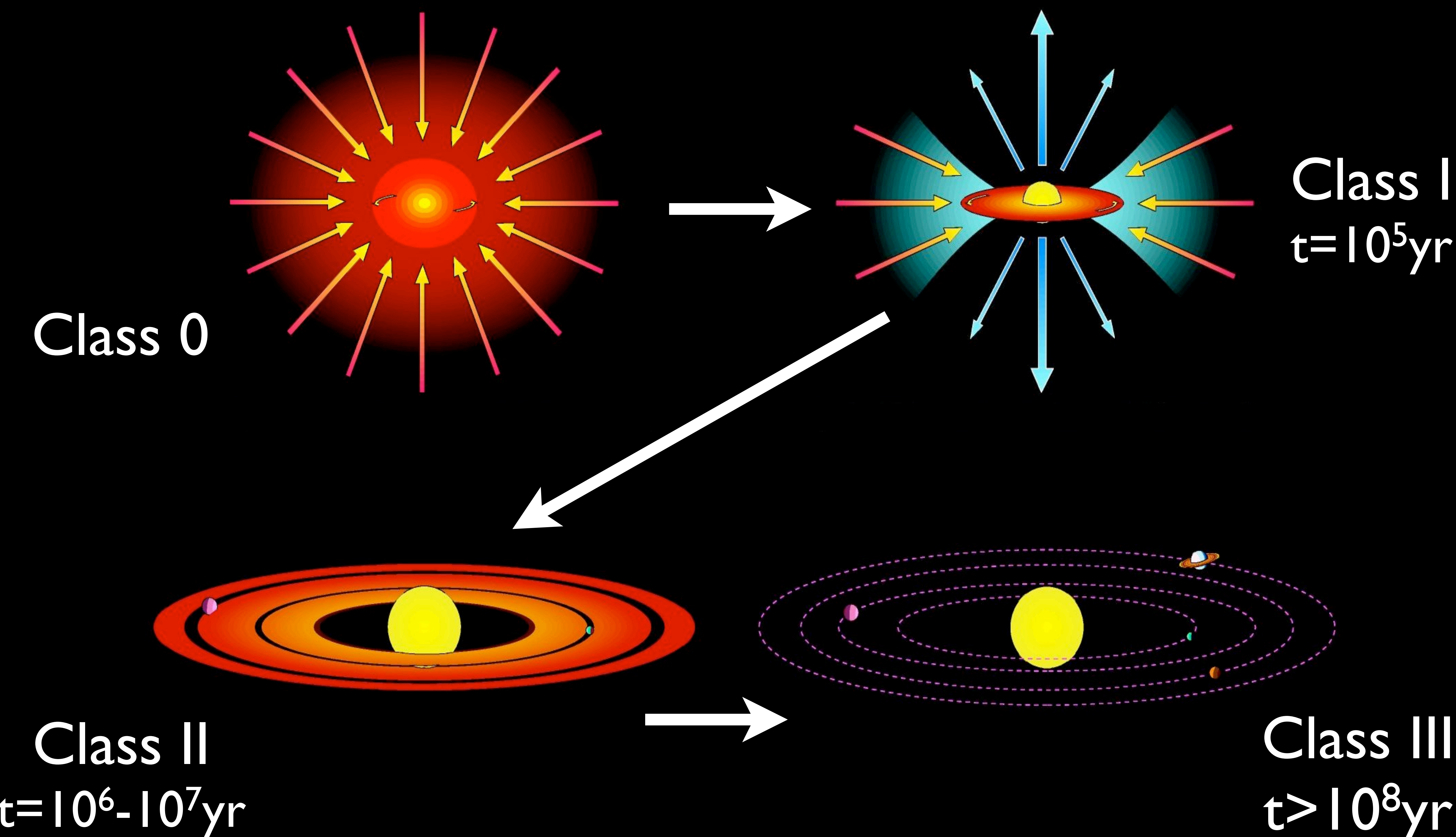
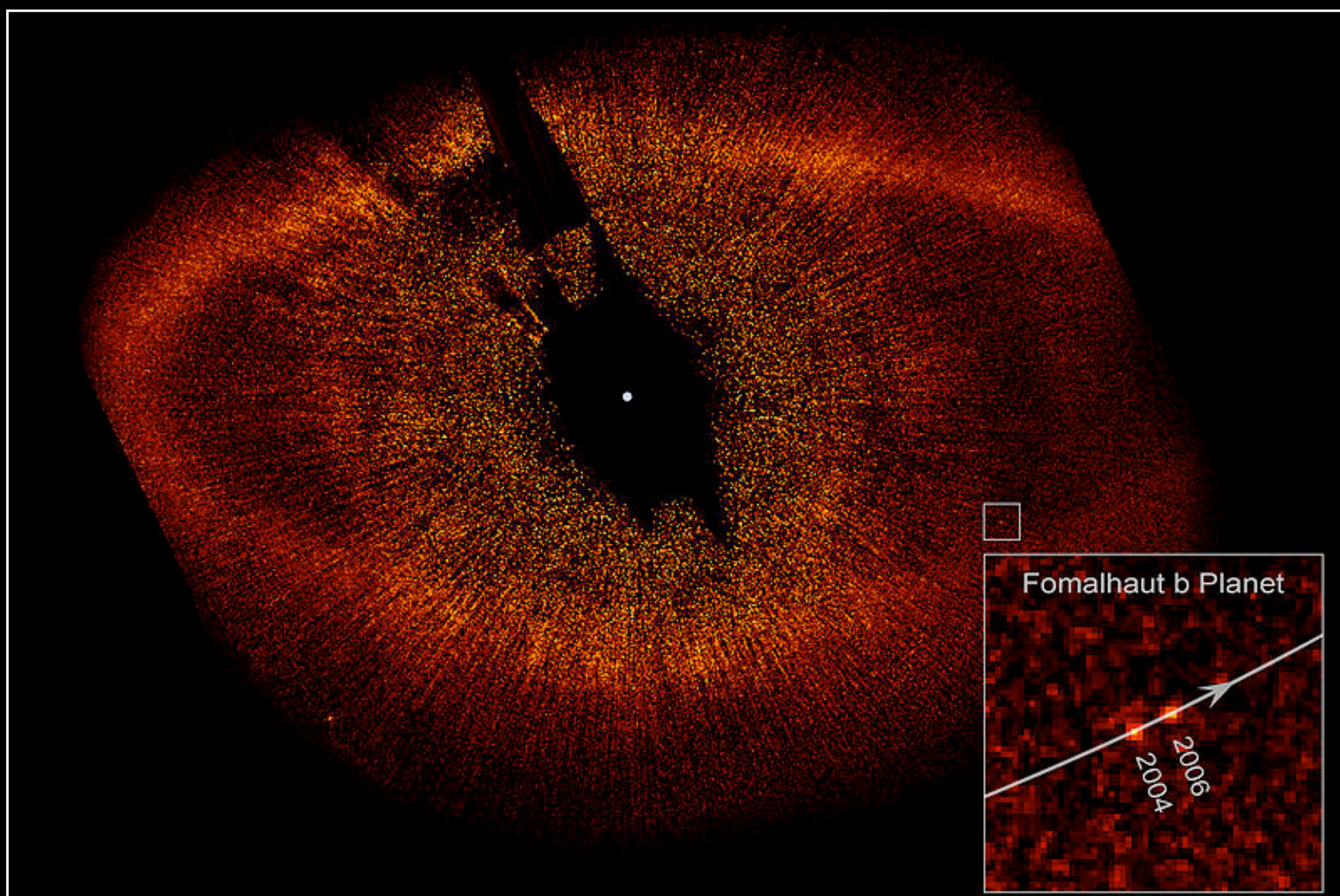
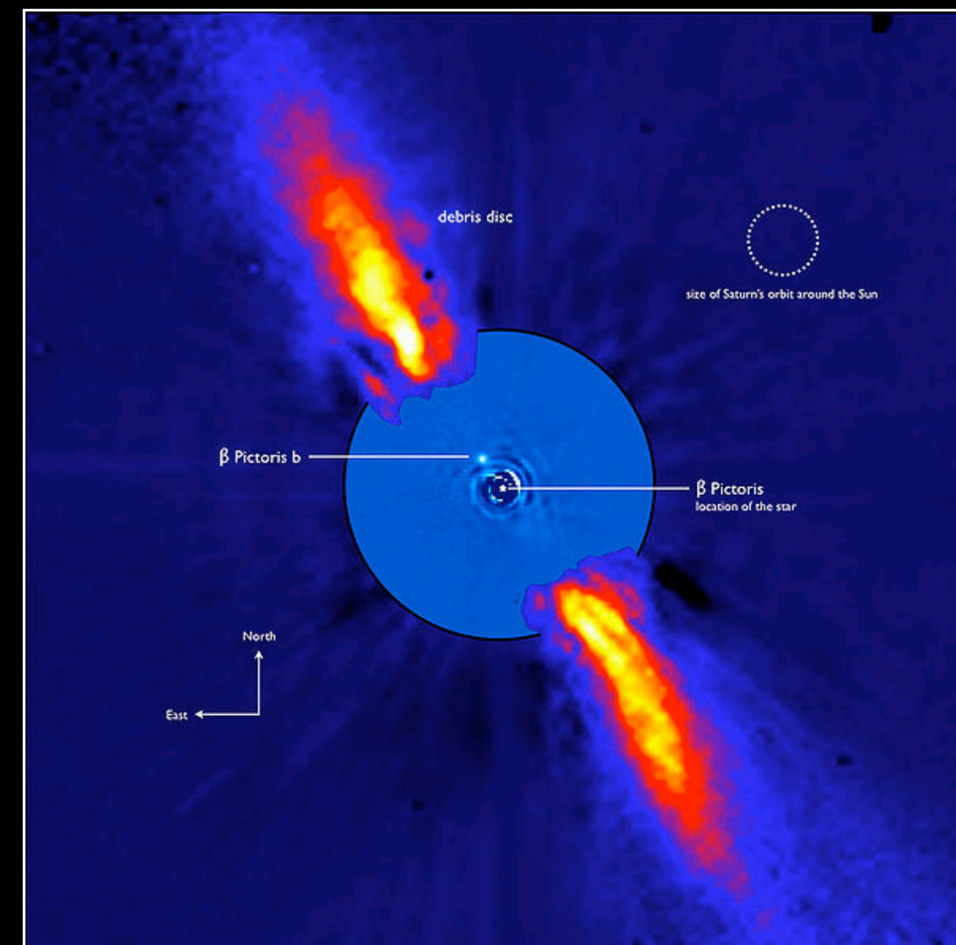
Evolution of circumstellar material



Debris disks



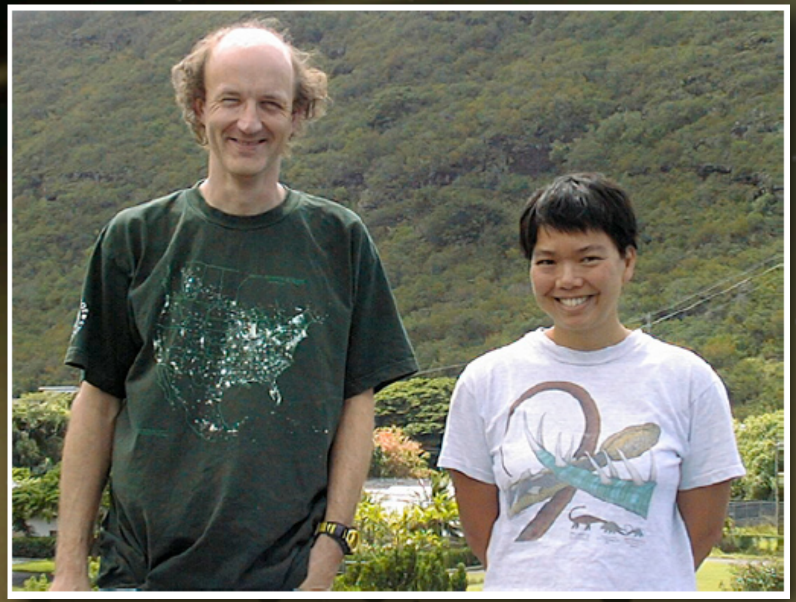


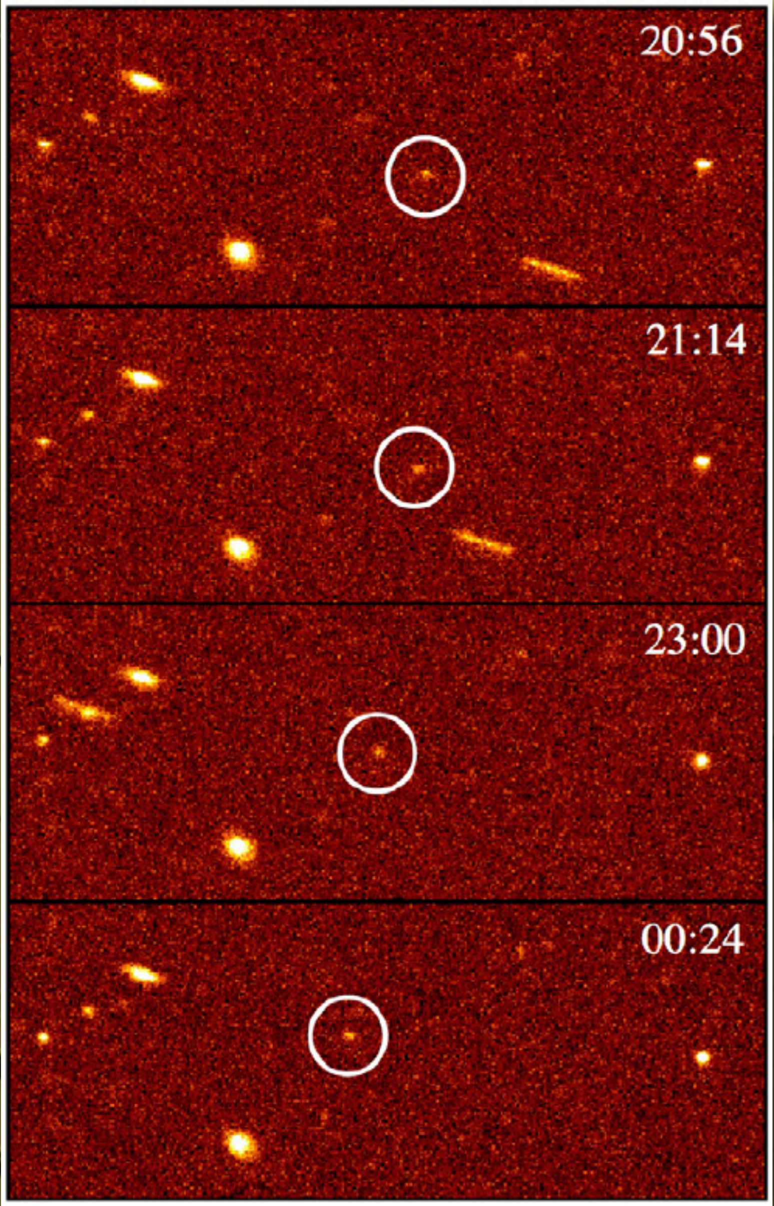
Debris disk of the Solar System

- Amount of material decreases around the star with time: transition from protoplanetary to debris disk
- It will last for billion years, but will be very tenuous at the end
- A part of the disk's material is built into planets (about 10% in the case of the Solar System), the leftover disappears from the system
- Solar System: our debris disk consists of bodies of size from ~2000km (Pluto, Eris) to micrometer sized dust
- Everything (but the eight "classical" planets) is part of the debris disk:
  - Interplanetary dust cloud (zodiacal light)
  - Asteroid (main) belt (2-3.5AU)
  - Kuiper belt (30-100AU), including many dynamical classes
- The mass and distribution of disk material change significantly during the disk's evolution (was much more massive in the past)
- How can we learn about disk evolution?
  - Orbits of planets and small bodies
  - Size distributions and dynamical structures in the debris zones
  - Surface cratering and/or geochemistry of the planets and smaller bodies
  - Deep-sea sediments on Earth

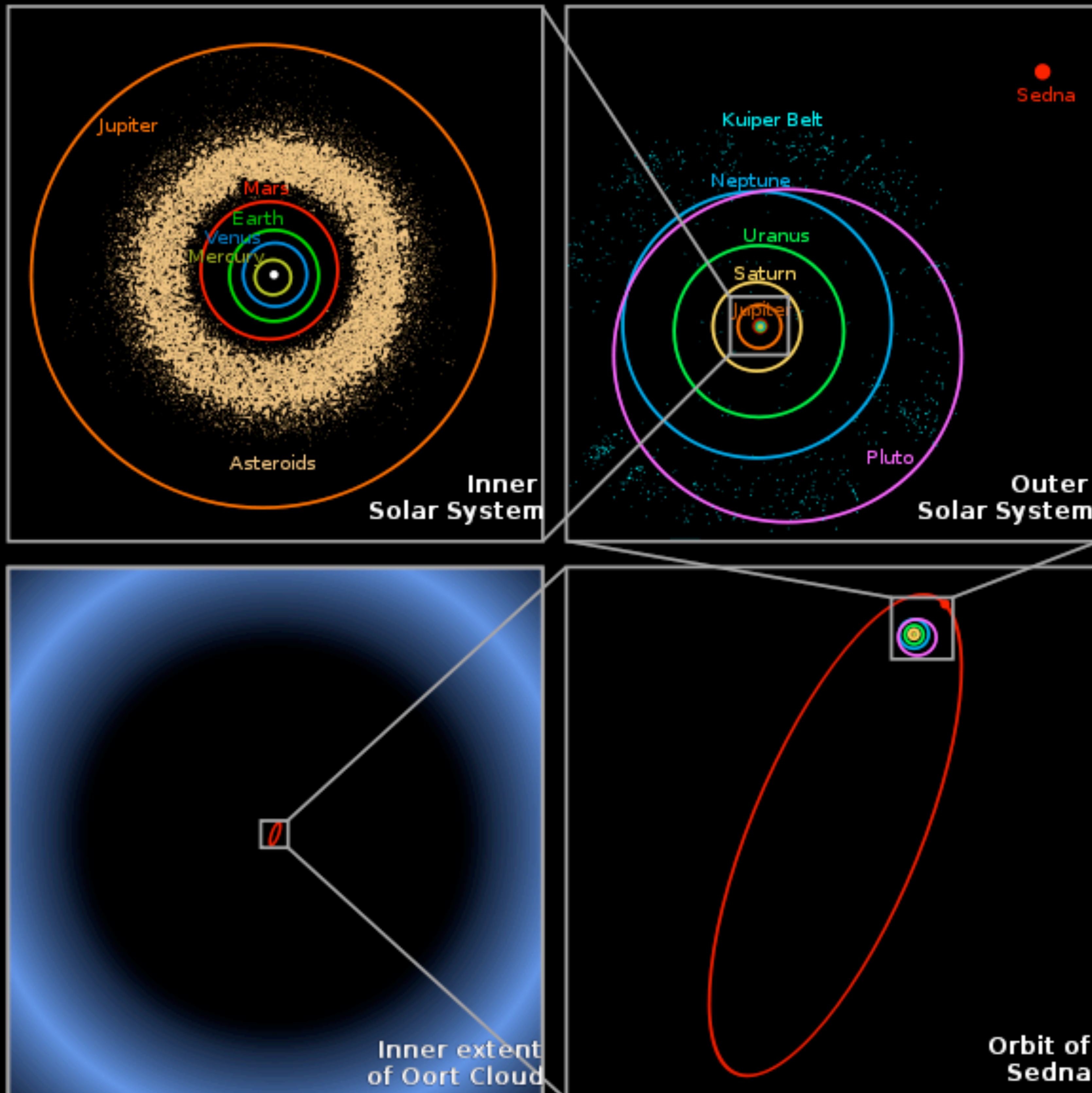
Debris disk of the Solar System

- Our one is the only debris system that we can study in detail: we can see the individual “peebles” building up the disk
- Zodiacal light and the main belt was known for a long time
- Existence of the Kuiper belt was suspected for many decades, however, the first discovery was only 20 years ago...





