Trans-Neptunian Objects

A Brief history, Dynamical Structure, and Characteristics of its Inhabitants

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The Solar System beyond Neptune: History

- 1930: Pluto discovered
  - Photographic survey for Planet X
    - Directed by Percival Lowell (Lowell Observatory, Flagstaff, Arizona)
    - Efforts from 1905 – 1929 were fruitless
    - discovered by Clyde Tombaugh, Feb. 1930 (33 cm refractor)
      - Survey continued into 1943

- Kuiper, or Edgeworth-Kuiper, Belt?
  - 1950’s: Pluto represented (K.E.), or had scattered (G.K.) a primordial, population of small bodies – thus KBOs or EKBOs
  - J. Fernandez (1980, MNRAS 192) did pretty clearly predict something similar to the trans-Neptunian belt of objects
  - Trans-Neptunian Objects (TNOs), trans-Neptunian region best?
  - See http://www2.ess.ucla.edu/~jewitt/kb/gerard.html

The Solar System beyond Neptune: History

- 1978: Pluto's moon, Charon, discovered
  - Photographic astrometry survey
    - 61" (155 cm) reflector
    - James Christy (Naval Observatory, Flagstaff)
  - Technologically, discovery was possible decades earlier
    - Saturation of Pluto images masked the presence of Charon

- 1988: Discovery of Pluto's atmosphere
  - Stellar occultation
    - Kuiper airborne observatory (KAO: 90 cm) + 7 sites
    - Measured atmospheric refractivity vs. height
    - Spectroscopy suggested N2 would dominate ➔ P(z), T(z)

- 1992: Pluto's orbit explained
    - Outward migration by Neptune results in capture into 3:2 resonance
    - Pluto's inclination implies Neptune migrated outward ~5 AU

The Solar System beyond Neptune: History

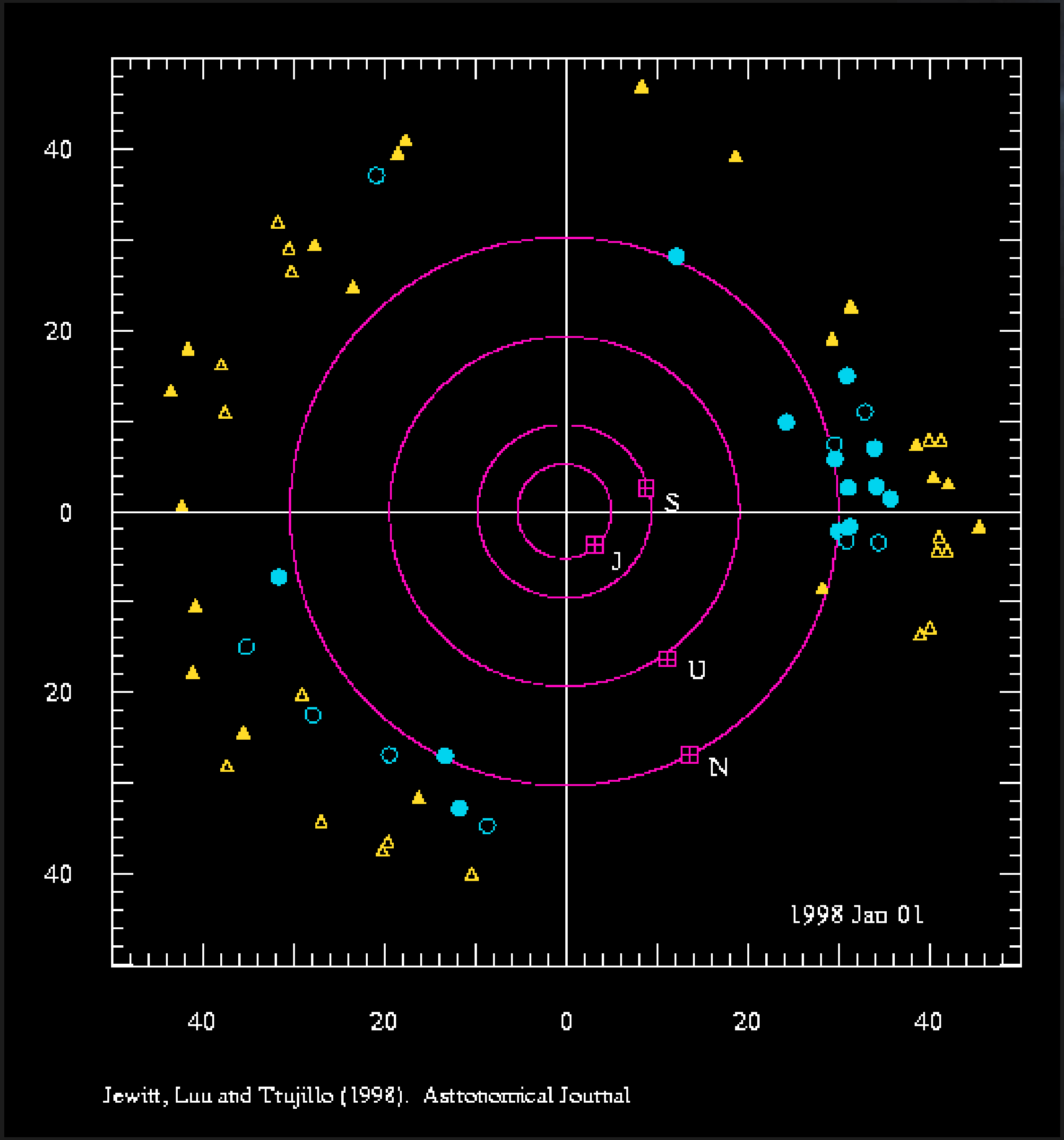
- 1992: Discovery of 2nd TNO
  - 1976 – 92: Multiple dedicated surveys for *small* (m_V > 20) TNOs
  - Fall 1992: Jewitt and Luu discover 1992 QB_1
    - Orbit confirmed as ~circular, trans-Neptunian in 1993
  - 1993 – 4: 5 more TNOs discovered
- c. 1997: Dynamical structure of KB revealed
- 2001: Discovery of 1st binary TNO (after Pluto…)
  - 1998 WW31 shown to be binary by Viellet et al.
- 2003 – 5: Discovery of Large and Strange TNOs
  - Eris ($03UB_{313}$): Pluto-size (D=2400km), 2 moons, CH_4 ice spectrum
  - Sedna ($03VB_{12}$): D=1500km, CH_4 ice, very large orbit with high *e* and *i*
  - Haumea ($03EL_{61}$): D=1500km, 4-hr rotation, 2 moons, pure H2O-ice spectrum
  - Makemake ($05FY_9$): D=1500km, no moons, most CH_4 ice of any object

The Solar System beyond Neptune: History

- 2005: Pluto’s moons Nix and Hydra discovered
- 2007: First TNO collisional family
  - Haumea and several other TNOs result from disruption of a larger parent body
- Present Day:
  - ~2500 known TNOs
    - ~10^5 with D > 100 km thought to exist
  - Orbits mostly 32 AU < a < 50 AU
  - Dynamical classes record effects of outer planet migration
    - Hot & Cold Classicals; Resonants; Scattered Disk
  - ~30% of cold-classicals are binary
  - Extreme diversity of composition and color
  - Sizes & albedos known for > 100
  - Masses known for 38, Densities for 16

The Growing Population of TNOs

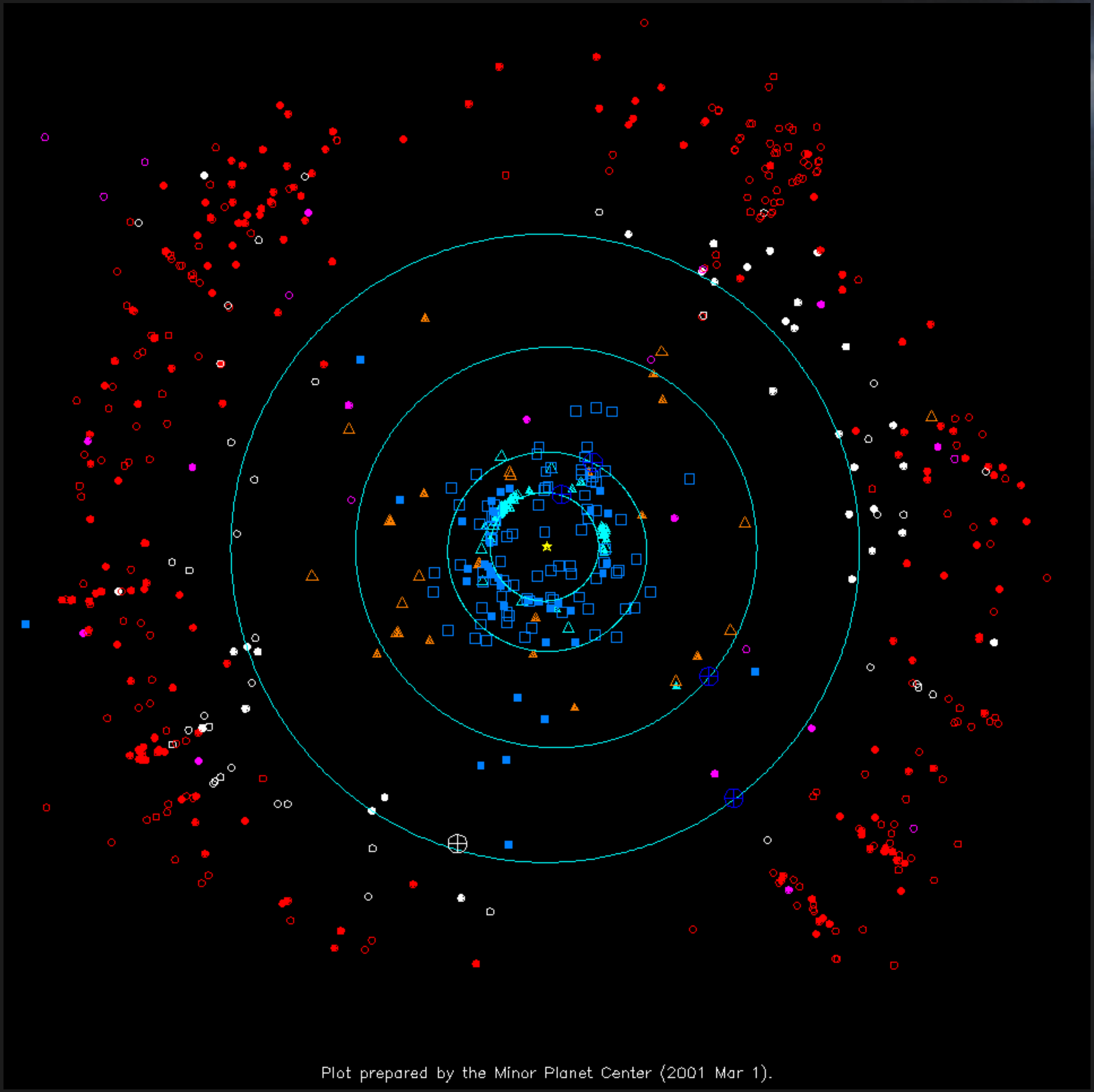
- 1998



The Growing Population of TNOs

- 2001

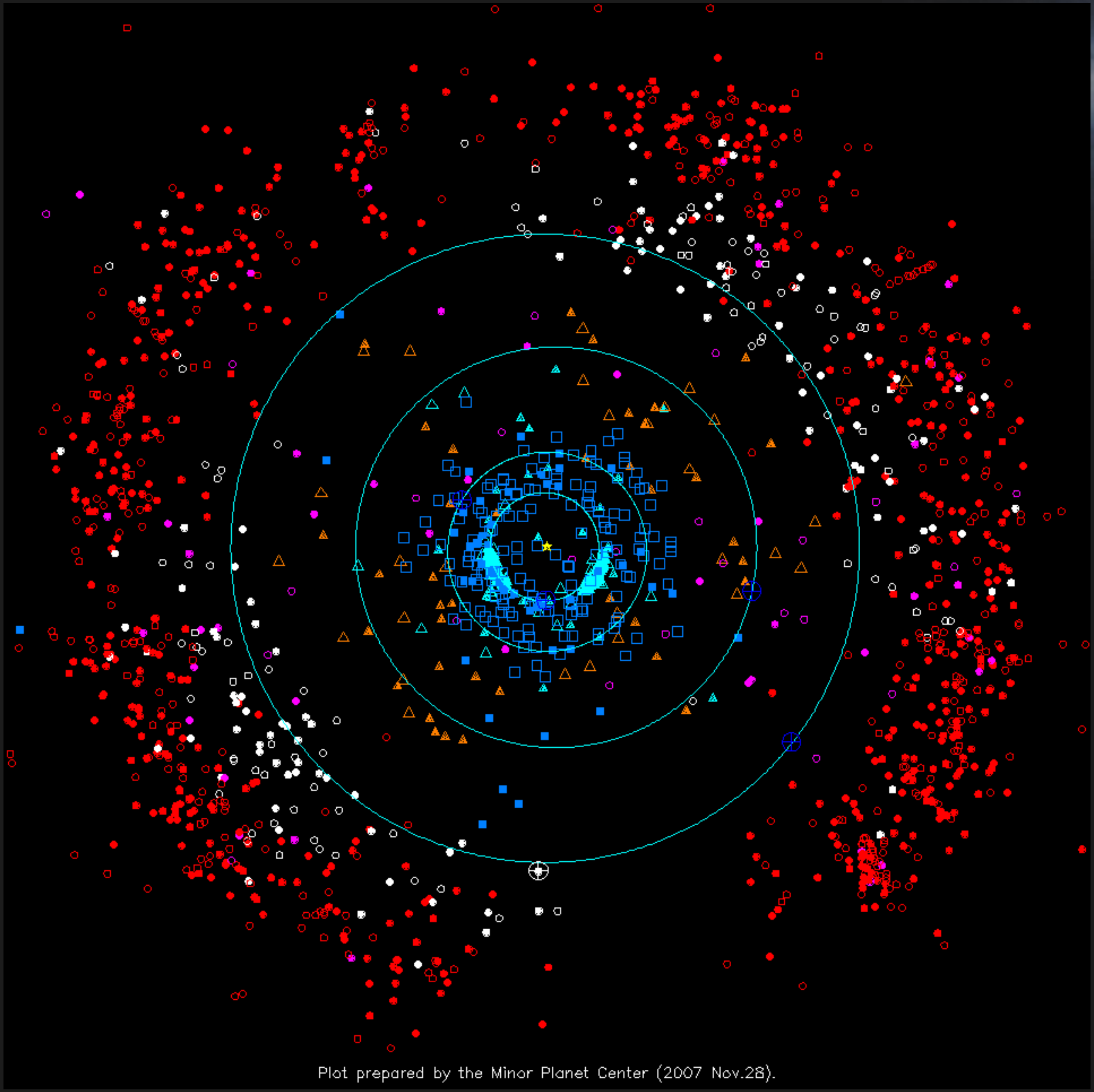
Comets
Centaurs
Plutinos
Classicals
SDOs



The Growing Population of TNOs

- 2007

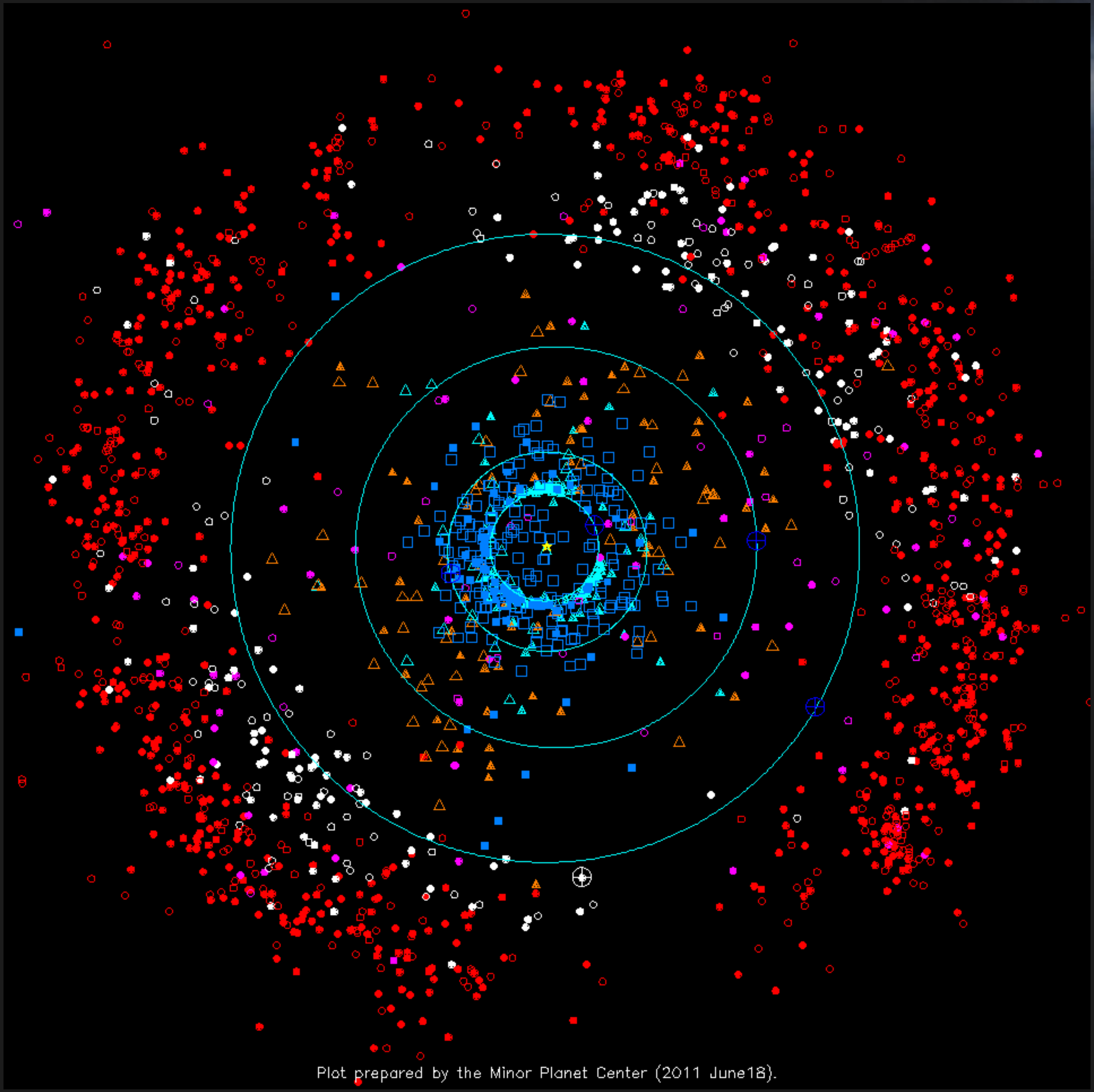
Comets
Centaurs
Plutinos
Classicals
SDOs



The Growing Population of TNOs

- 2011

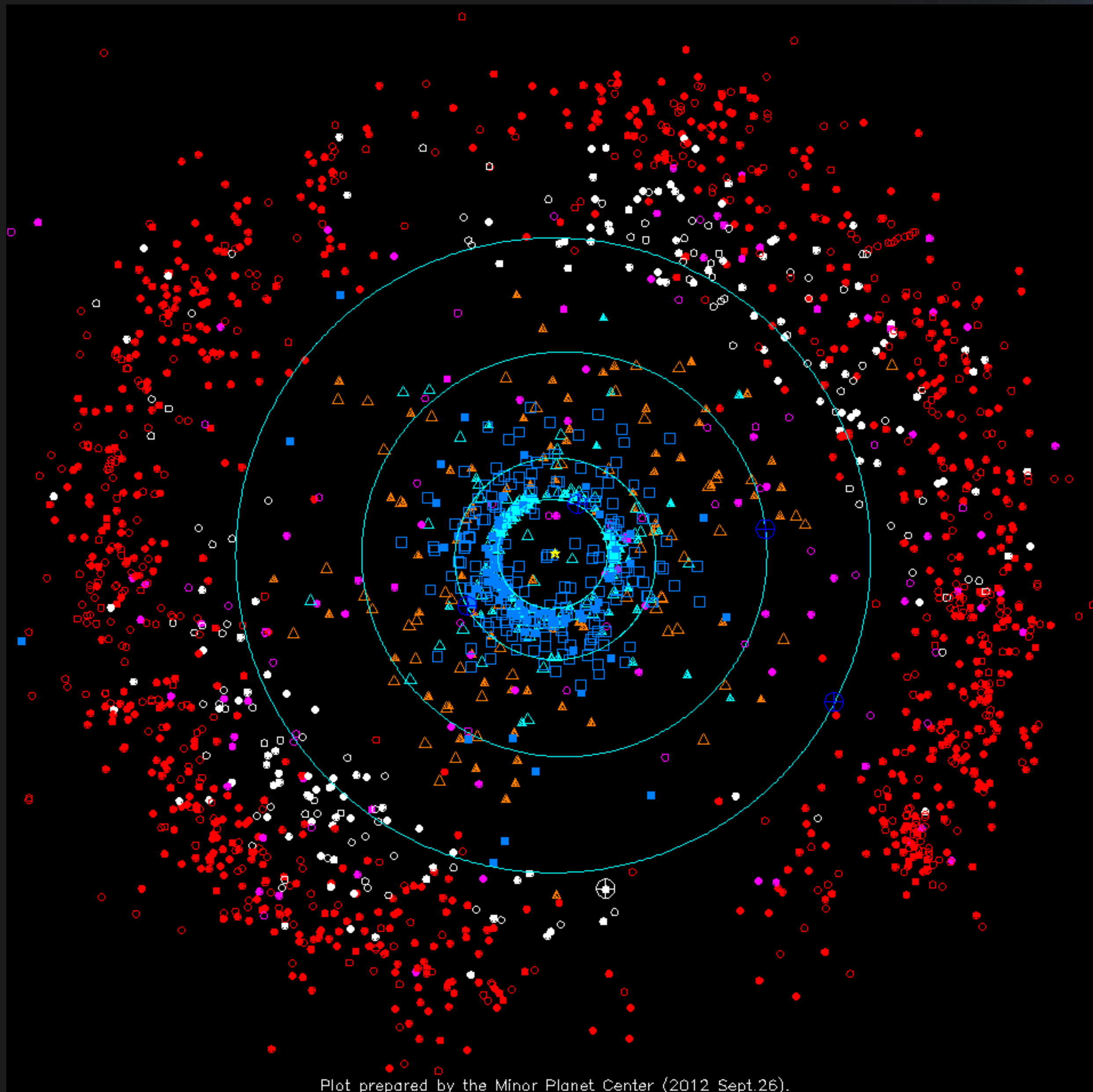
Comets
Centaurs
Plutinos
Classicals
SDOs



