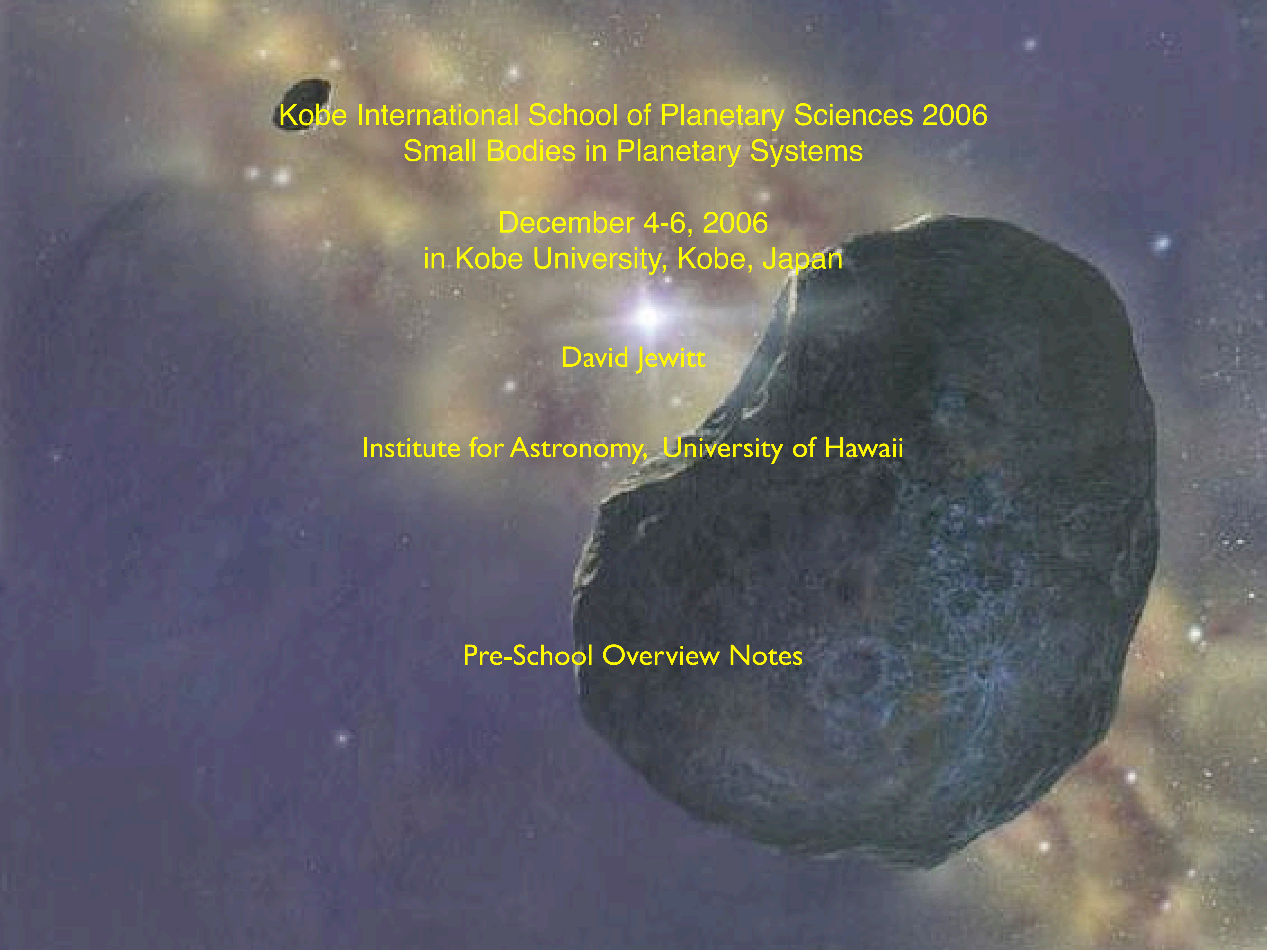


Kobe International School of Planetary Sciences 2006
Small Bodies in Planetary Systems

December 4-6, 2006
in Kobe University, Kobe, Japan

David Jewitt

Institute for Astronomy, University of Hawaii

Pre-School Overview Notes

Notes

• All good teachers know that Powerpoint slides are a terrible way to teach. The way to do a good job with teaching is to use a blackboard and to derive and calculate things in class. Powerpoint packs too much material in too small a space and time and encourages distracting images and visuals. Writing by hand on a blackboard keeps the lecturer at a more human speed. The act of taking notes embeds the material more deeply in the brain because it is, on the part of the students, active rather than passive. And we all know that bad lecturers use Powerpoint as a cover to hide the fact that they don't know what they are talking about. Watch out for that from me and the other lecturers!

• The disadvantage with writing on the blackboard is that it is very slow. In a graduate class this is not too bad but in a winter school like this one in Kobe, we could not cover enough material in the limited time alloted to the lectures. So, even though I don't like Powerpoint so much, I am forced to use it by the format of the Kobe winter school. You'll get a lot of pretty visuals from me and the other lecturers, but you probably won't get much deep understanding out of it.

• The main things you can get from a winter school like this are A) a broad but shallow perspective of a subject to help you see what is known and what is mysterious and B) some energy and motivation, when you see how little we know about this subject.

Notes - Part 2

- You can make the Kobe Planetary Winter School a success by talking and interacting with me and the other lecturers. Questions and discussion and arguments are STRONGLY encouraged. Sure, language is a problem, but we'll figure it out.

- The following slides were requested by the meeting organizers to provide reading material before the lectures begin. Whether or not I will use these notes in detail depends on how much time I have between today (Nov 17) and the start of the winter school. Probably, I will have no time, and so the lectures will follow the outline here, more or less.

-David Jewitt

Notes - Part 3

- In the last few years, I've spent a lot of time writing articles that try to capture the essence of the science areas I'm working on. This helps me to understand what I'm doing and what to do next. The resulting papers provide a pretty good and mostly up-to-date overview of the subject in the right kind of style for this School.

So, I encourage you to look at some of these papers before the Winter School starts. They are all on my www site:

http://www.ifa.hawaii.edu/faculty/jewitt/bib.html

as indicated on the next page.

Kobe Reading Material -1

D. Jewitt, S. Sheppard and J. Kleyna. (2006). The Strangest Satellites in the Solar System. Scientific American, August issue. [*This paper tries to explain why the irregular satellites matter, scientifically, for a general audience. The direct readership of Scientific American is about 600,000 (several million once you count people reading old copies). This is 10,000 to 100,000 times the number of people who would normally read one of my papers.*]

http://www.ifa.hawaii.edu/faculty/jewitt/papers/2006/JSK06.pdf

D. Jewitt (2006). Kuiper Belt and Comets: An Observational Perspective. Saas Fee Lectures 2005 (eds. N. Thomas and W. Benz), in press. *[This is for a Winter School in Switzerland a little bit like the one in Kobe, but colder]*

http://www.ifa.hawaii.edu/faculty/jewitt/papers/2006/J06b.pdf

D. Jewitt, L. Chizmadia, R. Grimm and D. Prialnik (2006). Water in Small Bodies of the Solar System. In Protostars and Planets V (eds. B. Reipurth, D. Jewitt and K. Keil), Univ. Az. Press, Tucson, in press. *[The aim here is to synthesize work on watery bodies in the astronomical, meteorite and thermal modeling communities].*

http://www.ifa.hawaii.edu/faculty/jewitt/papers/2006/JCGP06.pdf

A. Delsanti and D. Jewitt (2006). The Solar System Beyond the Planets. In Solar System Update, edited by Ph. Blondel and J. Mason, Springer-Praxis, Germany, pp. 267-294. *[This book aims to compete with Annual Reviews of Astronomy and Astrophysics with a planetary focus.]*

http://www.ifa.hawaii.edu/faculty/jewitt/papers/2006/DJ06.pdf

D. Jewitt and S. Sheppard (2005). Irregular Satellites in the Context of Giant Planet Formation. ISSI Conference on the Outer Solar System. Ed. R. Kallenbach, Space Sci. Rev. 116, 441-456. *[More Swiss-connection: this one sets out our belief that the standard models for irregular satellite capture lack supporting evidence]*

http://www.ifa.hawaii.edu/faculty/jewitt/papers/2005/JS2005.pdf

Kobe Reading Material -2

D. Jewitt (2005) . From Cradle to Grave: The Rise and Demise of the Comets. In COMETS II, edited by M. Festou, H. Weaver and U. Keller. Univ. Az. Press, Tucson. *[I got the title from a Jet Li (2003) movie that I particularly liked:* http://www.imdb.com/title/tt0306685/*. The movie is good and the chapter is better. Comets, dormant comets, dead comets,main-belt comets, asteroids, Trojans, Centaurs- what's the difference?]*

http://www.ifa.hawaii.edu/faculty/jewitt/papers/2005/J2005b.pdf

D. Jewitt, S. Sheppard and C. Porco (2004). Jupiter's Outer Satellites and Trojans. Invited review for JUPITER, edited by Fran Bagenal, Cambridge University Press, Cambridge. *[Attempt to paint the irregular satellites and the Trojans with the same brush, drawing close connections between the two].*

http://www.ifa.hawaii.edu/faculty/jewitt/papers/2004/JSP2004.pdf

D. Jewitt (2004). Project Pan-STARRS and the Outer Solar System. Earth, Moon and Planets, 92, 465-476. *[Early paper outlining the kinds of science Pan STARRS can do: Pan STARRS 1 is almost ready to start taking data on Haleakala, Maui]*

http://www.ifa.hawaii.edu/faculty/jewitt/papers/2004/J2004.pdf

J. Luu and D. Jewitt (2002). Kuiper Belt. Annual Reviews of Astronomy and Astrophysics, 40, 63-101. *[Overview of the Kuiper belt for astronomers.]*

http://www.ifa.hawaii.edu/faculty/jewitt/papers/2002/LJ02.pdf

Main Difficulty for Me: Language

Main Difficulty for Me: Language

Main Difficulty for You: Language

Main Difficulty for Me: Language

Main Difficulty for You: Language

Please do ask questions to make sure we do not diverge!

WE NEED AN ICE BREAKER:

Letter of Introduction from my Japanese colleague in Hawaii

ジューイット博士について

- 彼はたった今、多大なプレッシャーを感じています。
- しかもどうやら時差で苦しんでいるようです。
- 肉食系の彼は日本では生魚を食べさせられるのではないかと、恐怖におののいています。
- そんな彼はとある人々に　狂人　だとさえいわれています。

こんなふつつか者の彼ですが、どうかよろしくお願いします。

The Way It Is

Observers: Provide the "dots" (data).

Ideal: Objective seekers of truth and reality, free from bias.

Reality: We tend to find only the dots we expect to find.
Many of the dots are irrelevant to the big picture.
Good measurements are really hard.
Many measurements are wrong, at least in detail and at first.

Modelers: Connect the dots.

Ideal: Provide inspiring syntheses of the data, make realistically testable predictions.