Overall structure of the Solar System

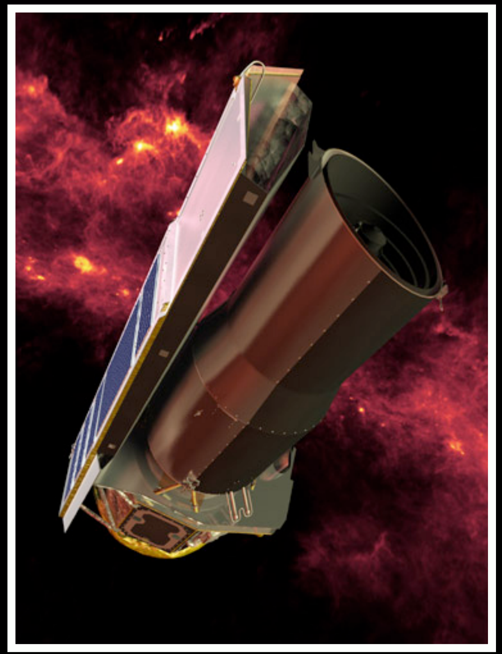


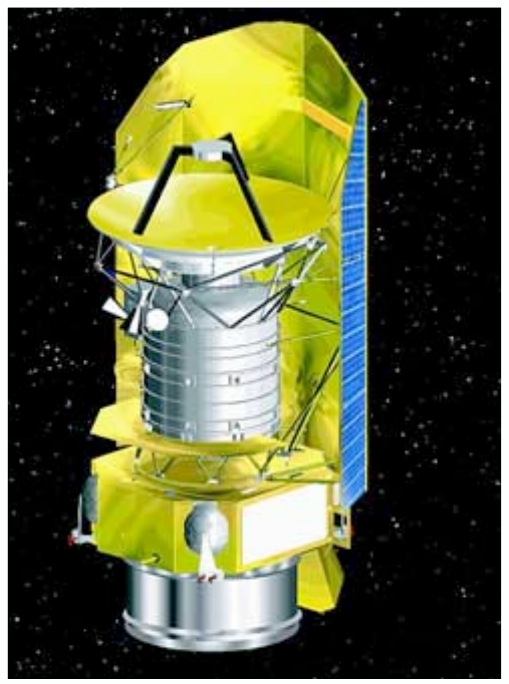
What do we know about TNOs?

- About 1400 are known
- Most measurement are performed in the visual range
- We know some things about their orbital characteristics and distributions, but very little about their physical properties (size, albedo, surface properties, etc.) except for the very large/bright ones.
- Visual range measurements are only a part of the game: absorbed sunlight is re-emitted in the infrared (thermal radiation)
- Optical and infrared measurements together can constrain the size, albedo, surface thermal inertia, surface roughness and other characteristics very well

What do we know about TNOs?

- Previous thermal IR measurements:
  - Spitzer Space Telescope: most of the TNOs are too cold for the MIPS 24/70um cameras (typical TNO temperatures are in the 30...50K range)
  - IRAM MAMBO-II 1.2mm: this is very far end of the thermal SED, most objects are already extremely dark here...
- PACS camera of the Herschel Space Observatory is just at the right wavelengths (70, 100, 160um) for the usual TNO temperatures
- TNOs are Cool!:
  - Herschel Open Time Key Program, starting at the end of 2009 with about 40 participants
  - One of the biggest Key Programs with ~500 h time for 140 targets
  - Main aim: determination of the main characteristics of TNOs using optical and IR data via radiometric models.

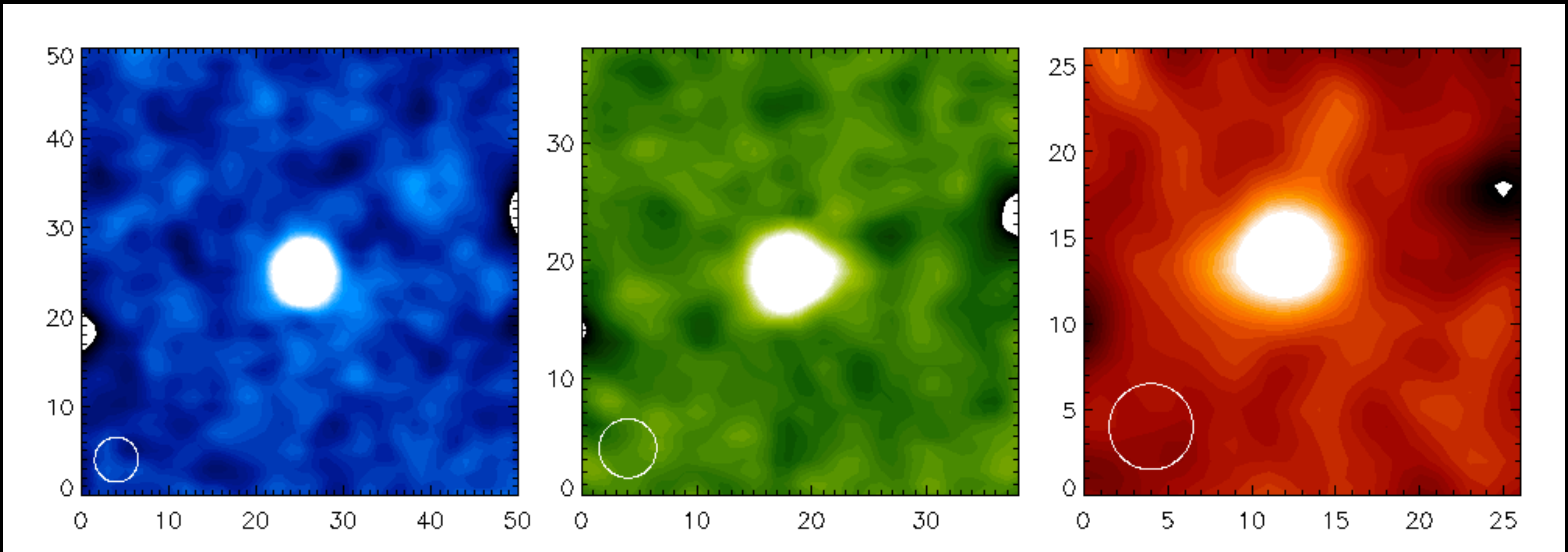




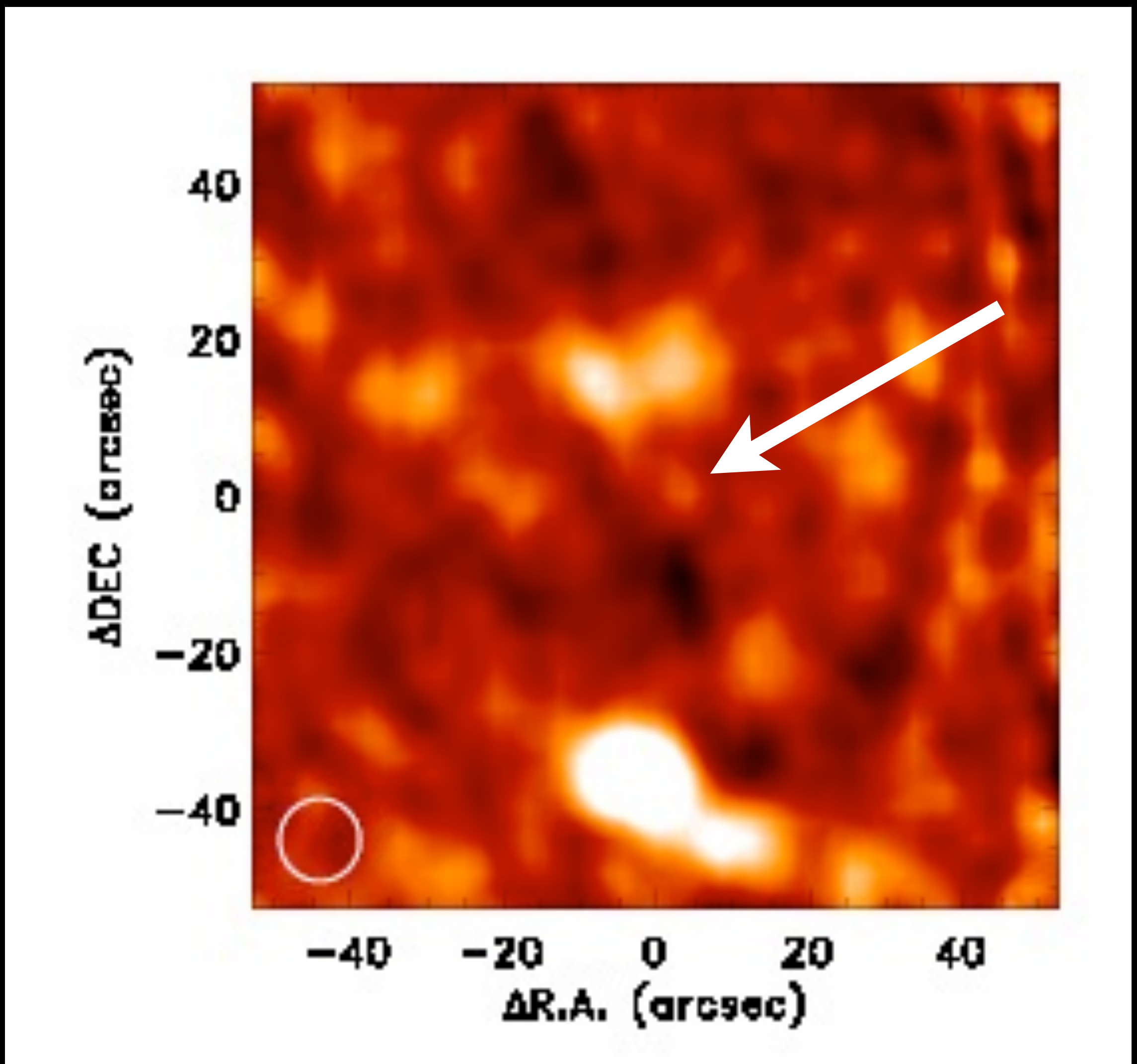
TNOs are Cool! “portfolio”

- Measurements: 100% ready, ~500 hours PACS or SPIRE measurement (~25 M€)
- Papers appeared so far:
  - Müller, T.G.; Lellouch, E.; Böhnhardt, H; ...; Kiss, Cs., et al.; 2009, “TNOs are Cool!: A Survey of the Transneptunian Region”, EM&P, 105, 209
  - Müller, T.G.; Lellouch, E., Stansberry, J., Kiss, Cs., et al., 2010, “``TNOs are Cool'': A survey of the trans-Neptunian region. I. Results from the Herschel science demonstration phase (SDP)”, A&A 518, L146
  - Lellouch, E.; Kiss, C.; Santos-Sanz, P.; et al., 2010, “``TNOs are cool'': A survey of the trans-Neptunian region. II. The thermal lightcurve of (136108) Haumea”, A&A 518, L147
  - Lim, T. L.; Stansberry, J.; Müller, T. G.;...; Kiss, C.; et al., “``TNOs are Cool'': A survey of the trans-Neptunian region . III. Thermophysical properties of 90482 Orcus and 136472 Makemake”, A&A 518, L148
  - Santos-Sanz, P., Lellouch, E., Fornasier, S., Kiss, Cs., Pál, A., ..., Szalai, N., ... et al., 2012, “"TNOs are Cool": A Survey of the Transneptunian Region IV. Size/albedo characterization of 15 scattered disk and detached objects observed with Herschel Space Observatory-PACS”, A&A 541, A92
  - Mommert, M., Harris, A.W., Kiss, Cs., Pál, A.,... Szalai, N., et al., 2012, “TNOs are Cool: A survey of the trans-Neptunian region V. Physical characterization of 18 Plutinos using Herschel PACS observations”, A&A 541, A93
  - Barucci, M.A., Merlin, F., Perna, D., ..., Kiss, Cs., et al., 2012, “The extra red plutino (55638) 2002 VE_{95}”, A&A 539, A152
  - Pál, A., Kiss, Cs., Müller, T.G., ..., Szalai, N., et al., 2012, “Size and surface characteristics of (90377) Sedna and 2010 EK_{139}”, A&A 541, L6
  - Vilenius, E., Kiss, Cs., Mommert, M., ... Pál, A., ..., Szalai, N., et al., 2012, “Herschel/PACS observations and thermal modeling of 19 classical Kuiper belt objects”, A&A 541, L94

An easy target: (50000) Quaoar

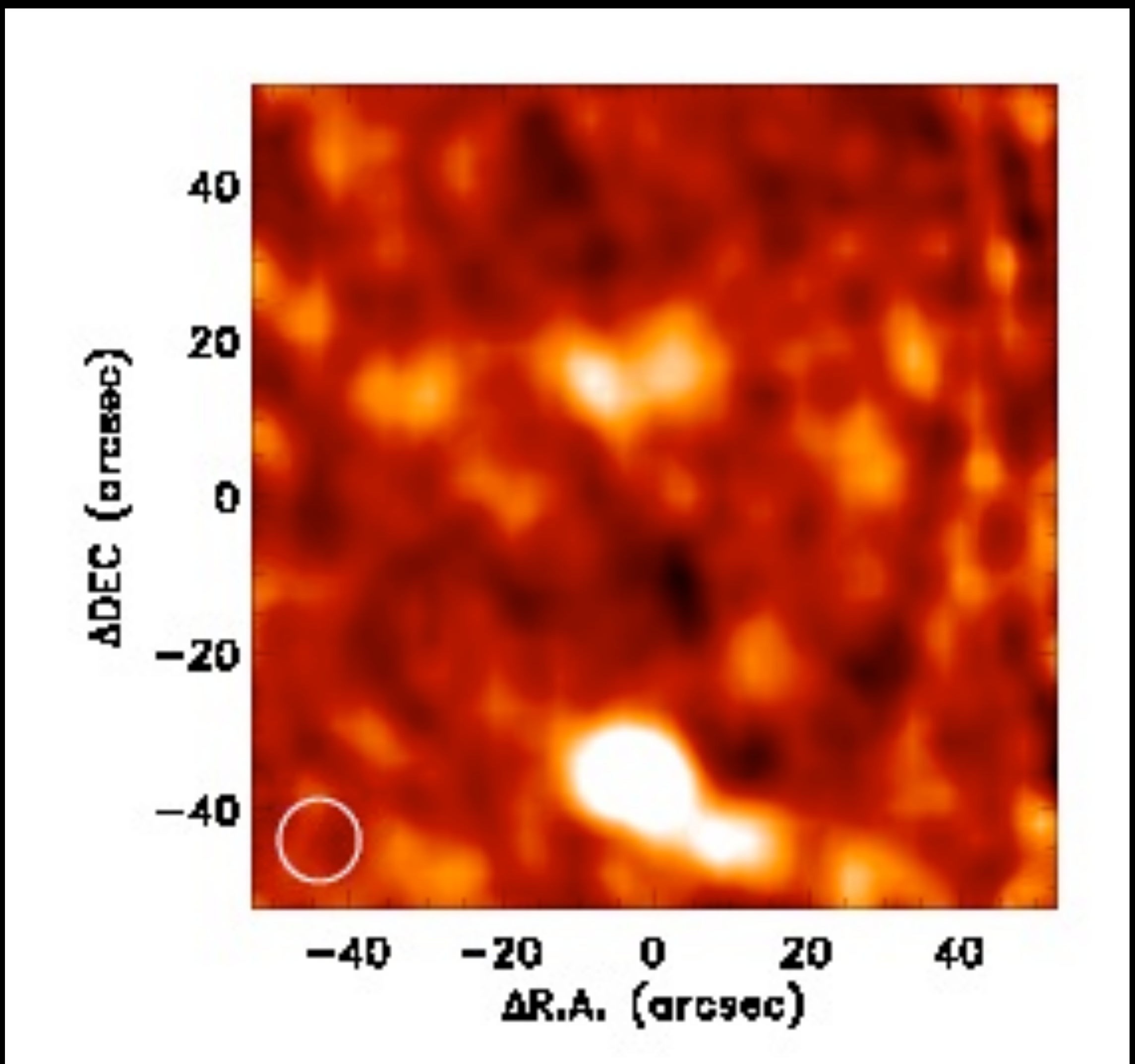


A very faint object: Eris



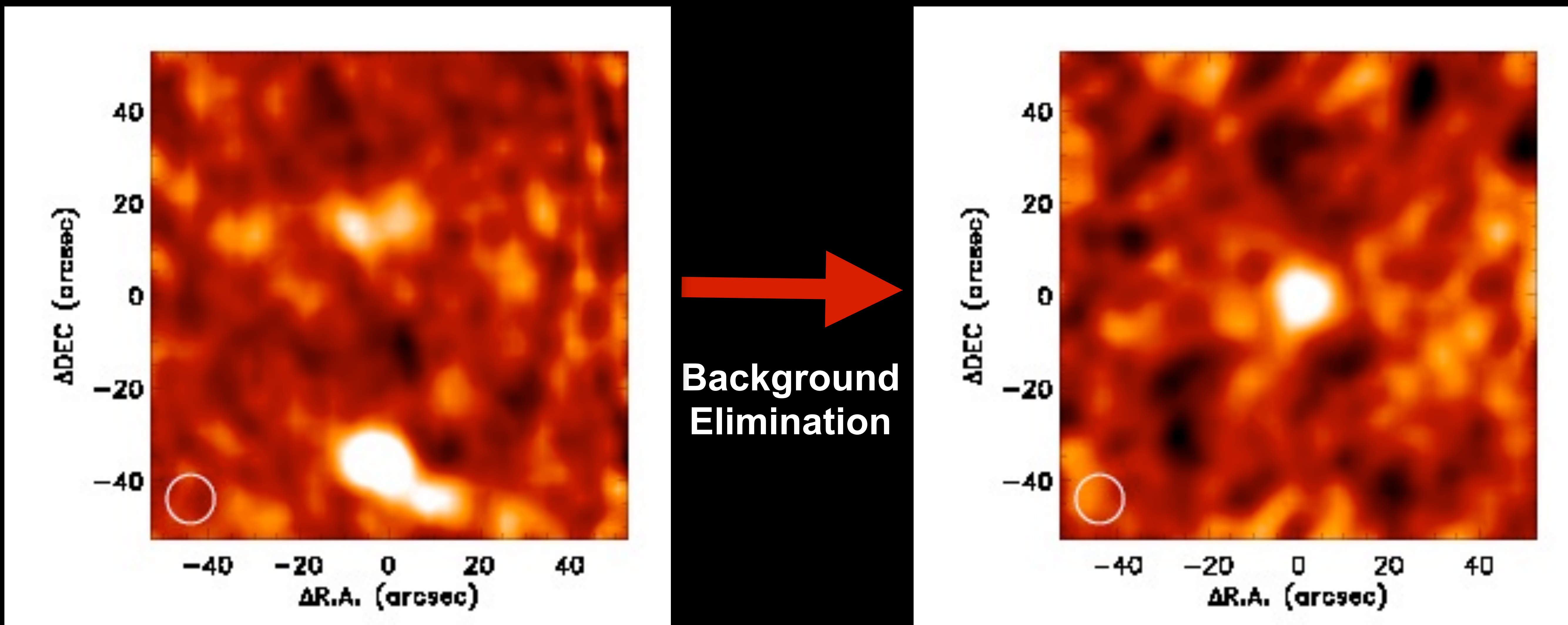
it has a very high albedo (~96%) -- only very little is emitted in the infrared!