The Growing Population of TNOs

- 2012

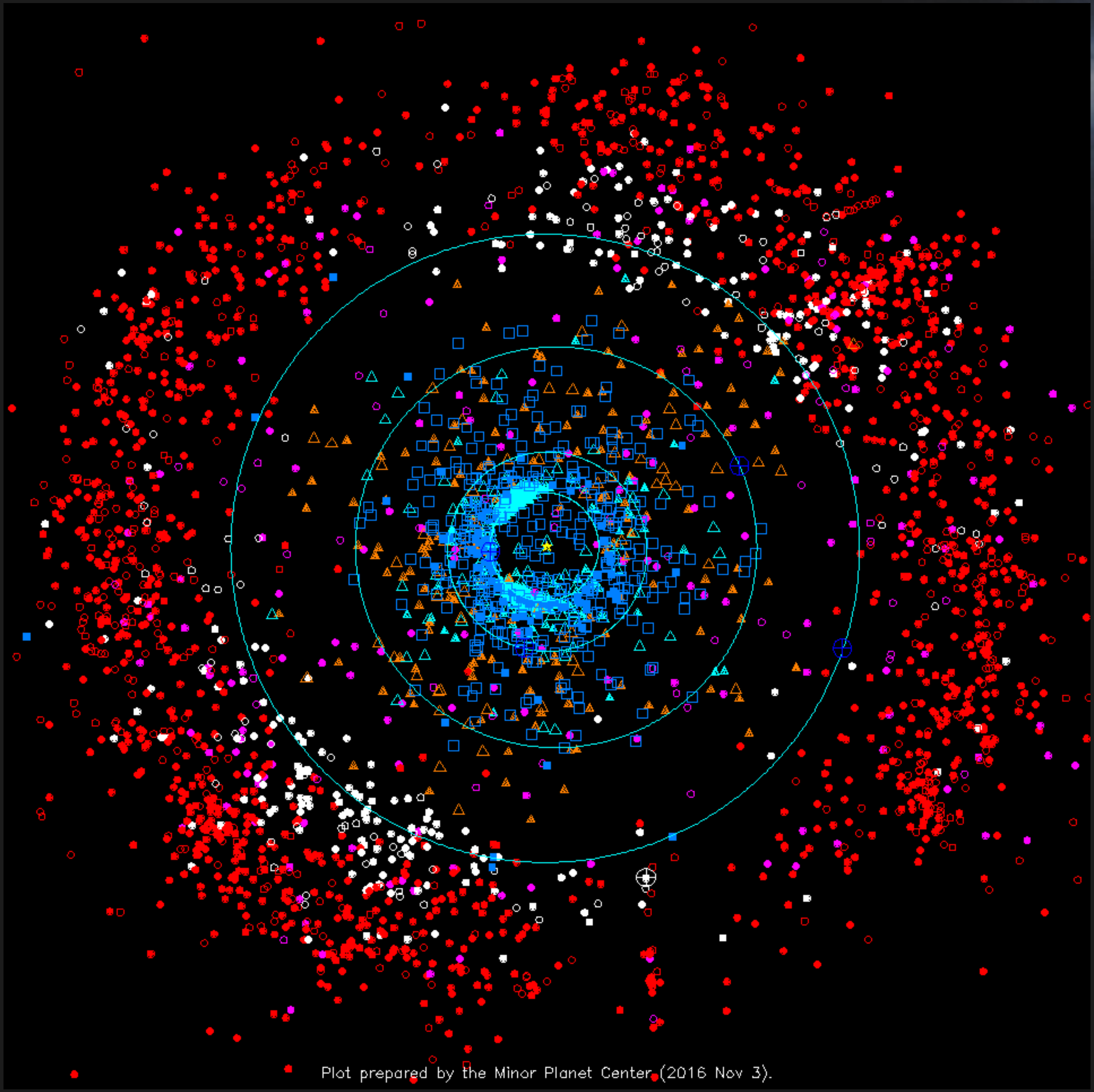
Comets
Centaurs
Plutinos
Classicals
SDOs



The Growing Population of TNOs

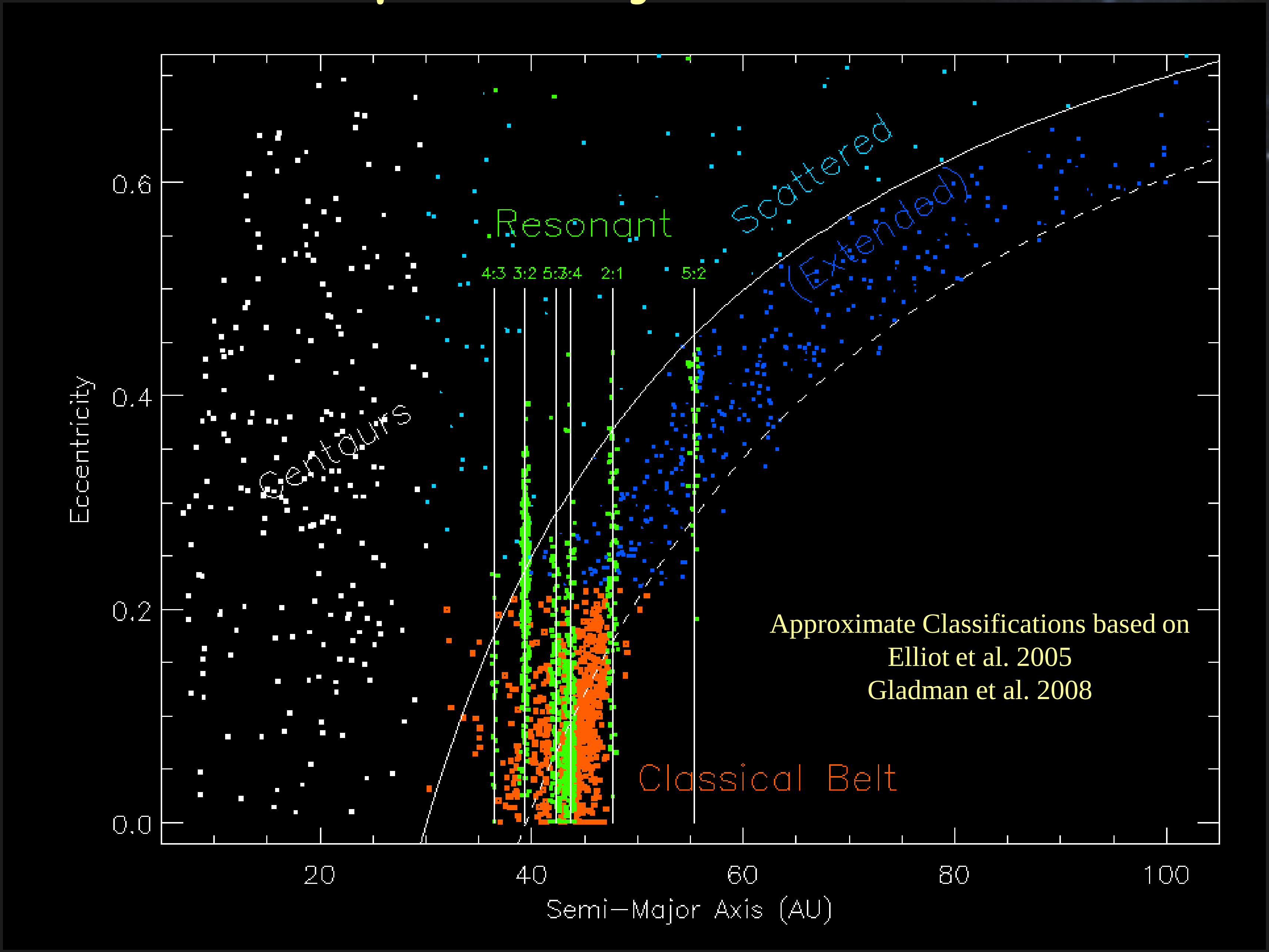
- 2016

Comets
Centaurs
Plutinos
Classicals
SDOs

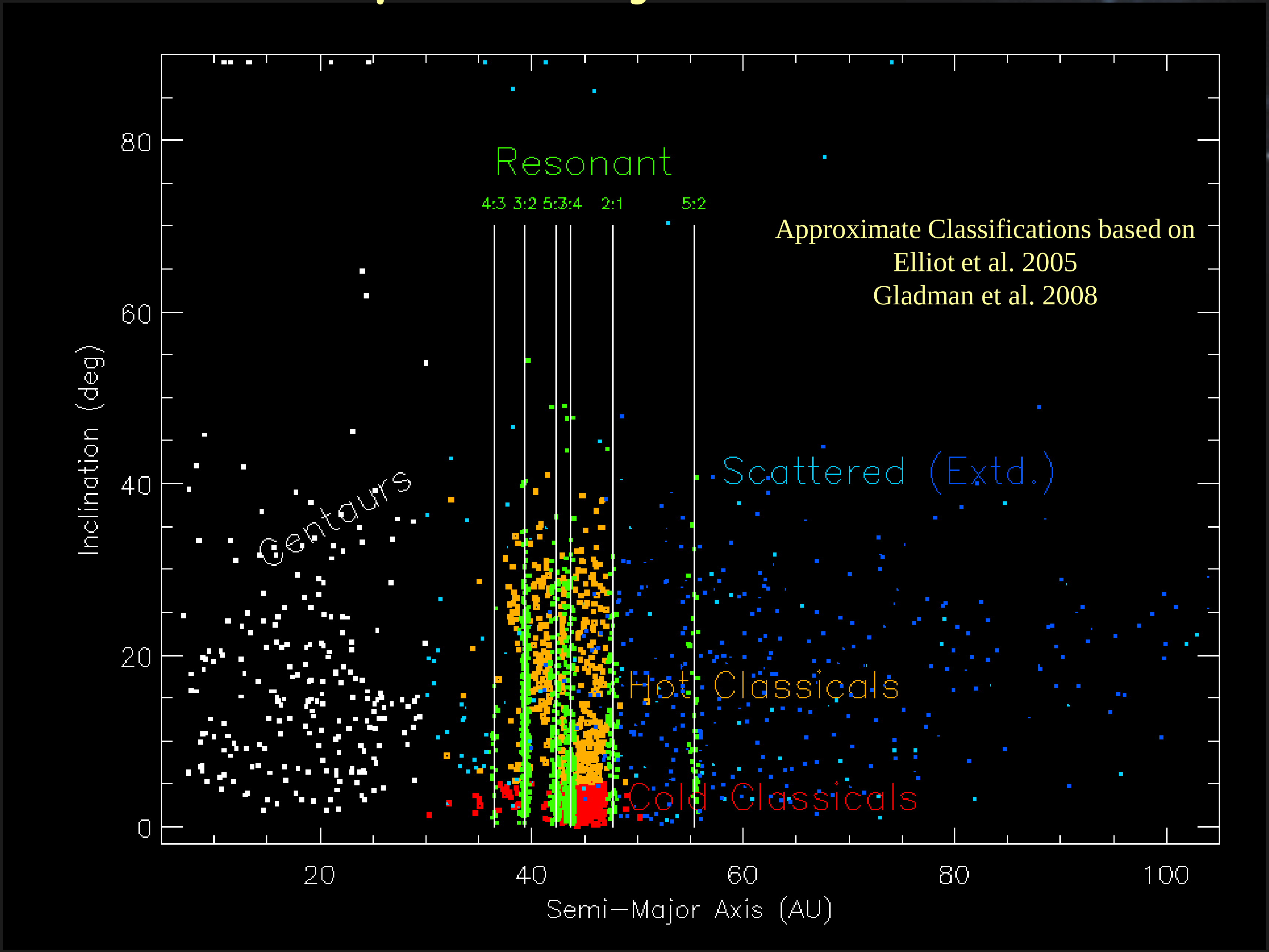


Dynamical Structure beyond Neptune

Trans-Neptunian Dynamical Structure



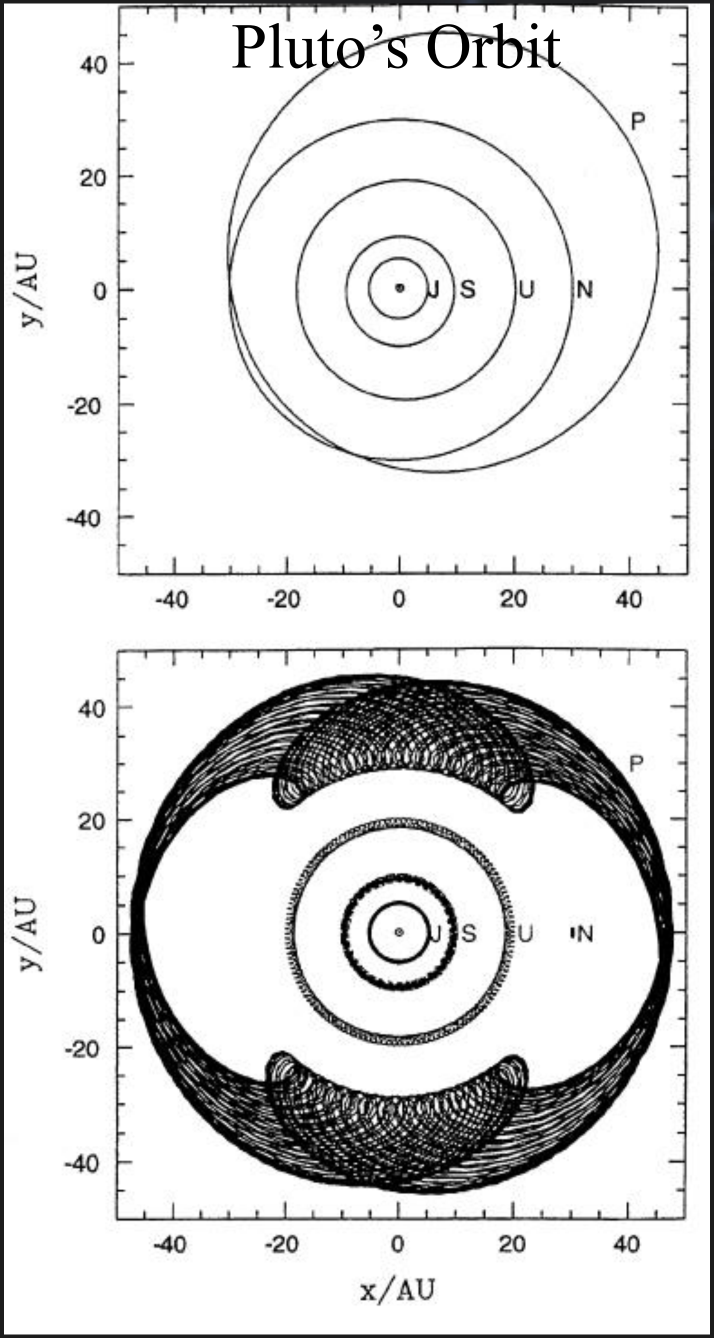
Trans-Neptunian Dynamical Structure



Pluto's Story

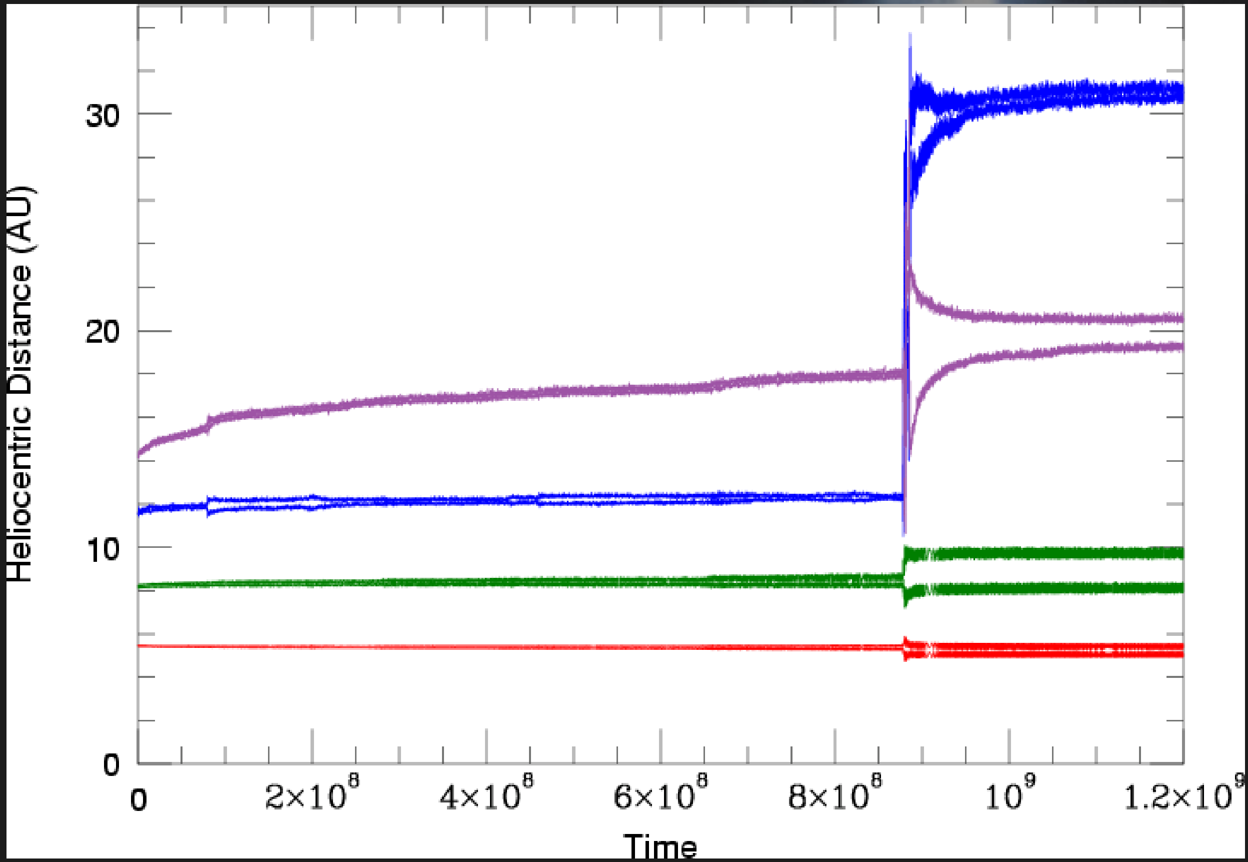
- Pluto's Neptune-resonant orbit explained in 1993
  - Giant planet orbital migration due to planetesimal scattering
    - Jupiter and Saturn migrate inward, Uranus and Neptune outward (Fernandez & Ip, 1984)
  - Resonances sweep outward w/ Uranus and Neptune (Malhotra, 1993)
    - Neptune's resonances can trap planetesimals as it moves outward
- "Nice" model
  - V. low present-day mass of KB
  - Observed dynamical structure

(Gomes 2003, Levison, Morbidelli et al.)



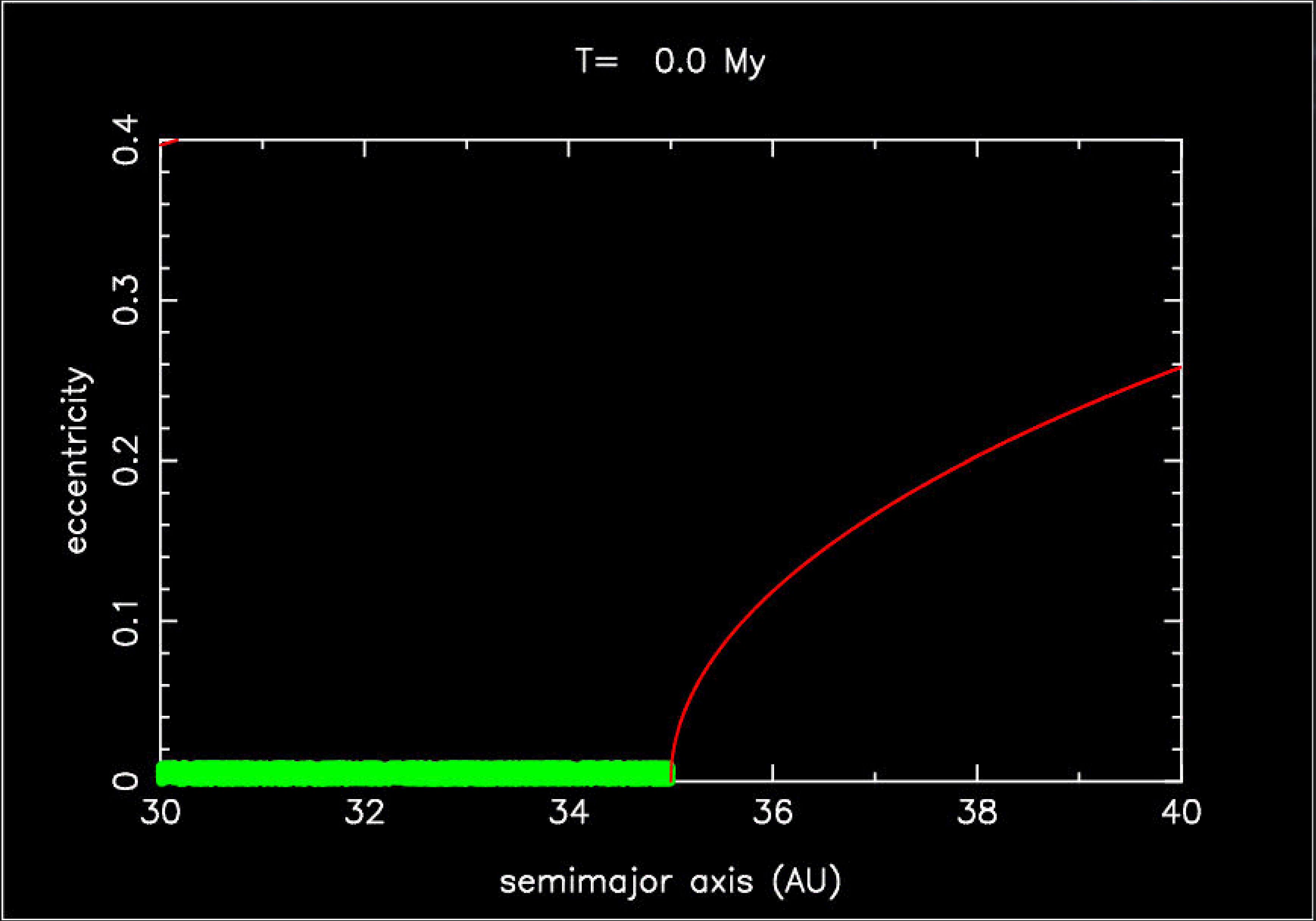
Magnitude & Implications of GP Migration

- U & N migrate many AU
- Model explains:
  - KB dynamical structure
  - Low present-day mass of the KB
  - Non-0 GP eccentricities
  - Timing, projectile make-up of LHB