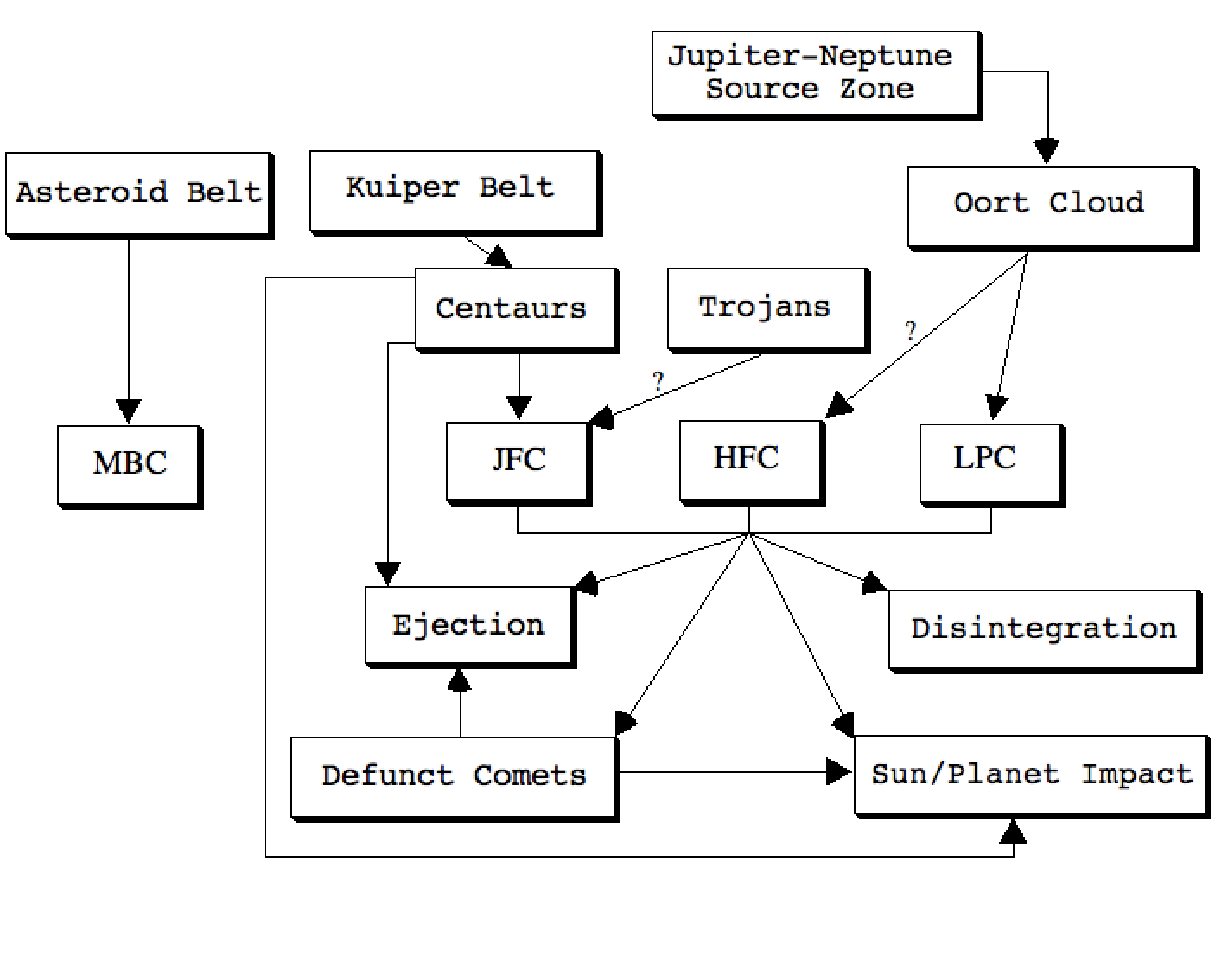
Reality: The number of free parameters exceeds the number of constraints.
Connecting the dots is possible in many ways, most or all of them wrong.
Significance of the models is routinely exaggerated by their creators.

Art by Michael Carroll

Background:

The Three Domains of the Solar System

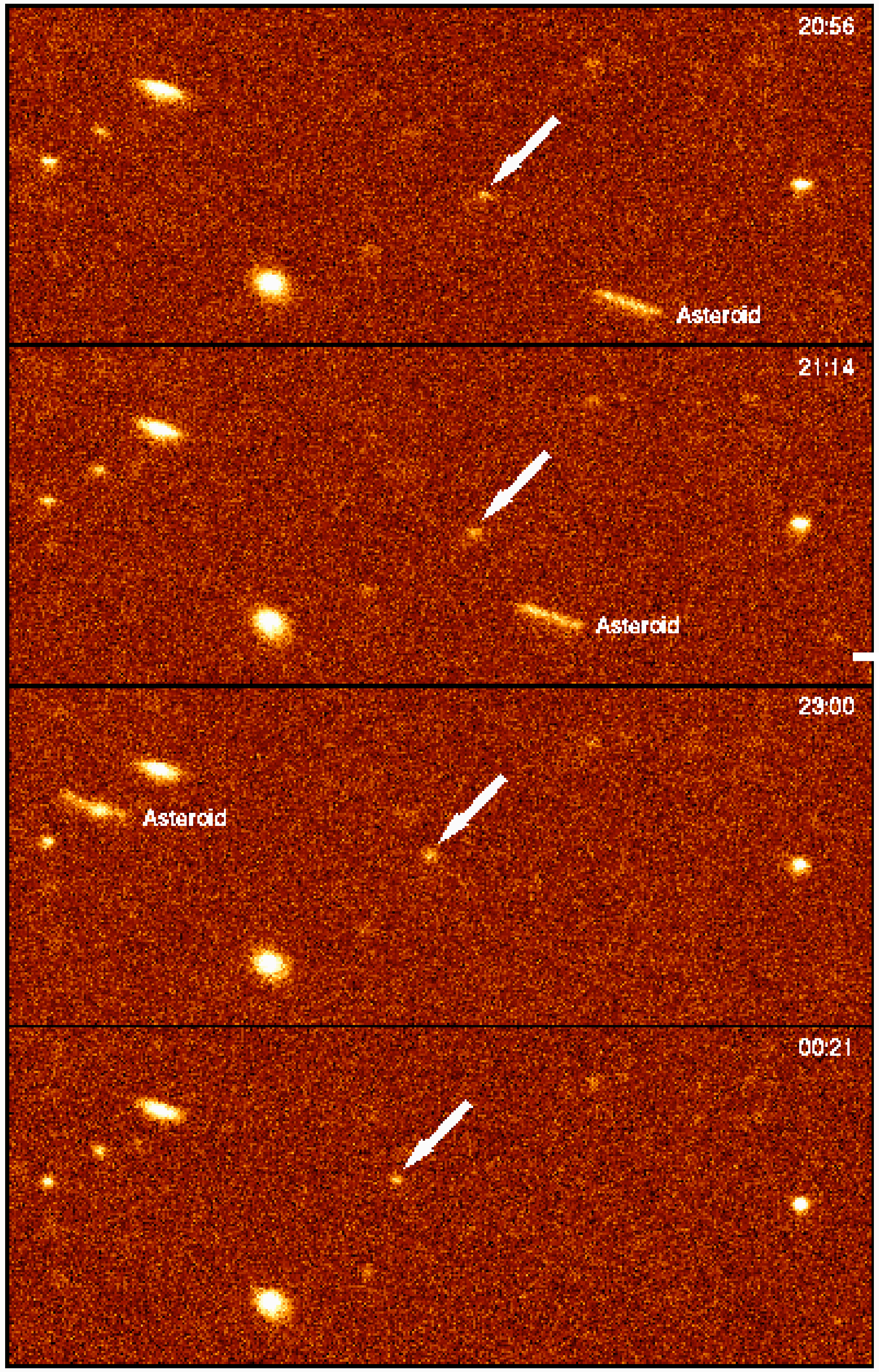
- Terrestrial planet domain (intensively studied and visited)
- Giant planet domain (exploration just beginning)
- Comet domain (only recently discovered, almost unexplored)


Jupiter-Neptune Source Zone
Asteroid Belt
Kuiper Belt
Oort Cloud
Centaurs
Trojans
?
?
MBC
JFC
HFC
LPC
Ejection
Disintegration
Defunct Comets
Sun/Planet Impact

Kuiper Belt: Major Mysteries

- Where did 99% of the mass go and when? (Dynamical erosion too small. Collisional grinding questionable. Other ways?)
- Is there a tie to the late-heavy bombardment? (Do craters record the clearing of the KB?)
- Origin of the color diversity? (how is color related to collisional processing, exogenic processes?)
- Which properties of the KBOs are primordial? (any?)
- From where in the KB are JF comets derived? (SKBOs? Chaotic zones near resonances? Other?)