A very faint object: Eris

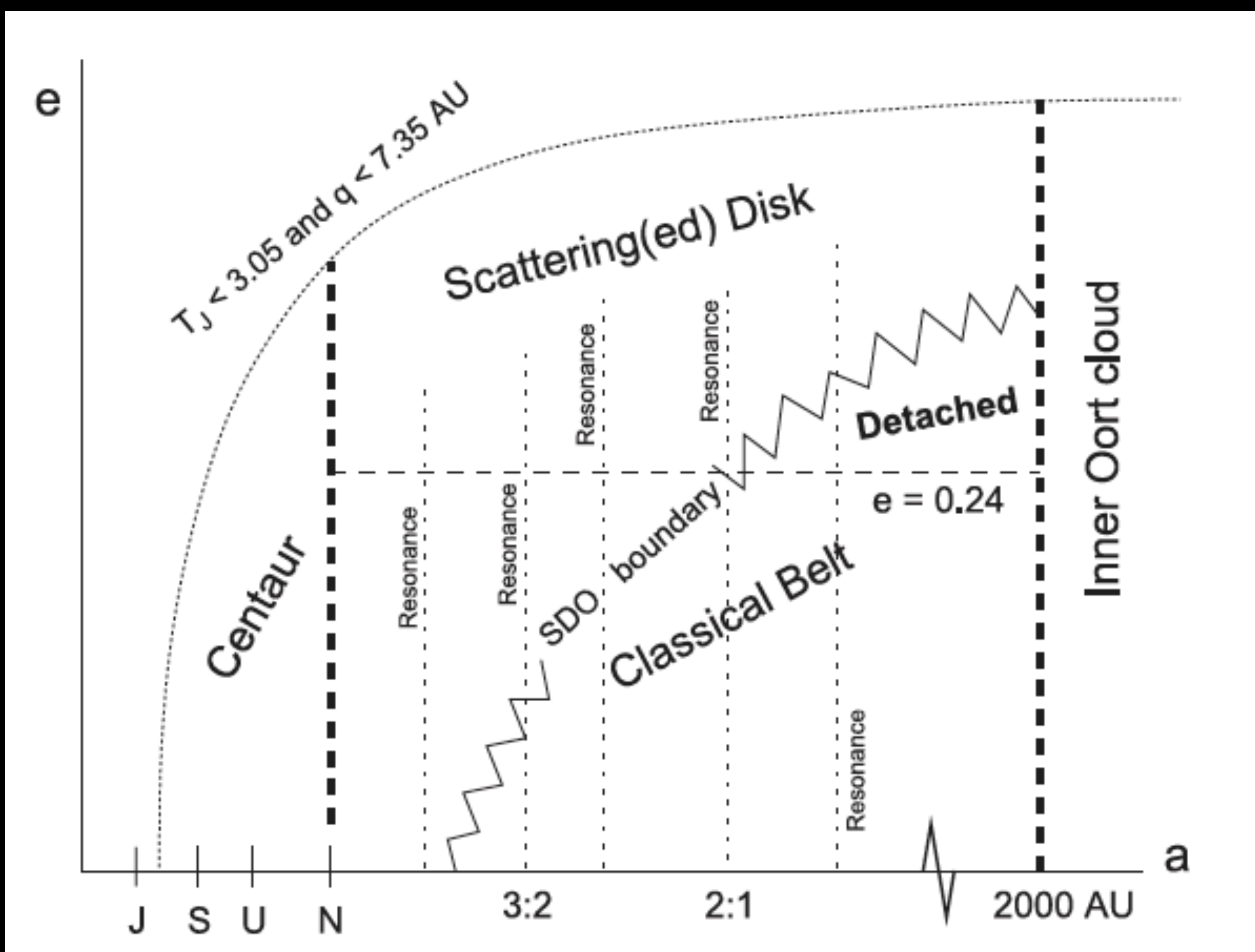


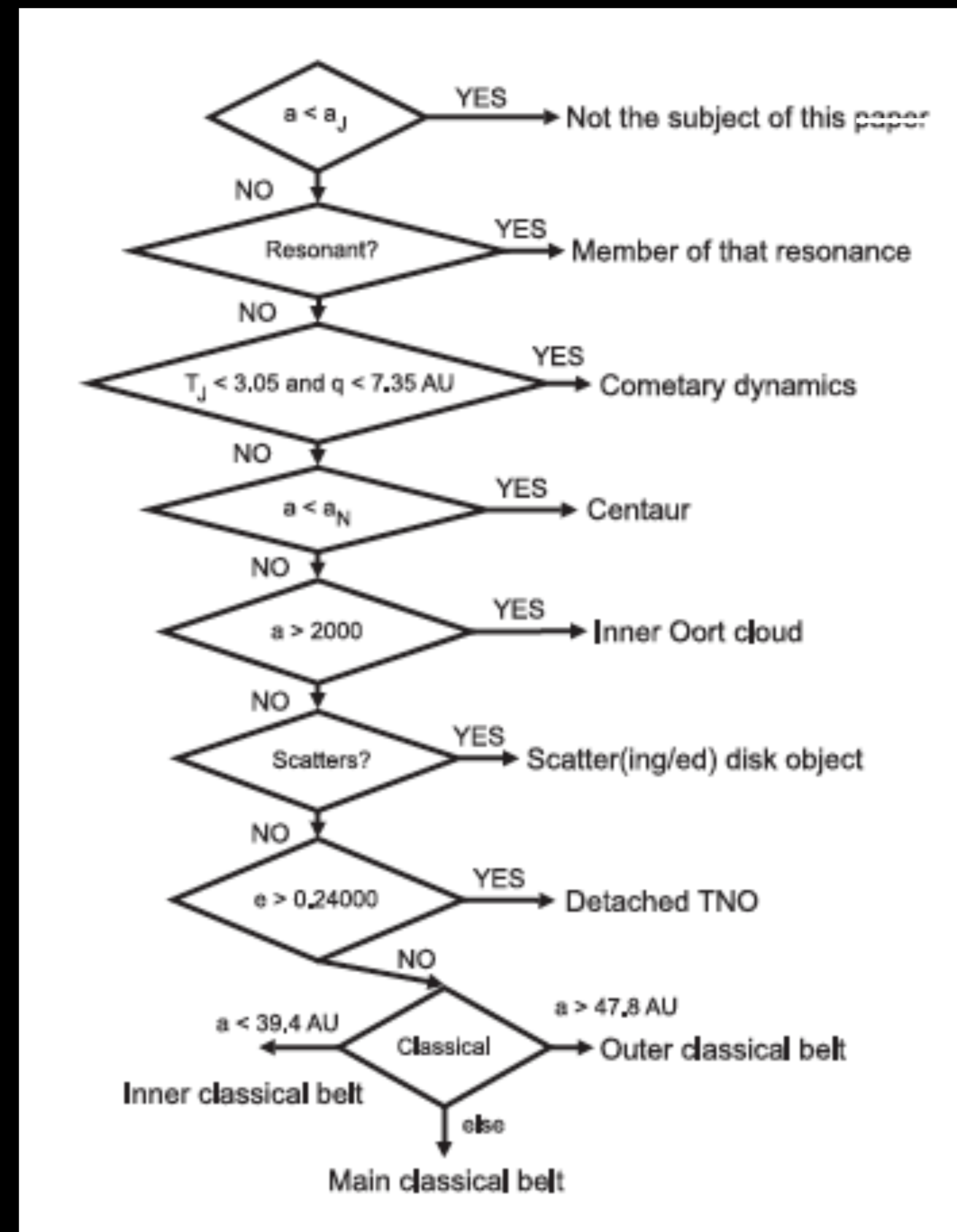
Background Elimination

A very faint object: Eris



Dynamical classes in the outer Solar System (SSBN07)





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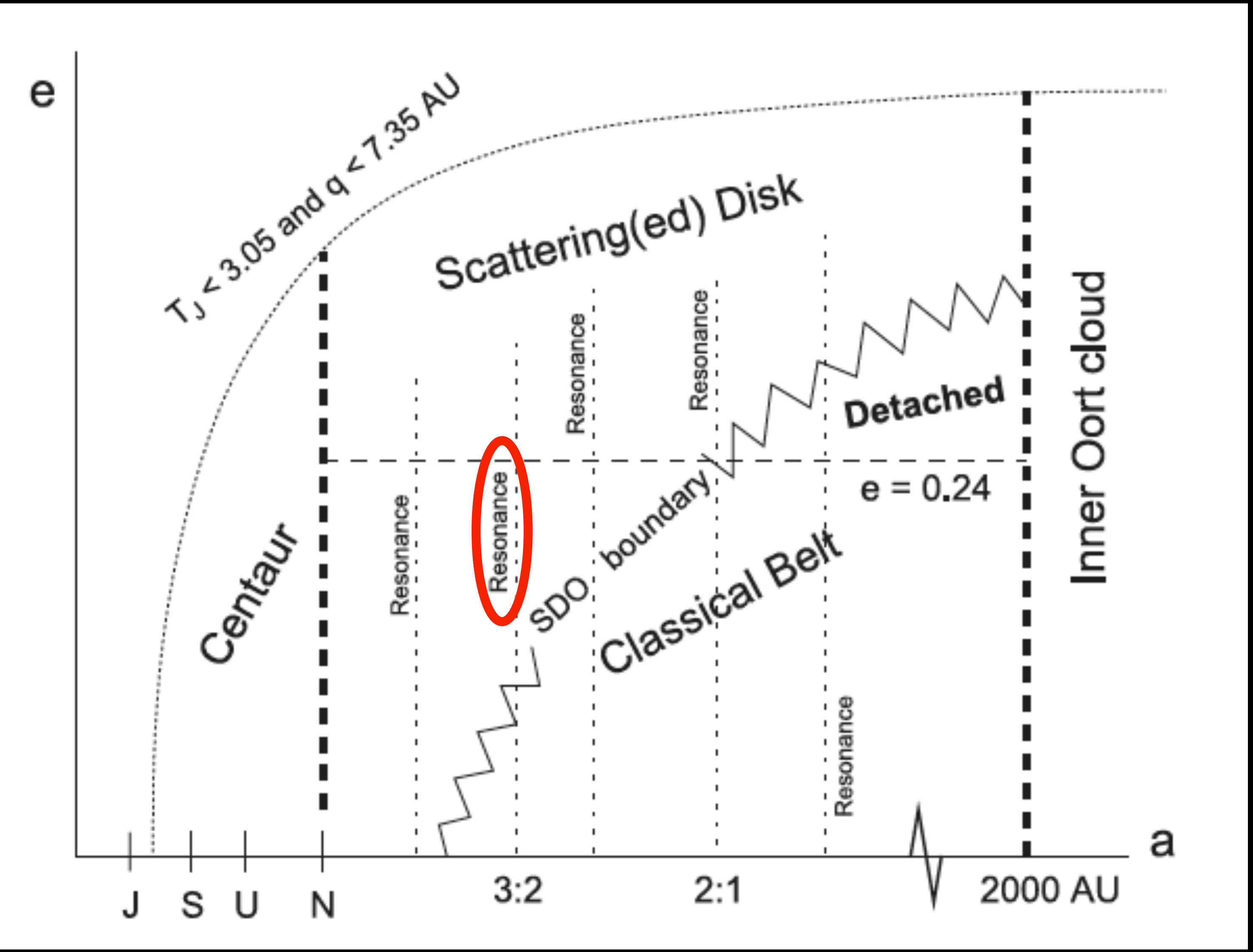
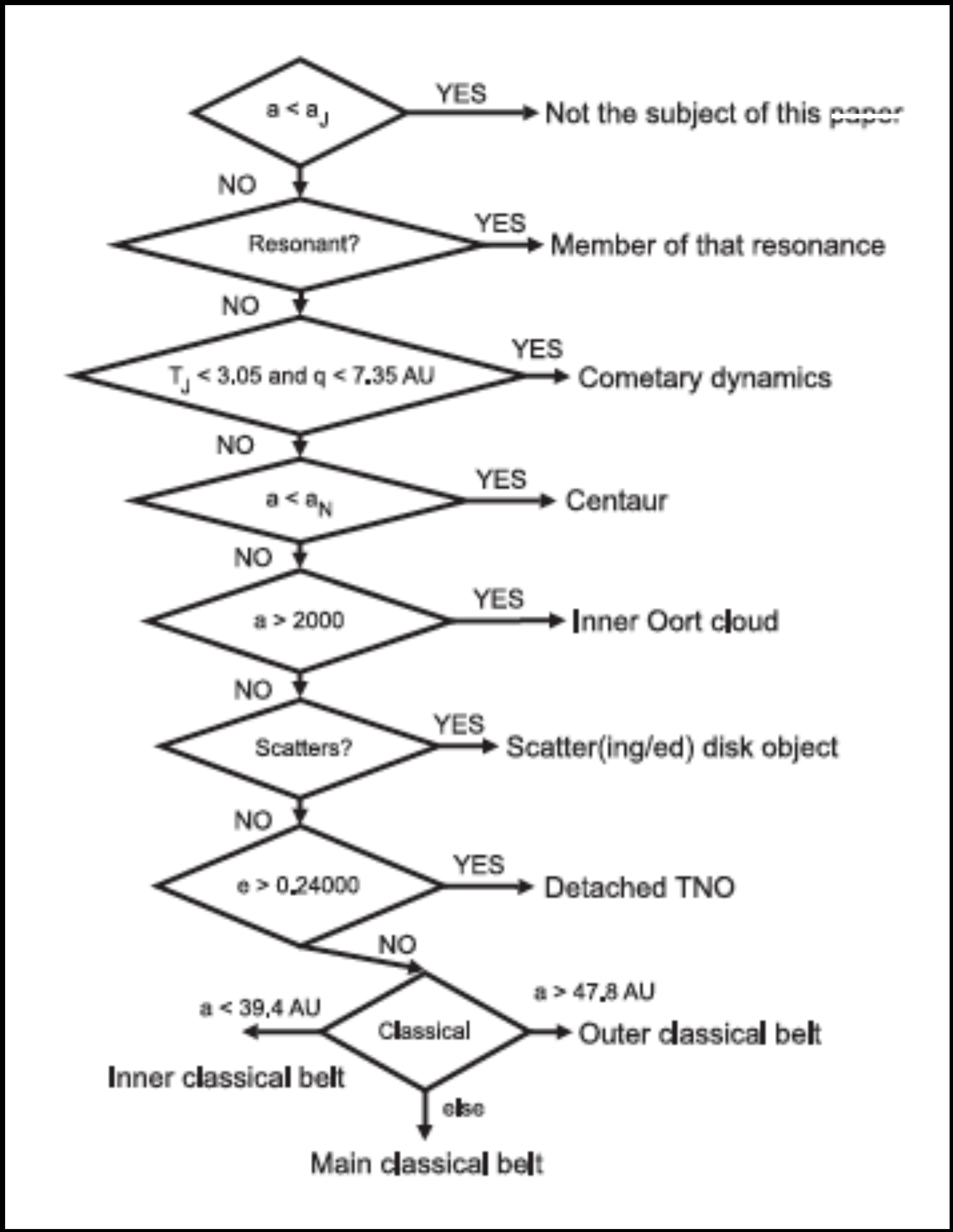
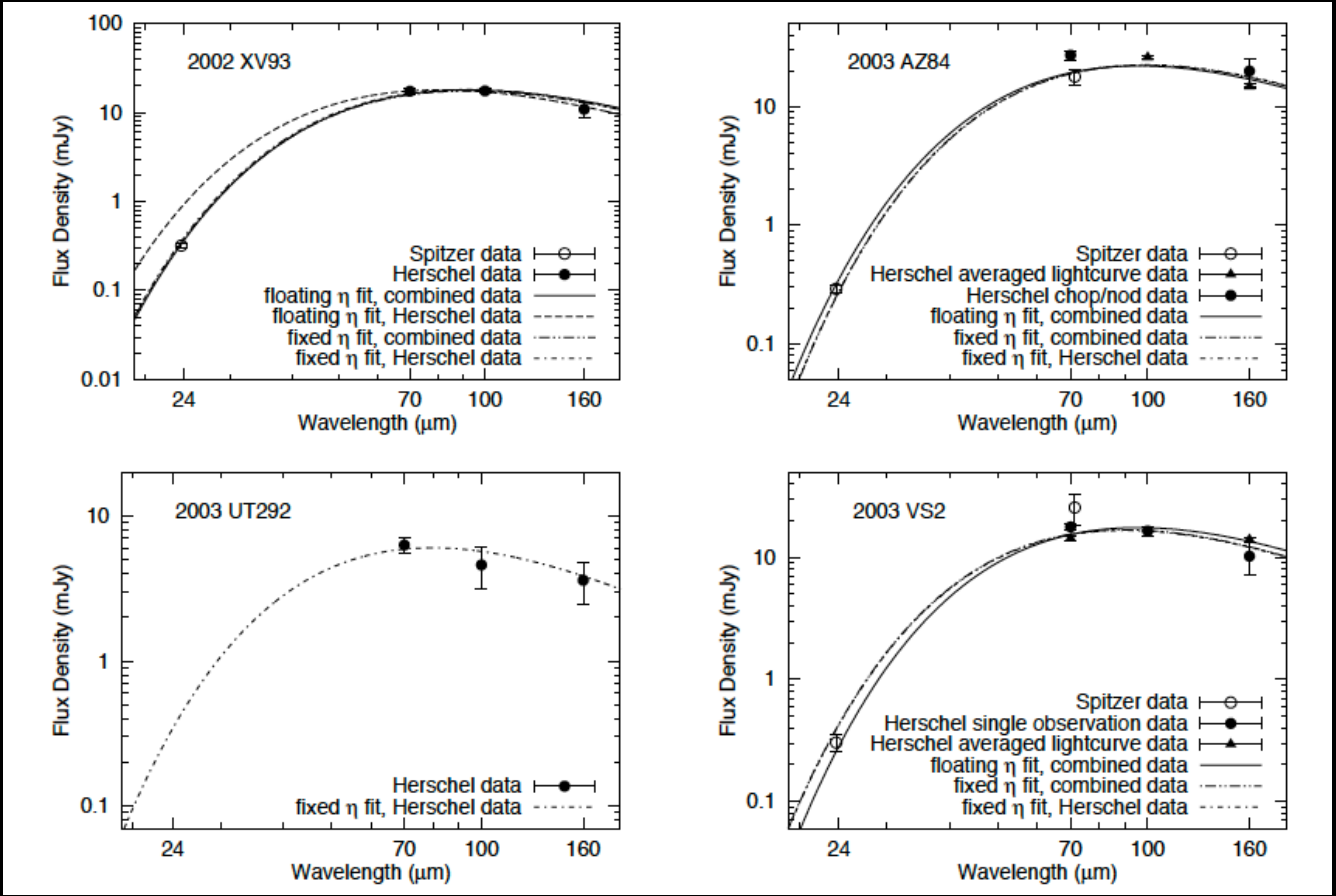