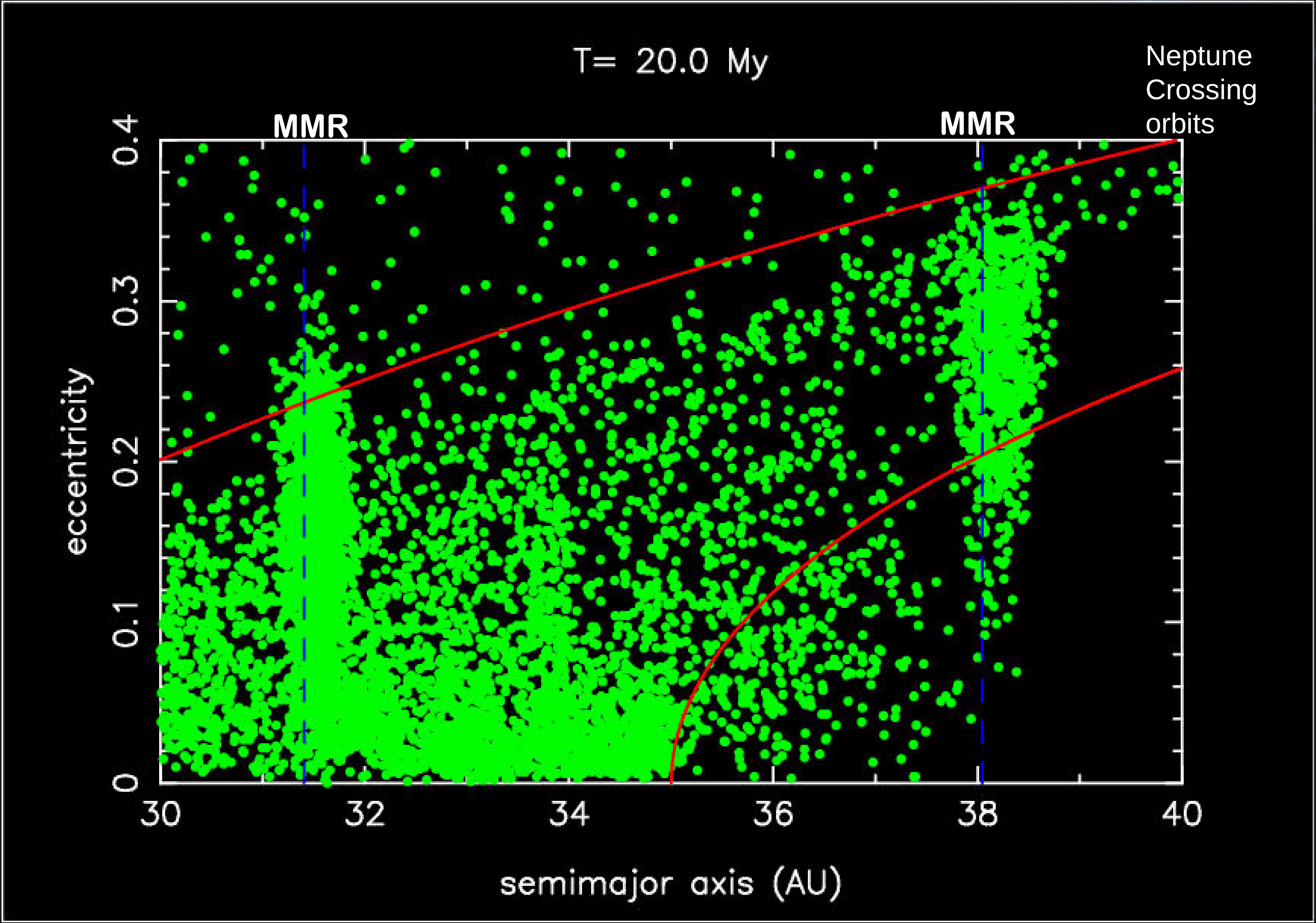


- Requires particular initial conditions
  - Saturn starts just inside the Jovian 2:1
  - 30 M_E primoridal Kuiper disk of planetesimals
  - Disk truncated at 30AU

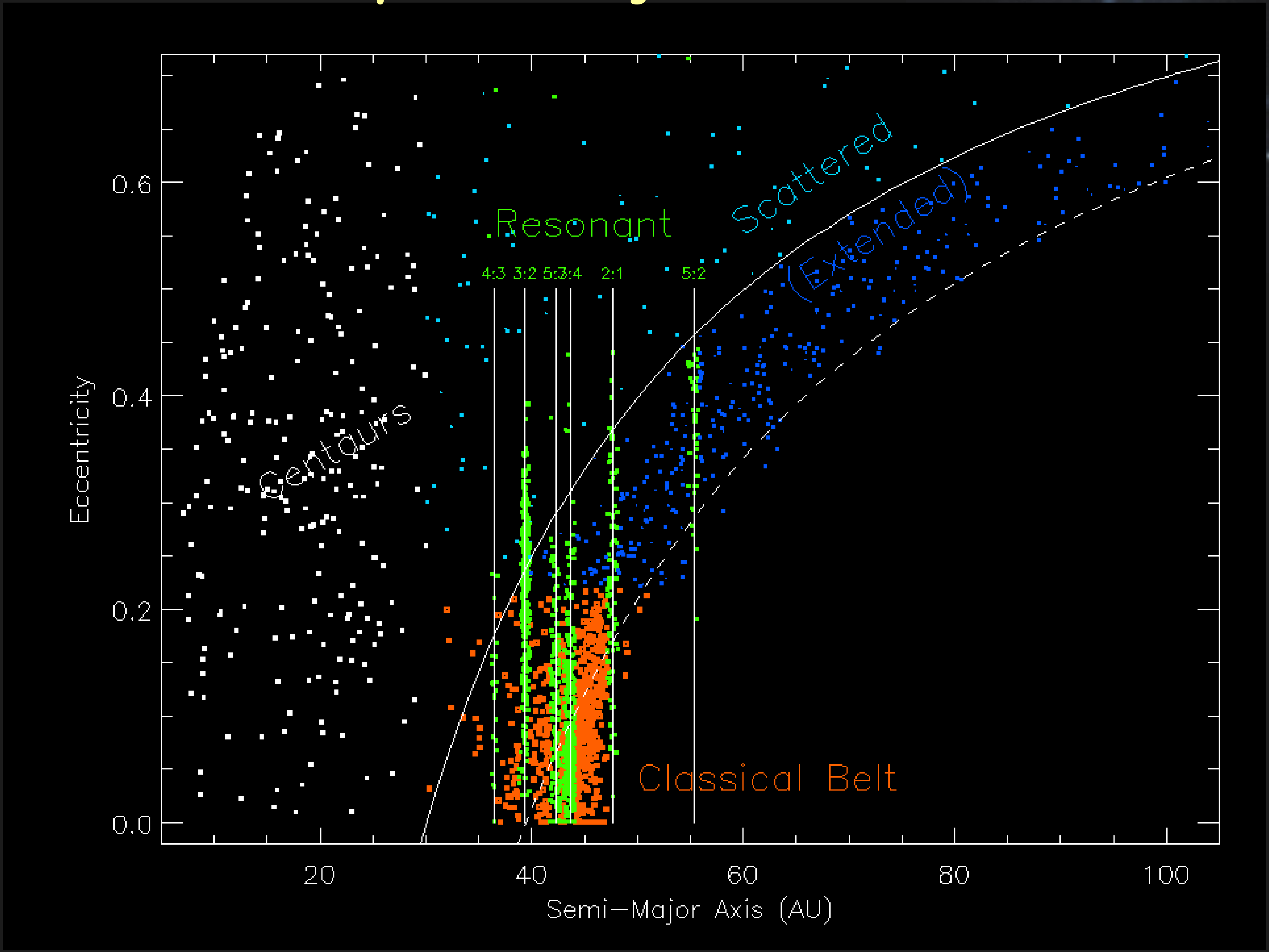
Neptune's Orbit, Resonances Migrate



Planetesimal Trapping, Migration



Trans-Neptunian Dynamical Structure



Trans-Neptunian Dynamical Structure

Gladman et al. 2008

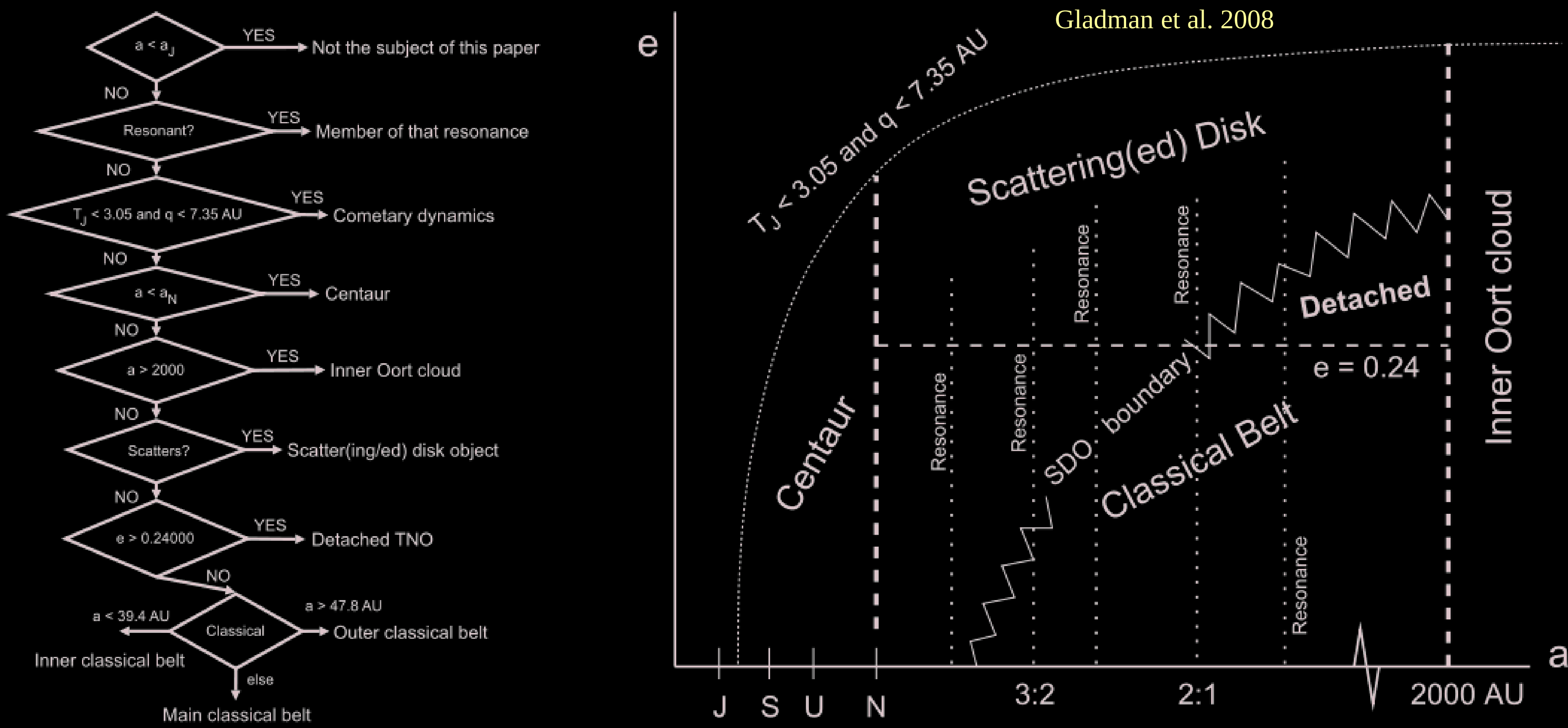
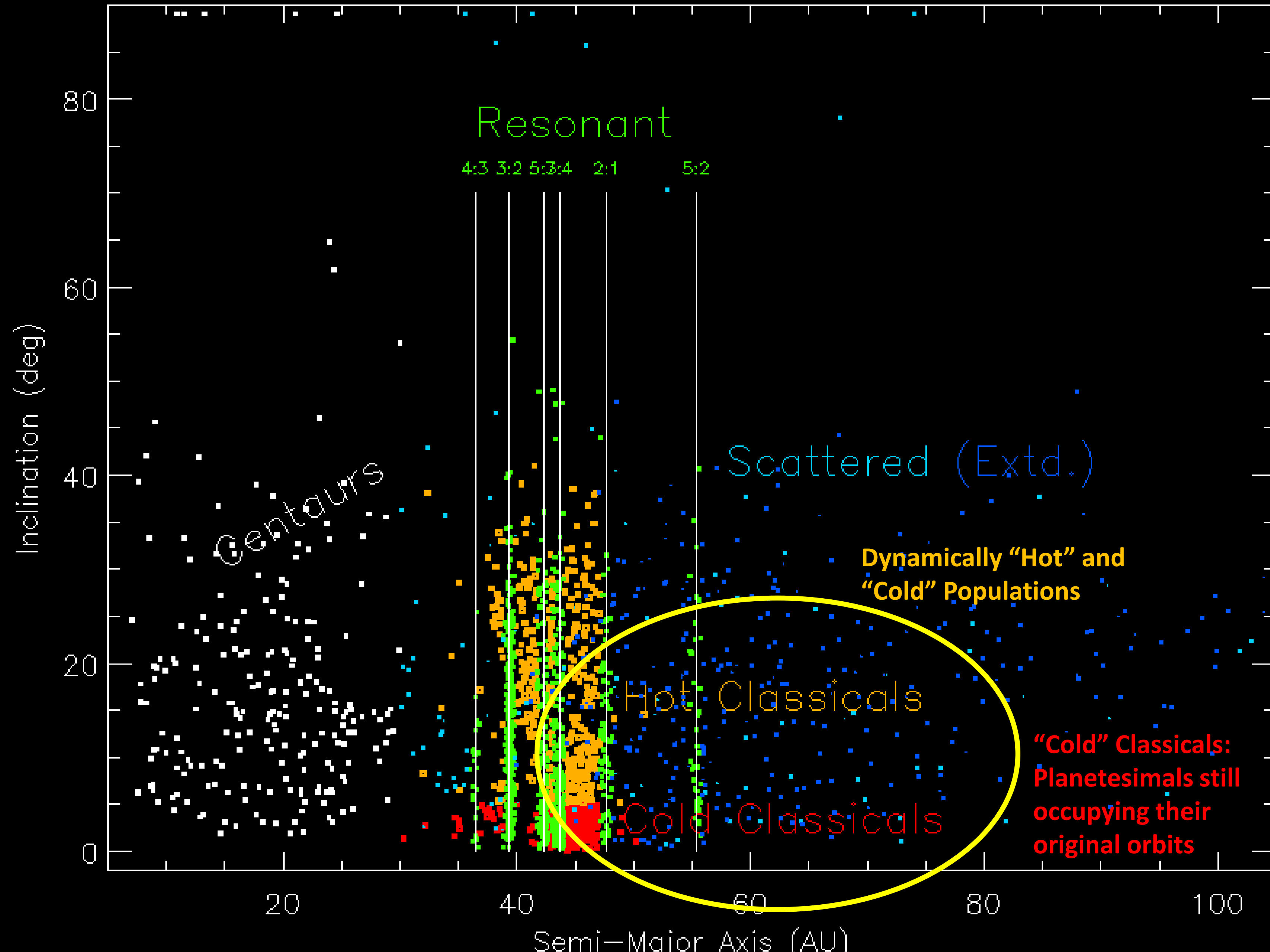


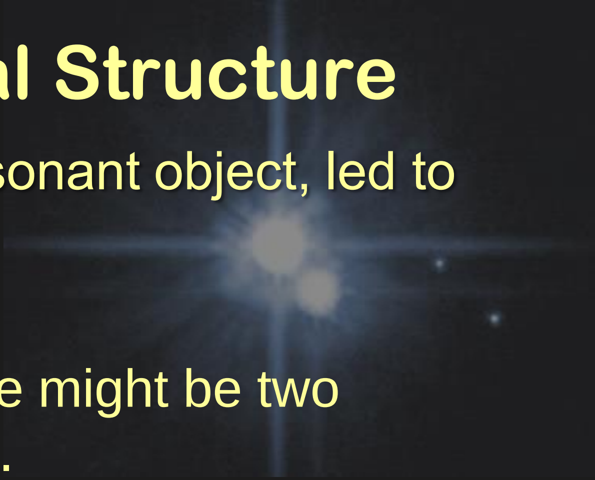
Fig. 1. *Left:* Flowchart for the outer solar system nomenclature. When orbital elements are involved they should be interpreted as the osculating barycentric elements. *Right:* A cartoon of the nomenclature scheme (not to scale). The boundaries between the Centaurs, JFCs, scattered disk, and inner Oort cloud are based on current orbital elements; the boundaries *are not* perihelion distance curves. Resonance inhabitance and the "fuzzy" SDO boundary are determined by 10-m.y. numerical integrations. The classical belt/detached TNO split is an arbitrary division.

Also see Elliot et al. 2005 for the Deep Ecliptic Survey classification scheme.

Kuiper Belt Dynamical Structure



Kuiper Belt History & Dynamical Structure



- Pluto's discovery, and the accident that it was a resonant object, led to the hypothesis that Neptune migrated outward.

- The discovery of 1992 QB1 demonstrated that there might be two dynamical populations beyond the orbit of Neptune.

- Within 10 years it was known that there were KBOs in multiple resonances, a classical belt, objects scattered by Neptune, and that giant planet migration had occurred.

- Soon it became clear that there was a dynamically cold population, that binaries were much more common than elsewhere in the solar system.

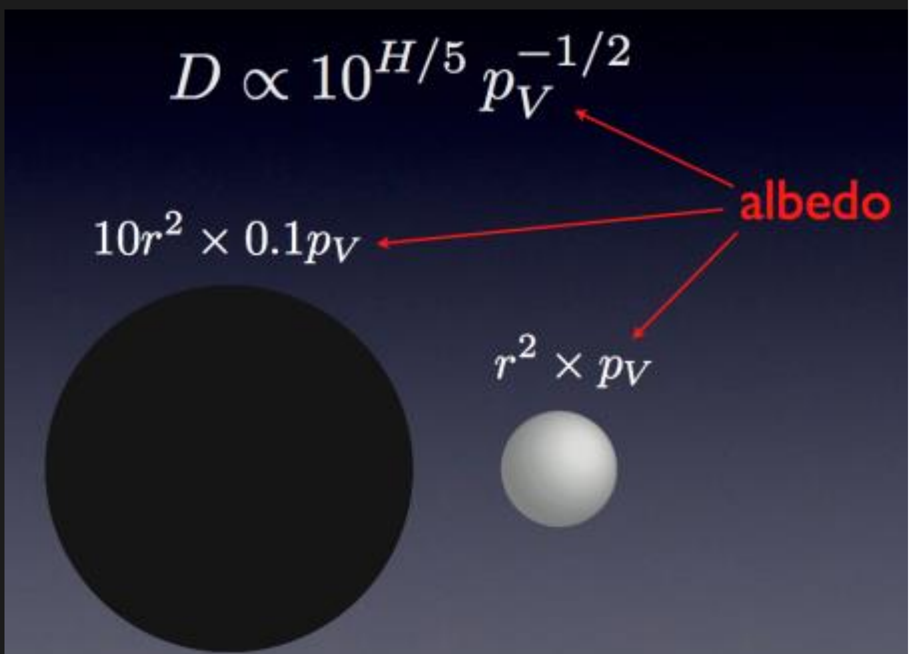
- By 2008 the discovery of the Kuiper belt and characterization of KBO orbits had completely re-written our concept of solar system history.