Distribution of Orbits



Jewitt and Luu 1993

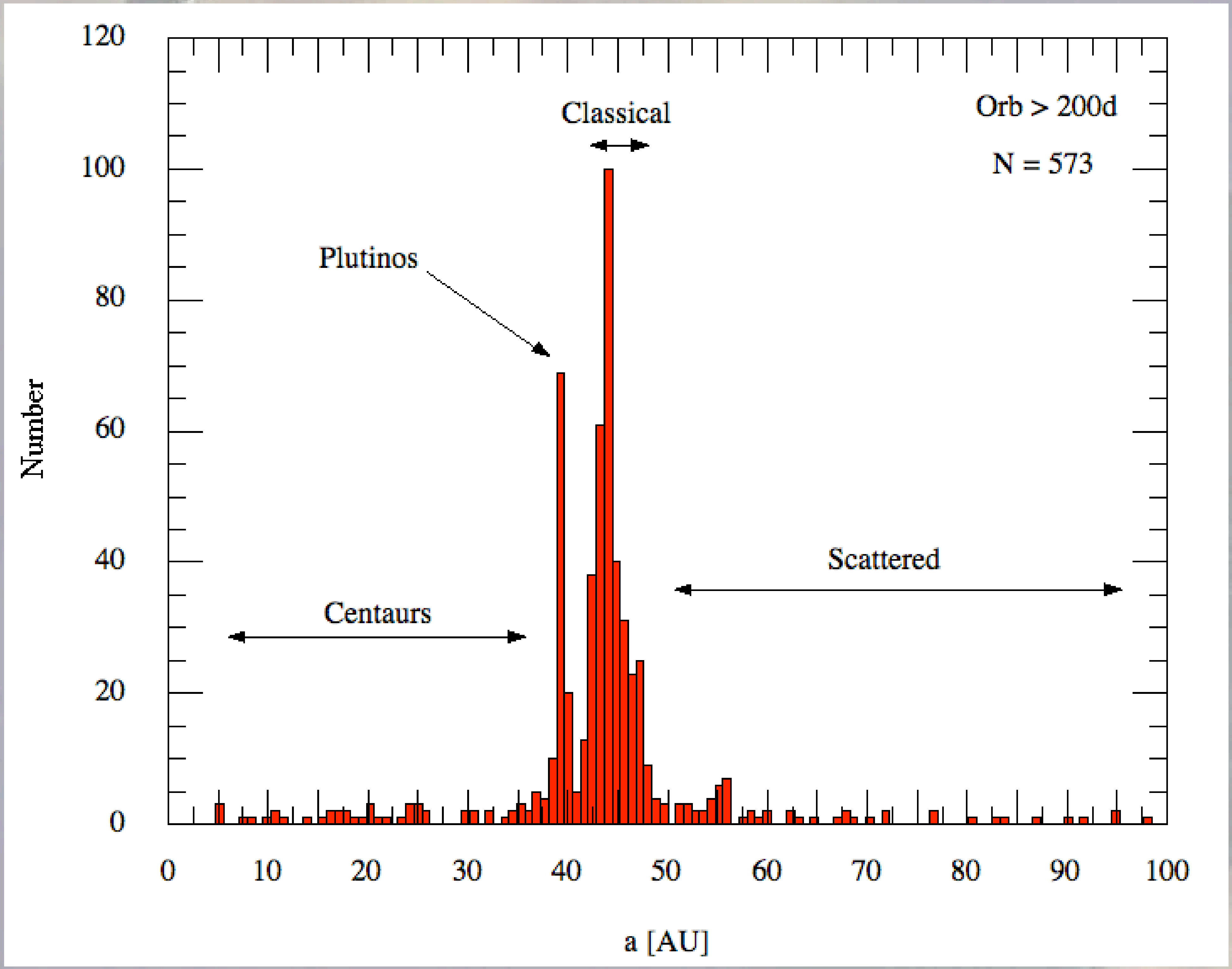
Text

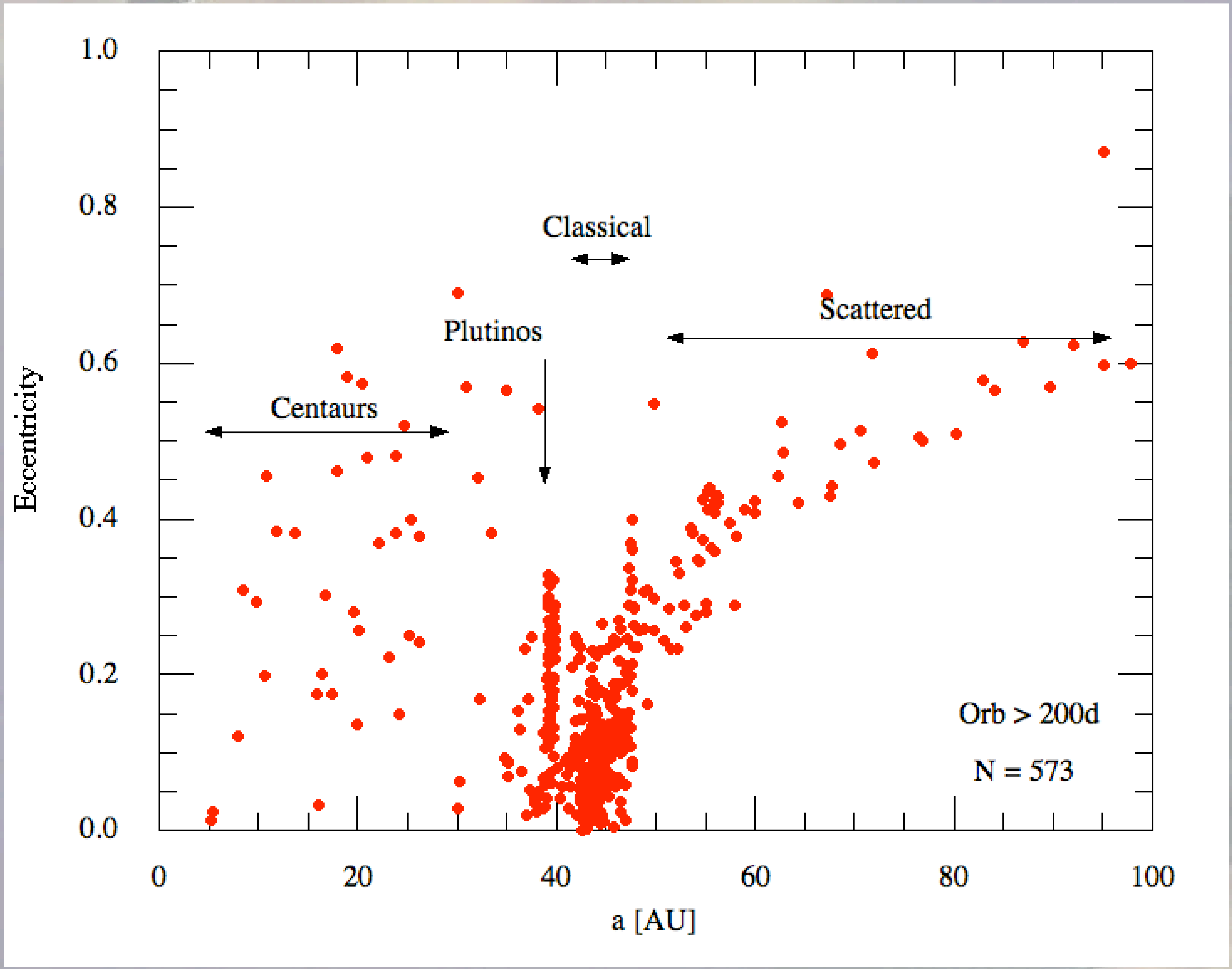
The Beginning

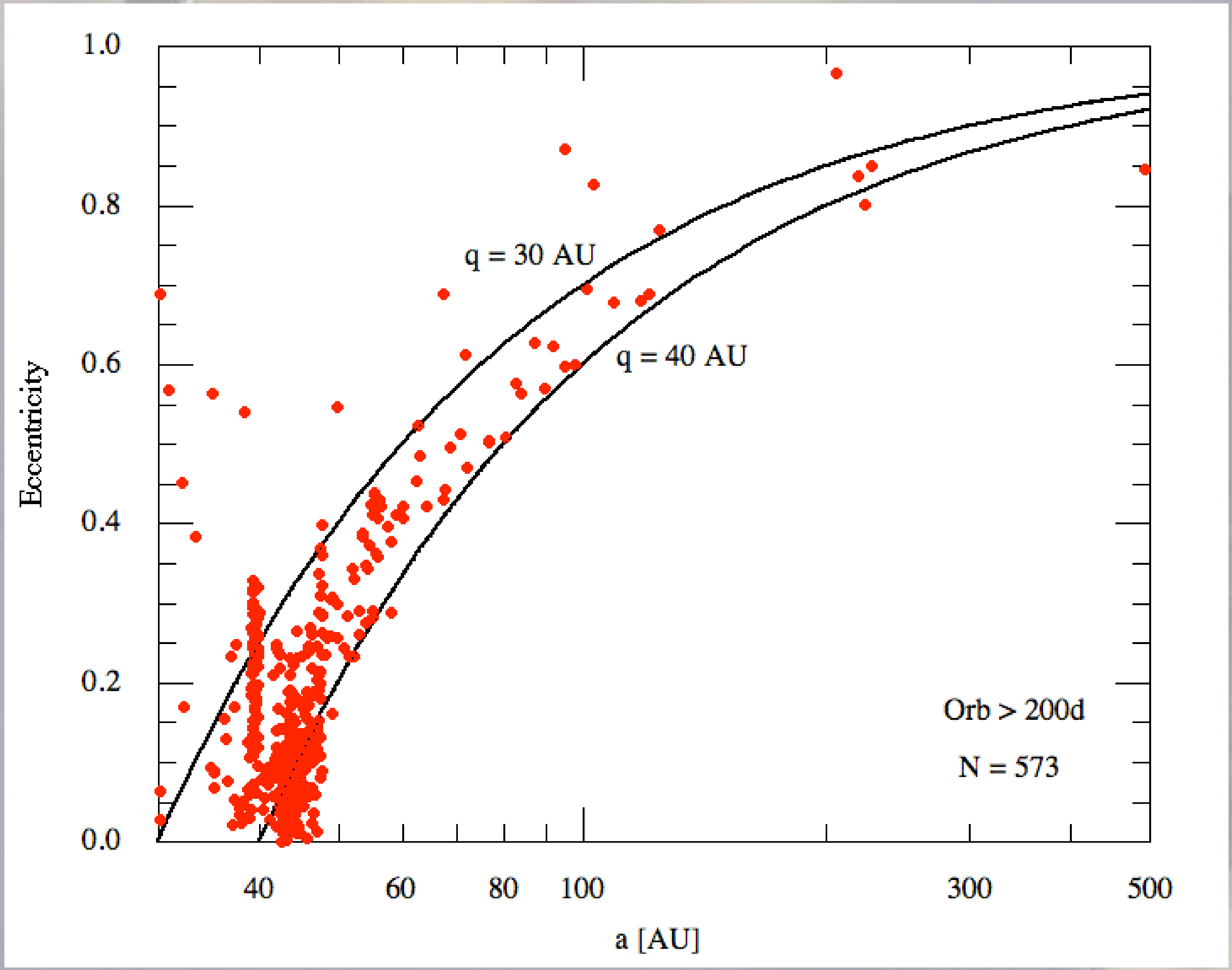
1992 QB1
R ~ 42 AU
D ~ 200 km

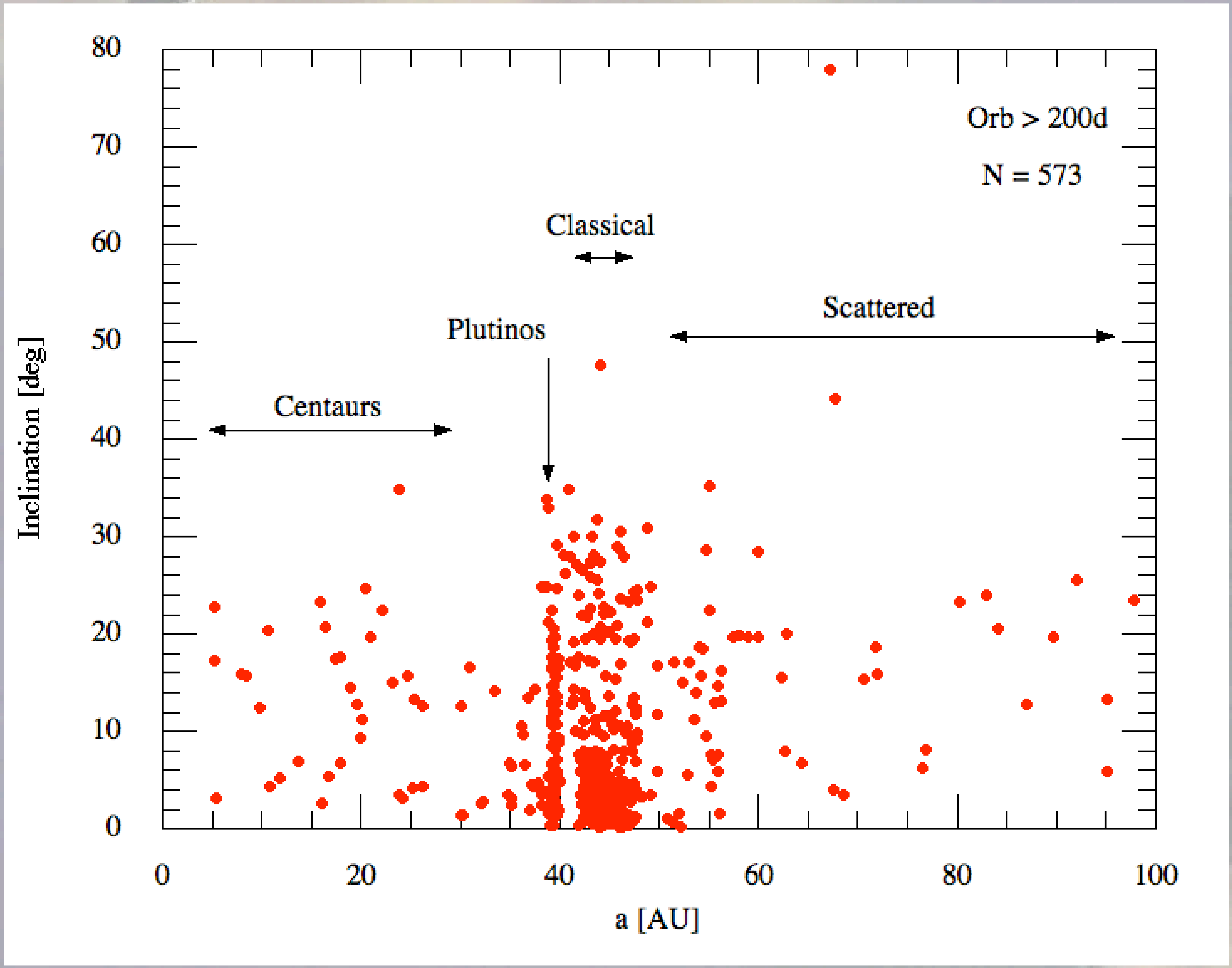
Detection by parallactic motion

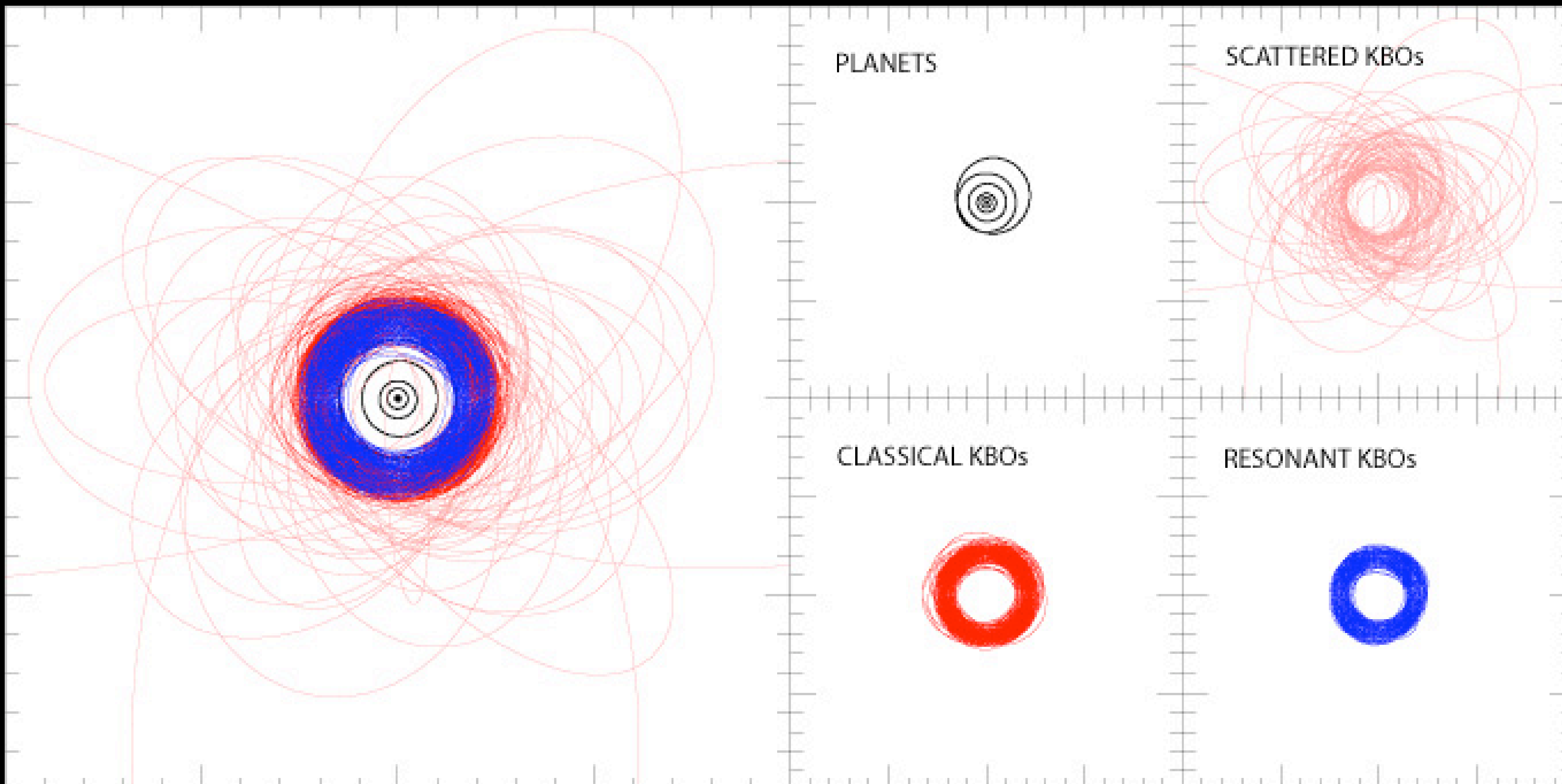
Surface density
S ~ 1 per sq. deg
at m ~ 23


Classical
Orb > 200d
N = 573
Plutinos
Scattered
Centaurs
Number
a [AU]
120
100
80
60
40
20
0
0
10
20
30
40
50
60
70
80
90
100


1.0
0.8
0.6
0.4
0.2
0.0
Eccentricity
0
20
40
60
80
100
a [AU]
Classical
Plutinos
Scattered
Centaurs
Orb > 200d
N = 573