Plutinos

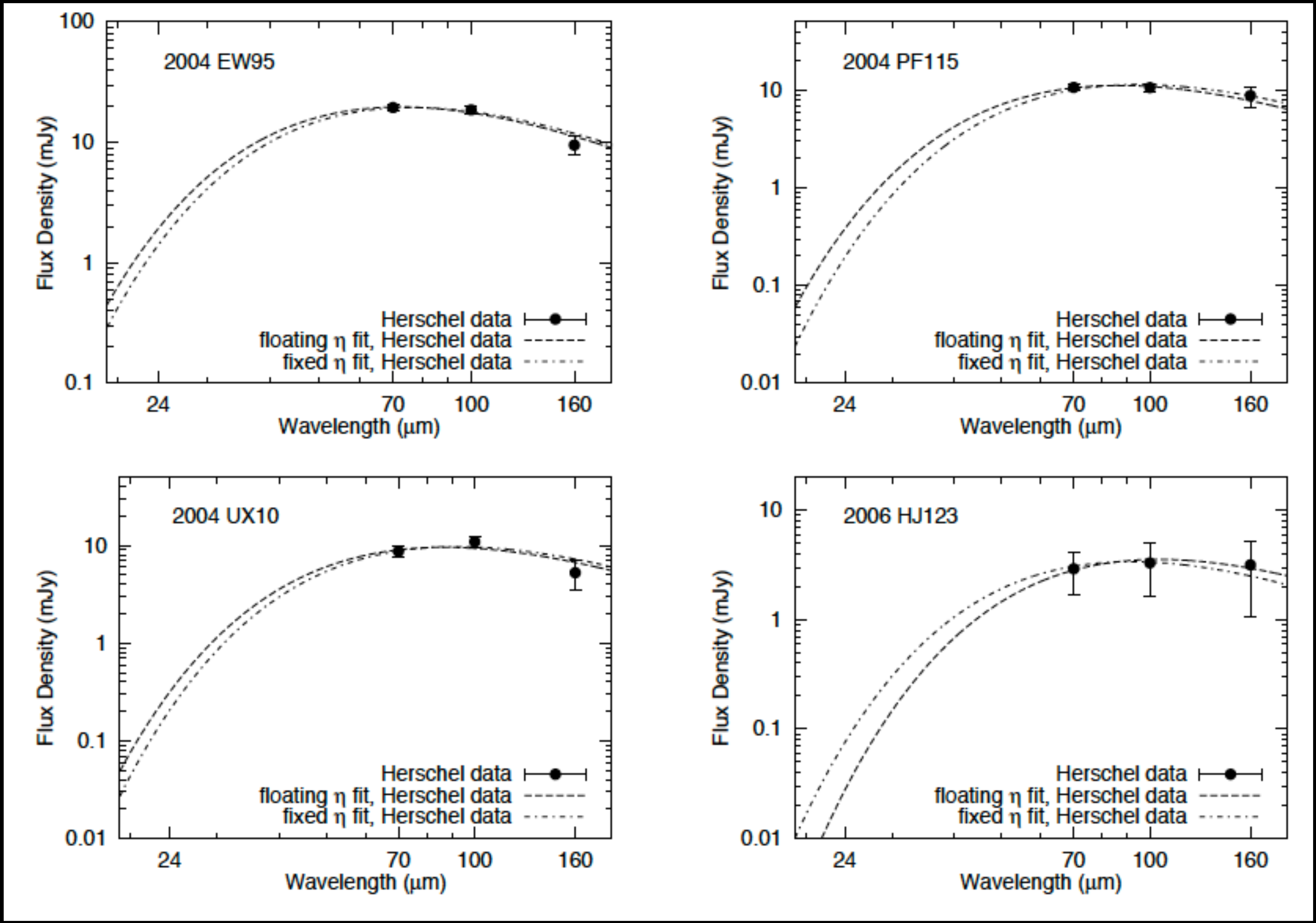
Object	ObsIDs	Dur. (min)	Mid-time (UT)	r (AU)	Δ (AU)	α (°)	PACS Flux Densities (mJy) 70 μm	100 μm	160 μm
1996 TP66	1342202289/...2310	113.3	08-08 03:28	27.3175	27.6467	2.0	≤ 0.8	≤ 1.1	≤ 1.5
1999 TC36	1342199491/...9630	75.7	07-01 10:10	30.6722	30.8956	1.9	27.2 ± 1.4	22.3 ± 1.9	11.0 ± 1.6
2000 GN171	1342202906/...2971	150.9	08-12 18:19	28.2876	28.4320	2.0	3.2 ± 0.7	5.8 ± 1.1	3.2 ± 1.3
2001 KD77	1342205966/...6009	150.9	10-07 05:54	35.7854	36.1111	1.5	5.4 ± 0.6	1.0 ± 1.1	4.1 ± 1.8
2001 QF298	1342197661/...7681	113.3	06-03 06:43	43.1037	43.3727	1.3	7.2 ± 0.8	6.5 ± 1.7	5.0 ± 1.3
2002 VE95	1342202901/...2953	113.3	08-12 15:17	28.5372	28.8990	1.9	10.6 ± 0.8	8.6 ± 1.1	6.8 ± 1.6
2002 VR128	1342190929/...0990	109.3	02-22 11:57	37.4636	37.7851	1.4	15.8 ± 0.9	13.1 ± 1.2	8.8 ± 1.3
2002 VU130	1342192762/...2783	112.8	03-26 05:04	41.6877	42.1392	1.2	3.2 ± 0.8	2.4 ± 1.0	2.1 ± 1.3
2002 XV93	1342193126/...3175	112.8	03-31 22:35	39.7152	40.0645	1.4	17.3 ± 1.1	17.4 ± 1.2	10.8 ± 2.1
2003 AZ84[a]	1342187054	cf. (Müller et al. 2010)		45.376	44.889	1.1	27.0 ± 2.8	-	19.7 ± 5.2
2003 AZ84[b]	cf. Footnote *b*	484.5	09-27 13:42	45.3025	45.6666	1.2	–	25.7 ± 0.3	14.6 ± 0.8
2003 UT292	1342190949/...1025	145.6	02-22 22:33	29.4217	29.4484	1.9	6.3 ± 0.8	4.7 ± 1.4	3.6 ± 1.2
2003 VS2	1342191937/...1977	75.7	03-10 07:22	36.4694	36.7093	1.5	17.8 ± 1.1	16.5 ± 1.5	10.2 ± 3.0
2003 VS2[c]	cf. Footnote *c*	508.0	08-11 18:23	36.4760	36.8017	1.5	14.4 ± 0.3	–	14.0 ± 0.6
2004 EW95	1342199483/...9712	113.3	07-01 22:42	27.4708	27.1723	2.1	19.5 ± 0.9	18.7 ± 1.2	9.6 ± 1.8
2004 PF115	1342208462/...8841	113.3	11-11 10:53	41.4271	41.2712	1.4	10.7 ± 0.9	10.6 ± 1.0	8.8 ± 2.1
2004 UX10	1342199495/...9626	75.7	07-01 11:12	38.9500	39.3307	1.4	8.7 ± 1.1	10.9 ± 1.6	5.2 ± 1.8
2006 HJ123	1342204150/...4200	113.3	09-09 05:52	36.5383	36.9867	1.4	3.0 ± 1.2	3.5 ± 1.6	3.2 ± 2.1
Huya	1342202873/...2914	75.7	08-12 03:37	28.6648	28.7665	2.0	41.4 ± 1.6	37.6 ± 1.8	22.5 ± 2.2
Pluto/Charon	1342191953/...1988	75.7	03-10 12:46	31.7985	32.0470	1.7	283.9 ± 8.6	354.8 ± 11.2	289.2 ± 17.2

Plutinos

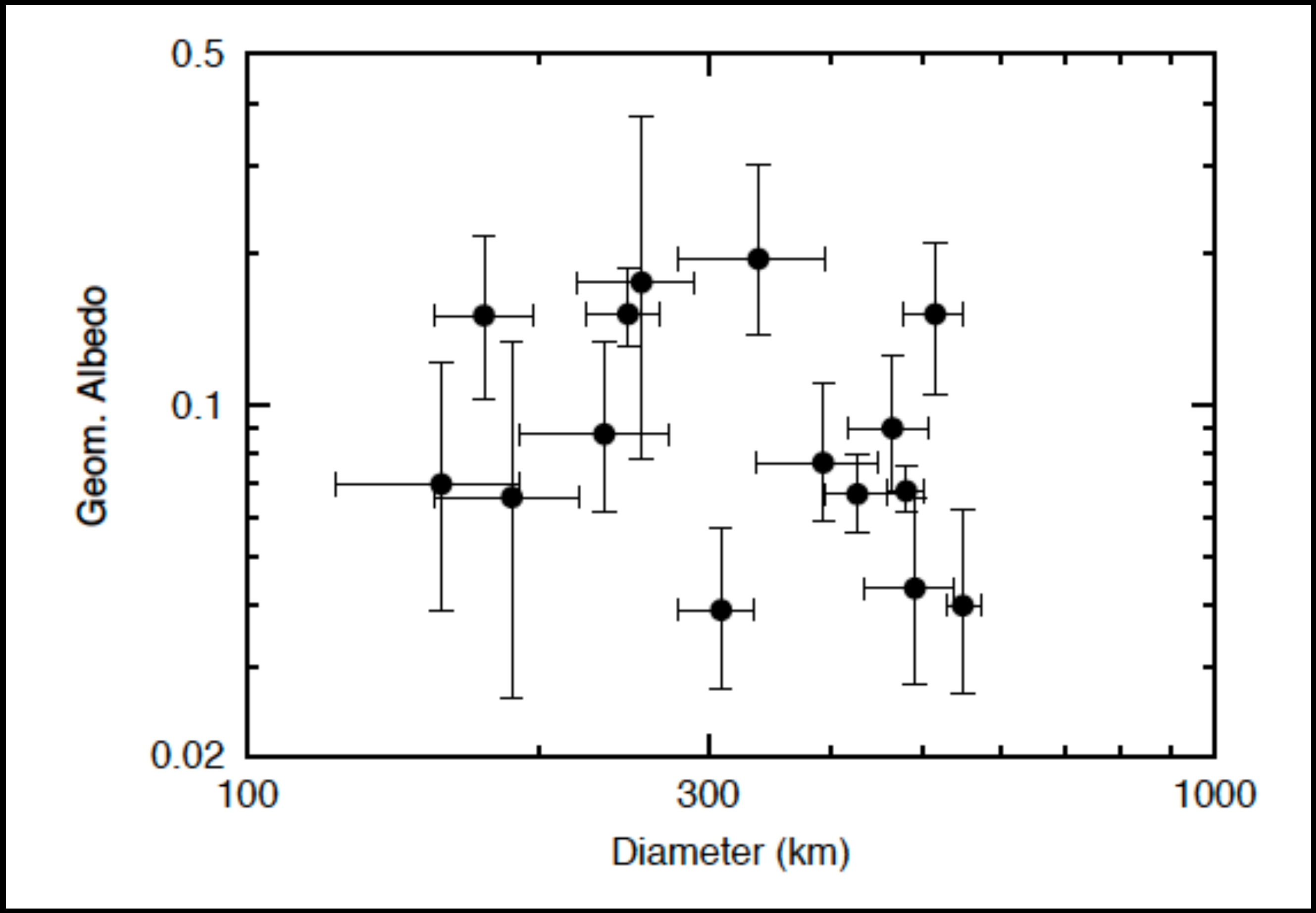


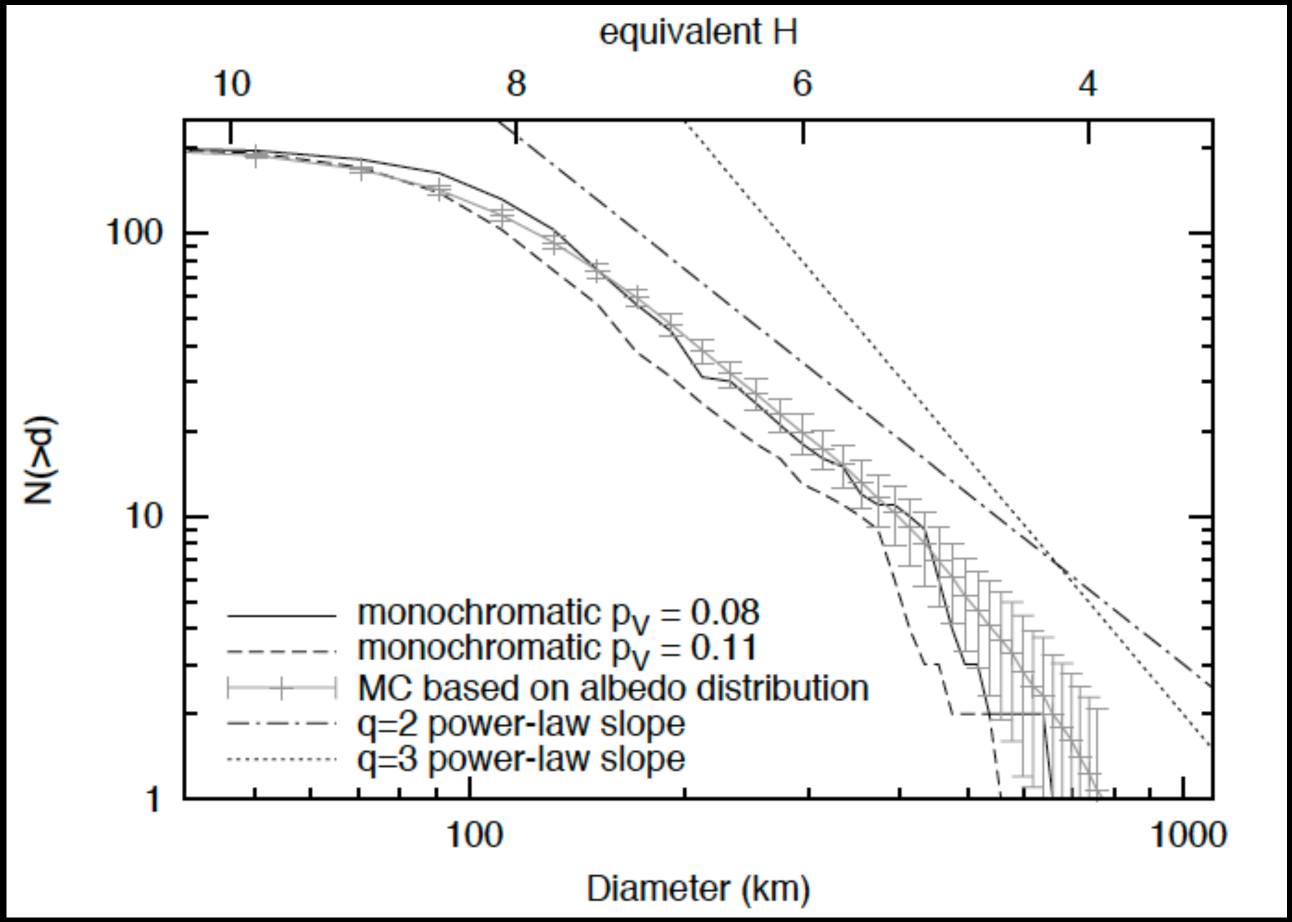
2002 XV93
Flux Density (mJy)
Wavelength (µm)
Spitzer data
Herschel data
floating η fit, combined data
floating η fit, Herschel data
fixed η fit, combined data
fixed η fit, Herschel data
2003 AZ84
Spitzer data
Herschel averaged lightcurve data
Herschel chop/nod data
floating η fit, combined data
fixed η fit, combined data
fixed η fit, Herschel data
2003 UT292
Herschel data
fixed η fit, Herschel data
2003 VS2
Spitzer data
Herschel single observation data
Herschel averaged lightcurve data
floating η fit, combined data
fixed η fit, combined data
fixed η fit, Herschel data

Plutinos


2004 EW95
2004 PF115
2004 UX10
2006 HJ123
Flux Density (mJy)
Wavelength (µm)
24
70
100
160
0.01
0.1
1
10
100
Herschel data
floating η fit, Herschel data
fixed η fit, Herschel data