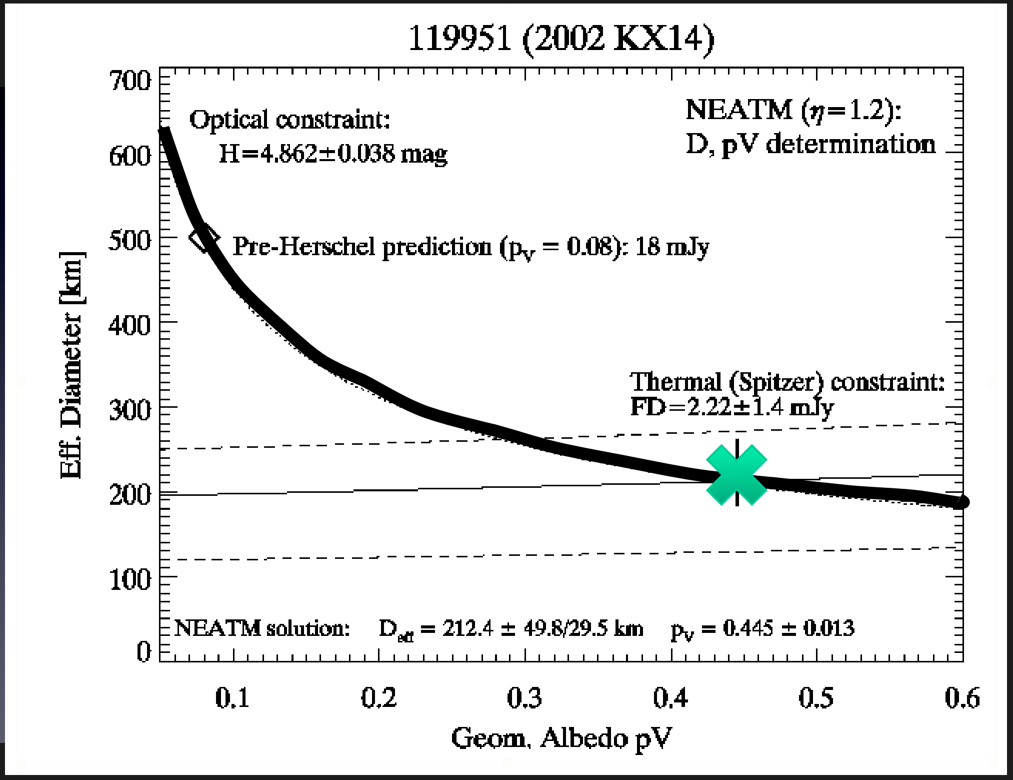
TNO Physical Properties

Thermal Method: Size and Visual Albedo

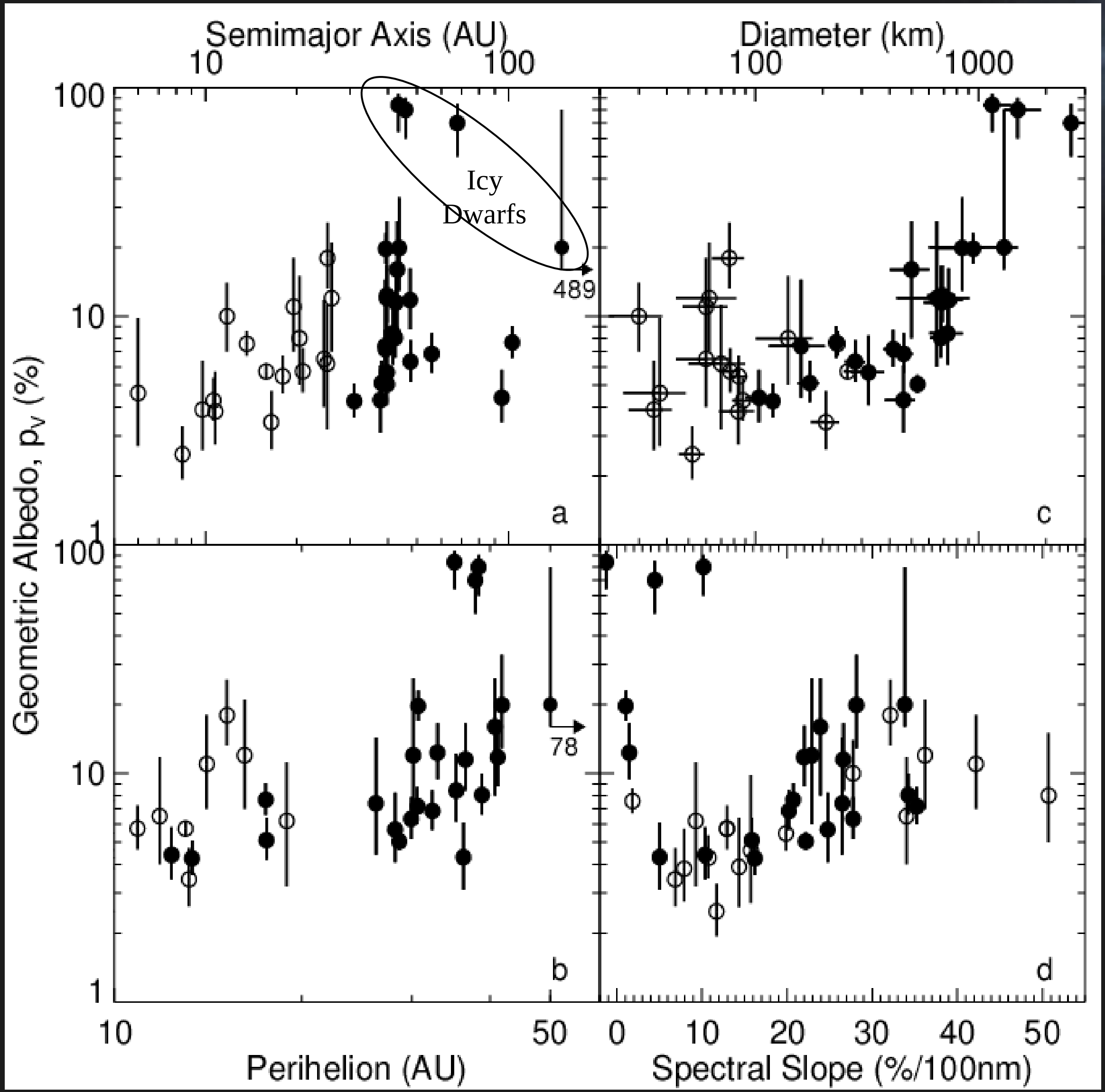
Large low-albedo objects reflect as much light as small high-albedo objects…

but small high-albedo objects are much fainter at thermal wavelengths (> 20um)





TNO Albedos and Sizes: *Spitzer* Results

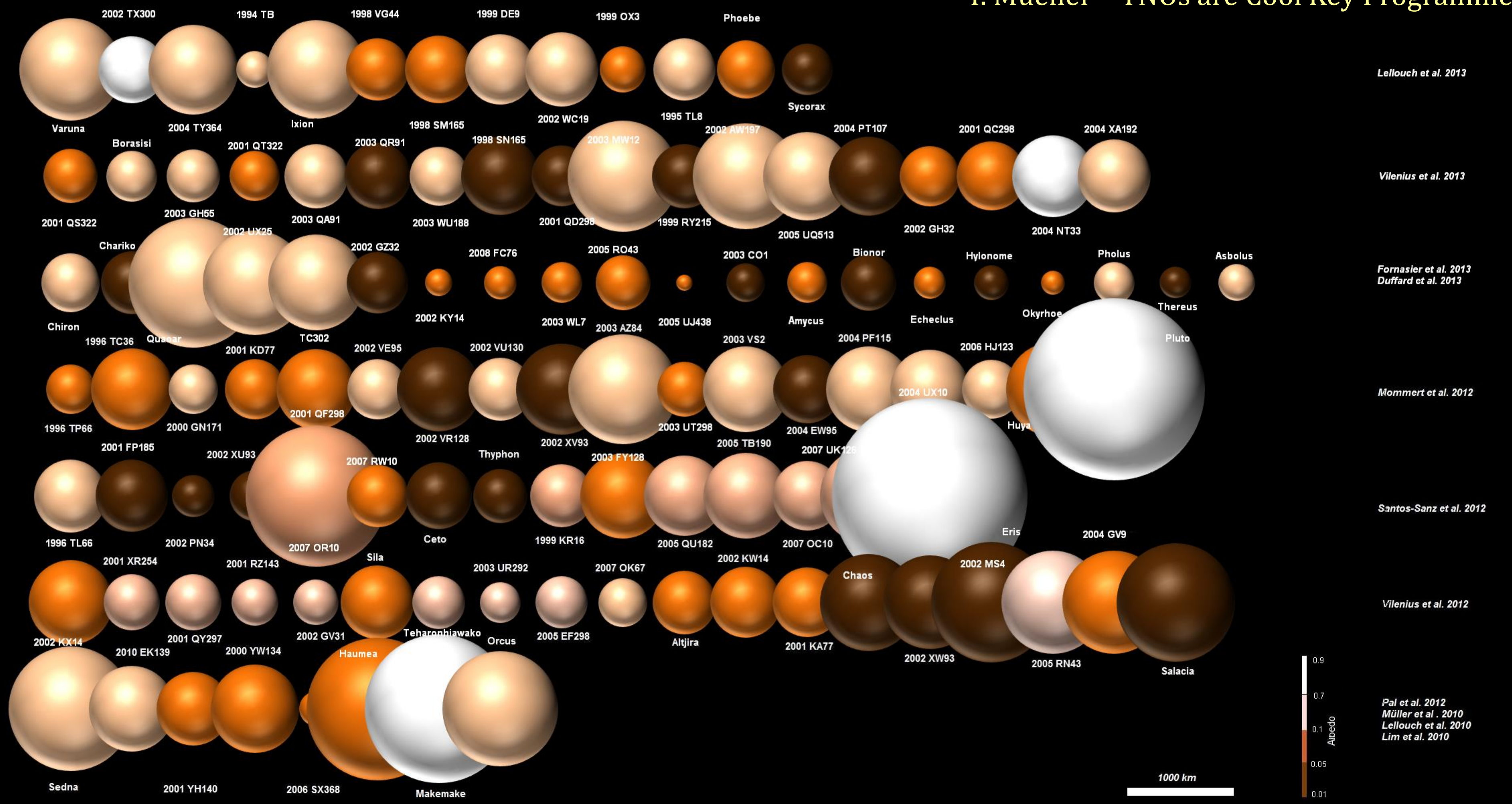


Stansberry et al. 2008
32 objects
Spitzer 24um & 70um

Open points: Centaurs
Filled points: TNOs

TNO Size & Albedo: *Herschel* Results

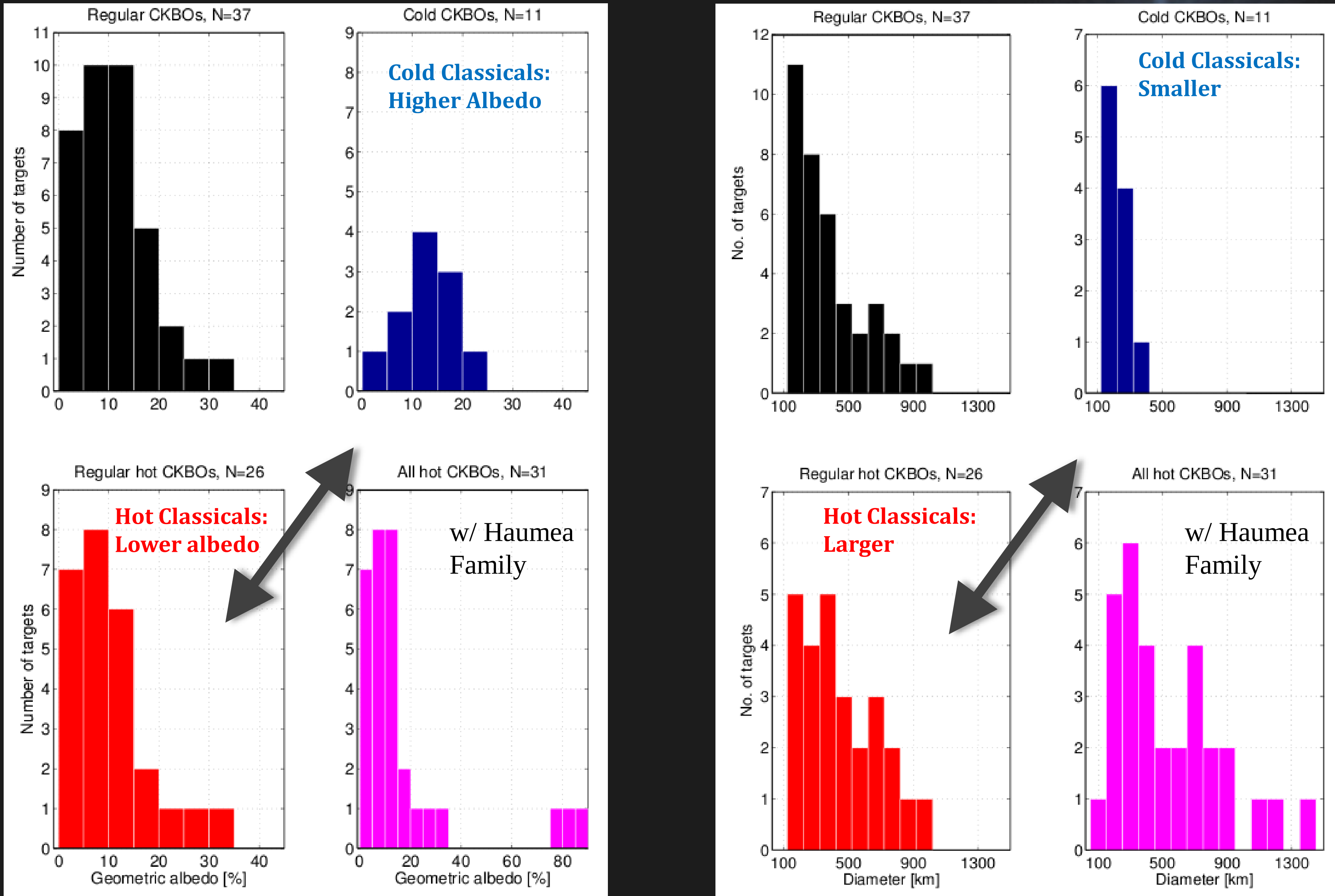
T. Mueller – TNOs are Cool Key Programme



Note that red ≠ dark, at least for cold-classical TNOs…

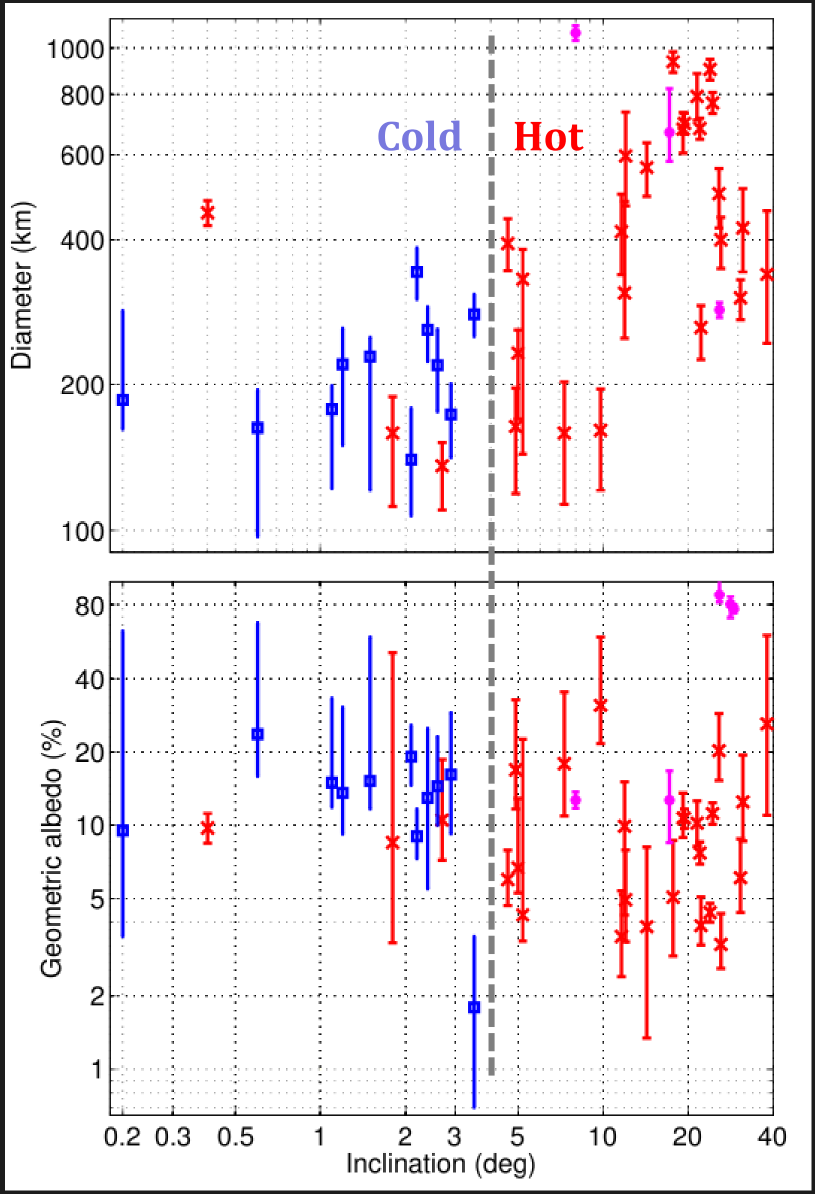
Classical TNO Albedo and Size Distributions

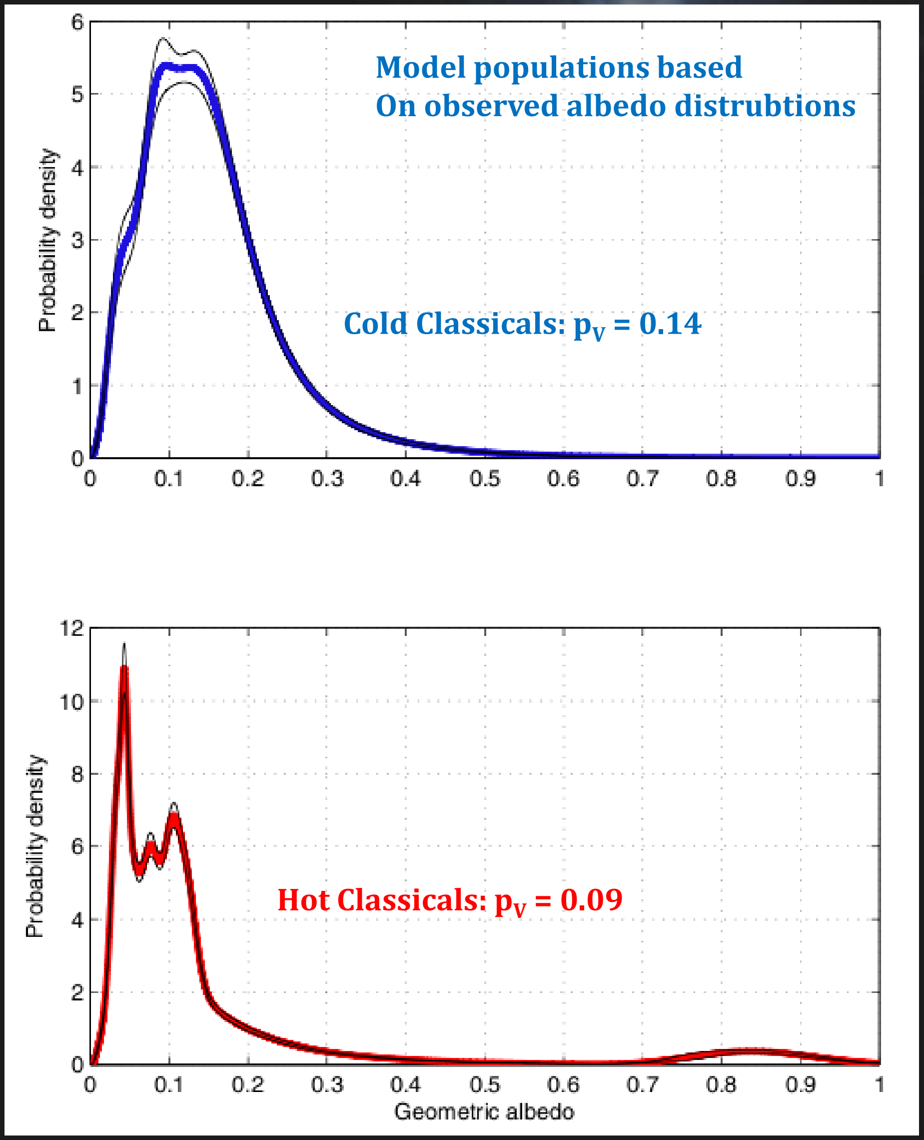
Vilenius *et al.* 2014



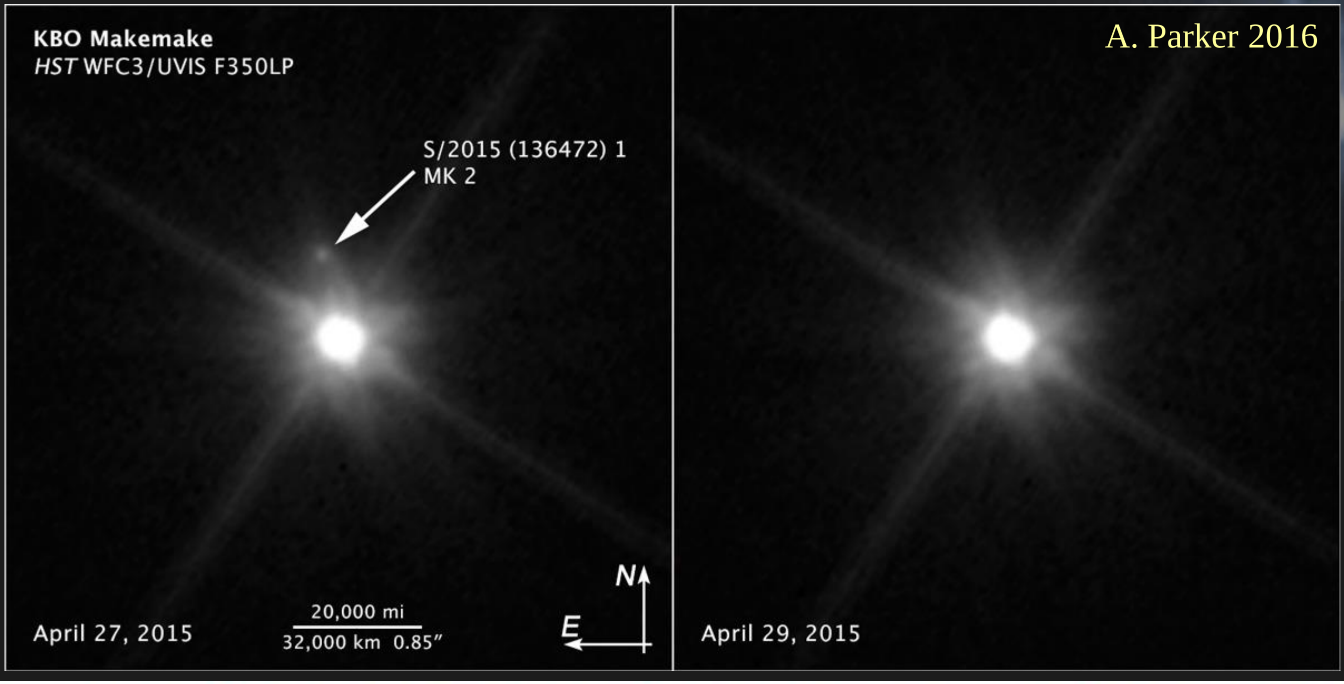
Classical TNO Albedo, Size and Inclination