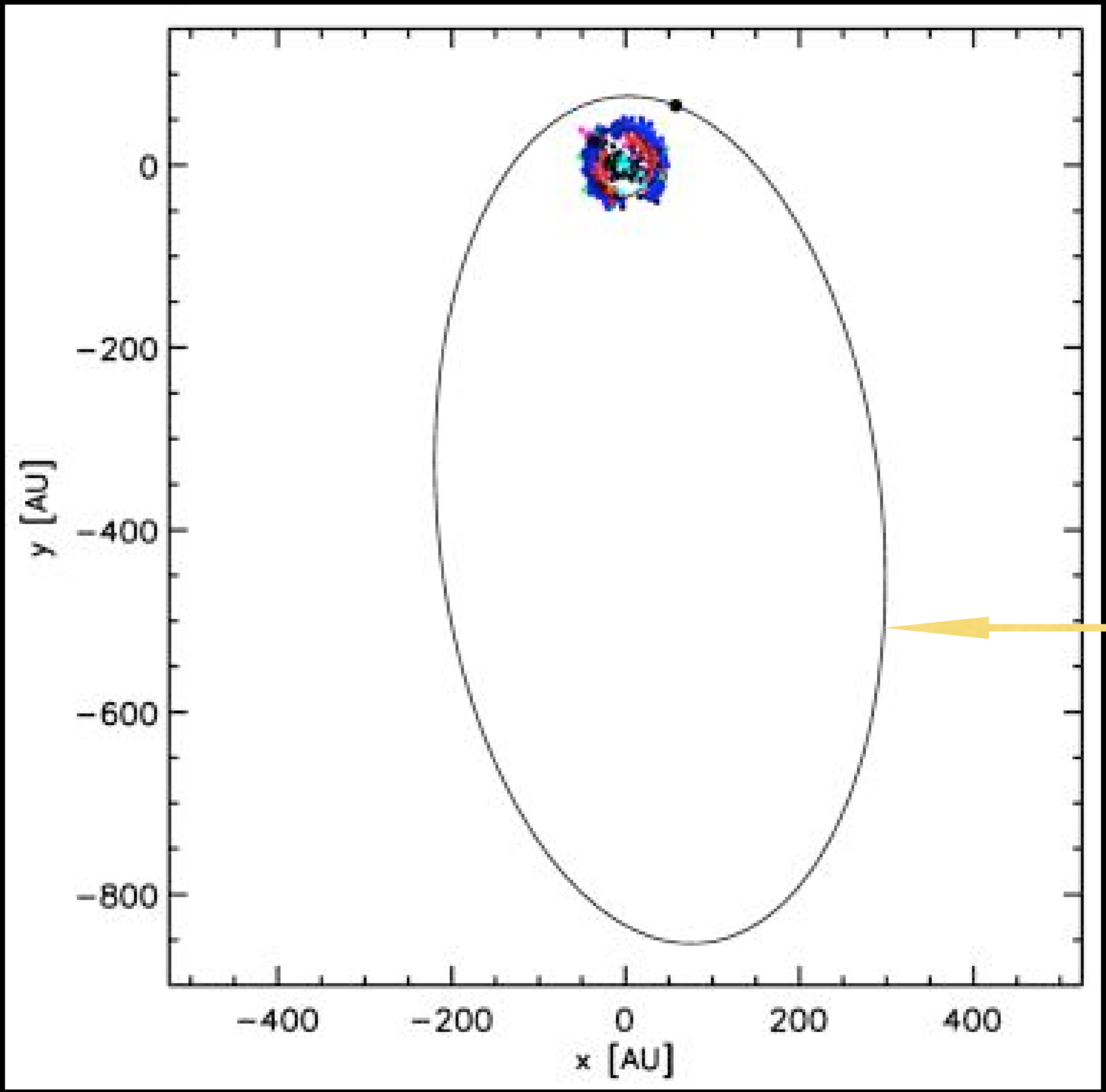

1.0
0.8
0.6
0.4
0.2
0.0
Eccentricity
q = 30 AU
q = 40 AU
Orb > 200d
N = 573
40
60
80
100
300
500
a [AU]


Orb > 200d
N = 573
Classical
Scattered
Plutinos
Centaurs
Inclination [deg]
a [AU]
0
20
40
60
80
100
10
30
50
70



400 X 400 AU

Detached KBOs: 2001 CR105 & Sedna



2001 CR105
q ~ 44 AU
Q ~ 410 AU
i ~ 23

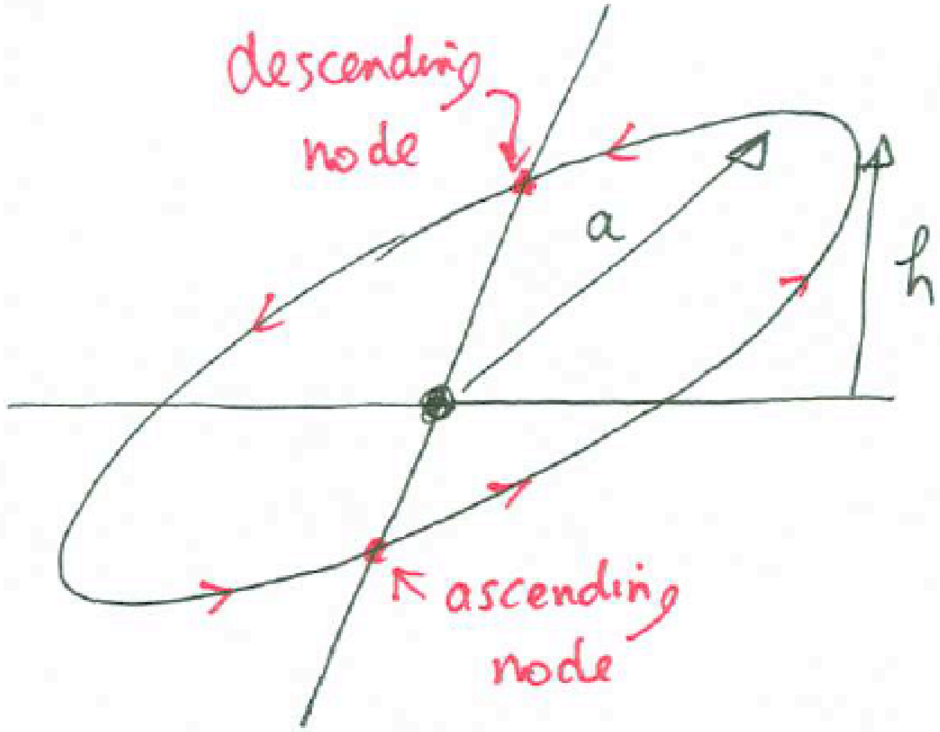
Sedna
q ~ 76 AU
Q ~ 940 AU
i ~ 12

Perihelia beyond the controlling influence of Neptune

4 Dynamical Sub-Groups

- Classical KBOs (CKBOs)
- Resonant KBOs (inc. 3:2 Plutinos)
- Scattered KBOs (SKBOs)
- Detached KBOs (2000 CR105, Sedna)