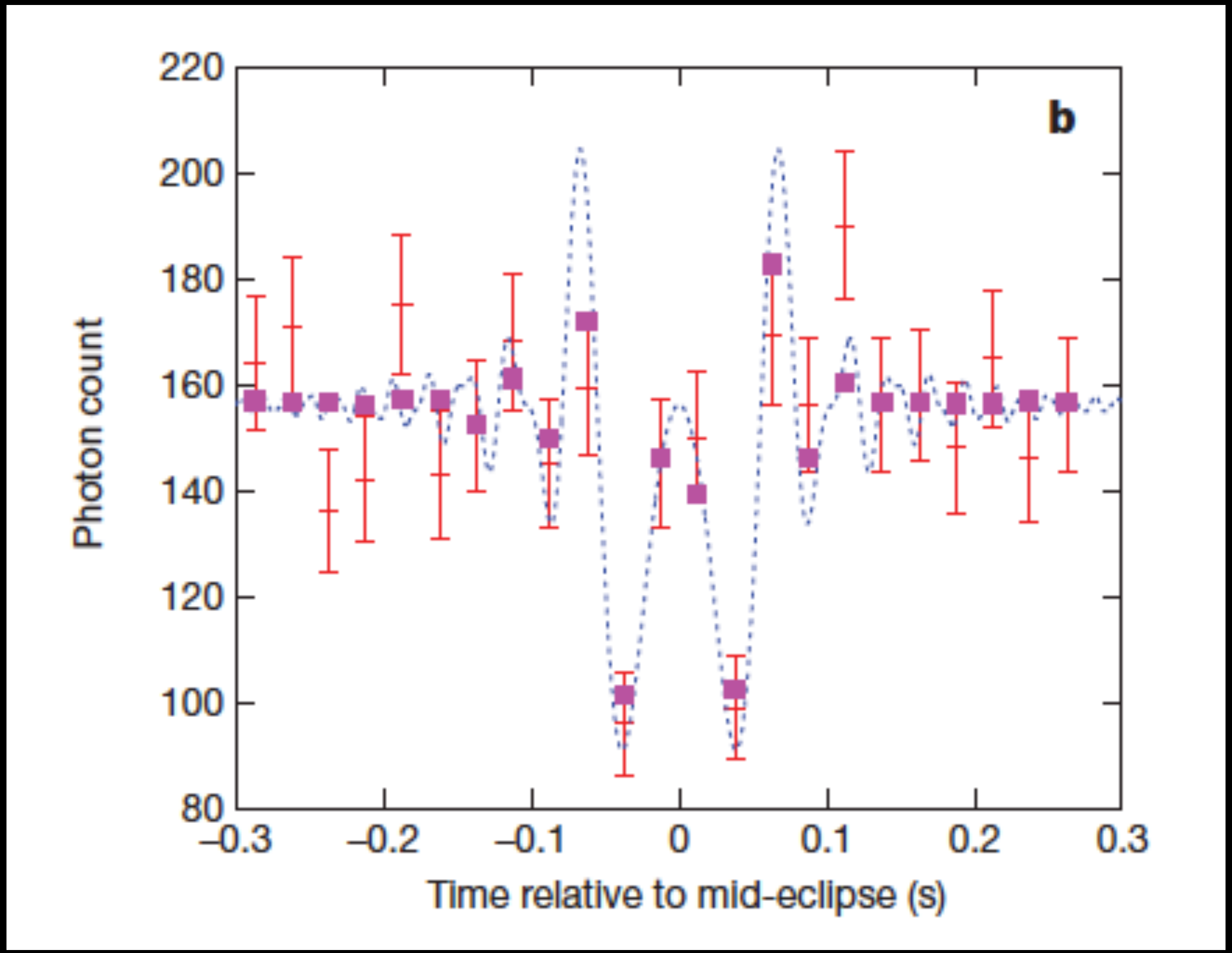
Plutinos





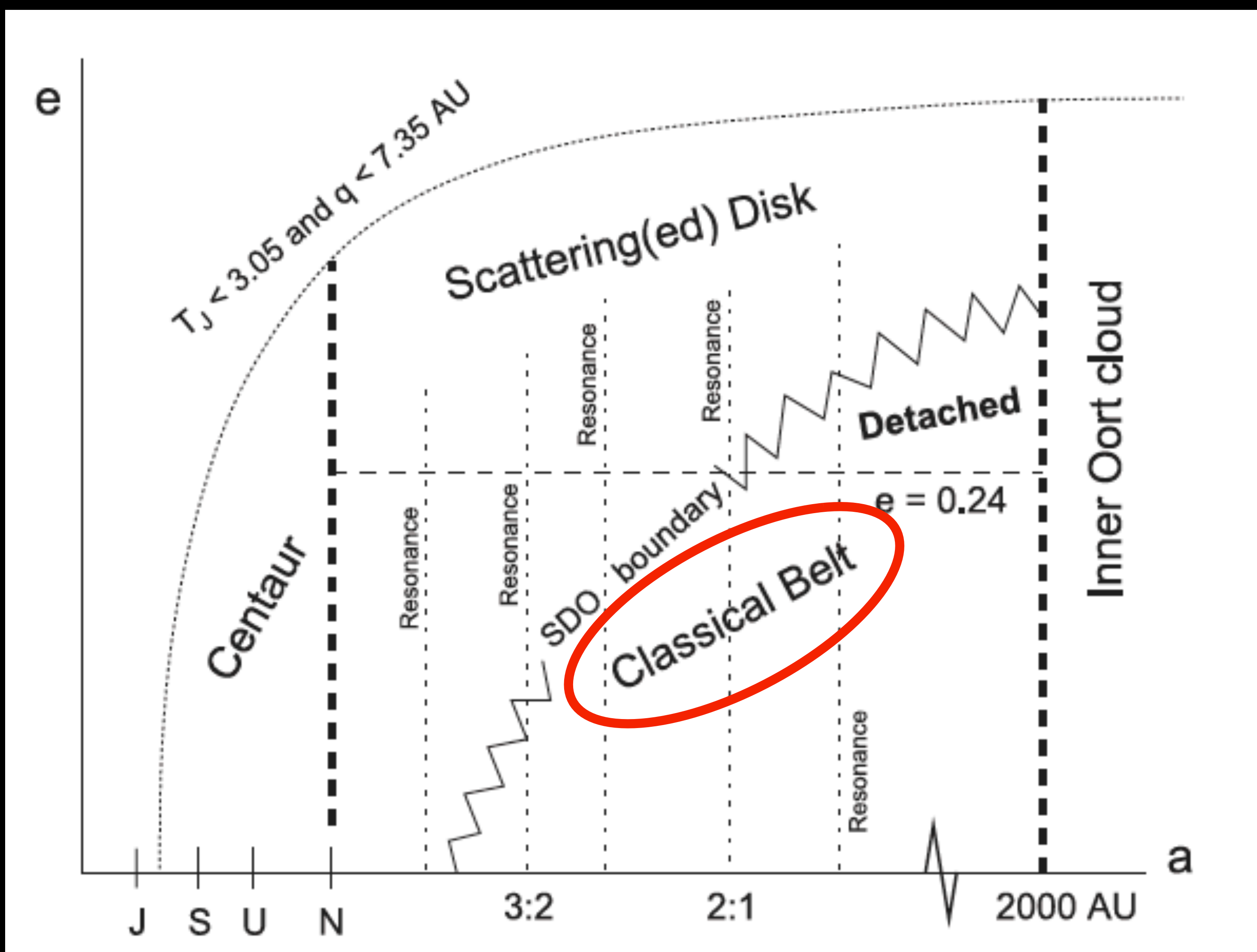
- No correlation between H (absolute magnitude) and albedo, or between albedo and size
- Cumulative size distribution -- extended to other objects, based on our sample: albedo randomly assigned to an absolute magnitude (H), and then the size is derived
- Between 120 and 450 km q=2, for >450 km q=3 (Kenyon-Bromley collisional models) ...+ flattening at ~120 km (bias) -- this distribution should keep track of the conditions in the early Solar System (e.g. starting size distribution, starting velocity distribution)
- If Pluto itself is not considered, then p_V=0.08±0.03 -- very similar to Centaurs, to scattered disk objects, and to JFC -- JFCs may be originated from here.

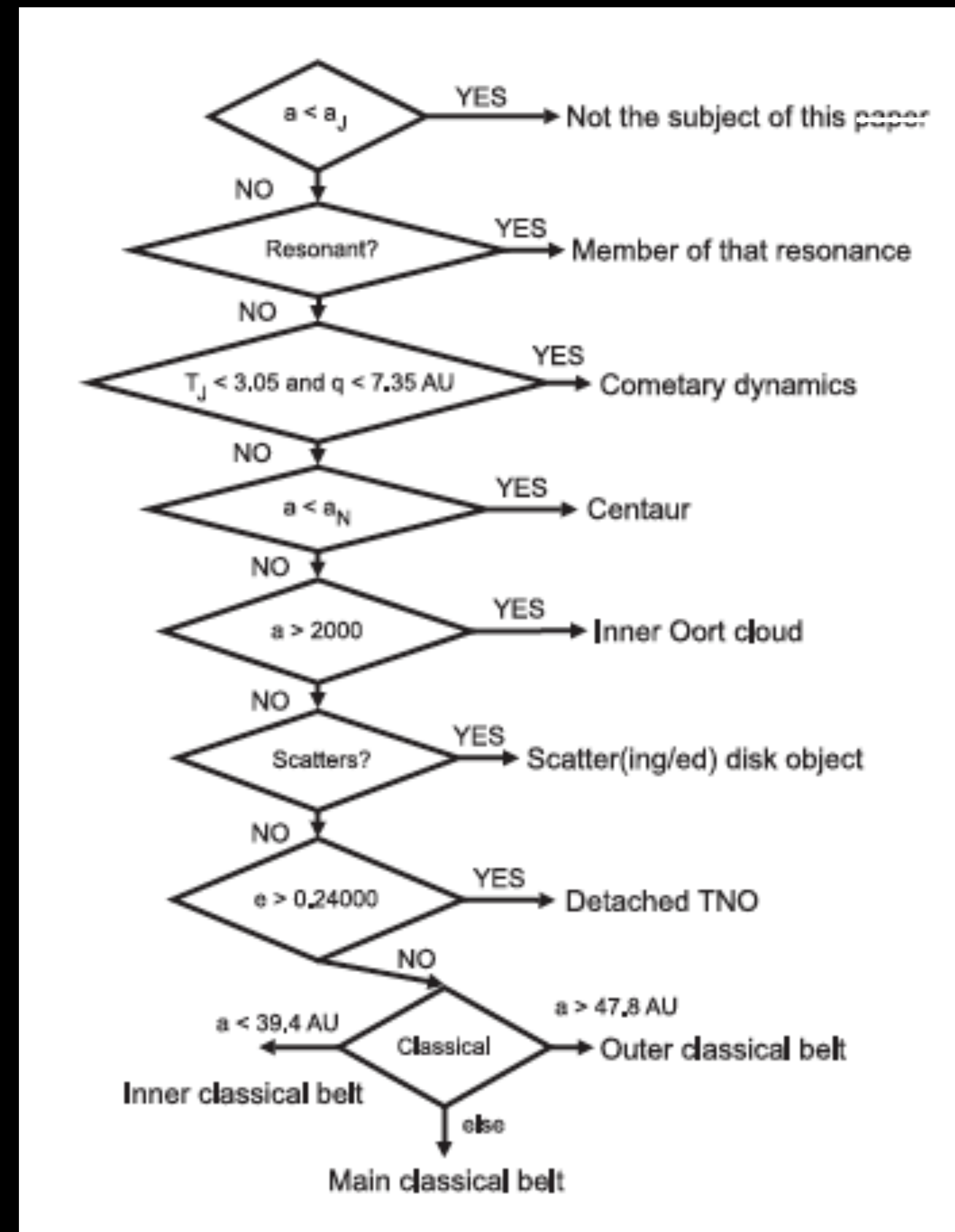
What can cause the lack of occultation events?



- Small bodies in the outer Solar System can cause “occultation events” (or diffraction events) when they pass in front of a Galactic star
- Figure: HST startracker, diffraction of a star’s light due to a ~500m object in the foreground (Schlichting et al., 2009)
- TAOS projekt (Bianco et al., 2010)
- These kind of events are too rare, we expected many more
- A shallow size distribtion ($q<3$) can explain the missing events
- Deep surveys in the near future will be able to detect many of these sub-km bodies (GAIA, EUCLID, LSST) -- at the same time, this is a serious source of confusion for them

Dynamical classes in the outer Solar System (SSBN07)





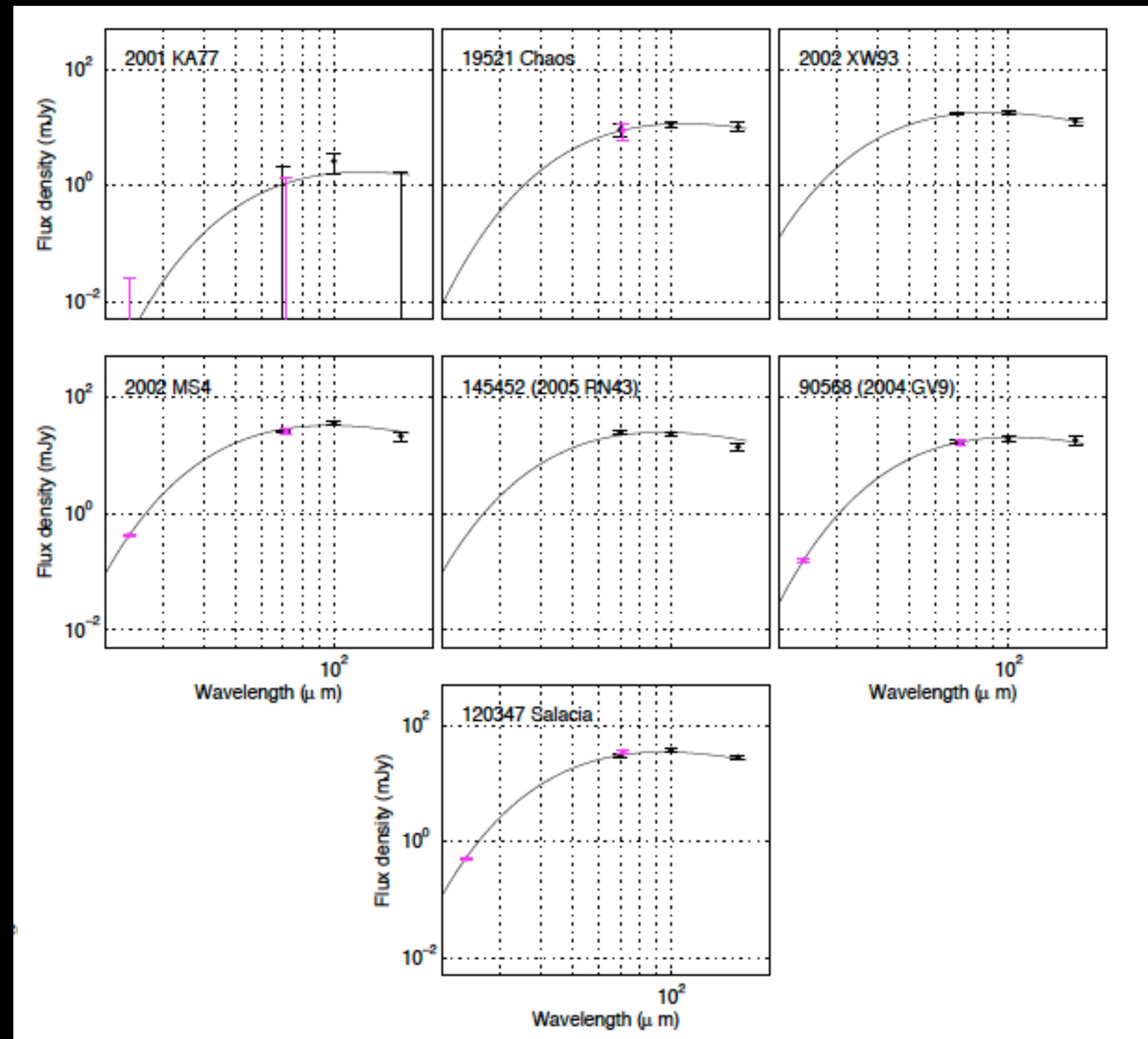
The “Classicals”

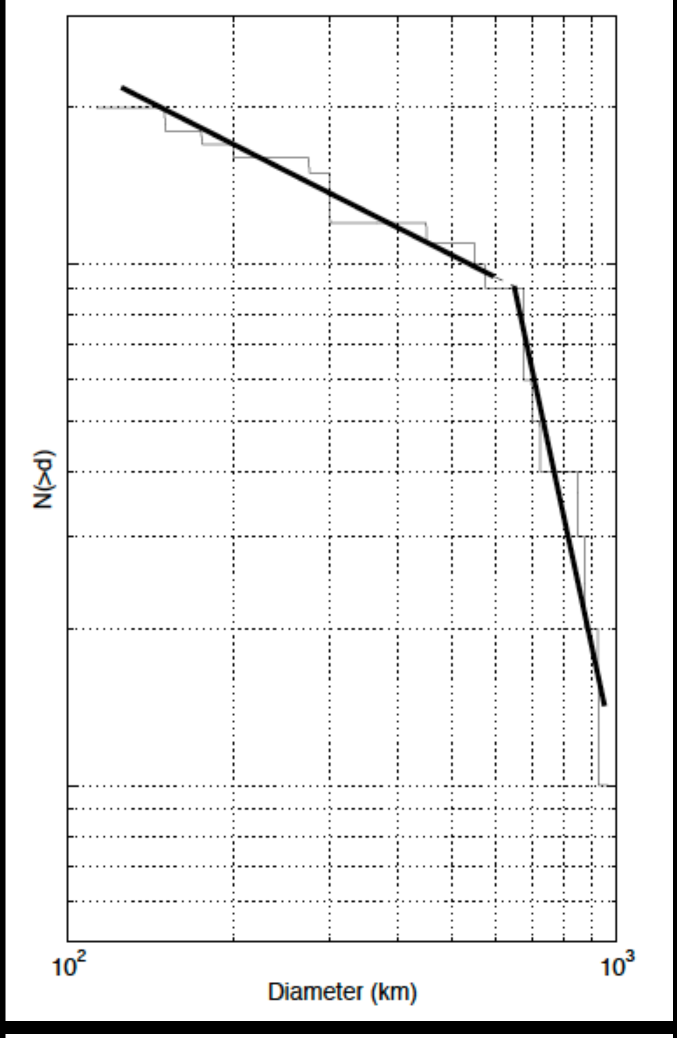
“TNOs are Cool!” sample: 19 objects, 9 “cold” and 10 “hot” objects (i>4.5)

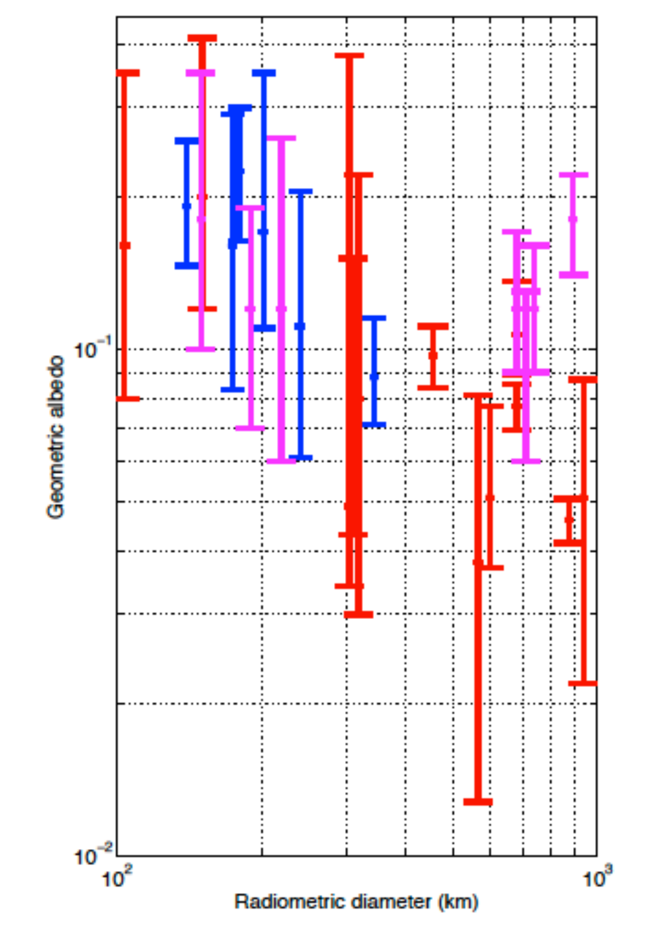
Target	KBO location	a [a] (AU)	q (AU)	i [a] (°)	e [a]	Color [b]	Spectral slope (% / 100 nm)	H_V (mag)
119951 (2002 KX$_{14}$)	**inner**	38.9	37.1	0.4	0.05	RR-IR [u]	27.1 ± 1.0 [m]	4.862 ± 0.038 [c]
(2001 XR$_{254}$)*	main	43.0	41.7	1.2	0.03	...	10 ± 3 [e]	6.030 ± 0.017 [d]
275809 (2001 QY$_{297}$)*	main	44.0	40.4	1.5	0.08	BR	24 ± 8 [e,k,s]	6.09 ± 0.03 [e]
(2001 RZ$_{143}$)*	main	44.4	41.3	2.1	0.07	...	13 ± 6 [f,s,t]	6.69 ± 0.10 [f]
(2002 GV$_{31}$)	main	43.9	40.0	2.2	0.09	...	...	H_R = 5.5 [g] ±0.4
79360 (1997 CS$_{29}$)*	main	43.9	43.4	2.2	0.01	RR	27.0 ± 3.0 [m]	5.59 ± 0.06 [e,h]
88611 Teharonhiawako (2001 QT$_{297}$)*	main	44.2	43.2	2.6	0.02	...	1 ± 2 [e]	5.97 ± 0.03[e]
120181 (2003 UR$_{292}$)	**inner**	32.6	26.8	2.7	0.18	...	28 ± 5 [n]	H_R = 6.7 [g] ±0.3
(2005 EF$_{298}$)	main	43.9	40.1	2.9	0.09	RR	...	H_R = 5.8 [g] ±0.3
138537 (2000 OK$_{67}$)	main	46.8	40.0	4.9	0.14	RR	20 ± 3 [i,j,o,s,t]	6.47 ± 0.09 [i,j]
148780 Altjira (2001 UQ$_{18}$)*	main	44.5	41.8	5.2	0.06	RR	35 ± 6 [e,k,s,t]	6.47 ± 0.13 [e,k]
(2002 KW$_{14}$)	main	46.5	37.3	9.8	0.20	...	...	5.88 ± 0.05 [w]
(2001 KA$_{77}$)	main	47.3	42.8	11.9	0.10	RR	38 ± 3 [j,k,p,s,t]	5.64 ± 0.08 [k]
19521 Chaos (1998 WH$_{24}$)	main	46.0	41.1	12.0	0.11	IR	23 ± 2 [q,r,o,j,s,t]	4.97 ± 0.05 [h,k]
78799 (2002 XW$_{93}$)	**inner**	37.6	28.3	14.3	0.25	...	...	H_R = 4.8 [g] ±0.6
(2002 MS$_{4}$)	main	41.7	35.6	17.7	0.15	...	2 ± 2 [n]	H_R = 3.5 [g] ±0.4
145452 (2005 RN$_{43}$)	main	41.8	40.6	19.2	0.03	RR-IR [u]	23.0 ± 1.1 [m]	3.89 ± 0.05 [w]
90568 (2004 GV$_{9}$)	main	41.8	38.7	22.0	0.07	BR [v]	15 ± 3 [n]	4.25 ± 0.04 [l]
120347 Salacia (2004 SB$_{60}$) *	main	42.2	37.9	23.9	0.10	...	12.6 ± 2.0 [m]	4.26 ± 0.02 [e]