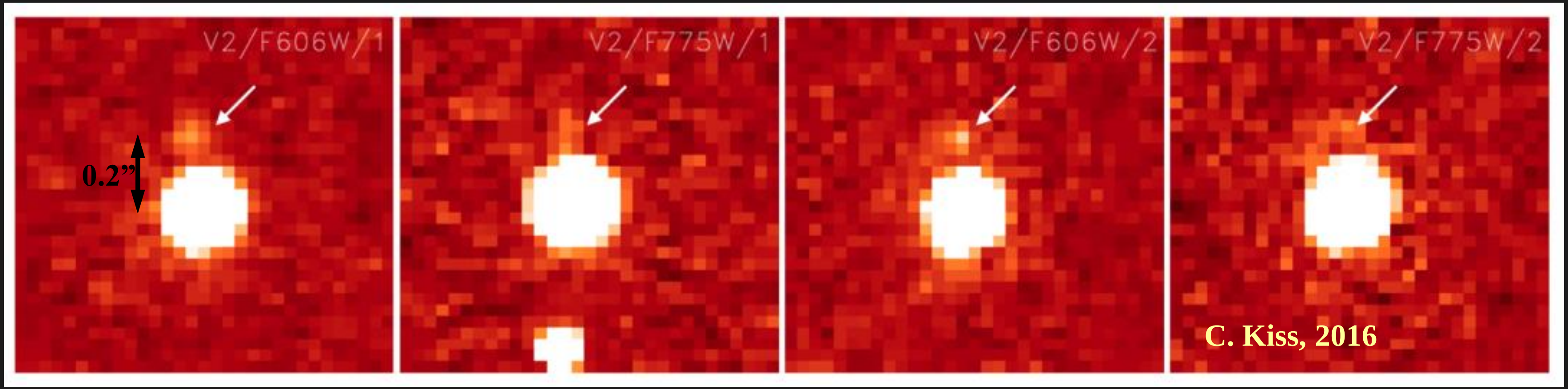
Vilenius *et al.* 2014

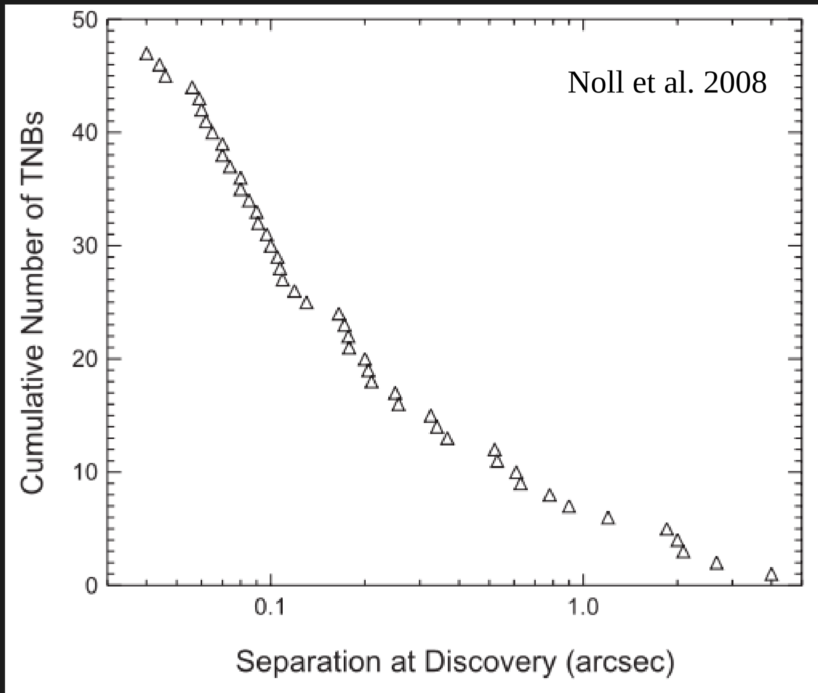


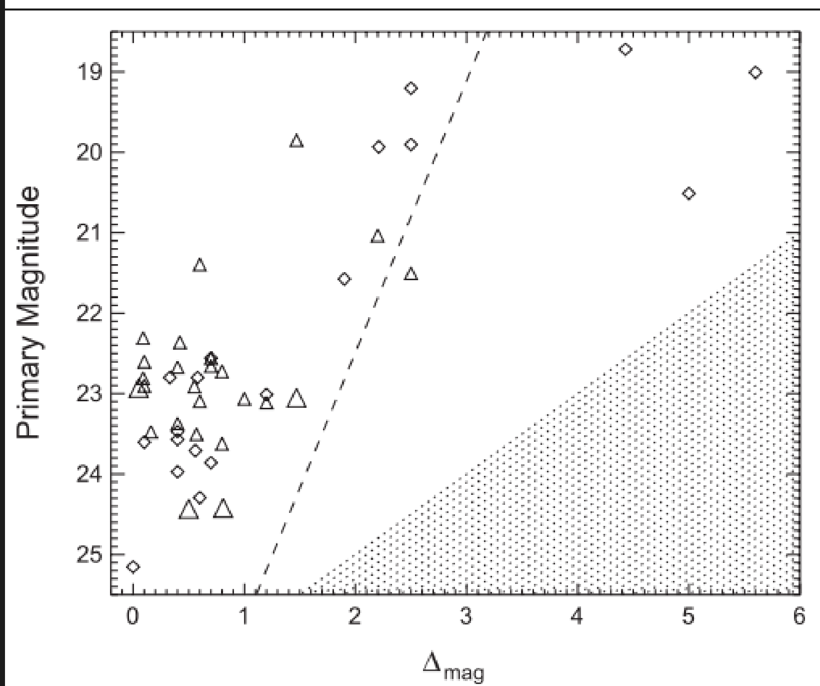


New Moons of TNO Dwarf-planets

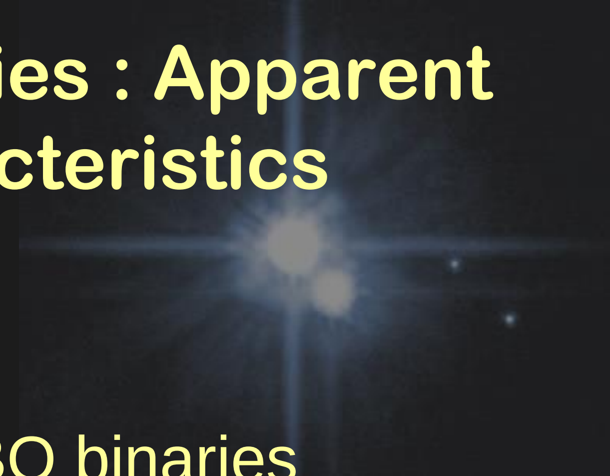








TNO Binaries : Apparent Characteristics



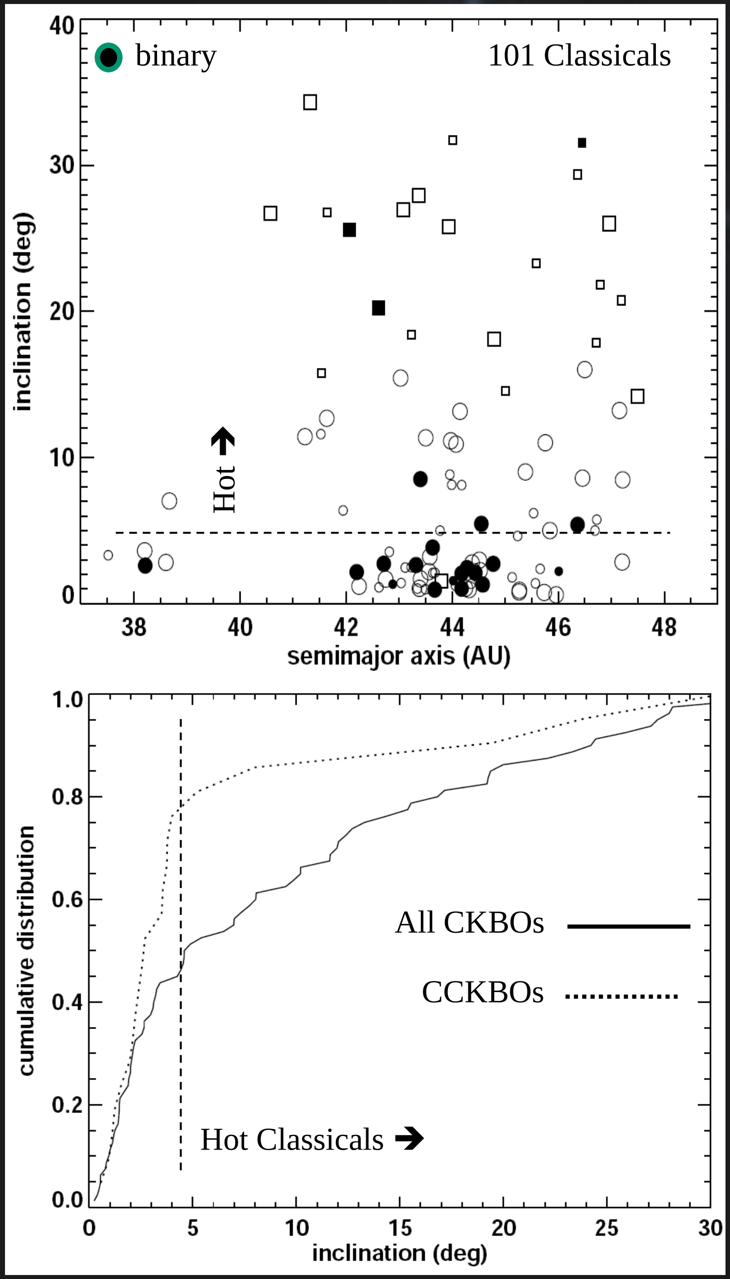
- 75 known KBO binaries
  - 43 are Classical KBOs
- Mass is known for 38
  - Density is known for 16 of those

- Probably many more at separations < 0.5”

- Fainter (smaller) objects tend to have similar brightness (size) satellites

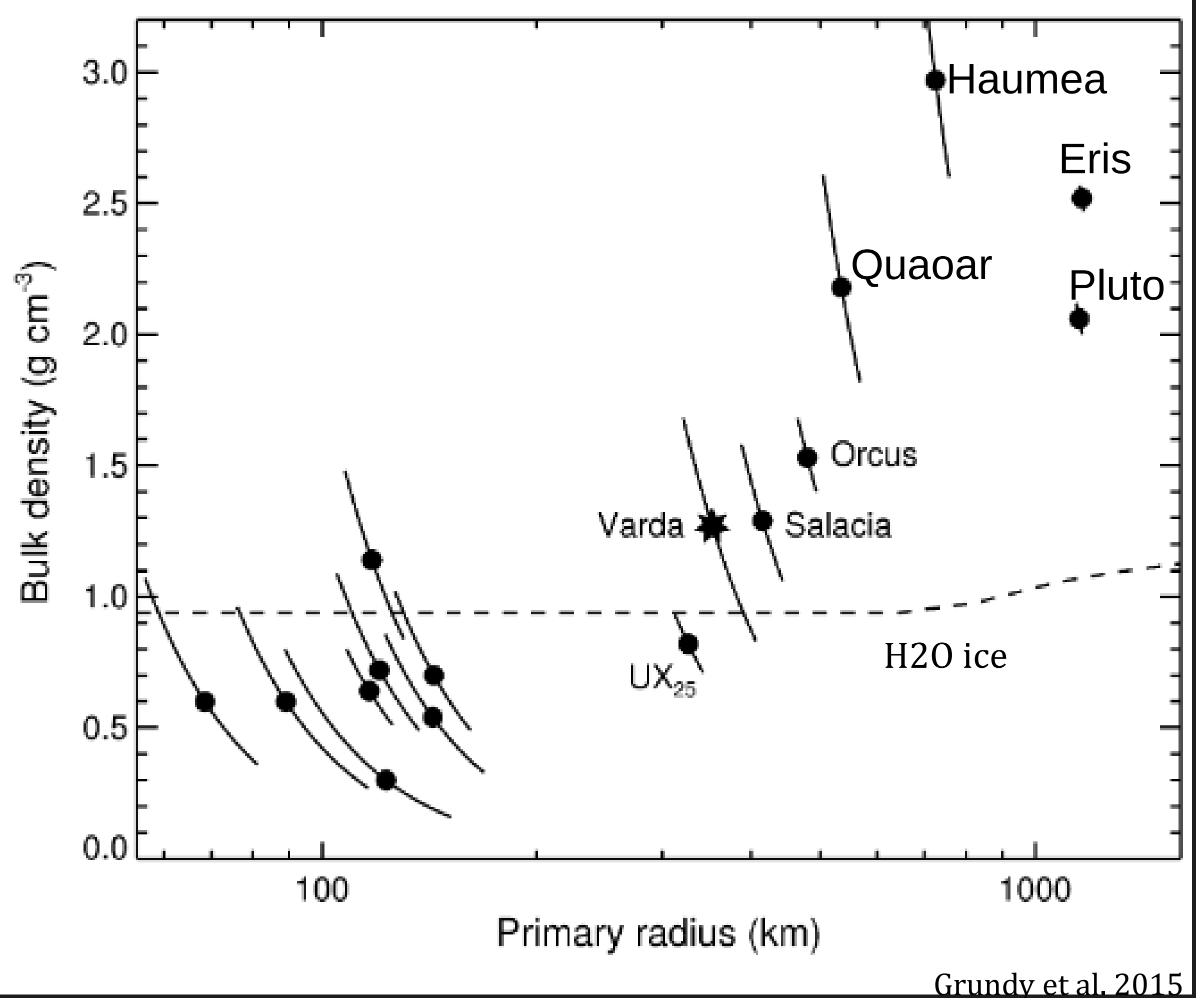
Classical TNO Binarity vs. Inclination

- Classical KBOs are dynamically 'Hot' or 'Cold'
  - Cold-classicals are redder, have higher albedos
- KBO Binaries are common
  - ~10% of all KBOs
  - ~2% MBAs
- CKBO Binaries very common
  - ~20% of 101 CKBOs
- CCKBO Binaries even more so
  - ~30% of 58 in CC sample



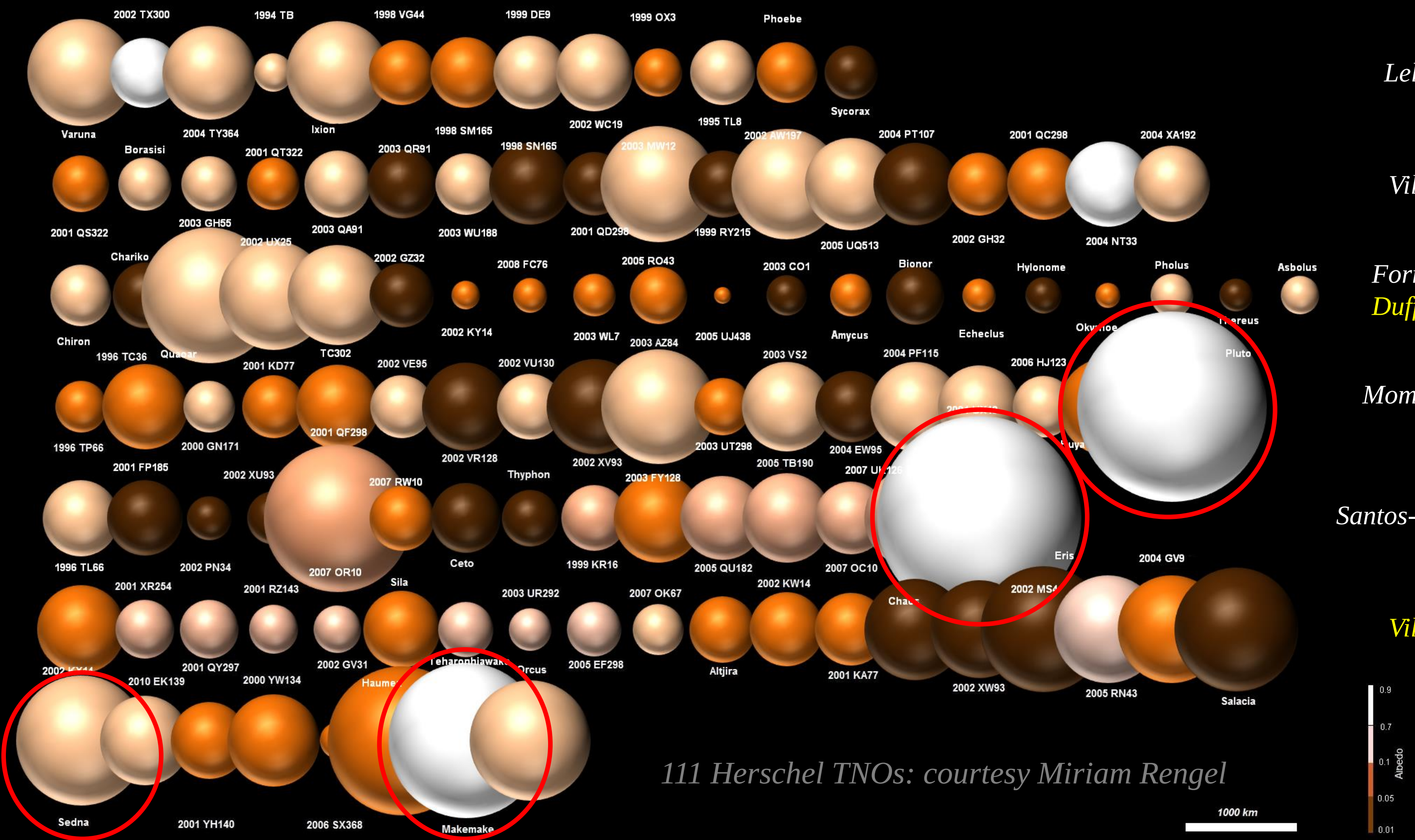
Noll et al. 2008

TNO Densities



- Binary orbit ➔ mass
- Thermal size ➔ density
- Large = more dense
  - Fully compressed
  - 40% - 60% "rock"
- Small = very porous
  - Expect ~50% rock
  - ➔ 50% porosity
  - For R=100km KBOs… !
  - Similar to comet nuclei

Size & Albedo: *Herschel* Results



Lellouch et al. 2013

Vilenius et al. 2012

Fornasier et al. 2013
Duffard et al. 2013

Mommert et al. 2012

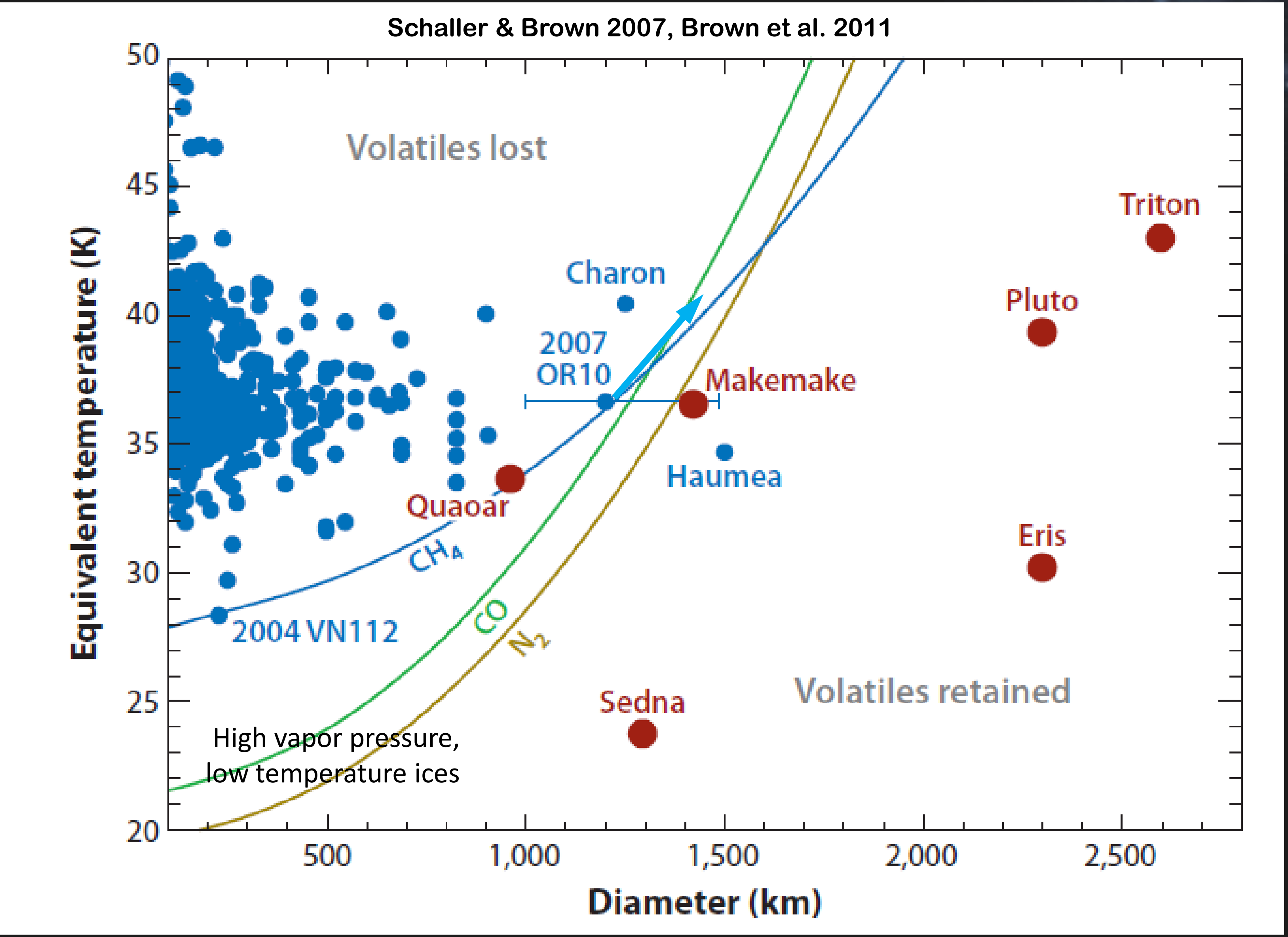
Santos-Sanz et al. 2012

Vilenius et al. 2013

Pal et al. 2012
Mueller et al. 2010
Lim et al. 2010
Lellouch et al. 2010

Note that red ≠ dark, at least for cold-classical TNOs…

Hydrodynamic Escape of Volatiles from TNOs



TNO Physical Properties

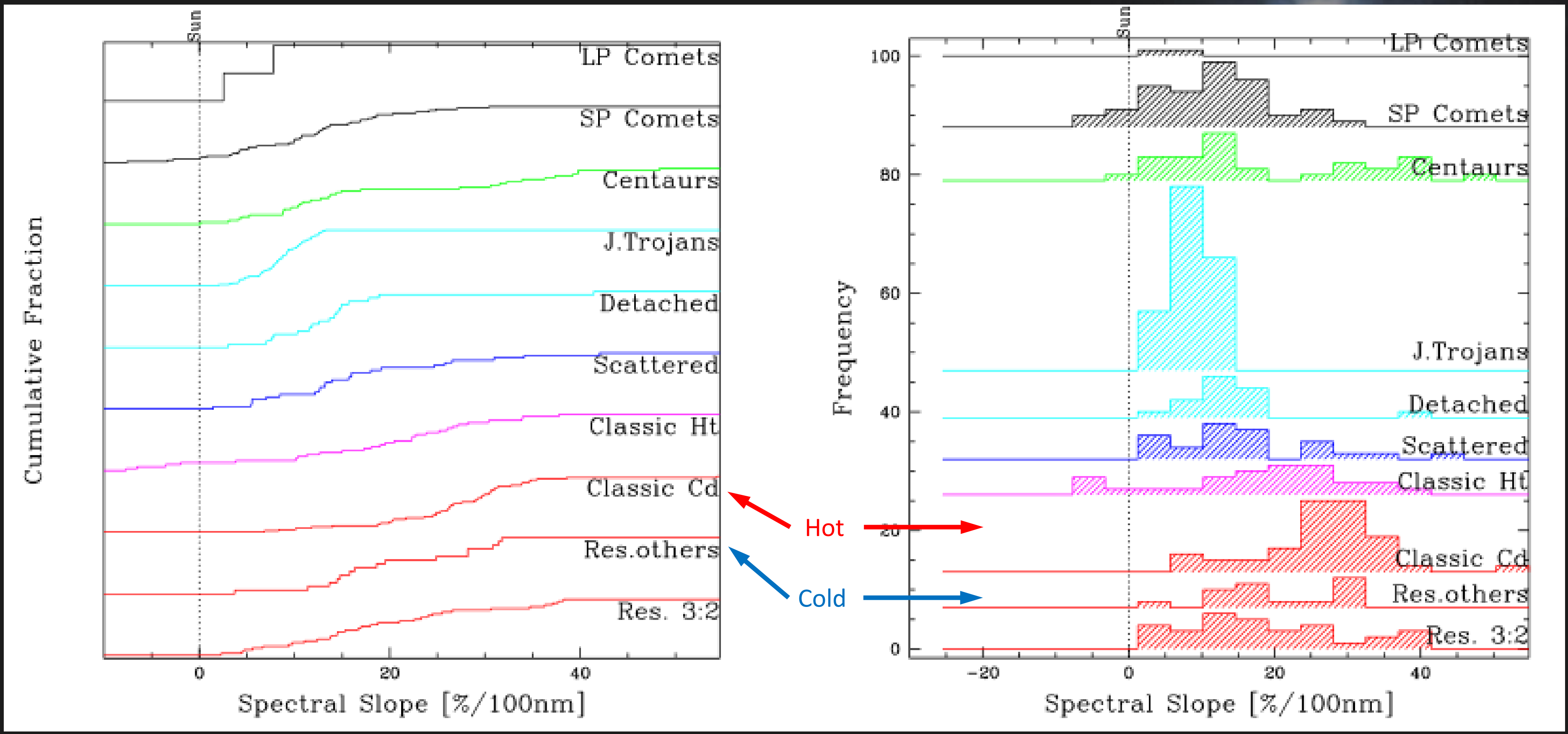
- The albedos of KBOs span the full range found for all other small bodies in the solar system, and that range significantly exceeds the range seen for asteroids, Centaurs and comets.
- The densities of large KBOs are consistent with roughly equal portions of H2O ice and silicates.
  - The densities of small KBOs challenge our understanding of strength vs. gravitational forces, and collisional processing.
- KBO satellites appear to have formed either by collisions (small satellites of large KBOs), or by a co-accretional process (small, coequal sized systems).
- The Kuiper belt contains 8 of the solar system’s 9 dwarf planets.
- KBO dwarf planets in many cases are large enough to have retained significant amounts of volatile ices over the age of the solar system.