Inclination & Velocity Dispersion



$$h \sim V_\perp \frac{P}{4}$$

$$i \sim \frac{h}{a} \sim \frac{V_\perp P}{4a}$$

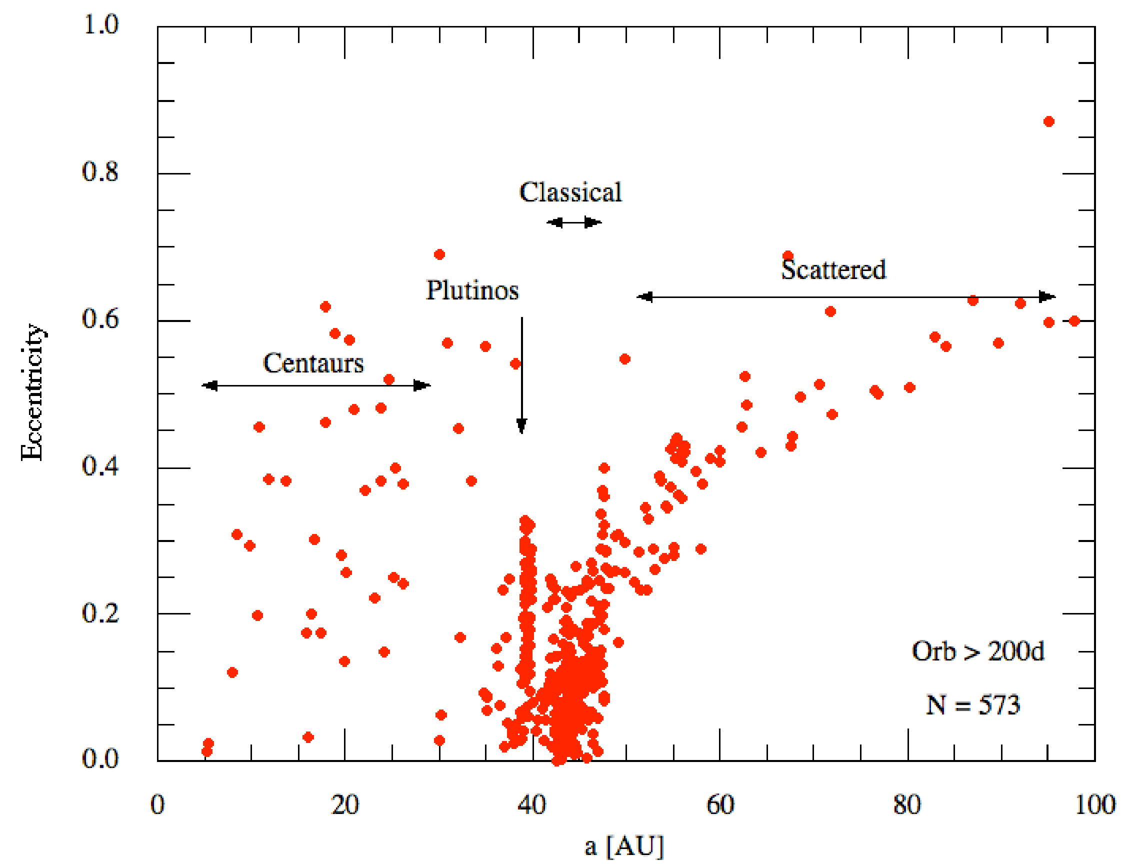
eg: $a = 40\,AU$, $P \sim 250\,yr$

$V_\perp = 1.7\,km\,s^{-1} \rightarrow i = 30^\circ$

eg:
$V_\perp \sim V_e(10\,km) \sim 10\,m\,s^{-1} \rightarrow i \sim 0.2^\circ$

Current i distribution is too fat to have permitted accretion

* i has been pumped


1.0
0.8
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0.4
0.2
0.0
Eccentricity
Classical
Scattered
Plutinos
Centaurs
Orb > 200d
N = 573
0
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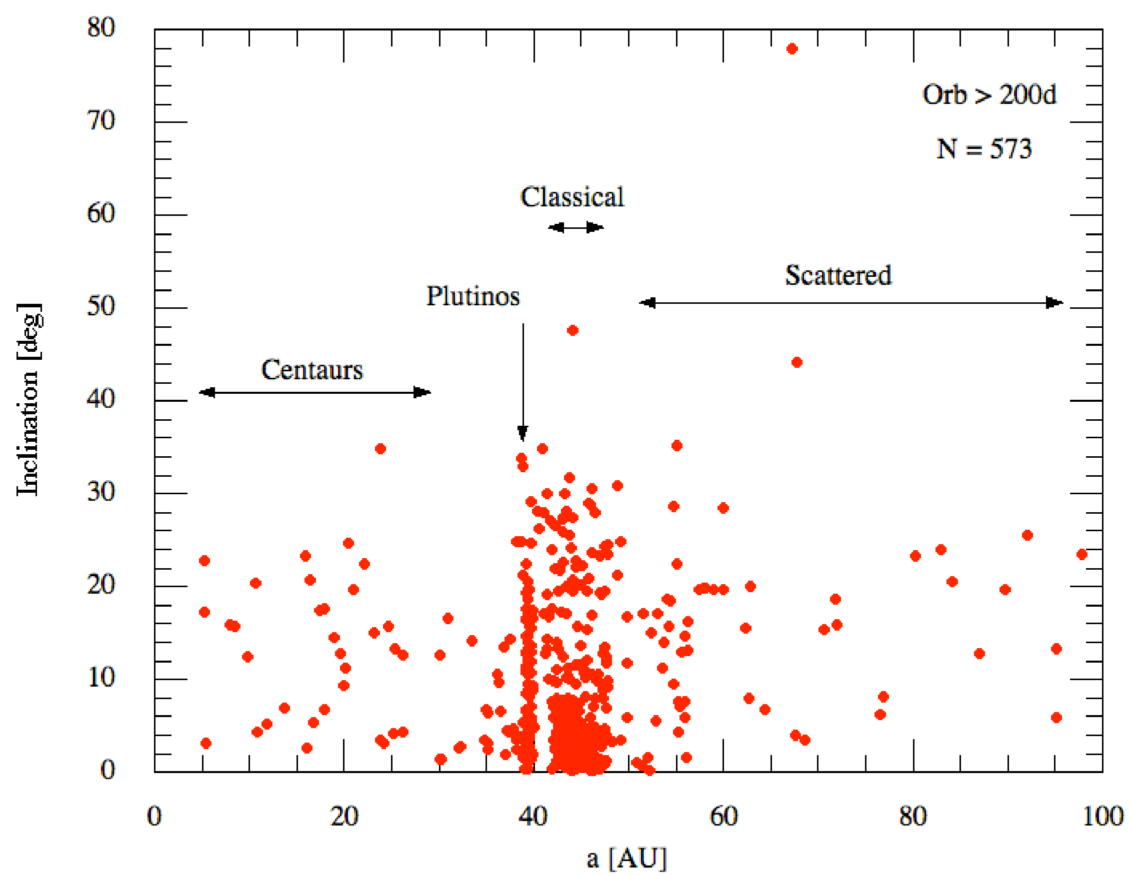
a [AU]


80
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Inclination [deg]
Orb > 200d
N = 573
Classical
Scattered
Plutinos
Centaurs
0
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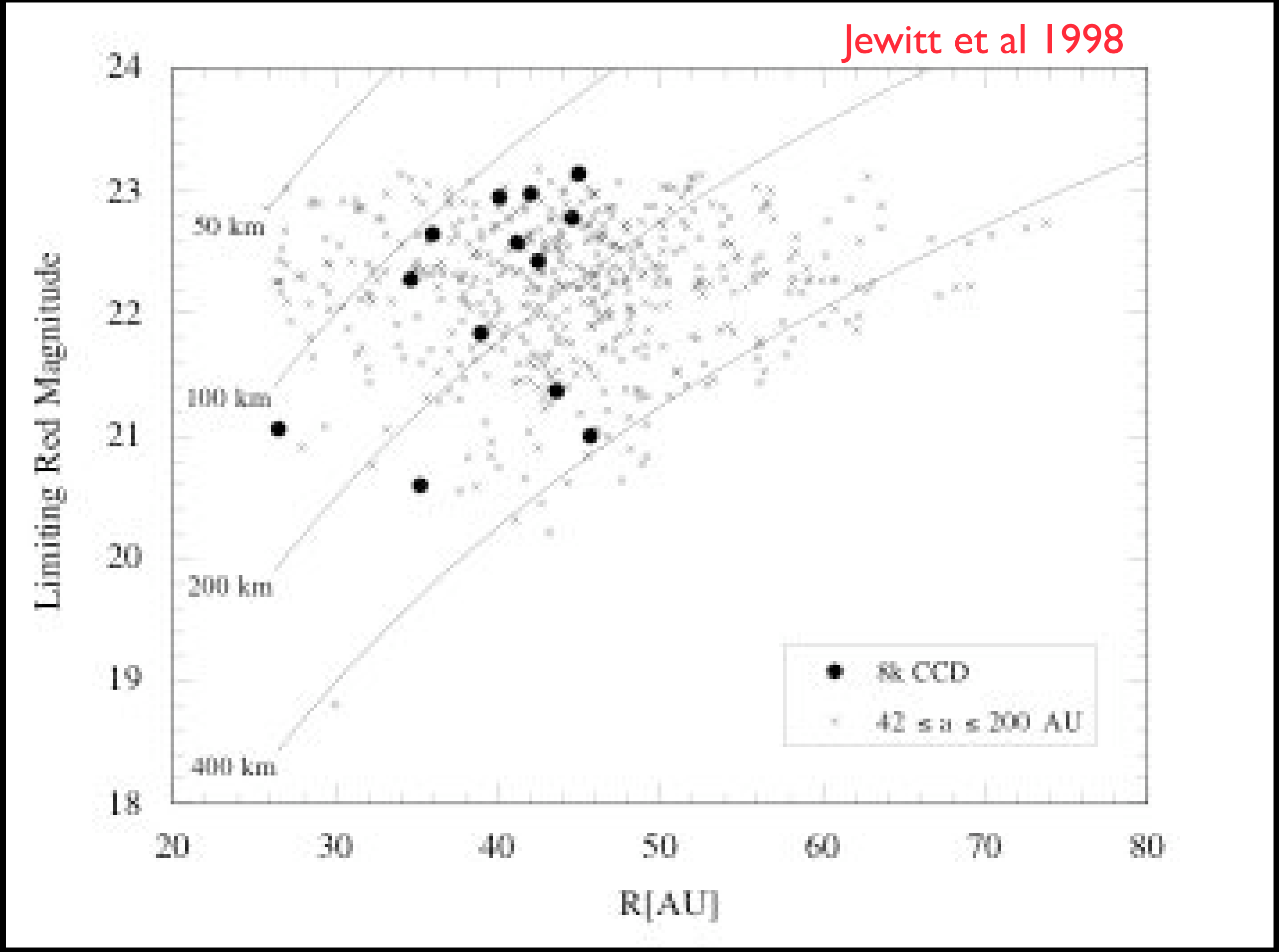
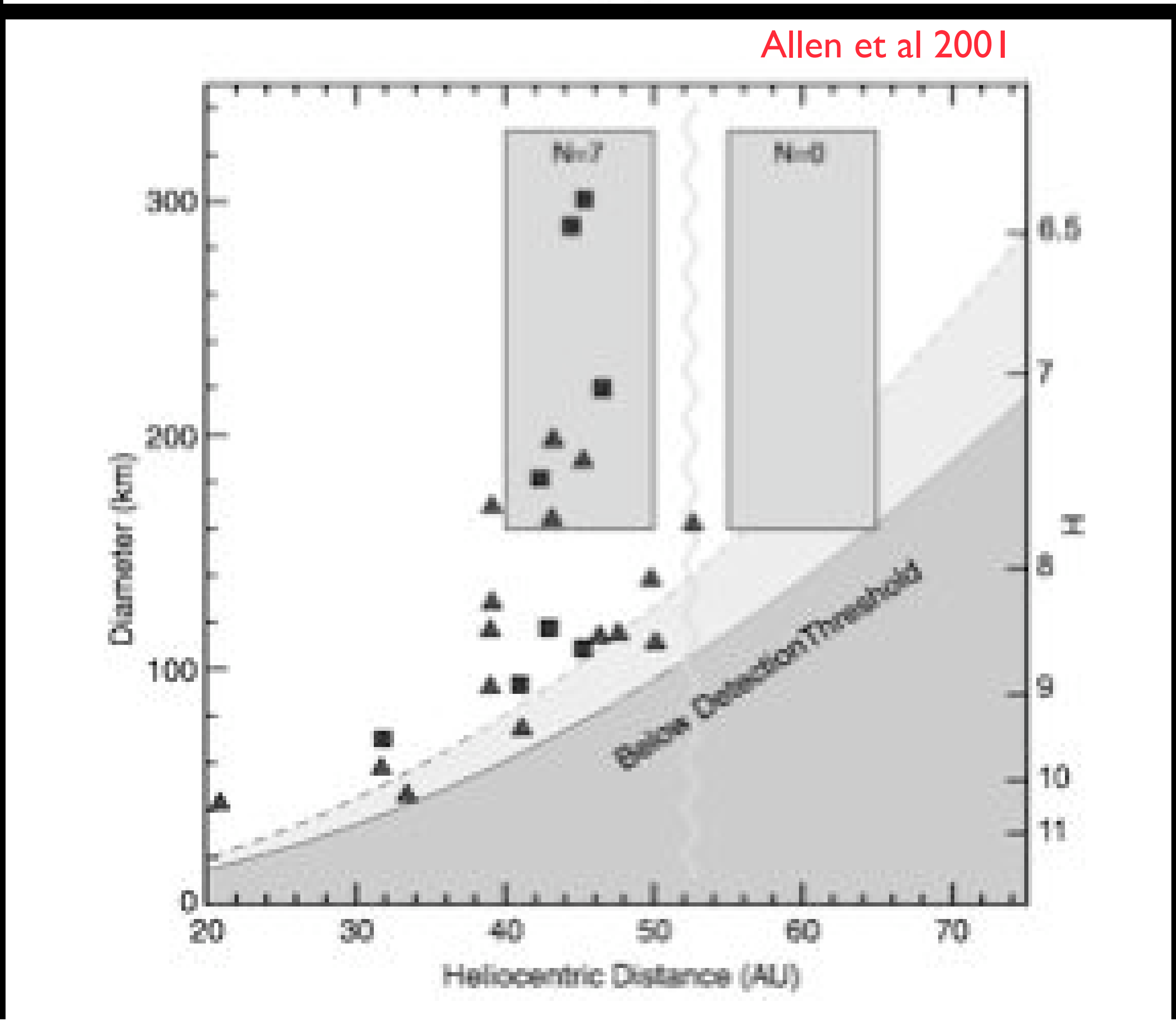
a [AU]