The "Classicals"

Target	F_{70} (mJy)	F_{100} (mJy)	F_{160} (mJy)
119951 (2002 KX_{14})	7.4 ± 0.7	10.2 ± 1.3	7.2 ± 1.7
(2001 XR_{254})	2.5 ± 0.7	< 1.0	< 1.4
275809 (2001 QY_{297})	1.1 ± 1.1	4.2 ± 0.8	2.4 ± 1.1
(2001 RZ_{143})	2.2 ± 0.7	< 1.1	< 1.1
(2002 GV_{31})	< 0.8	< 1.1	< 1.7
79360 (1997 CS_{29})	3.9 ± 0.8	5.5 ± 1.1	< 5.7
88611 Teharonhiawako	1.9 ± 0.7	2.1 ± 0.9	< 2.1
120181 (2003 UR_{292})	< 4.6	3.9 ± 1.1	< 3.8
(2005 EF_{298})	1.4 ± 0.6	1.7 ± 0.8	< 1.9
138537 (2000 OK_{67})	< 0.9	< 0.8	< 3.1
148780 Altjira	3.4 ± 1.0	4.3 ± 1.6	< 2.1
(2002 KW_{14})	1.9 ± 0.8	< 3.0	< 1.4
(2001 KA_{77})	< 2.1	2.7 ± 1.0	< 1.7
19521 Chaos	9.2 ± 2.2[a]	11.3 ± 1.2	10.3 ± 1.8
78799 (2002 XW_{93})	17.0 ± 0.9	17.8 ± 1.5	12.9 ± 1.9
(2002 MS_{4})	26.3 ± 1.3	35.8 ± 1.5	21.6 ± 4.2
145452 (2005 RN_{43})	24.8 ± 1.3	23.9 ± 1.8	13.9 ± 1.9
90568 (2004 GV_{9})	16.9 ± 1.0	19.3 ± 1.9[b]	18.3 ± 2.9
120347 Salacia	30.0 ± 1.2	37.8 ± 2.0	28.1 ± 2.7







The “Classicals”

- Size distribution similar to that of the Plutino’s (knee at ~650km)
- Between 100 and 600km diameter q≅2.4 (was q=2 for the Plutinos)
- Small bodies are not only “missing” from the Plutino population, but it seems to be a general trend in other classes as well.
- Disk evolution models should be able to explain this!
- + anticorrelation between albedo and size -- why are darker objects larger (or larger objects darker)? -- we will try to explain this later...

The "Classicals" -- Binary TNOs

- 6 binaries in the Classicals sample
- Why are they important?
  - Mass and density can be deduced
  - Important touchstones of the Solar System evolution theories
  - There are too many of them, it is unlikely that so many could be formed by captures
  - If formed together, how could they survive the past ~4-5 billion years?
  - Density can indicate the internal structure
  - E.g. (148780) Altjira: the smallest average density, must have a very porous interior

Target	Adopted ΔV (mag)	Mass ($\times 10^{18}$ kg)	Bulk density (g cm^{-3})
(2001 XR_{254})	0.43	4.055 ± 0.065	$1.3^{+1.2}_{-1.3}$
275809	0.20	4.105 ± 0.038	$0.79^{+0.50}_{-0.61}$
79360	0.1[a]	10.84 ± 0.22	0.73 ± 0.31
88611	0.70	2.445 ± 0.032	$1.09^{+0.90}_{-0.62}$
148780	0.23	3.986 ± 0.067	$0.38^{+0.32}_{-0.33}$
120347	2.32	466 ± 22	1.53 ± 0.31

The “Classicals” -- Binary TNOs

- 6 binaries in the Classicals sample
- Why are they important?
  - Mass and density can be deduced
  - Important touchstones of the Solar System evolution theories
  - There are too many of them, it is unlikely that so many could be formed by captures
  - If formed together, how could they survive the past ~4-5 billion years?
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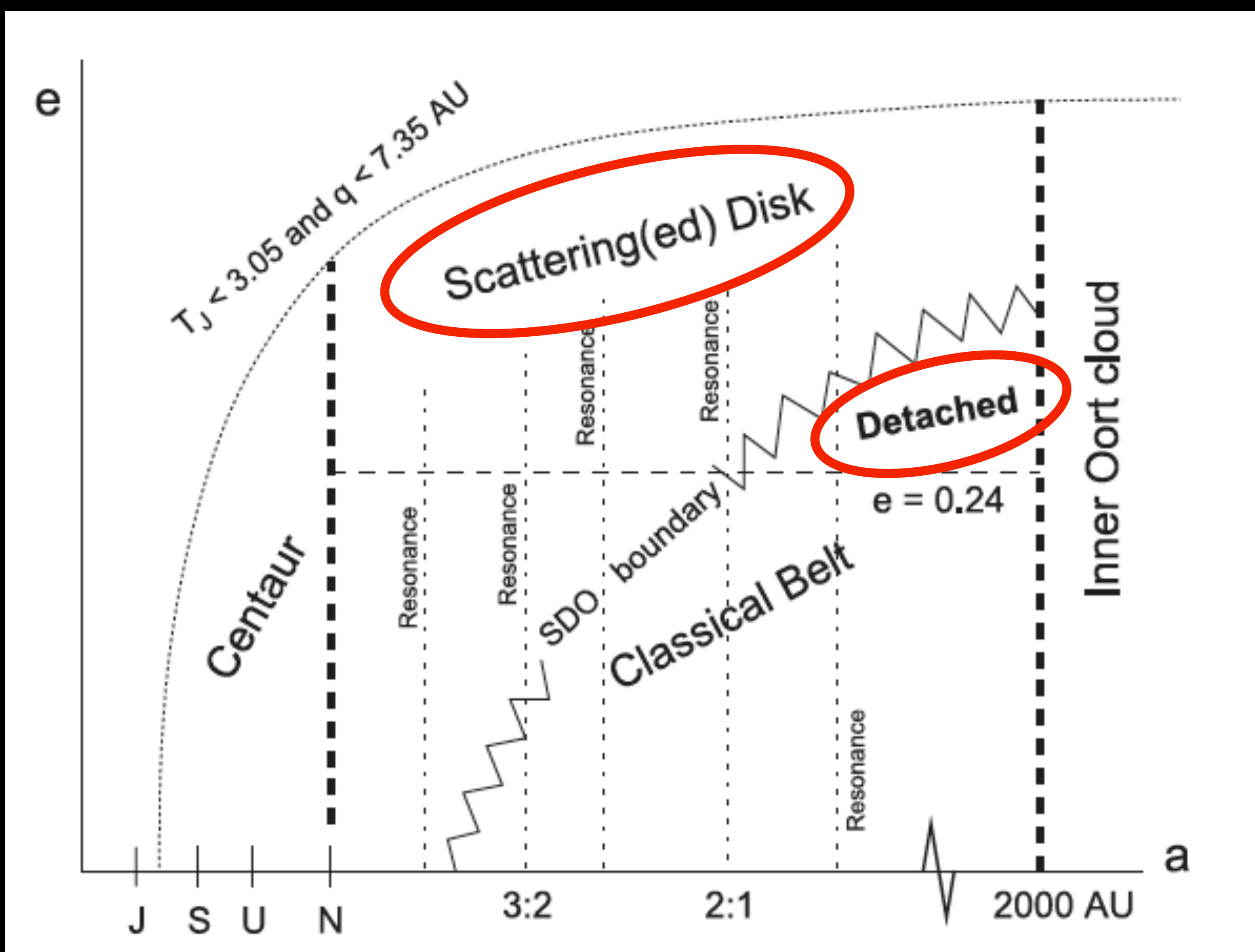
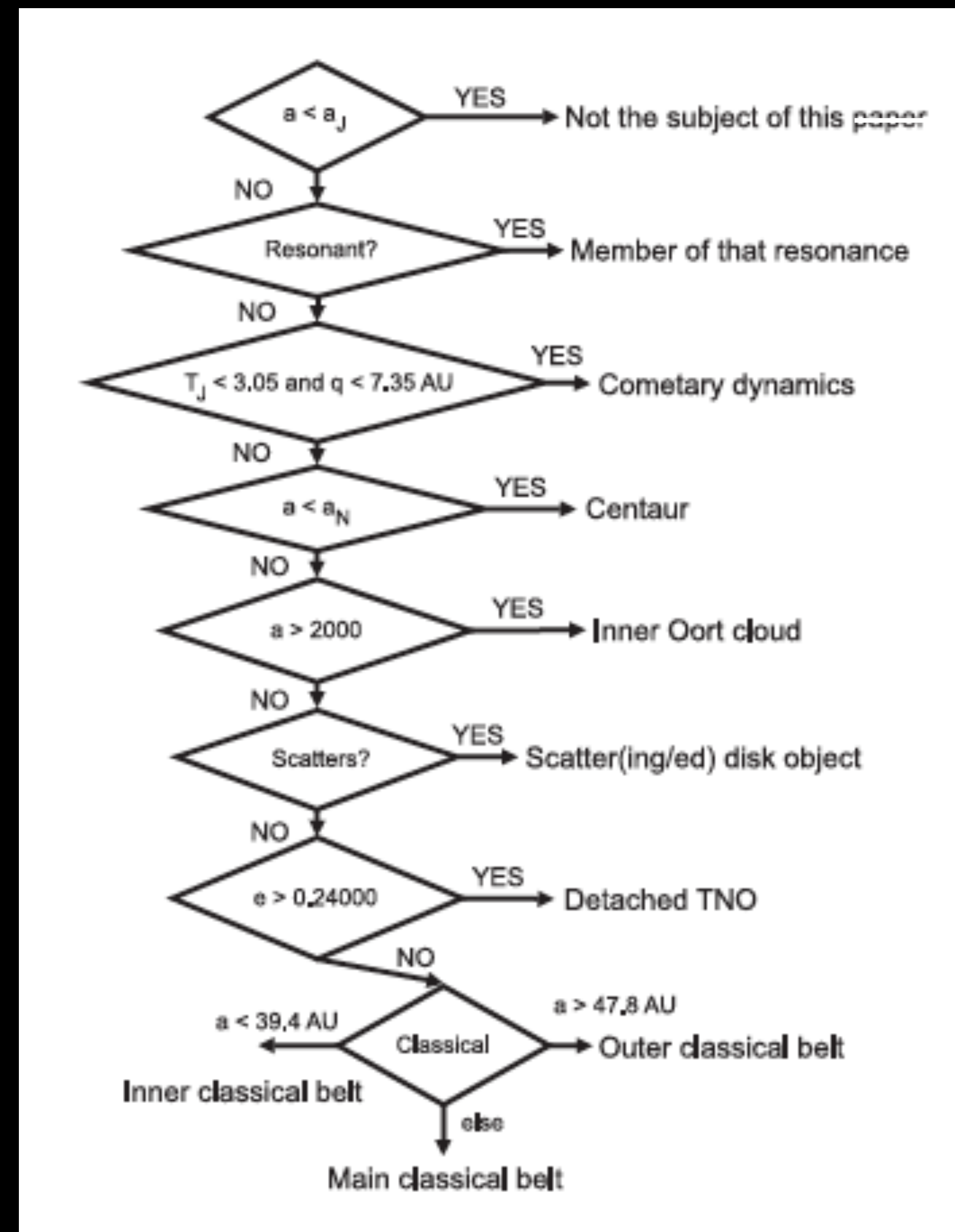
Dynamical classes in the outer Solar System (SSBN07)