TNO Composition

TNO Color vs Dynamical Class

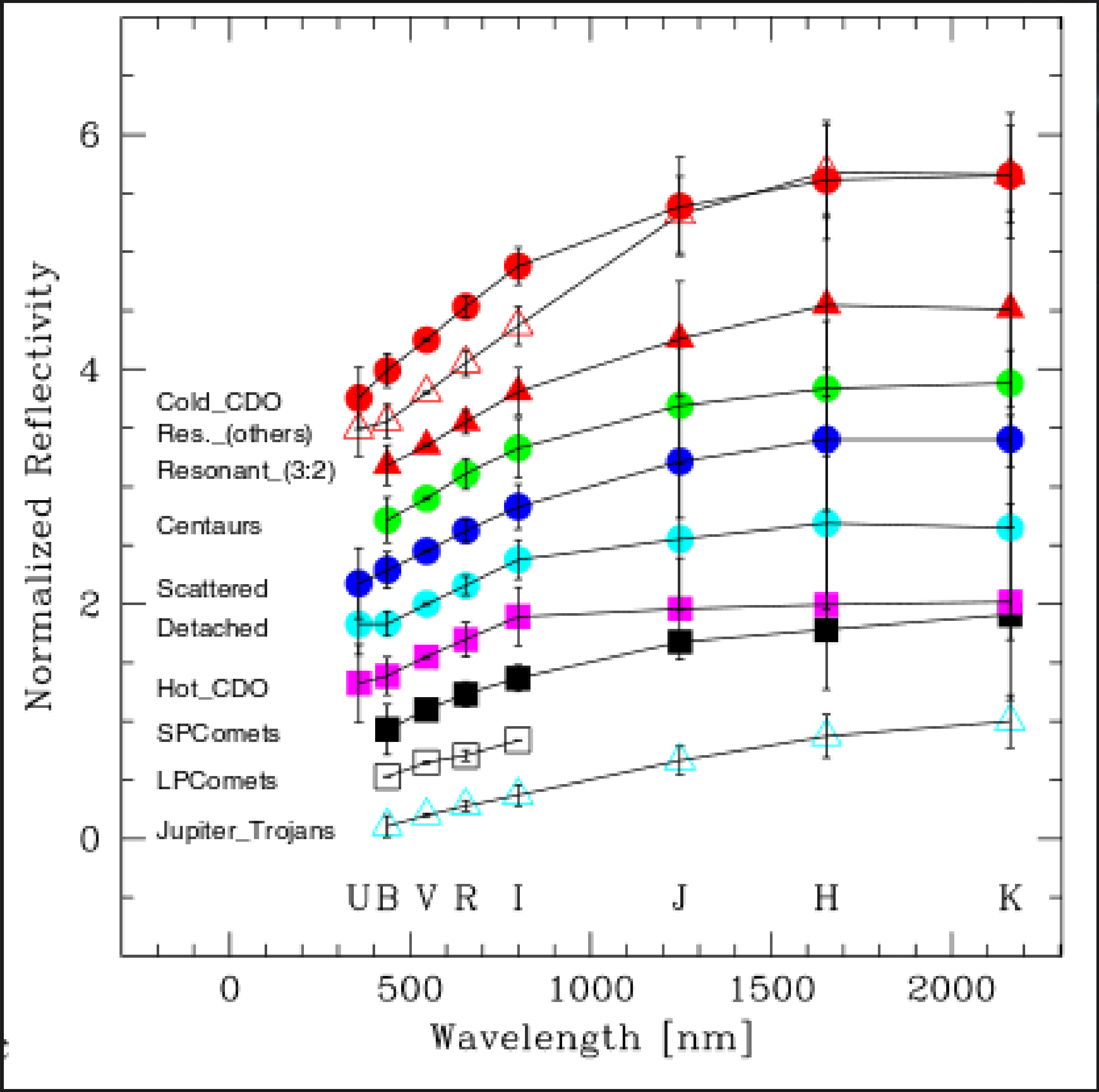
Hainaut et al., 2015

Color in the ~visual range: V-R represented as reflectance change per 0.1um



- For many years only color was known for a significant sample of TNOs, and it varied with dynamical classification.
- Relation to other properties (albedo, composition, size) wasn't clear.
- 'Tholins' (highly processed organics) were a candidate reddening agent.

In Search of the "Red Stuff" – nIR Colors

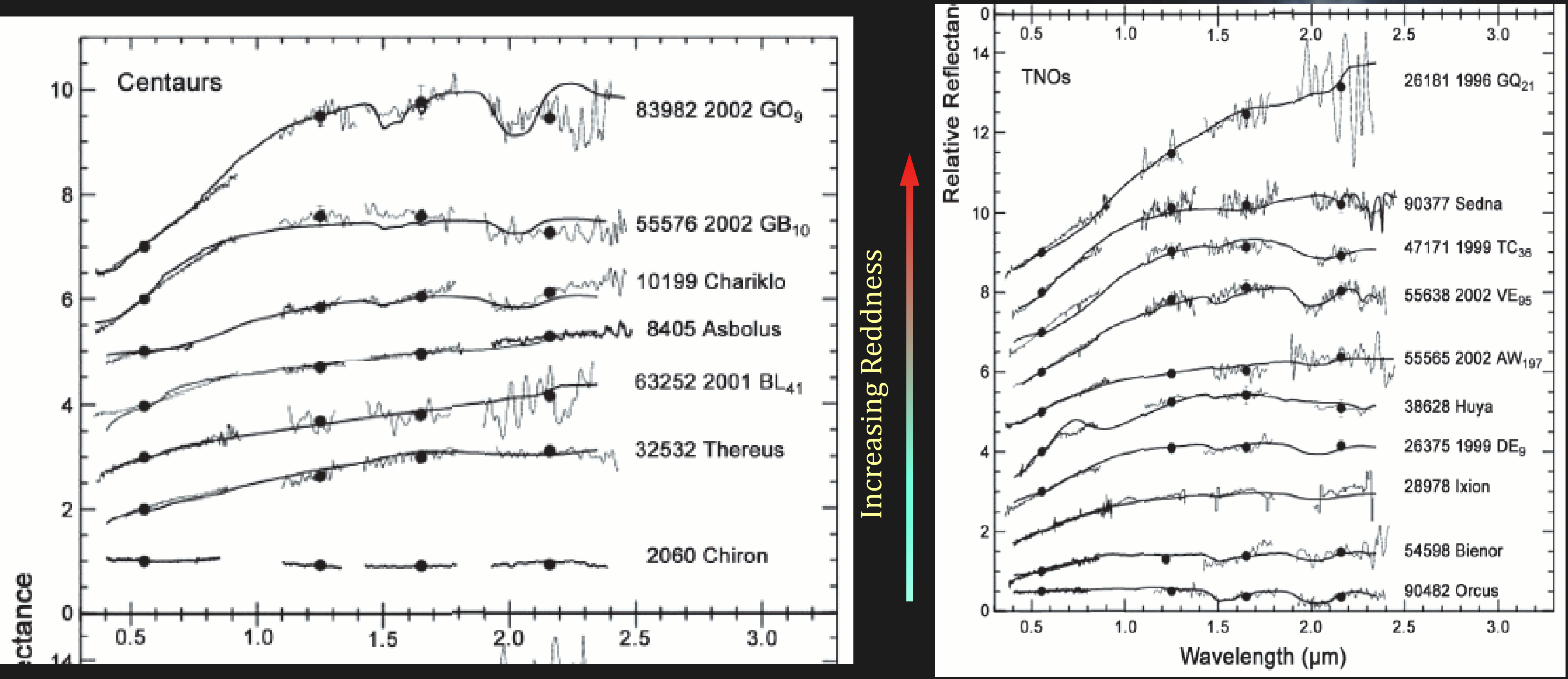


Averaged photometric spectra for various classes of objects.

Still not very revealing…

Hainaut et al., 2015

In Search of the "Red Stuff" – nIR Spectra



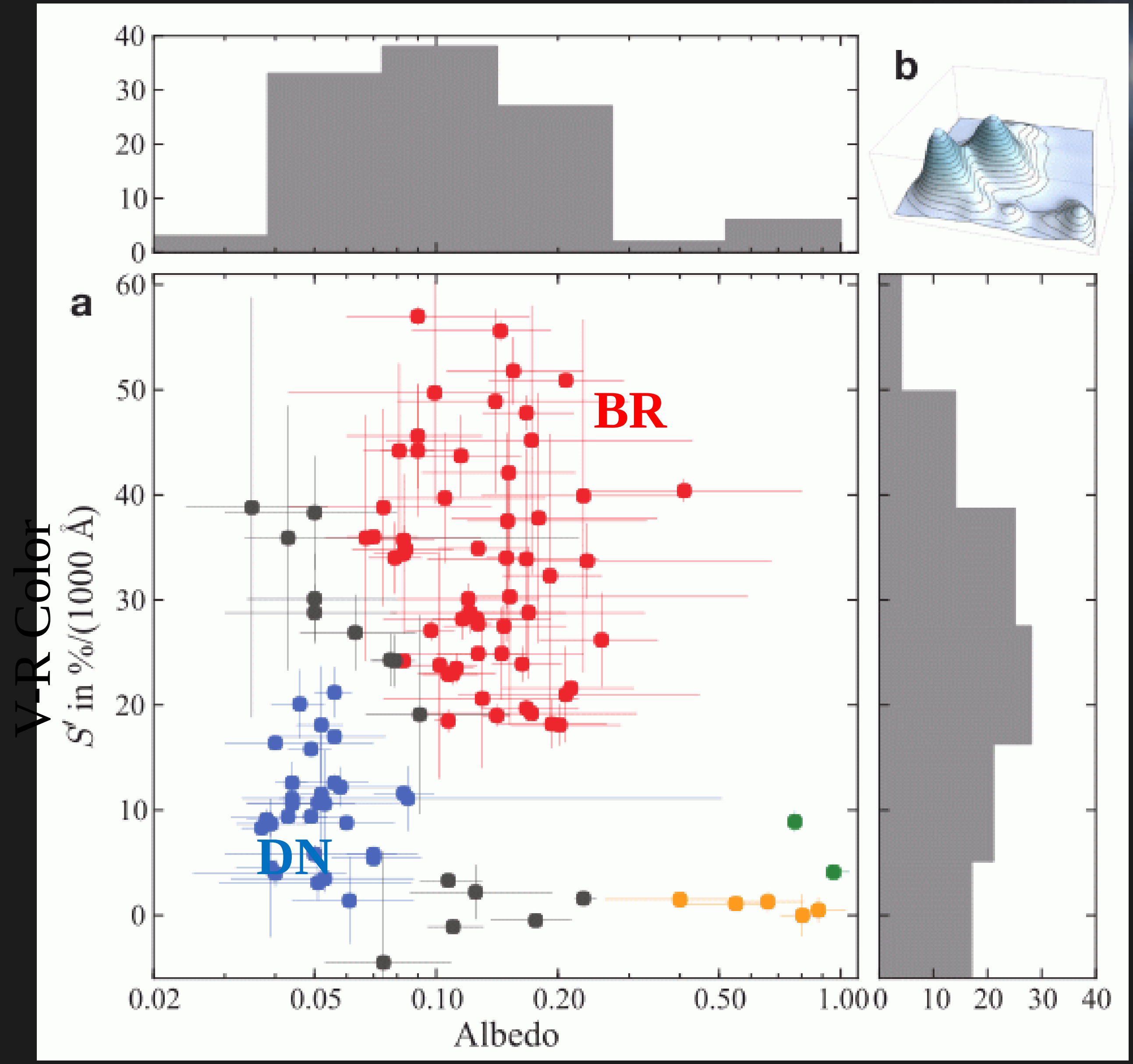
Barucci et al. 2008, SSBN

Spectra of TNOs are still fairly rare, typically low SNR and resolution.

Still not very revealing… What is the red stuff?

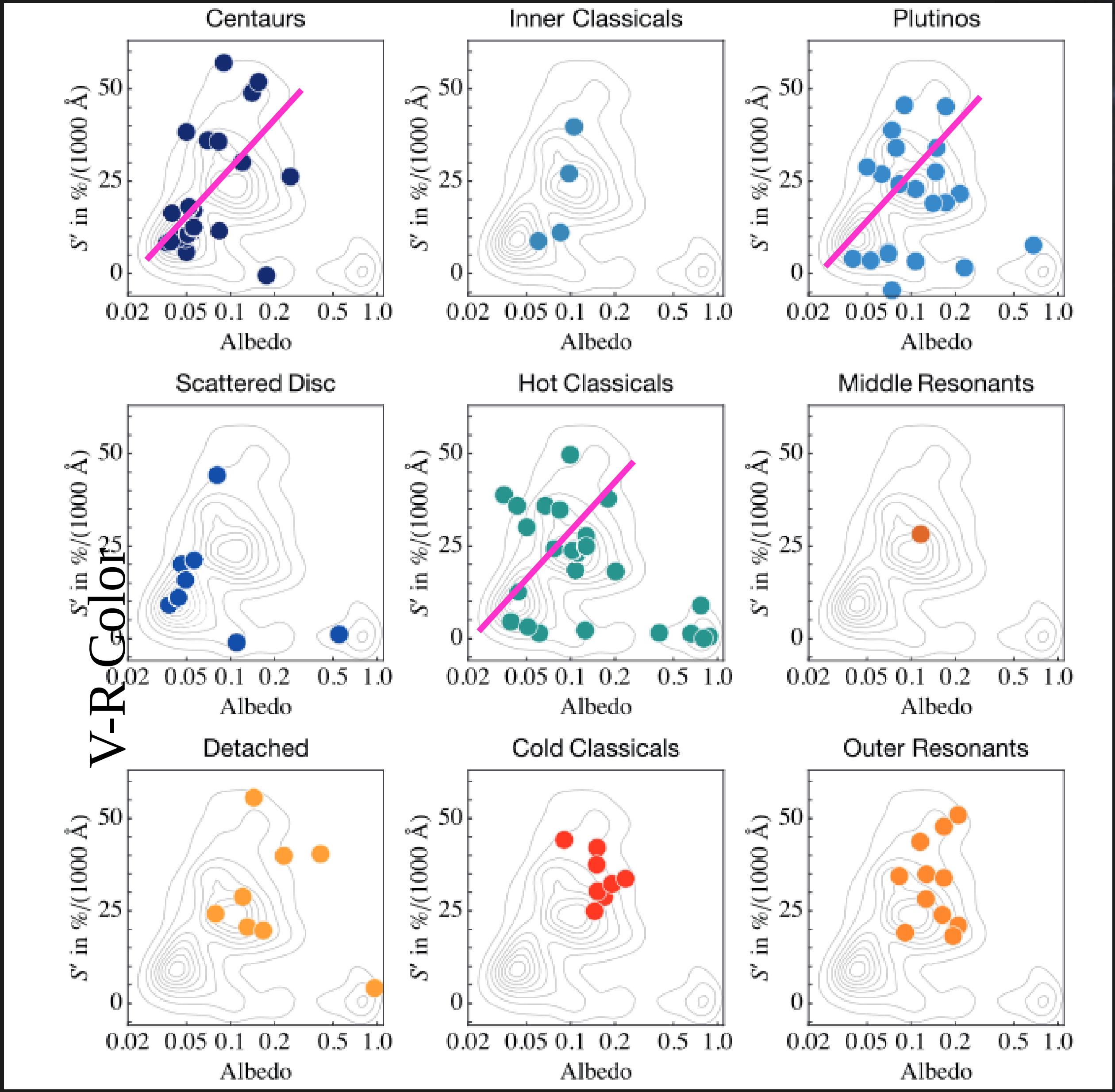
For more spectra / composition info, see e.g.:
Guilbert et al. 2009
Barucci et al. 2011 (very nice summary of ESO/VLT and other spectra)
recent papers by Brown &/or Fraser

TNO Color vs Albedo



Lacerda et al., 2015

TNO Color & Albedo vs. Dynamical Class

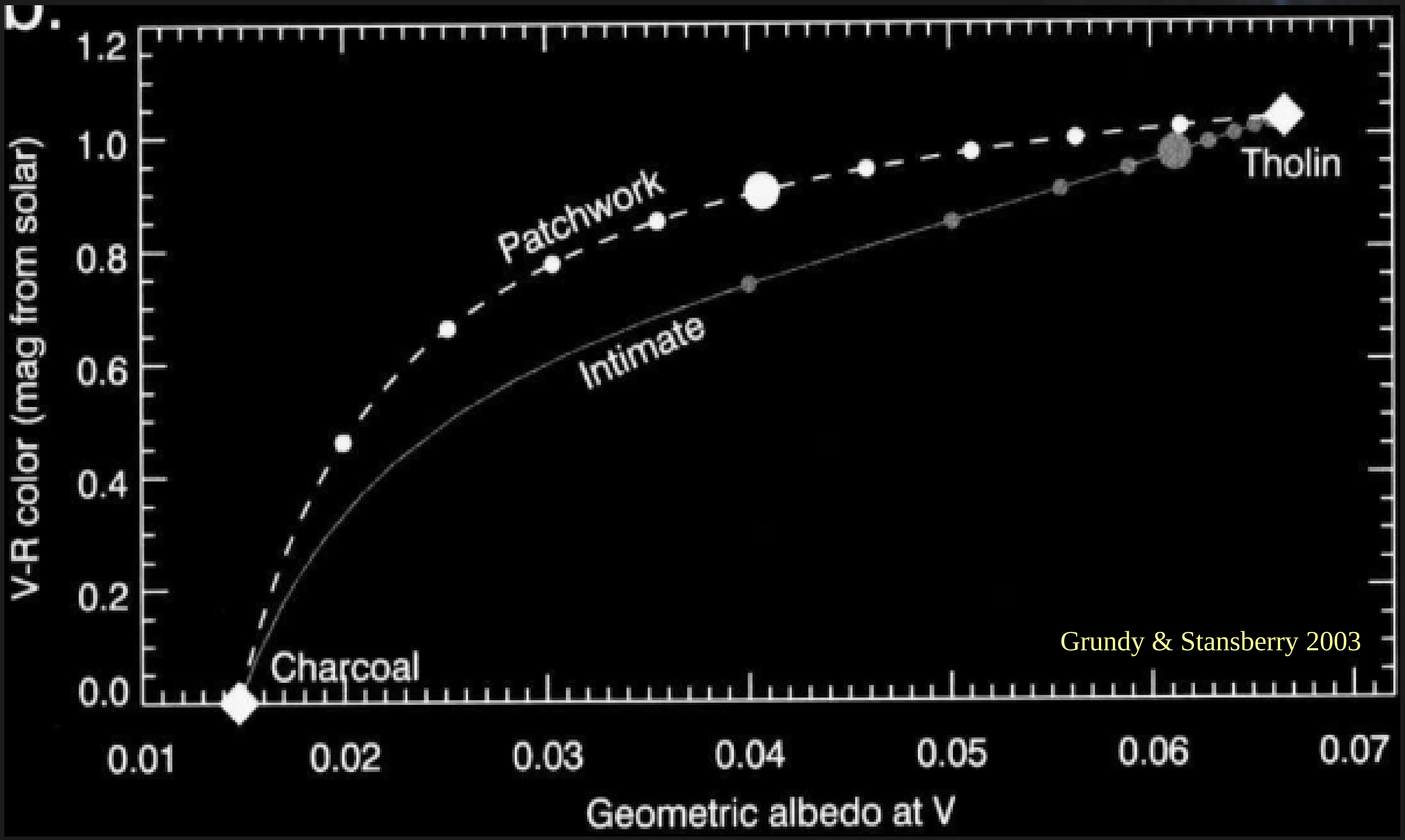


Color and albedo are correlated for TNOs in general, and within some dynamical groups

Lacerda et al., 2015

TNO Albedo-Color correlation means… ?