Edge to the Classical Belt

Edge ~ 47 AU

Origin: unknown

Suggestions:

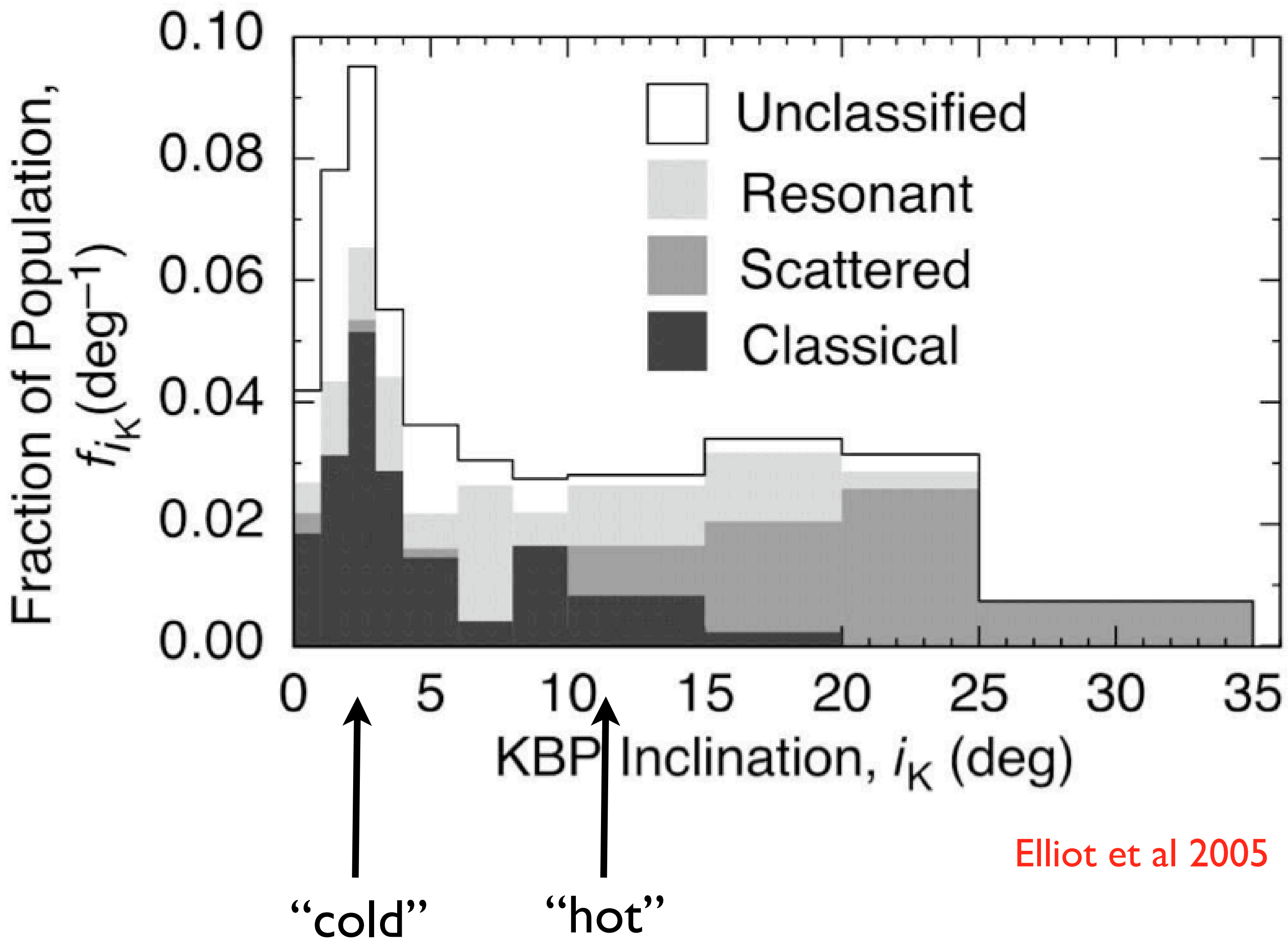
1) Tidal truncation by passing star (Ida et al 2000)

2) Truncation by unseen planet (Brunini & Melita '02)

3) Artifact of radially increasing growth times

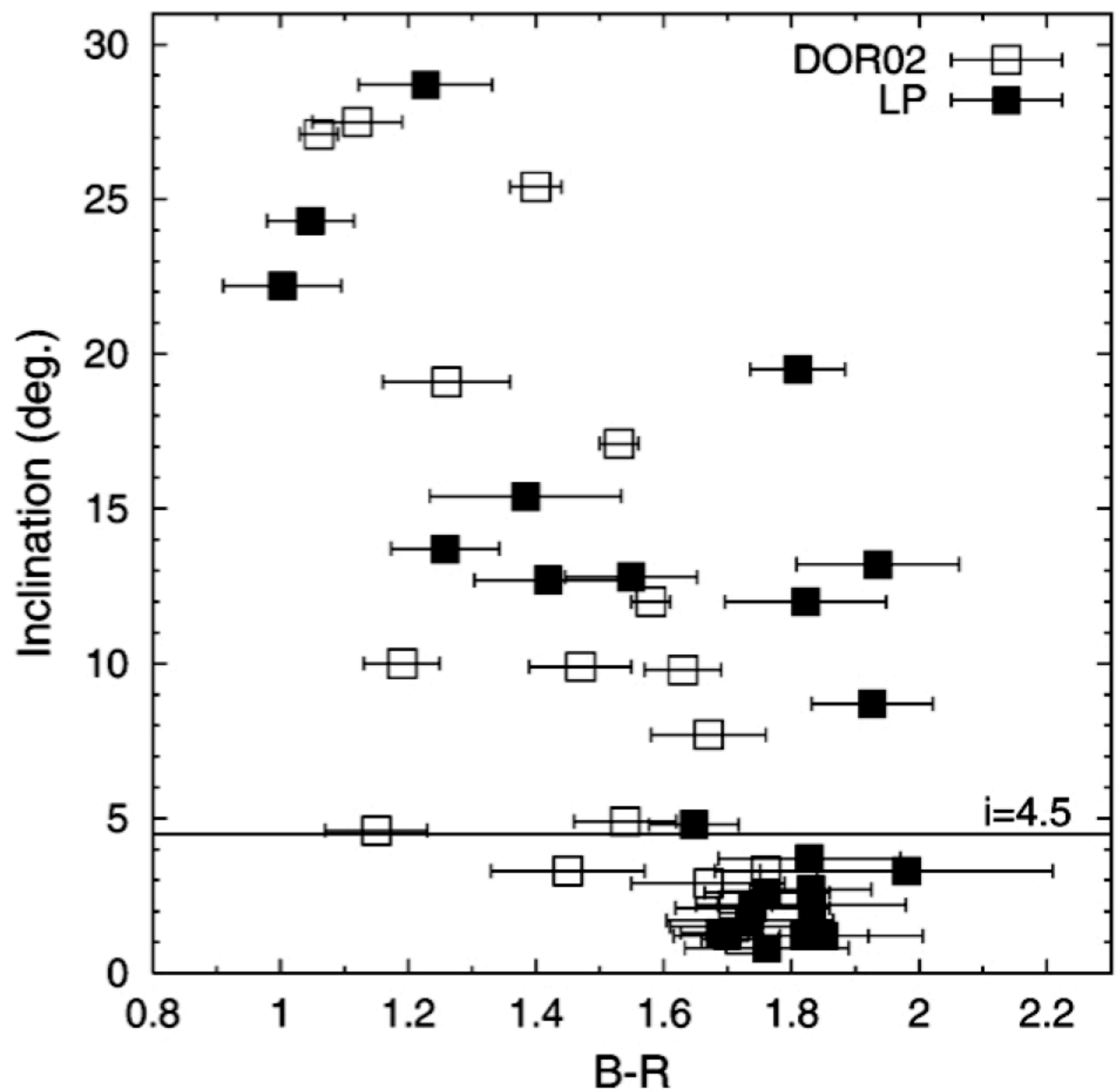
4) Leakage from radially migrating 2:1 resonance (Levison and Morbid '03)

Is *not* an edge to the Belt as a whole



Classical belt i-distribution appears bimodal: "hot" and "cold" components.

Weak evidence of color-dynamics relation in Classical Belt only



Delsanti 2006

Layout of the Kuiper Belt

A: Classical belt

(42 < a < 48 AU, distinct outer edge near 2:1 MMR)

B: Resonant objects

(mostly located at mean-motion resonances. e.g. Plutinos at 3:2 @ 39.4 AU. Others are located at secular resonances)

C: Scattered objects

(Perihelion scattered by Neptune, mostly $q \leq 35$ AU)

(Note: The scattered objects are described by some as separate from the Kuiper belt. The scattered objects are discovered in the same way (by the same people!) as the classical, resonant and detached populations and I don't see a good reason to label them as if they are not part of the Kuiper belt.)

D: Detached objects

(Perihelion beyond Neptune's influence)

Evidence for Migration

- Well-populated resonances (esp. 3:2 Plutinos)

Evidence for a Massive Progenitor Belt

- Mass now ~0.05 Earth Mass
- Surface density 100x smaller than extrapolation from planets
- Formation times implausible at current surface densities
- Binary formation ineffective at current surface densities

How to Clear it Away?