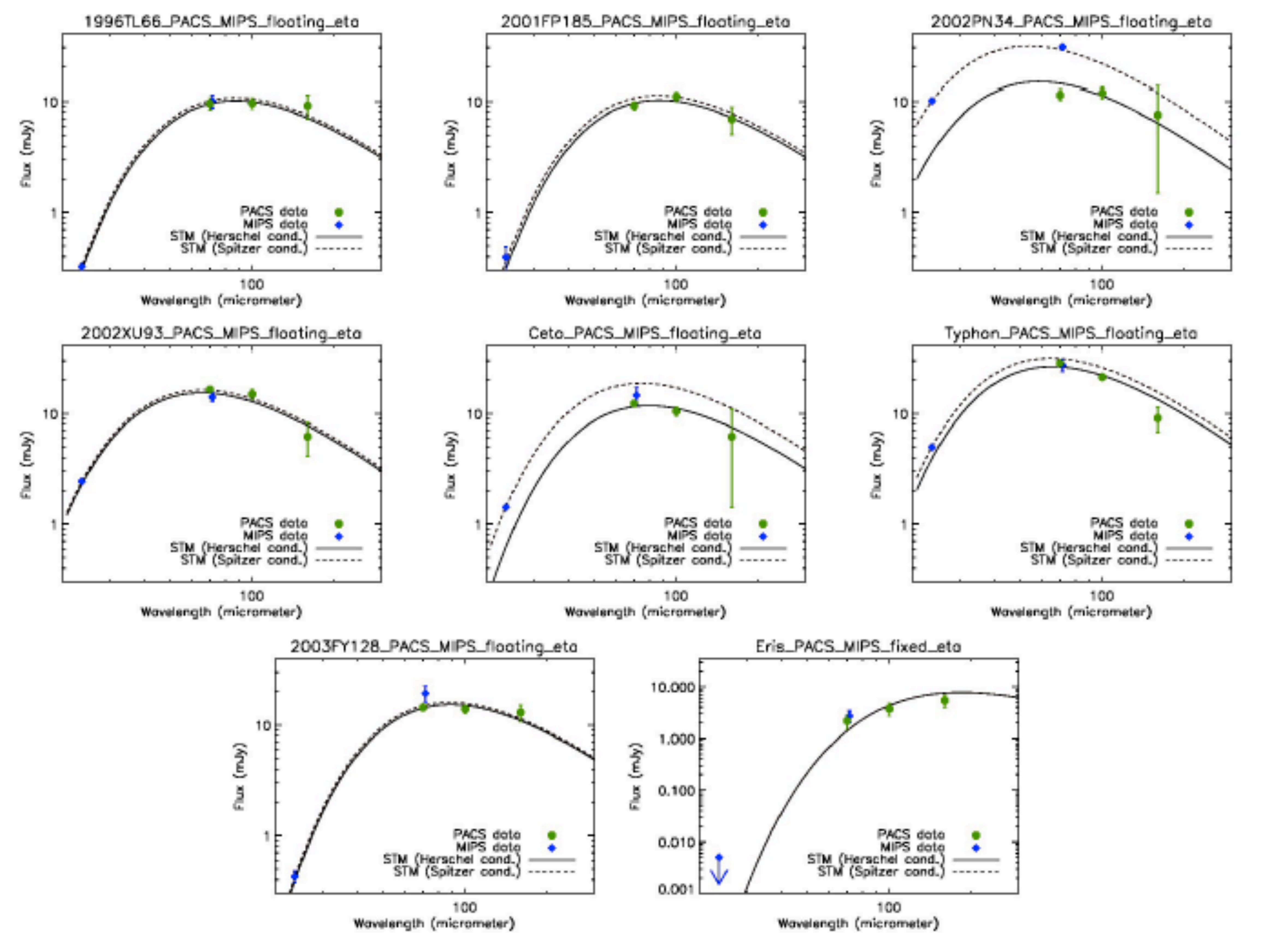


Scattered disk and detached objects

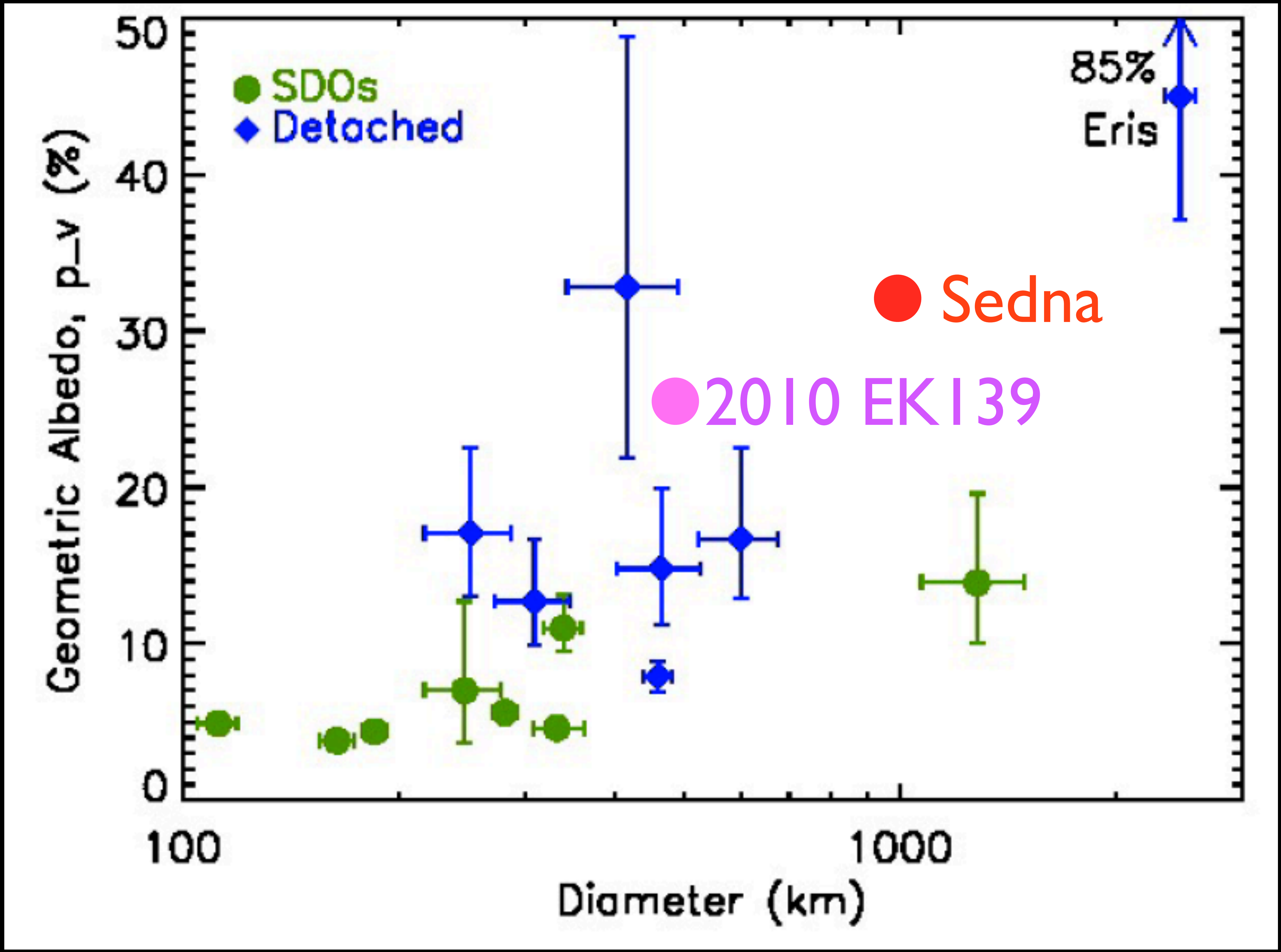
Object	a [AU]	q [AU]	i [deg]	e	H_V [mag]	B-R [mag]	P [h]	Δm_R [mag]	Taxon.	Class.
1996 TL$_{66}$	84.5	35.0	23.9	0.59	5.39±0.12[a,b,c]	1.11±0.07[c,q,r,s]	12.0[x]	<0.12, <0.06[x,y]	BB	SDO
2001 FP$_{185}$	212.0	34.3	30.8	0.84	6.39±0.07[a,b]	1.40±0.06[b,t]	...	<0.06[z]	IR	SDO
2002 PN$_{34}$	31.2	13.4	16.6	0.57	8.66±0.03[a,d]	1.28±0.02[t]	8.45/10.22[α]	0.18±0.04[α]	BB-BR	SDO
2002 XU$_{93}$	66.5	21.0	77.9	0.69	8.11±0.10[e,f]	1.20±0.02[e]	...	...	...	SDO
2007 OR$_{10}$	67.1	33.6	30.7	0.50	**1.96±0.16**[g]	...	...	...	...	SDO
2007 RW$_{10}$	30.4	21.2	36.0	0.30	**6.39±0.61**[g]	...	...	...	...	SDO
(2003 FX$_{128}$) Ceto*[δ]	99.7	17.8	22.3	0.82	6.54±0.06[h,i]	1.42±0.04[t]	4.43[n]	0.13±0.02[n]	...	SDO
(2002 CR$_{46}$) Typhon*[j]	37.6	17.5	2.4	0.54	7.72±0.04[a,d,f,h,j,k,m]	1.29±0.07[m,t]	9.67/19.34[y,α]	0.06±0.01[y,α]	BR	SDO
1999 KR$_{16}$	48.7	33.9	24.9	0.30	**5.37±0.08**[n,o]	1.87±0.07[c,u,v]	5.93/11.86[n]	0.18±0.04[n]	RR	DO
2003 FY$_{128}$	49.2	37.0	11.8	0.25	5.09±0.09[k]	1.65±0.02[e]	8.54[y]	0.15±0.01[y]	BR	DO
2005 QU$_{182}$	114.0	37.0	14.0	0.68	3.80±0.32[f]	...	...	...	...	DO
2005 TB$_{190}$	76.5	46.2	26.4	0.40	4.40±0.11[f]	1.54±0.03[e]	...	...	...	DO
2007 OC$_{10}$	50.0	35.5	21.7	0.29	5.43±0.10[f,i]	...	...	...	...	DO
2007 UK$_{126}$*[ζ]	74.0	37.7	23.4	0.49	3.69±0.10[k]	...	...	...	...	DO
(2003 UB$_{313}$) Eris*[ε]	68.1	38.6	43.8	0.43	-1.12±0.03[d,p]	1.21±0.09[d,w]	13.69/28.08[β] 32.13/25.92[β,γ]	<0.1, 0.01[β,γ]	BB	DO

Object	Flux$_{70}$[mJy]	Flux$_{100}$[mJy]	Flux$_{160}$[mJy]	Class.
(15874) 1996 TL$_{66}$	9.6±1.2	9.7±1.1	9.2±2.2	SDO
(82158) 2001 FP$_{185}$	9.2±0.8	11.1±1.1	7.0±1.9	SDO
(73480) 2002 PN$_{34}$	11.4±1.2	11.9±1.4	7.6±6.1	SDO
(127546) 2002 XU$_{93}$	16.5±0.9	15.0±1.6	6.2±2.1	SDO
2007 OR$_{10}$	3.7±1.1	4.8±1.4	6.7±2.3	SDO
2007 RW$_{10}$	13.2±0.9	11.3±1.3	10.3±2.1	SDO
(65489) Ceto	12.3±0.7	10.5±1.0	6.2±4.8	SDO
(42355) Typhon	28.5±1.2	21.4±1.2	9.1±2.4	SDO
(40314) 1999 KR$_{16}$	5.7±0.7	3.5±1.0	4.6±2.2	DO
(120132) 2003 FY$_{128}$	14.4±0.9	14.0±1.2	13.0±2.2	DO
2005 QU$_{182}$	4.5±0.9	2.5±1.1	8.4±3.0	DO
(145480) 2005 TB$_{190}$	5.8±0.9	8.6±1.4	5.4±1.8	DO
2007 OC$_{10}$	8.3±0.9	7.8±1.2	7.4±1.8	DO
(229762) 2007 UK$_{126}$	13.7±1.1	12.3±1.3	7.2±2.2	DO
(136199) Eris	2.0±0.6	3.7±1.0	5.6±1.6	DO

Scattered disk and detached objects

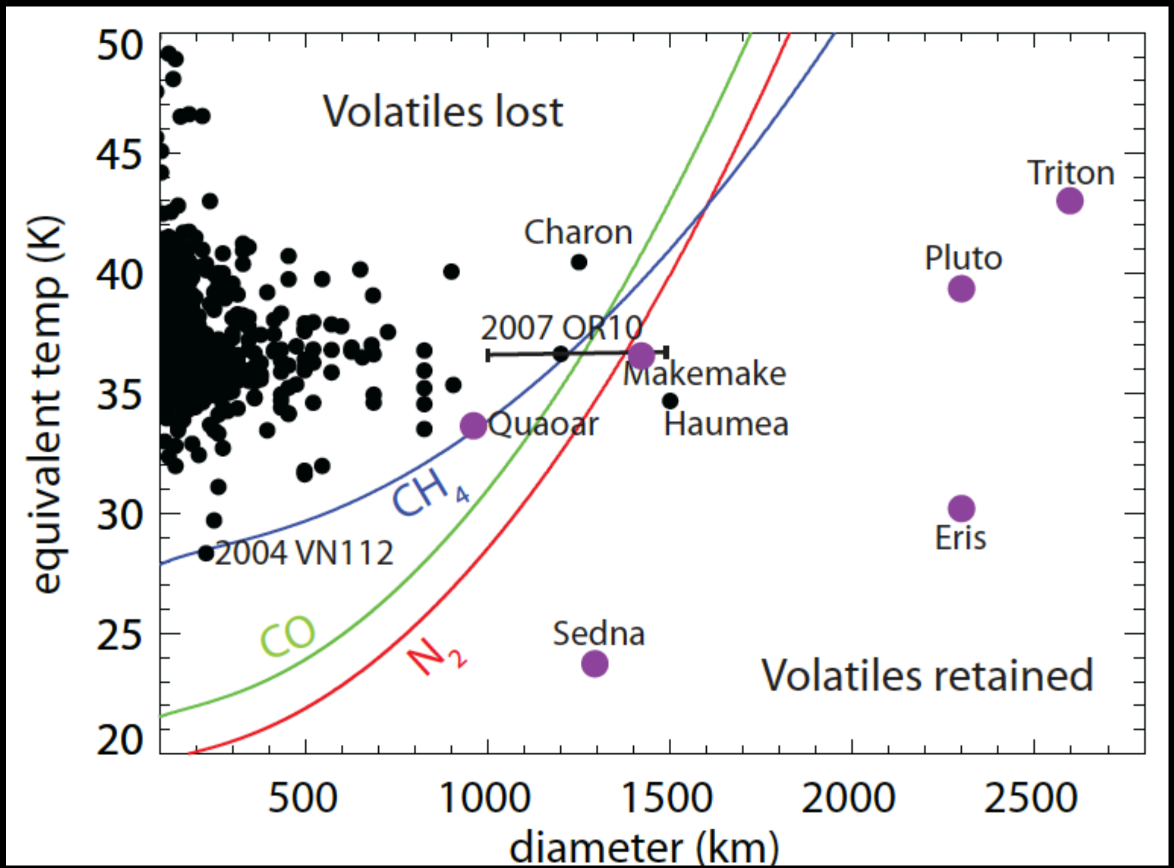


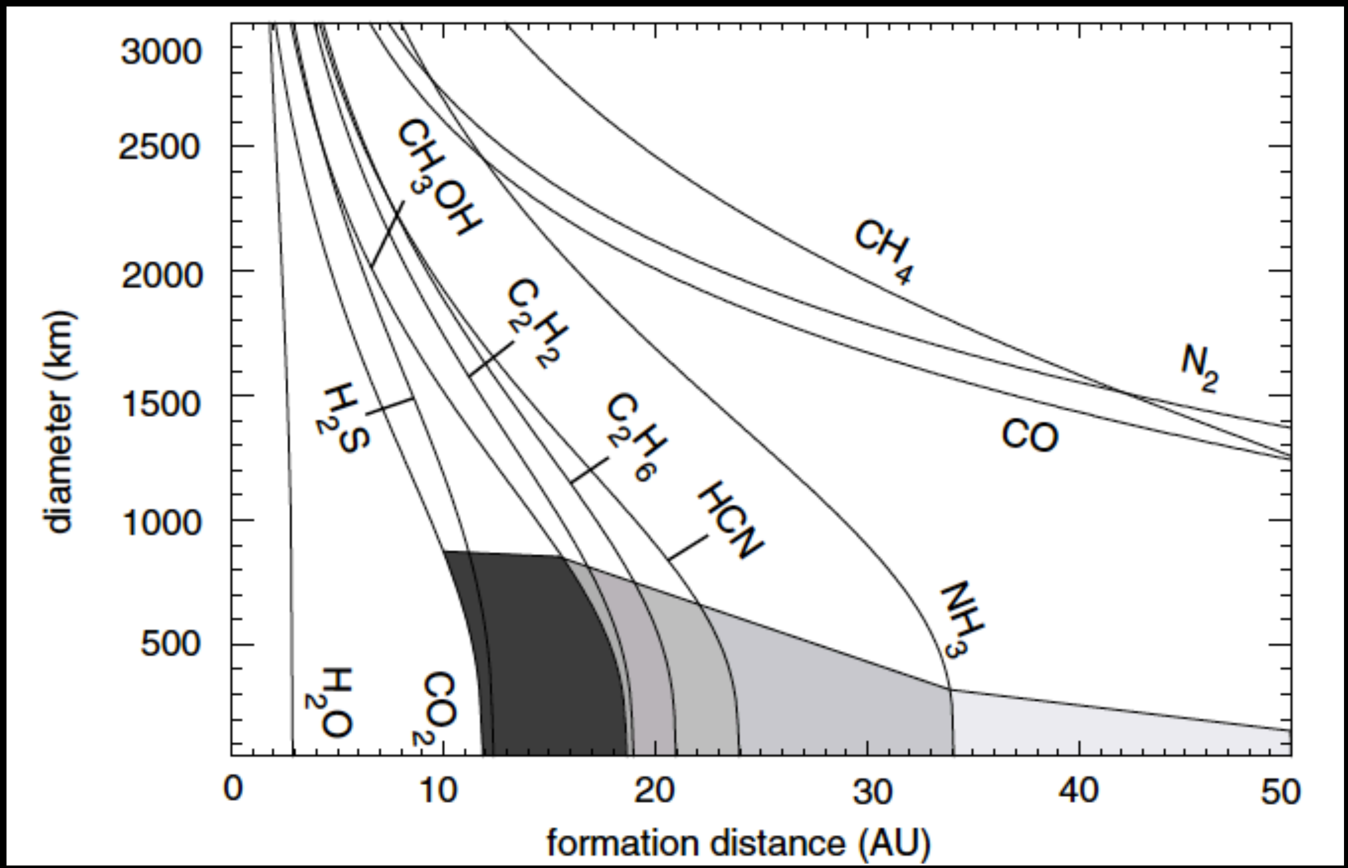
Scattered disk and detached objects



TNO surfaces in the various populations

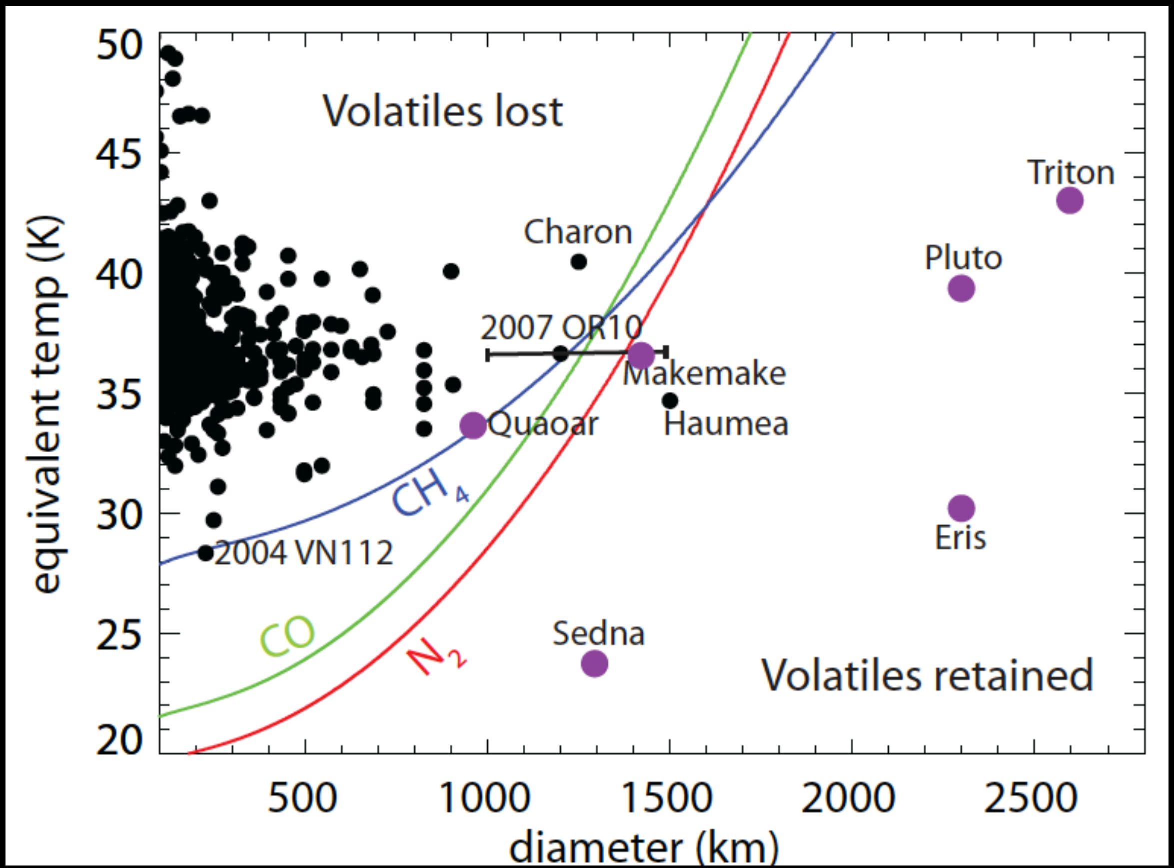
- Classicals: anticorrelation between size and albedo -- why are the larger objects darker?
- Plutino surfaces are dark, similar to that seen in the scattered disk and among Jupiter-family comets
- “Old” surfaces become dark with time anyway due to “space weathering” (formation of large organic molecules on the surface due to the solar radiation and cosmic rays)
- Small objects cannot retain the volatile elements on the surface, however, methanol and other hydrocarbons can survive