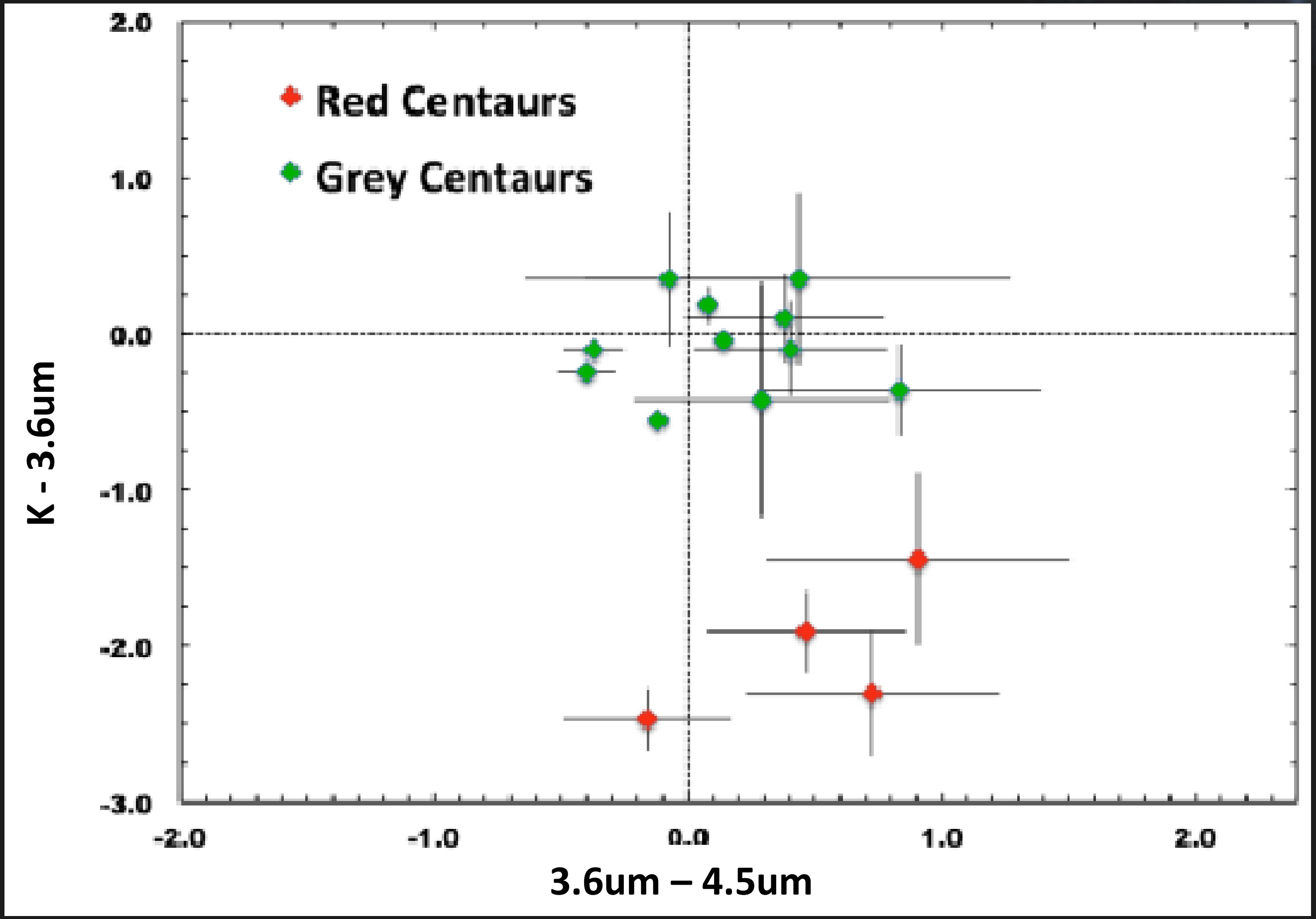
- One answer – nothing very profound
  - Mixtures of dark-gray stuff and more reflective red stuff naturally show the same correlation
  - However – dark-red stuff and more reflective gray stuff doesn't work.



TNO Albedo-Color correlation means… ?

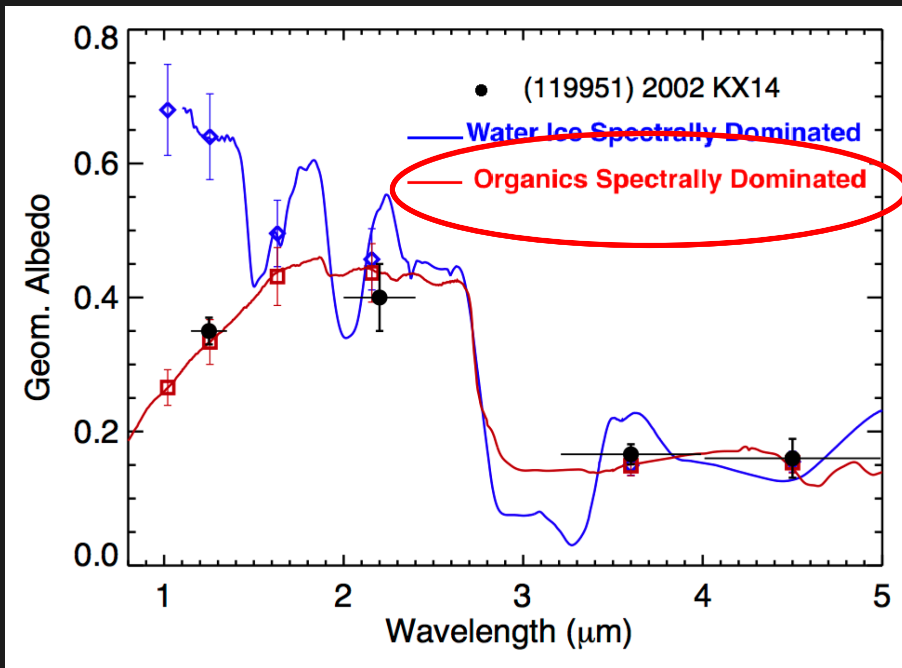
Figure courtesy of N. Pinilla-Alonso, *in prep.*

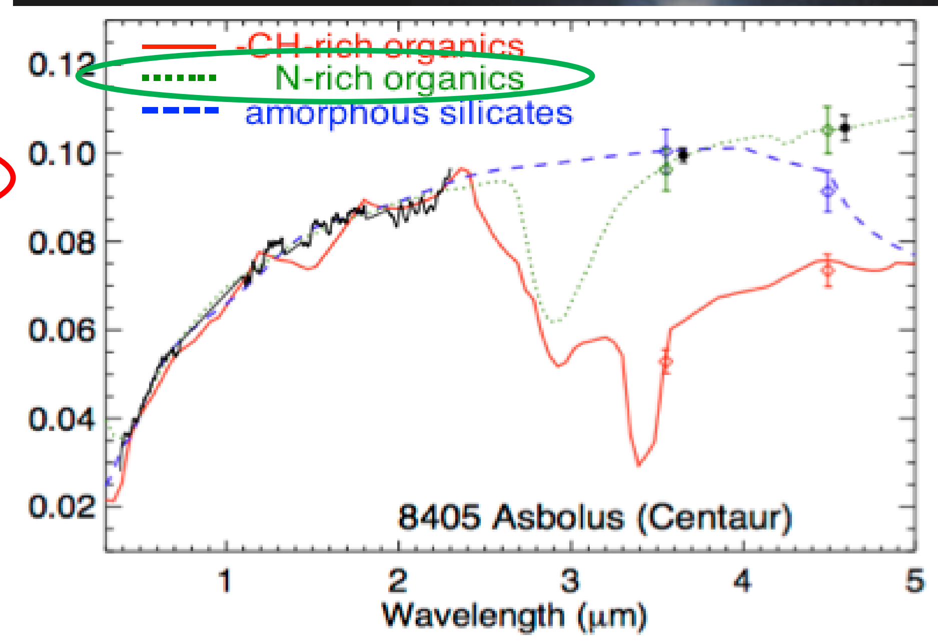
- Another answer…. ***Something Profound!***
  - *Spitzer* 3.6 & 4.5 micron data show red objects also have strong absorptions at those wavelengths



Spitzer/IRAC Composition Constraints

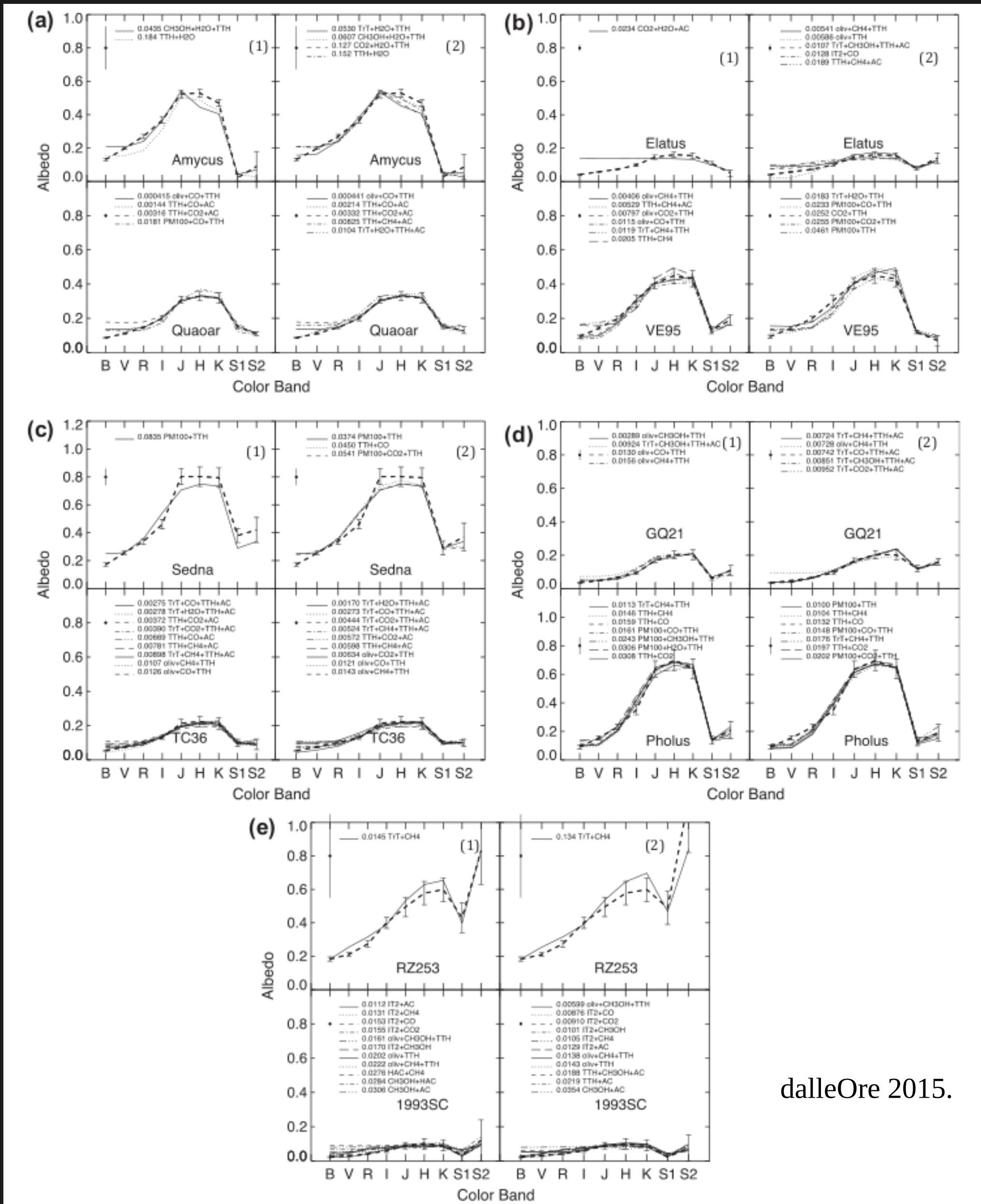
Figures courtesy of N. Pinilla-Alonso, *in prep.*





- IRAC 3.6 & 4.5 micron photometry + vis & nIR
  - Silicates, H2O, different kinds of organics can be differentiated
  - Molecular ices can as well (N2, CO, CO2, CH4)

Spitzer/IRAC: K/3.6/4.5 Composition Map

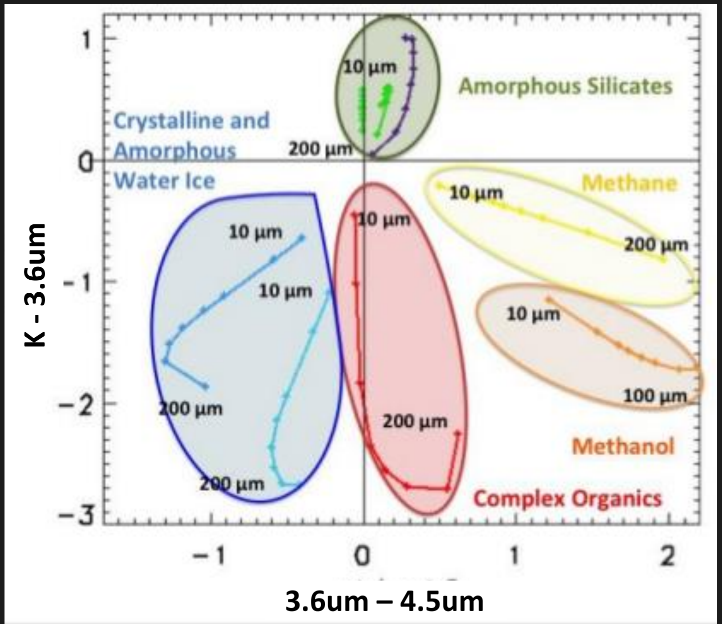


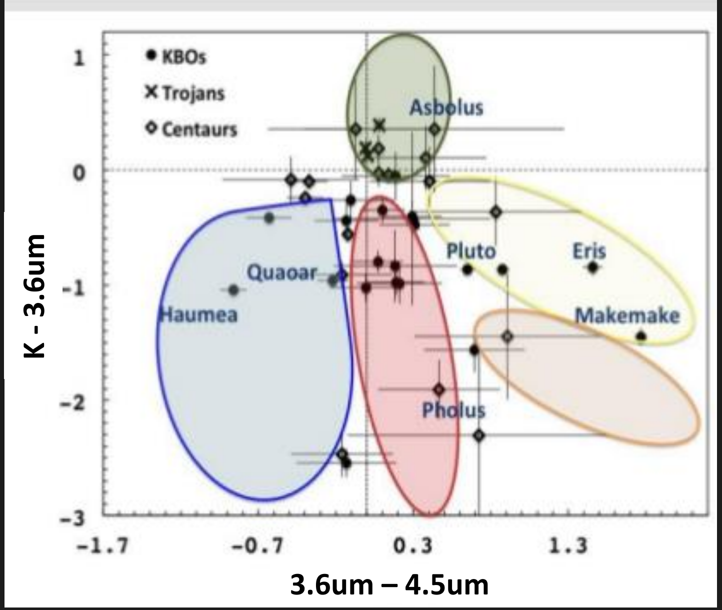
dalleOre 2015.

Many TNOs and Centaurs exhibit absorptions > 2.5 microns.

There is almost no spectroscopic data at those wavelengths (Pluto, Triton)…

Spitzer/IRAC: K/3.6/4.5 Composition Map

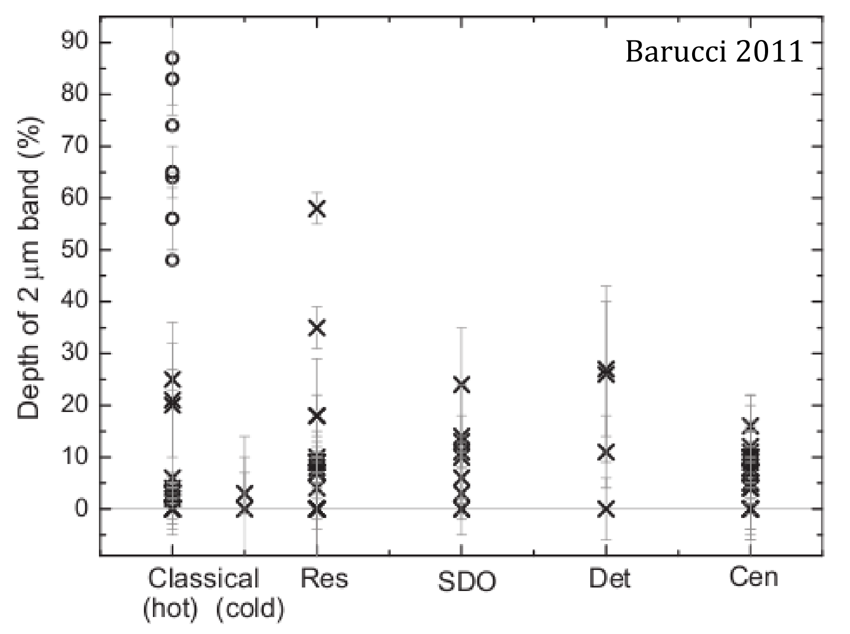


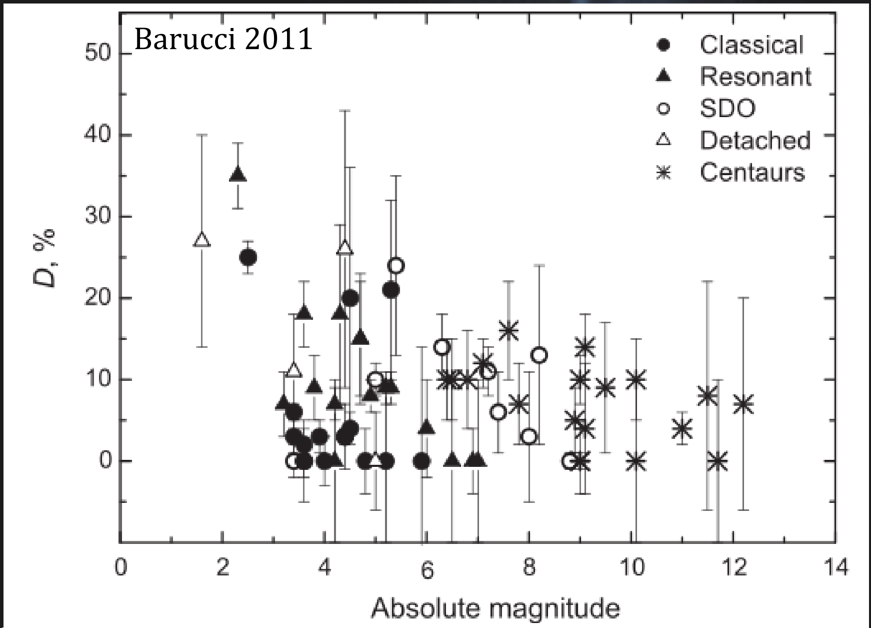


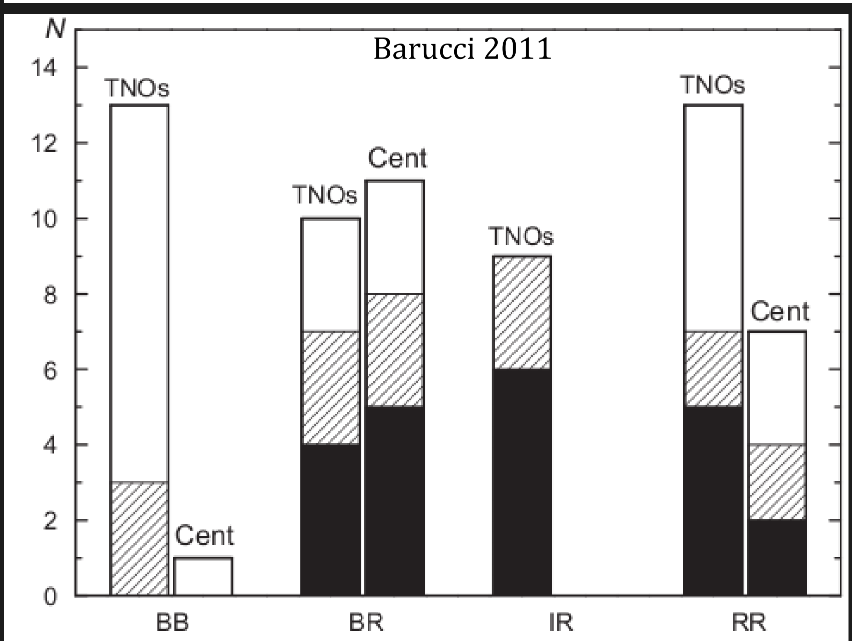
Figures courtesy of N. Pinilla-Alonso, *in prep*.
See also dalleOre 2015.

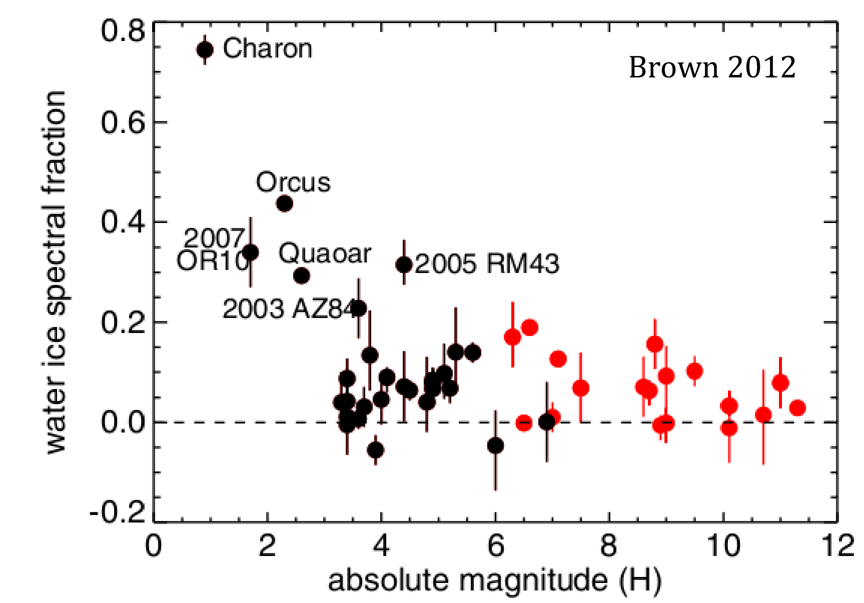
- Ice components map into unique regions in K + IRAC color/color space
- Much more Spitzer data available
  - ~50 KBOs + Centaurs w/ decent IRAC colors

Water Ice on TNOs









TNOs Composition Catalog

Table 4
List of the objects for which near-infrared spectral observations are available. In the last column the ice detection is reported (Y for "sure detection", T for "tentati
and N for "no detection"). H_2Ovar means that the presence of water ice is varialble on the object surface.