- Dynamical ejection (size independent, any q)

- Pulverization to dust then loss to radiation forces (size dependent: D < 50 km only, q > 4)

Art by Michael Carroll

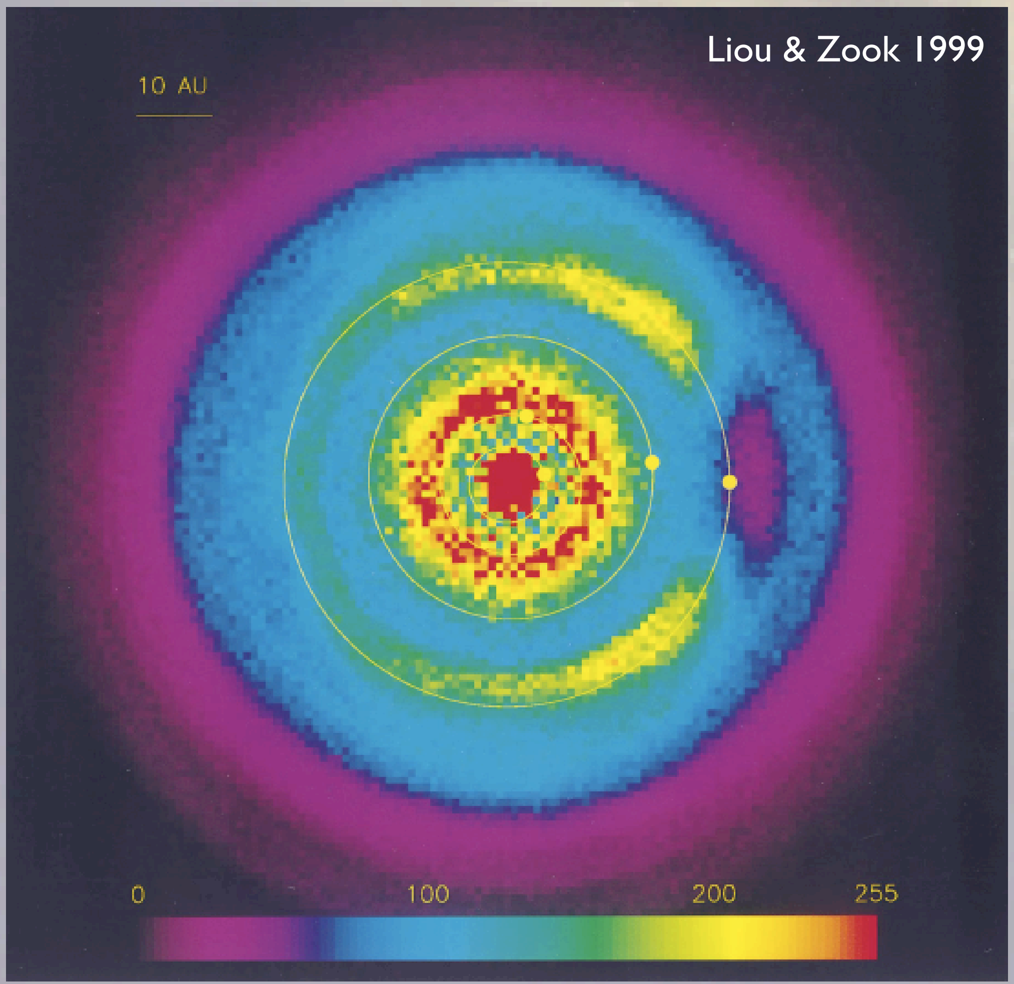
Observational Properties

- Broad inclination distribution (not expected)
- Velocity Dispersion Δv ~ 1.5 km/s (erosive)
- Number (D>100 km) ~ 70,000 (~300 times asteroid belt)
- Size distribution index q ~ -4.0 (for D > 50 km)
- Mass ~ 0.1 M(Earth) (very small)
- Voyager dust production ~ 1000 kg/s (tau ~ 10^{-7})

BREAK #1 (10 minutes)