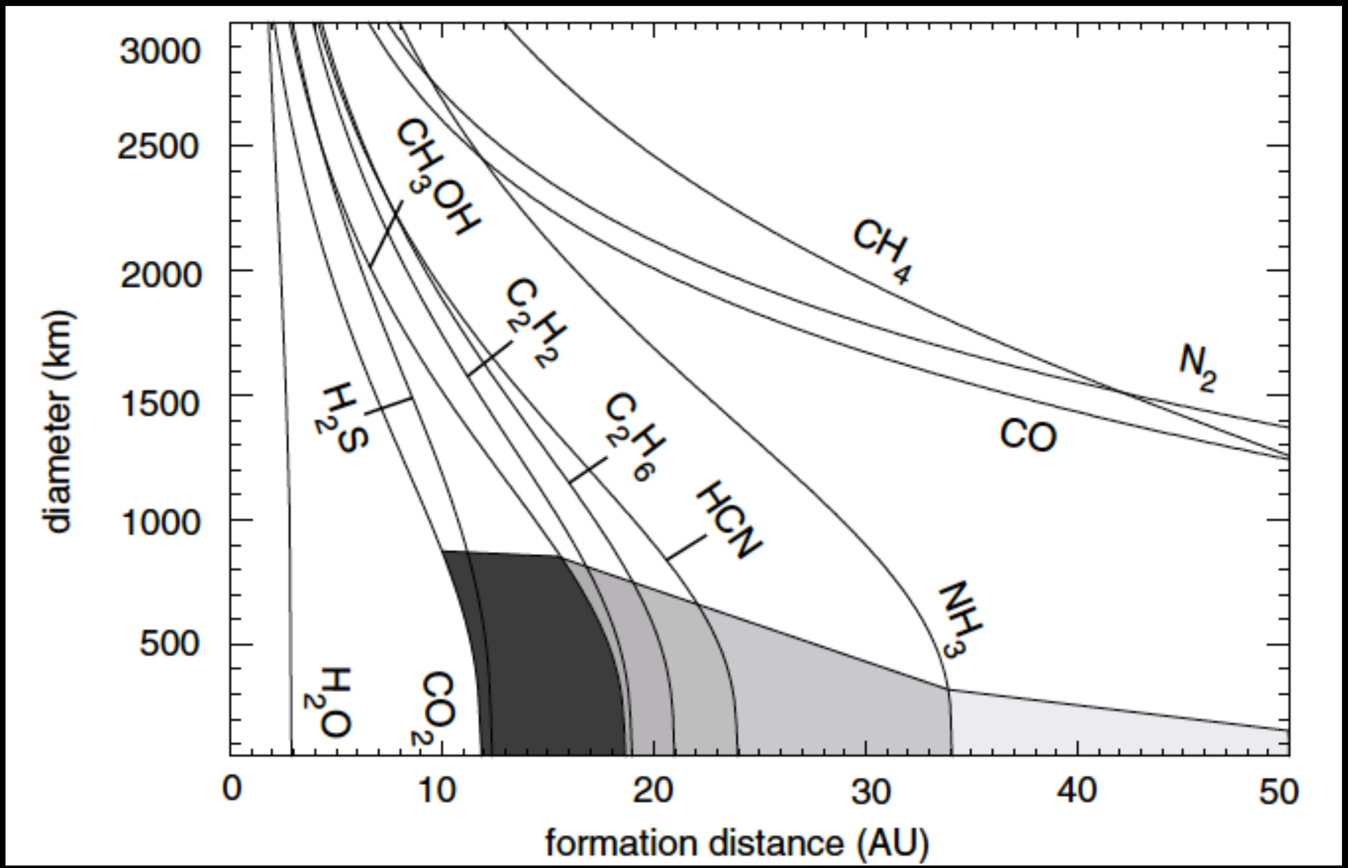




TNO surfaces in the various populations

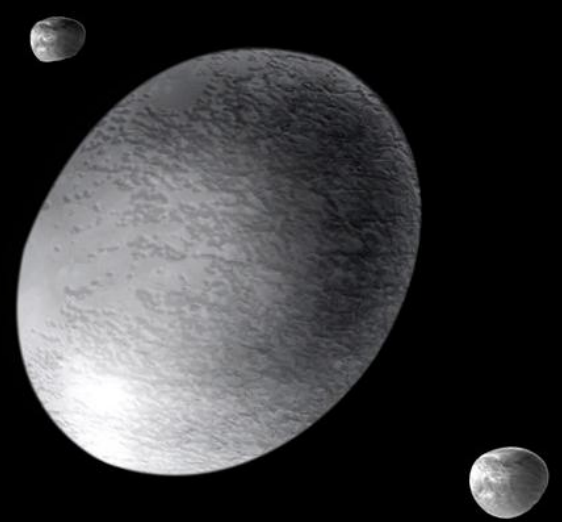
- Detached objects:
  - Larger objects have brighter surfaces: they can retain volatiles more easily due to their bigger size and their larger distance from the sun (low temperature and low solar flux)
  - Then we must see very ancient surfaces, the oldest ones in the Solar System.
  - Or: there is a continuous resurfacing (collisions?, cryovolcanic activity?)
  - In some cases it can be explained by seasonal changes (collapse of methane atmosphere at larger heliocentric distances on Eris)

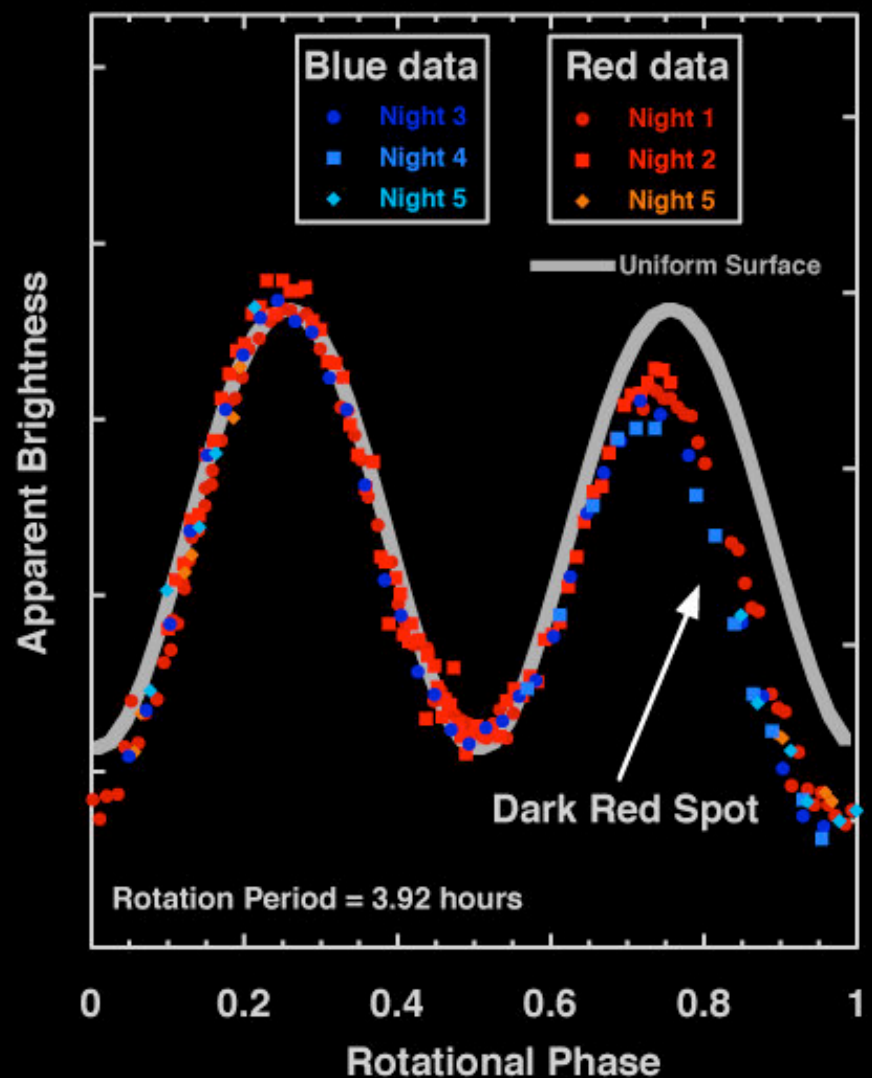




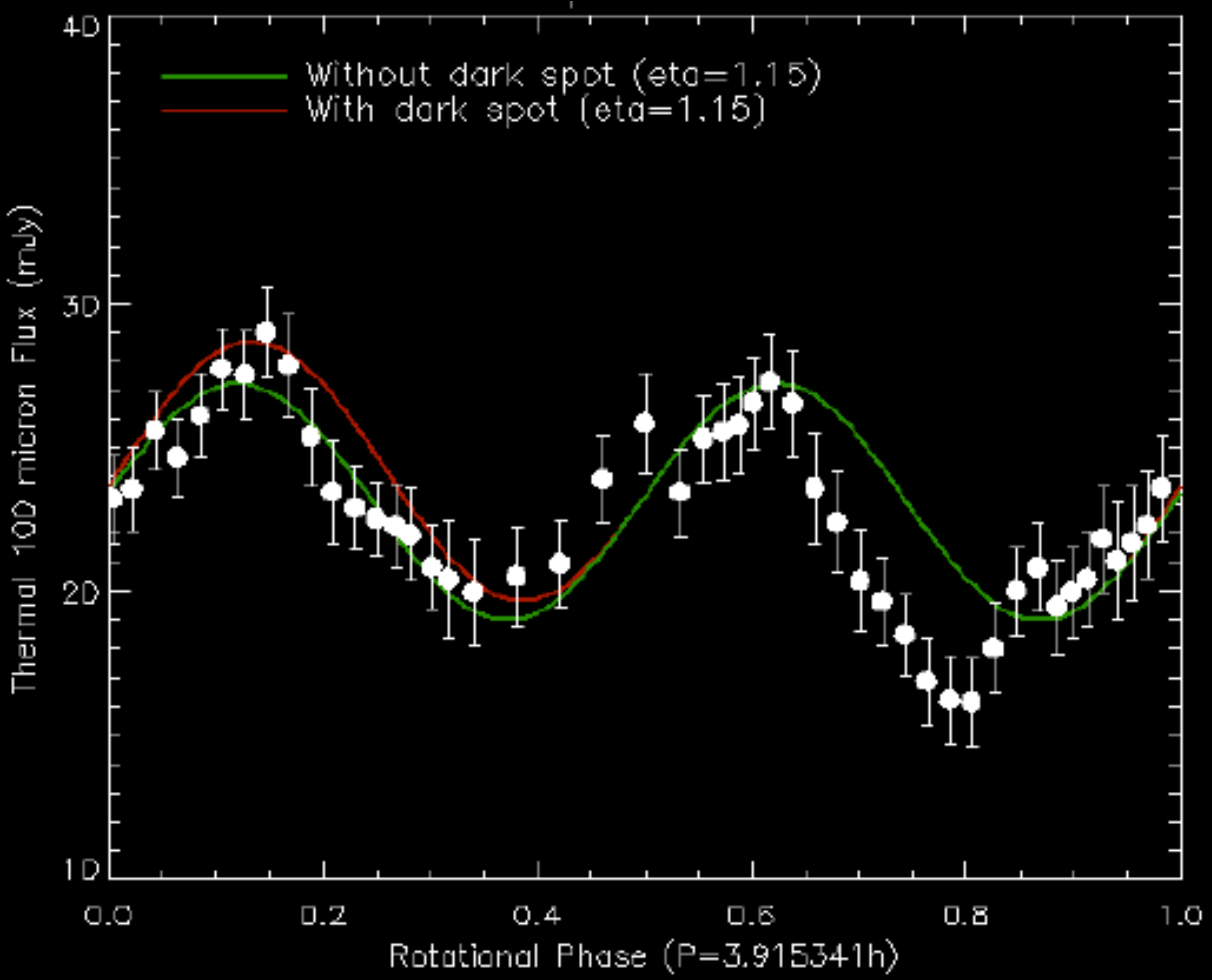
Haumea

- <u>Haumea</u>:
  - large amplitude light curve, short rotation period, very elongated object
  - neutral colour in the optical, strong H_2O absorption in the near infrared
  - The light curve indicate the presence of a large red spot on the surface
  - high density (~2.6 g cm^{-3})
  - the system contains at least two moons





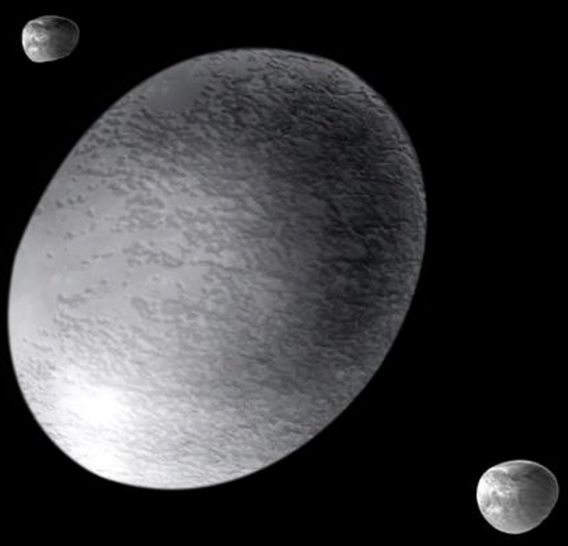
Haumea thermal light curve

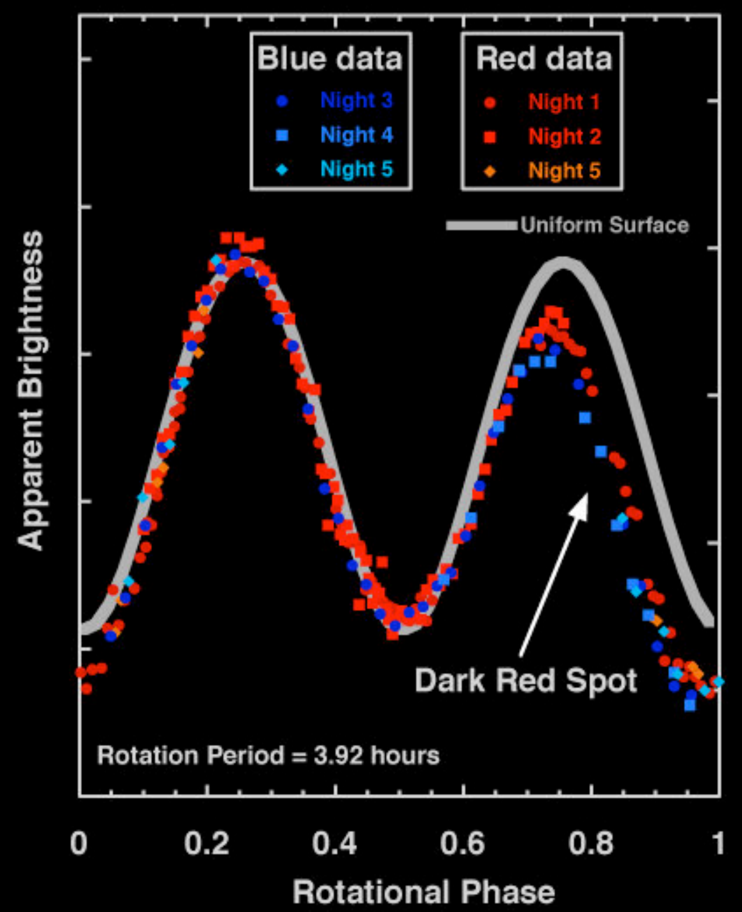


- The presently "best" thermal light curve consists of three full rotational period observations (PACS 100um)
- In general good match between the optical and infrared light curve
- However, there are differences which indicates the presence of heterogeneities on the surface
- This was the first detectable thermal light curve obtained for a trans-Neptunian object apart from Pluto

The Haumea (collisional ?) family

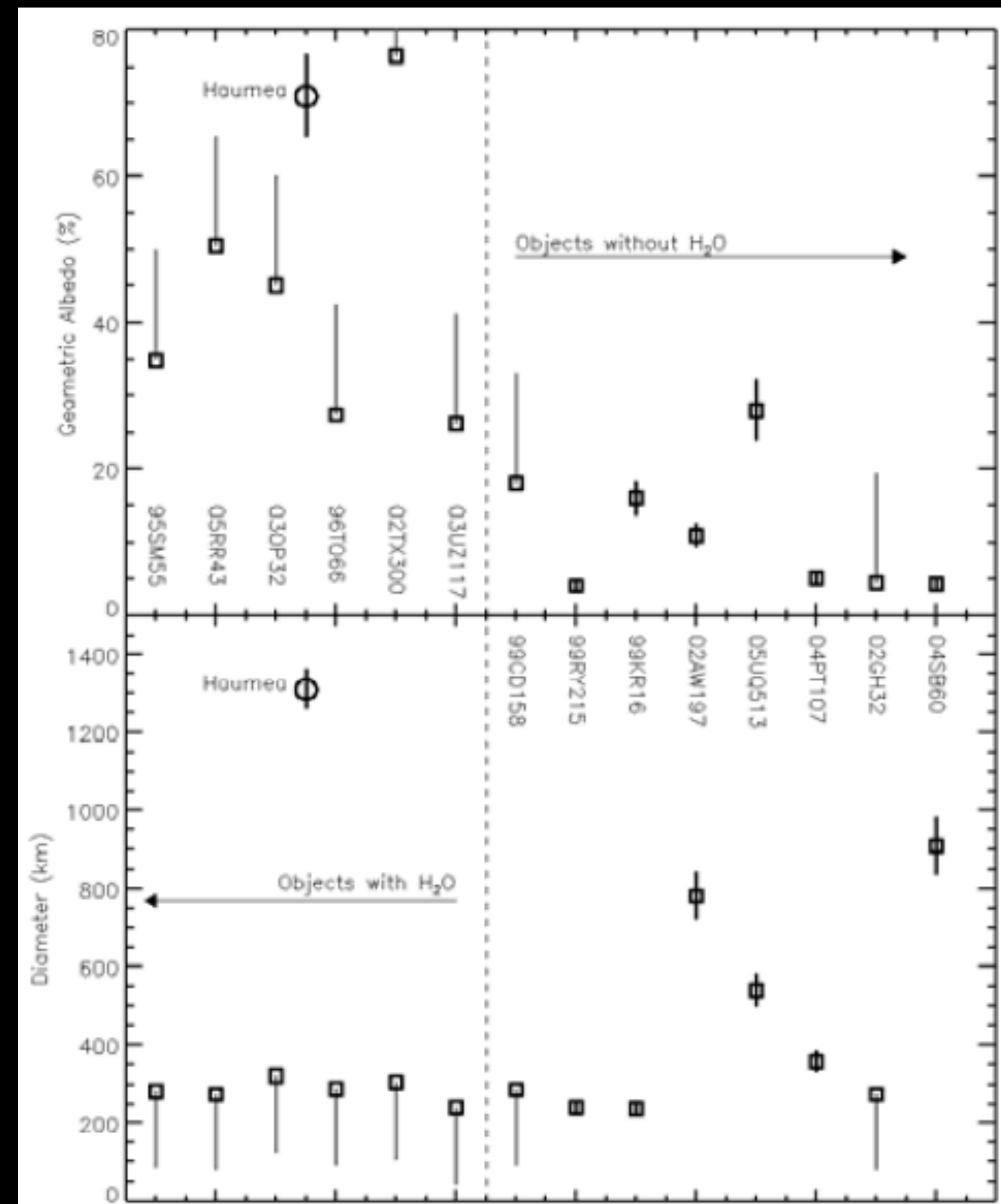
- J.A. Stansberry, T.G. Mueller, J.-L. Ortiz, P. Santos-Sanz, E. Vilenius, E. Lellouch, C. Kiss, “Physical Properties of the Haumea Family from Herschel”, EPSC-DPS meeting, 2011, ESPC-DPS2011-1437
- Haumea is likely the parent body of a group of smaller TNOs
- some of them has similar, neutral colours
- some of them show strong H_2O absorption as well
- Brown et al. (2007): TNOs on similar orbits and showing H_2O absorption at the same time, are impact-originated from Haumea.
- But: these tightly bonded to Haumea: dv=200m/s, an impact would cause a velocity dispersion of $\Delta v=v_{esc}$
- Exotic scenarios:
    - impact just peeling the ice mantle + merger
    - destruction of a large moon of proto-Haumea in a second collision
    - falling apart due to the fast rotation
- or: the family is much larger, but we made a wrong selection...





The Haumea (collisional ?) family

- "TNOs are Cool!": 14 members, 6 showing H_2O absorption
- All objects with H_2O are small, <200km, and have high albedos
- Their total mass is ~2% of Haumea's full mass -- if they are the only family members, the impact was NOT catastrophic, as was assumed previously (20%)
- In case of a large impact we should see many more TNOs (on which H_2O is not observable)
- There are a few objects with high albedo and no water detected -- az eloszlás alacsony albedojú farka?



Summary

- "TNOs are Cool! - A survey of the trans-Neptunian region" is a very successful Herschel Open Time Key Program
- Observation and data reduction strategies worked very well
- The results are very valuable both for statistical studies (evolution of the debris disk in our planetary system) as well as in studying the physics of individual objects
- Our statistical results can be applied to exosolar debris disk systems
- A debris disk evolution model should be able to reproduce the characteristics we observe in the Solar System
- There will be no FIR mission like Herschel in the near future with similar capabilities ⇒ our measurements will likely be unrepeatable for decades!
- You can read more about our results on our public web pages: http://www.mpe.mpg.de/~tmueller/tno_public/index.htm