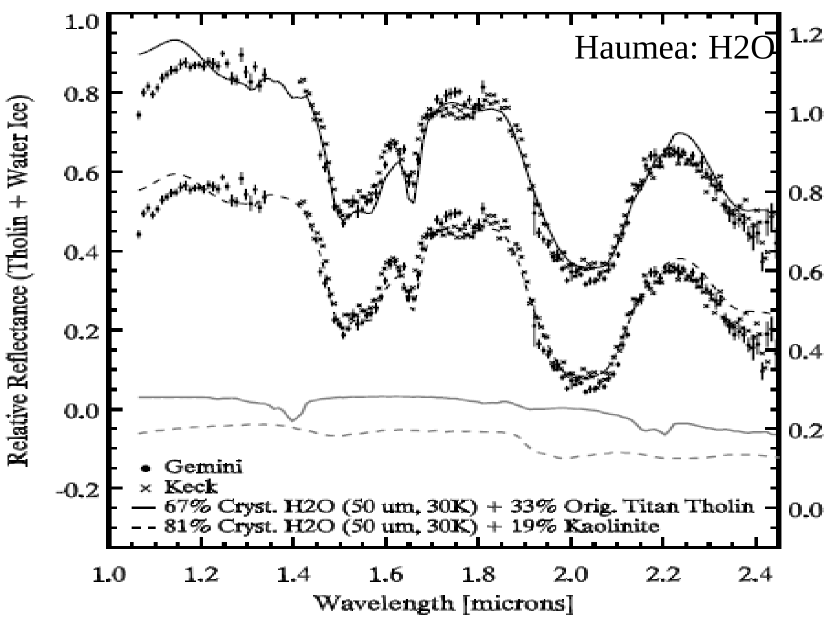
Table 4 (*continued*)

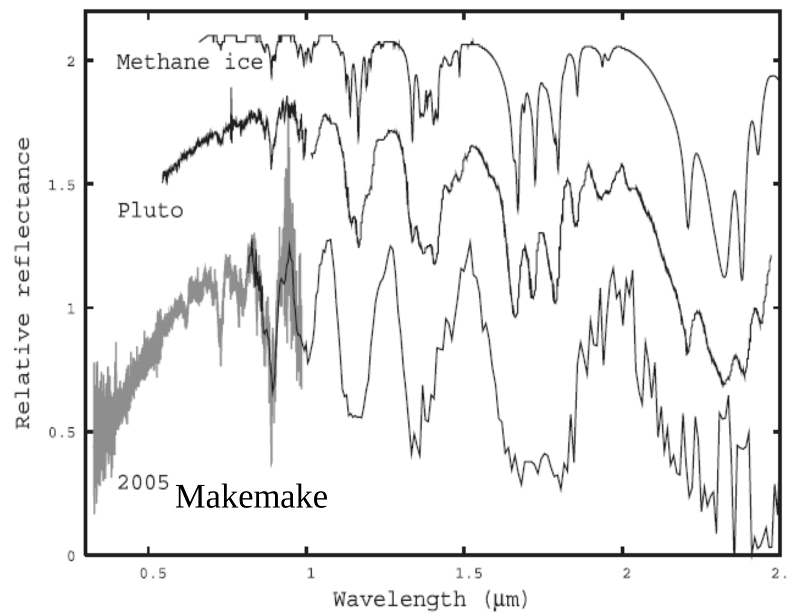
N	Object	Type	Class	H	Ices	D (%)	σ_D	Reference	Ice detection
1	2060 Chiron	Cen	BB	6.5	H_2Ovar	~5		Fos99	Y
						10		Lu00	
						+		Br00a	
						0		Ro03	
2	5145 Pholus	Cen	RR	7.1	H_2O, CH_3OH	12	3	Cr98	Y
						13		Br00a	
						13	12	LP-this paper	
3	8405 Asbolus	Cen	BR	9.0	None	0		Ba00	N
						0		Br00a, Ro02	
						<0	1	Bark08	
4	10199 Chariklo	Cen	BR	6.4	H_2Ovar	~10		BrK98	Y
						+		Br00a	
						7–14		Dot03b	
						<0		LP-Gu09b	
5	15789 1993 SC	3:2	RR	7.0	None?	0	10	Je01	N
6	15874 1996 TL_{66}	SDO	BB	5.4	H_2O	<20		Lu98	T
						24	11	LP-Gu09a	
						20	19	LP-this paper	
7	15875 1996 TP_{66}	3:2	RR	6.9	None	<0	4	Bark08	N
8	19308 1996 TO_{66}[a]	Cl	BB	4.5	H_2O	65	5	Br99	Y
9	19521 Chaos	Cl	IR	4.8	None	<0	4	Bark08	N
10	20000 Varuna	Cl	IR	3.6	None?	+		Li01	N
						<0	2	Bark08	
11	24835 1995 SM_{55}[a]	Cl	BB	4.8	H_2O	56	6	Bark08	Y
12	26181 1996 GQ_{21}	11:2	RR	5.2	H_2O	9	2	Bark08	Y
					CH_3OH?				
13	26375 1999 DE_9	5:2	IR	4.7	H_2Ovar?	~10		Je01	T
						15	8	Alv07	
						<0	2	Bark08	
						<0		LP-Gu09a	
						+		LP-Me10a	
14	28978 Ixion	3:2	IR	3.2	H_2O	6	4	Bark08	T
						7	4	LP-Gu09a	
15	29981 1999 TD_{10}	SDO	BR	8.8	None	<0	0	Bark08	N
16	31824 Elatus	Cen	RR	10.1	H_2Ovar	+		Bau02	Y
17	32532 Thereus	Cen	BR	9.0	H_2Ovar	+		Ba02, Me05	Y
						+		Li05	
						10	3	LP-Gu09a	
18	33340 1998 VG_{44}	3:2	IR	6.5	None?	<0	10	Bark08	N
19	38628 Huya	3:2	IR	4.7	H_2Ovar	+		Li01	T
	2000 EB_{173}					<7		Br00c	
						+		dB04	
						15	7	Alv07	
						<0	2	Bark08	
20	42301 2001 UR_{163}	9:4	RR	4.2	None?	0	10	Bark08	N
21	42355 Typhon	SDO	BR	7.2	H_2O	14	7	Alv10	Y
						11	3	LP-Gu09a	
22	44594 1999 OX_3	SDO	RR	7.4	H_2O?	6	5	LP-this paper	T
23	47171 1999 TC_{36}	3:2	RR	4.9	H_2Ovar	+		Dot03a, Me05	Y
						8	2	Bark08	
						4	3	LP-Gu09a, LP-Pr09	
24	47932 2000 GN_{171}	3:2	IR	6.0	None?	<0	16	dB04, Alv07	N
						<0		Bark08	
						4	6	LP-Gu09a	
25	50000 Quaoar	Cl	RR	2.5	H_2O, CH_4, NH_3, C_2H_6?	22	1	Je04	Y
						25	2	LP-Gu09a	
								Sch07, Da09	
26	52872 Okyrhoe	JC	BR	11.0	None?	+		Dot03a	T
						4	2	Bark08	
						2	2	LP-DM10a	
27	54598 Bienor	Cen	BR	7.6	H_2O	+		Dot03a	Y
						4	2	Bark08	
						16	6	LP-Gu09a	
28	55565 2002 AW_{197}	Cl	IR	3.4	None?	+		Dor05	N
						3	2	Bark08	
						3	7	LP-Gu09a	
29	55576 Amycus	Cen	RR	7.8	H_2O	+		Dor05	T
						7	5	LP-this paper	
30	55636 2002 TX_{300}[a]	Cl	BB	3.3	H_2O	67	10	Li06b	Y
						64	1	Bark08	
31	55637 2002 UX_{25}	Cl	IR	3.6	None?	2	2	Bark08	N
						12	14	LP-this paper	
32	55638 2002 VE_{95}	3:2	RR	5.3	H_2O, CH_3OH?	5	4	Ba06	Y
						9	2	Bark08	
						11	6	LP-Ba11	
33	60558 Echeclus	JC	BR	9.0	None	<0		LP-Gu09a	N
34	63252 2001 BL_{41}	Cen	BR	11.7	None?	–		Dor03	N
35	65489 Ceto	SDO	–	6.3	H_2O	14	4	Bark08	Y
36	66652 1999 RZ_{253}	Cl	RR	5.9	None?	<0	14	Bark08	N
37	73480 2002 PN_{34}	SDO	BR	8.2	H_2O	13	11	LP-DM10a	T
38	79360 1997 CS_{29}	Cl	RR	5.2	None?	0	10	Gr05	N
39	83982 Crantor	Cen	RR	9.1	H_2O	13		Dor05	Y
						14	4	Alv07	
						11	1	Bark08	
						6	4	LP-Gu09a	
40	84522 2002 TC_{302}	5:2	–	3.8	H_2O	9	4	Bark08	T
41	84922 2003 VS_2	3:2	–	4.2	H_2O	7	2	Bark08	Y
42	90377 Sedna	Det	RR	1.6	H_2O, CH_4, N_2	+		Ba05a, Tr05	Y
						27	13	LP-Ba10	
43	90482 Orcus	3:2	BB	2.3	H_2O, NH_3?	30		Fo04	Y
						+		Tr05, dB05	
						30	3	LP-Gu09a,	
						25	5	LP-Ba08	
						35	4	Del10	
								LP-DM10a	
44	90568 2004 GV_9	Cl	BR	4.0	None	0	3	LP-Gu09a	N
45	95626 2002 GZ_{32}	Cen	BR	6.8	H_2Ovar?	<0	2	Bark08	T
						10	6	LP-this paper	
46	119951 2002 KX_{14}	Cl	RR-IR[b]	4.4	None	<0	12	Bark08	N
						3	4	LP-Gu09a	
47	120061 2003 CO_1	Cen	BR[b]	8.9	None?	5	4	LP-this paper	T
48	120132 2003 FY_{128}	Det	BR	5.0	None?	7	16	Bark08	N
						<0		LP-Gu09a	
49	120178 2003 OP_{32}[a]	Cl	BB[b]	4.1	H_2O	74	0	Bark08	Y
50	120348 2004 TY_{364}	Cl	–	4.5	H_2O	4	2	Bark08	T
						6	5	LP-this paper	
51	127546 2002 XU_{93}	SDO	–	8.0	None?	3	8	Bark08	N
52	134340 Pluto	3:2	BR	−0.7	CH_4, CO, N_2, C_2H_6?			Ow93, DM10b, Me10b	Y
53	136108 Haumea[a]	Cl	BB	0.2	H_2O	+		Tr07, Me07	Y
						48	0	Bark08	
54	136199 Eris	Det	BB	−1.2	CH_4, N_2			Br05, Me09	Y
55	136472 Makemake	Cl	BR[b]	−0.3	CH_4			Li06a, Br07,Bark08	Y
56	144897 2004 UX_{10}	Cl	BR	4.5	H_2O?	6	10	LP-this paper	T
						20	16		
57	145451 2005 RM_{43}	Det	BB	4.4	H_2O	26	17	LP-this paper	T
58	145452 2005 RN_{43}	Cl	RR-IR[b]	3.9	None?	3	2	Bark08	N
						1	3	LP-Gu09a	
59	145453 2005 RR_{43}[a]	Cl	BB	4.0	H_2O	83	5	PA07	Y
						65	2	Bark08	
						74	13	LP-this paper	
60	174567 2003 MW_{12}	Cl	–	3.6	None?	<0	5	LP-this paper	N
61	202421 2005 UQ_{513}		–	3.4	H_2O	6	1	Bark08	Y
62	208996 2003 AZ_{84}	3:2	BB	3.6	H_2O	18	4	Bark08	Y
						17	6	LP-Gu09a	
						17	13	LP-this paper	
63	229762 2007 UK_{126}	Det	–	3.4	H_2O	11	7	LP-this paper	T
64	250112 2002 KY_{14}	Cen	RR	9.5	H_2O	9	8	LP-this paper	T
65	2003 QW_{90}	Cl	RR[b]	5.3	H_2O	21	11	LP-Gu09a	T
66	2003 UZ_{413}	3:2	BB	4.3	H_2O	18	11	LP-this paper	T
67	2004 NT_{33}	Cl	–	4.4	None?	3	1	Bark08	N
68	2004 PG_{115}	SDO	–	5.0	H_2O	10	2	Bark08	Y
69	2005 QU_{182}	SDO	–	3.4	None	<0	2	Bark08	N
70	2007 UM_{126}	Cen	BR	10.1	None?	<0	10	LP-this paper	N
71	2007 VH_{305}	Cen	BR	11.5	None?	8	14	LP-this paper	N
72	2008 FC_{76}	Cen	RR	9.1	None?	4	8	LP-this paper	N
73	2008 SJ_{236}	Cen	RR	12.2	None?	7	13	LP-this paper	N
74	Charon	3:2		0.9	H_2O, NH_3	58	3	Br00b, Me10a	Y
75	Hi'iaka[a]	Cl			H_2O	87	11	Bark06	Y

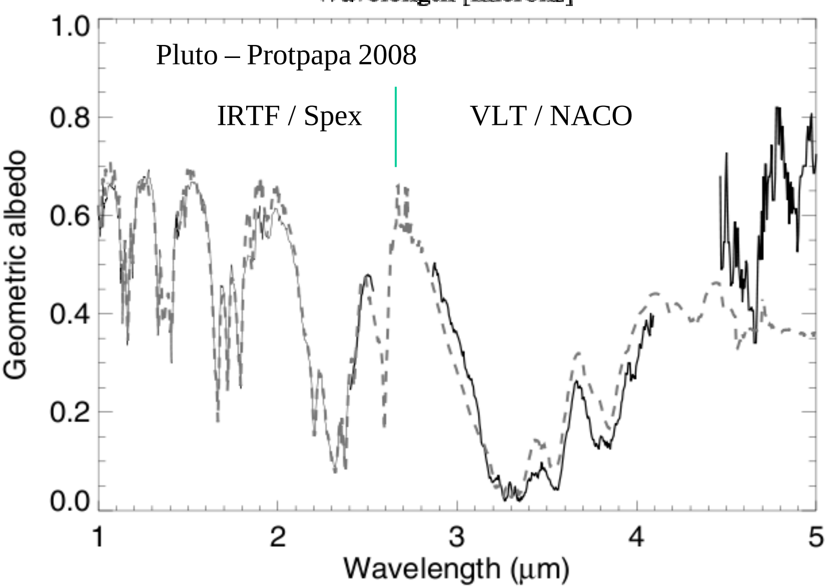
Barucci 2011

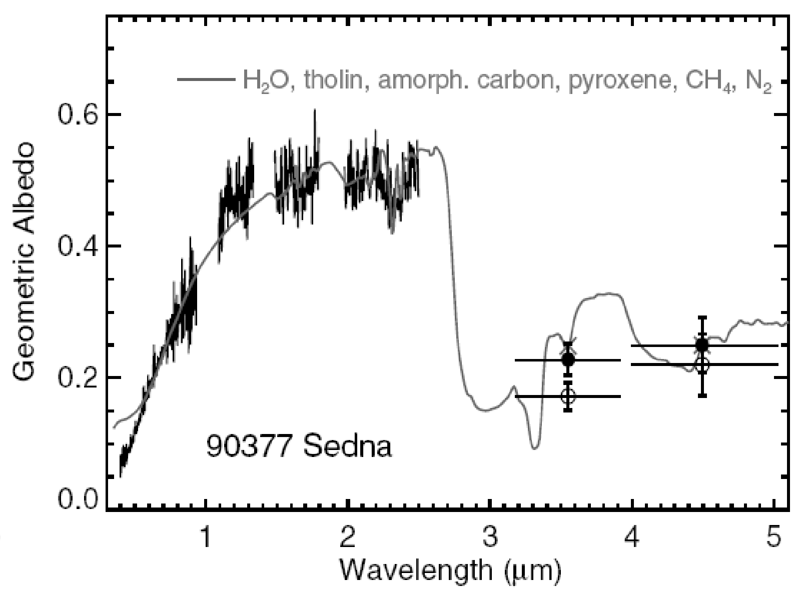
~75 (< 100 today?) TNOs with 'good' nIR spectra.
There are more objects with measured albedos and diameters than there are with IR spectra…

TNO Dwarf Planets – Spectra





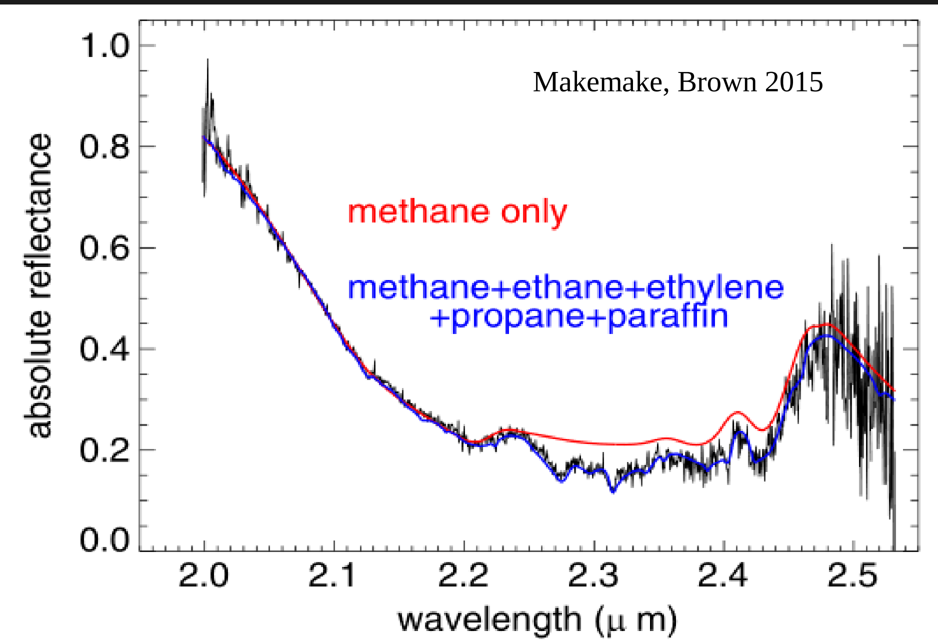


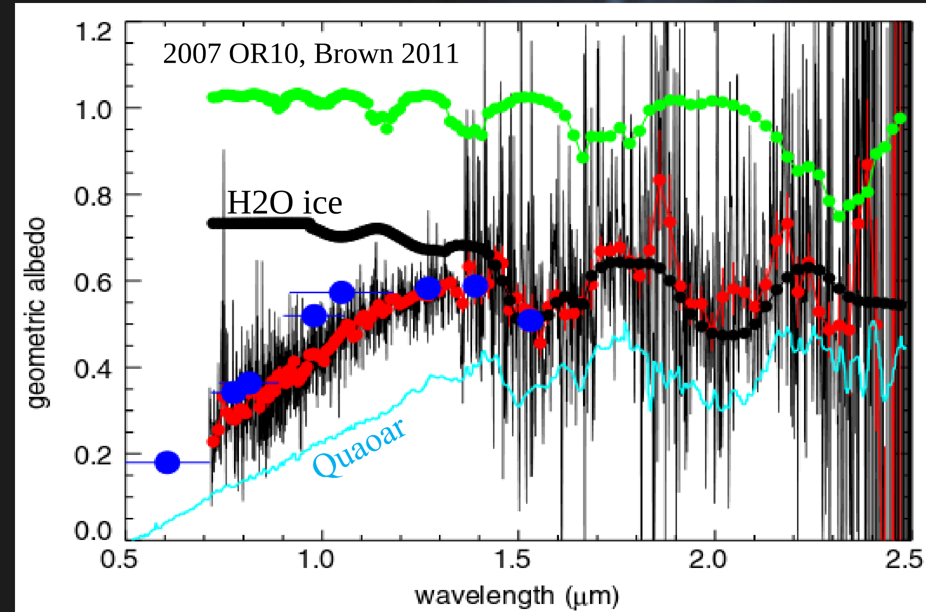


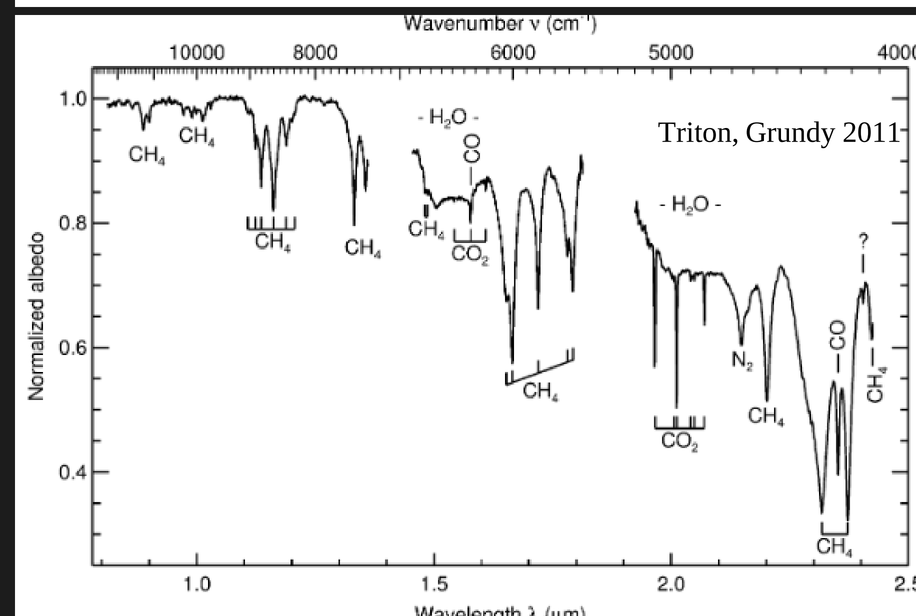
TNO Dwarf Planet spectra are dominated by molecular ices.

They, too, are red in the optical, probably due to organics (except Haumea?)

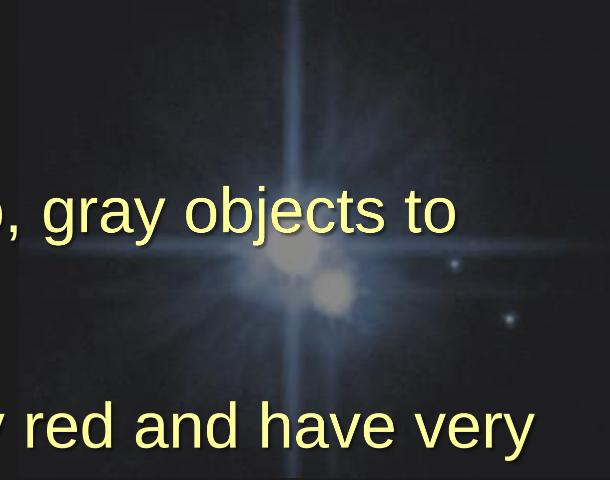
TNO Dwarf Planets – Spectra







TNO Composition



- Typical TNOs fall on a trend of low-albedo, gray objects to higher albedo red objects.
- TNO dwarf planets are gray to moderately red and have very high albedos.
  - Volatile ices are present on most (atmospheres, seasonal transport)
- Processed organics (tholins) are probably responsible for most of the redness.
  - Silicates may also play a role
- Spectroscopic data in the IR is still challenging to acquire and interpret.
  - Typically have low-SNR, low effective spectral resolution
- H_2O is the only unambiguously identified material identified on many TNOs.
  - Volatile molecular ices (CH_4, N_2, CO, CO_2) seen on the dwarf planets

What do TNOs Look Like?

In 2019 we will get one more (2014 MU69).

Next close-up views will be a long time coming…