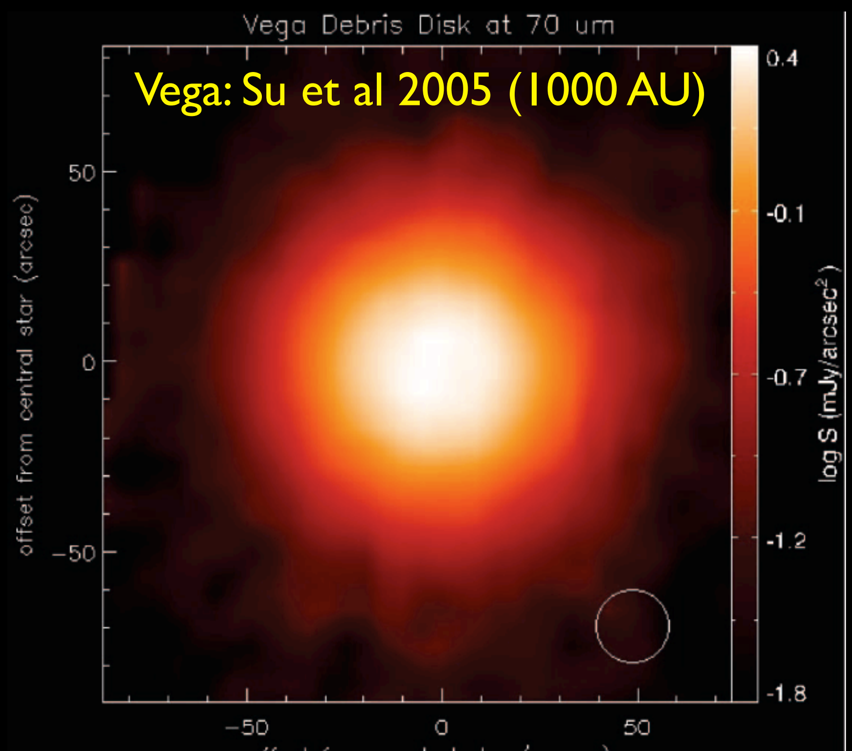
NEXT: PHYSICAL PROPERTIES

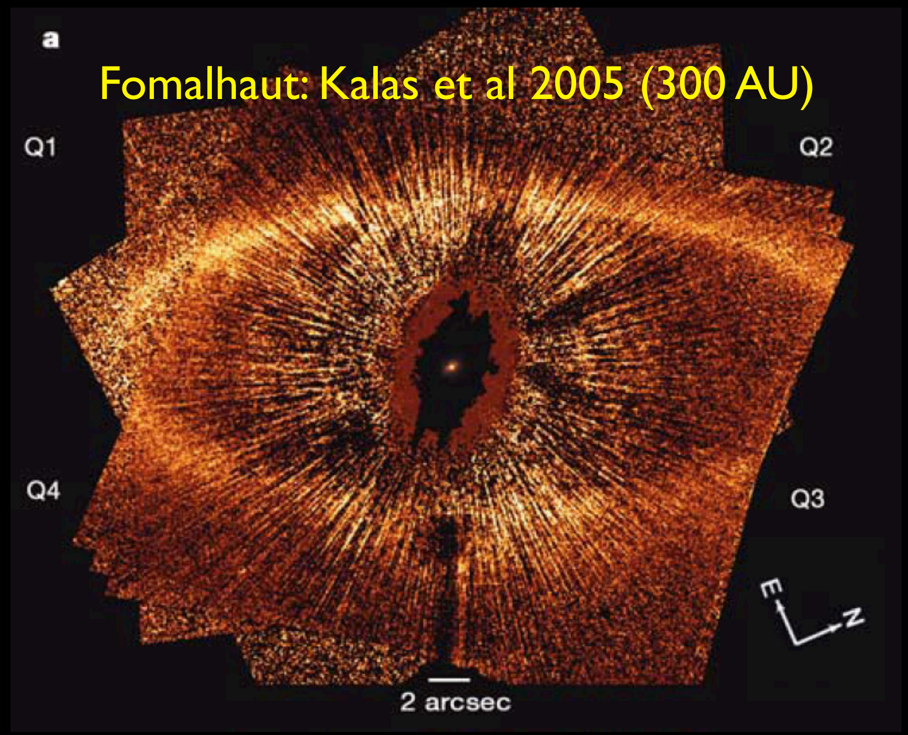
First, Dust

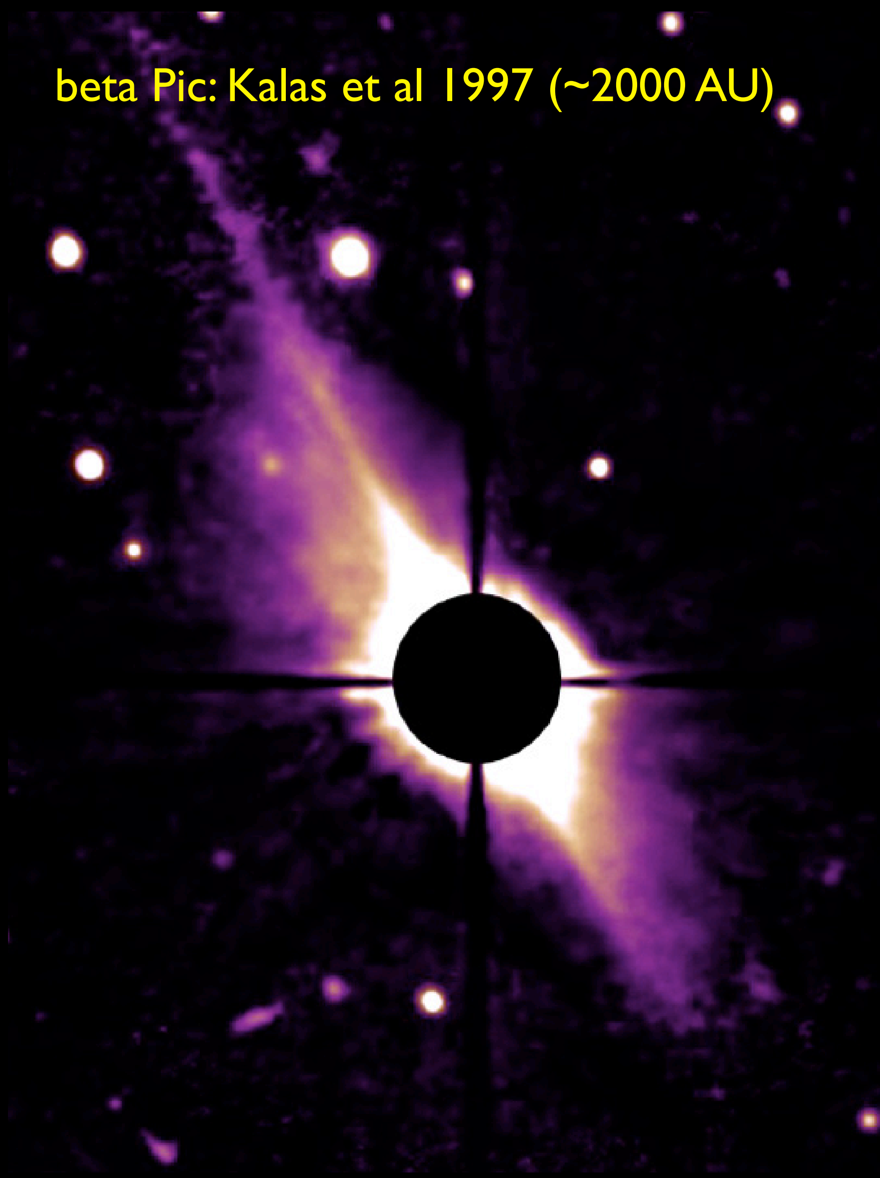


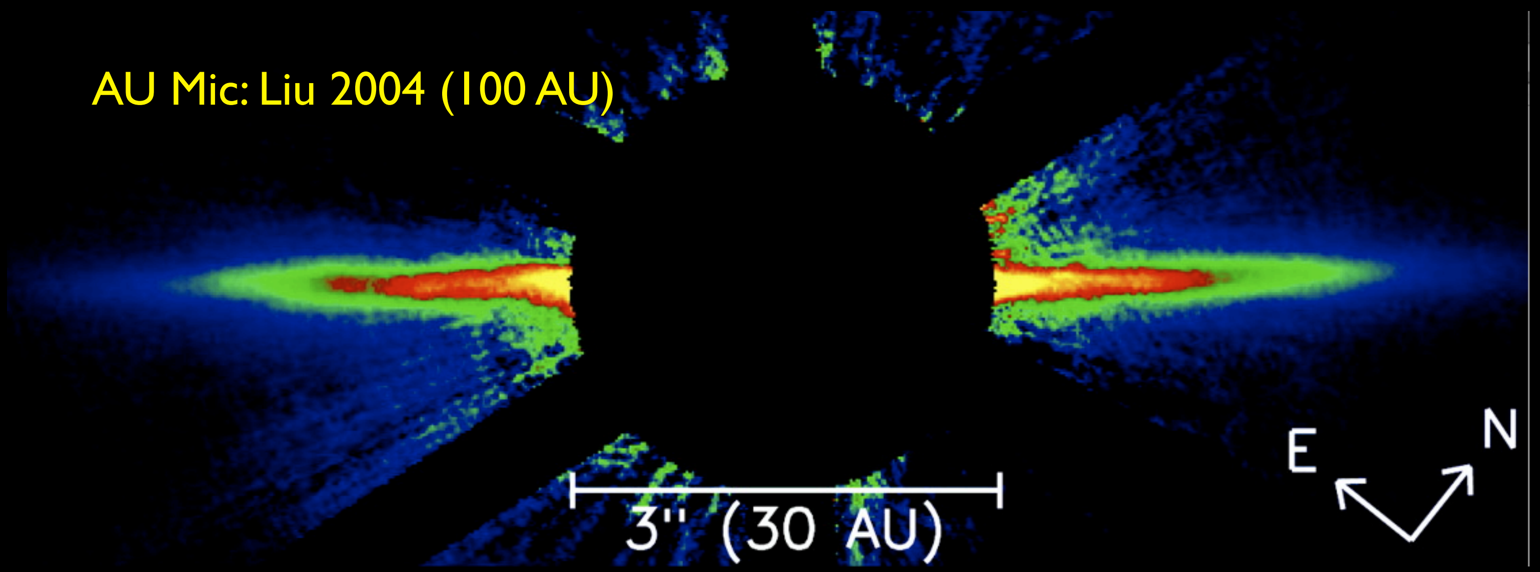
- μm-sized dust has been detected in-situ by Voyager
- Derived production rates ~1 to 10 tonne/sec
- Expect ~1 tonne/sec from interstellar grain erosion
- Grain lifetime ~1 to 10 Myr (PR, plasma drag, collisional shattering)
- Optical depth ~10^-7 (c.f. beta Pic ~10^-4)

Debris Disks (dust lifetime < star age)

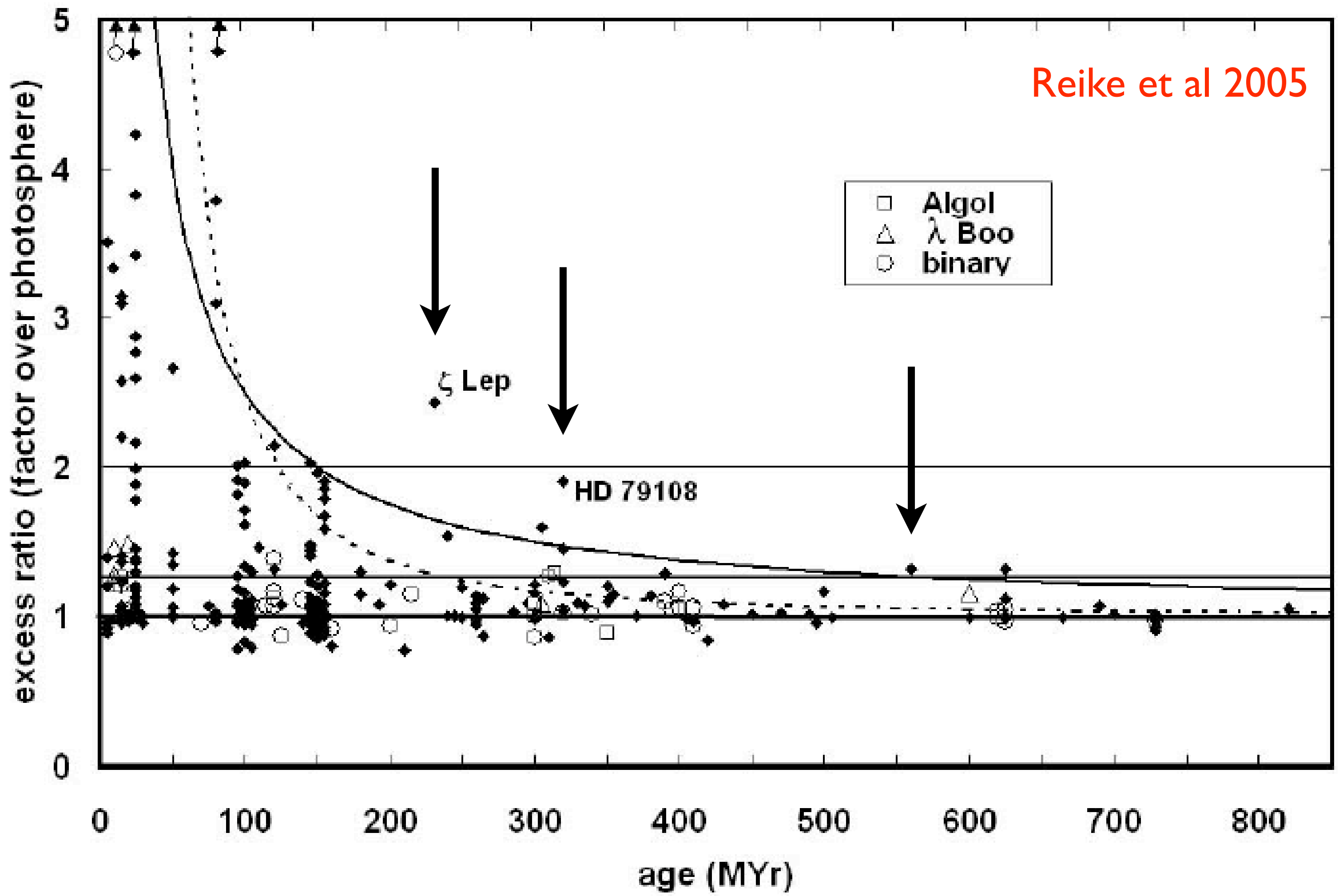








Debris Disks



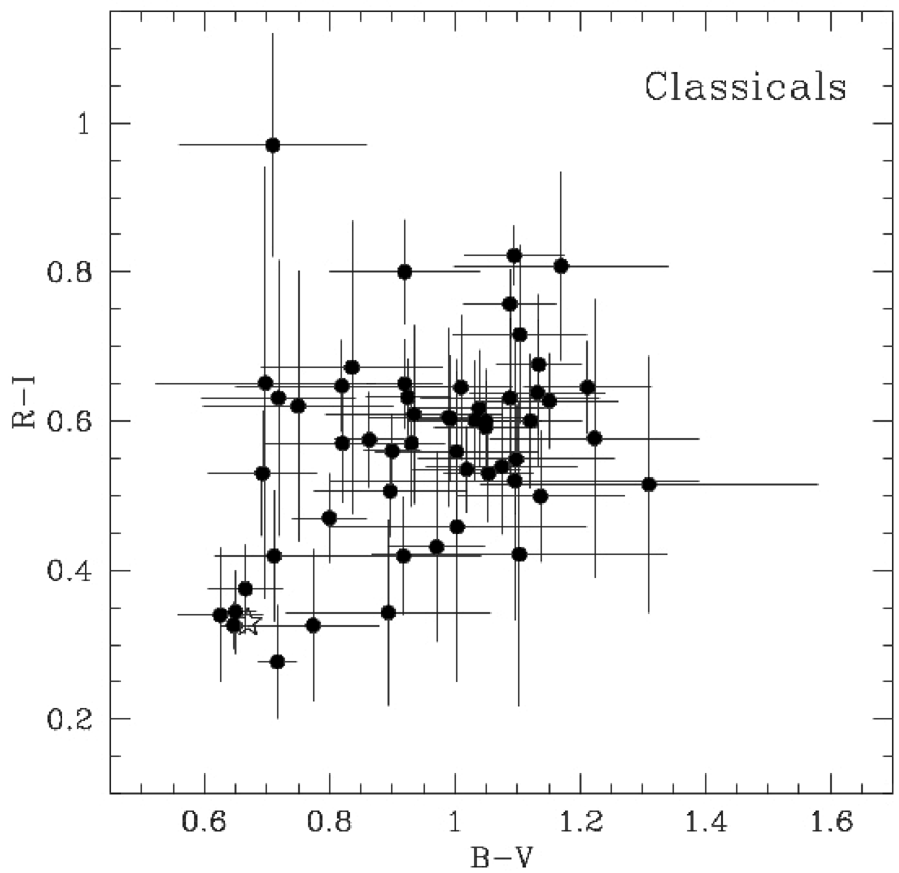
- General decline in optical depth with time

- Occasional spikes perhaps due to massive collisions

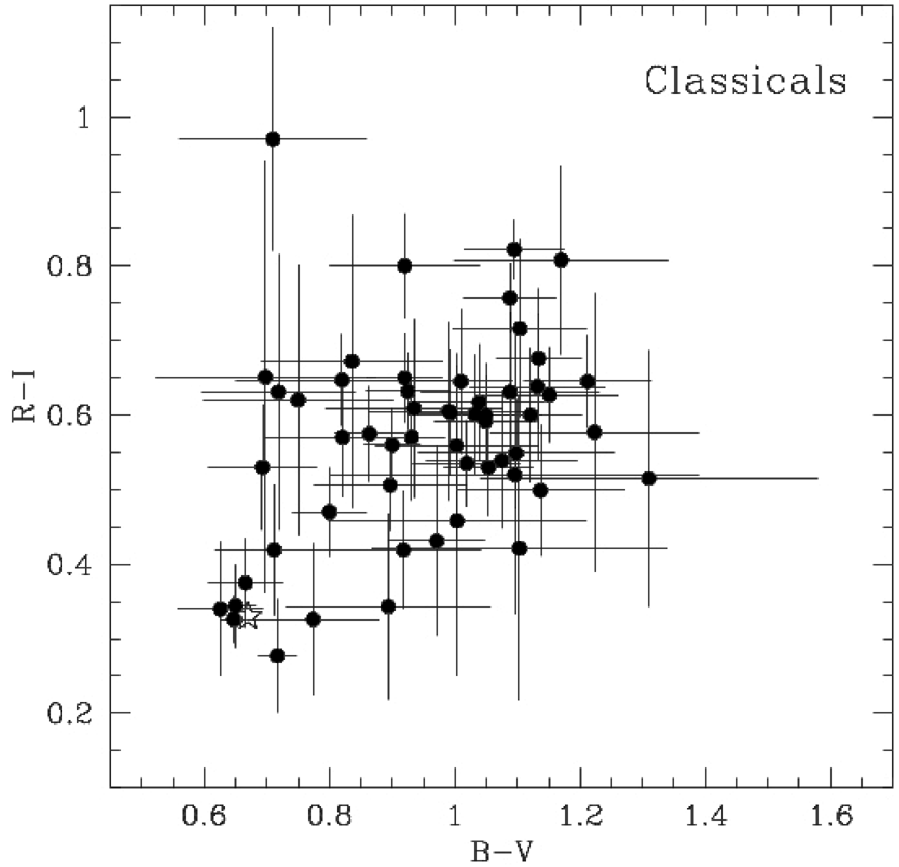
Surfaces of KBOS: Colors

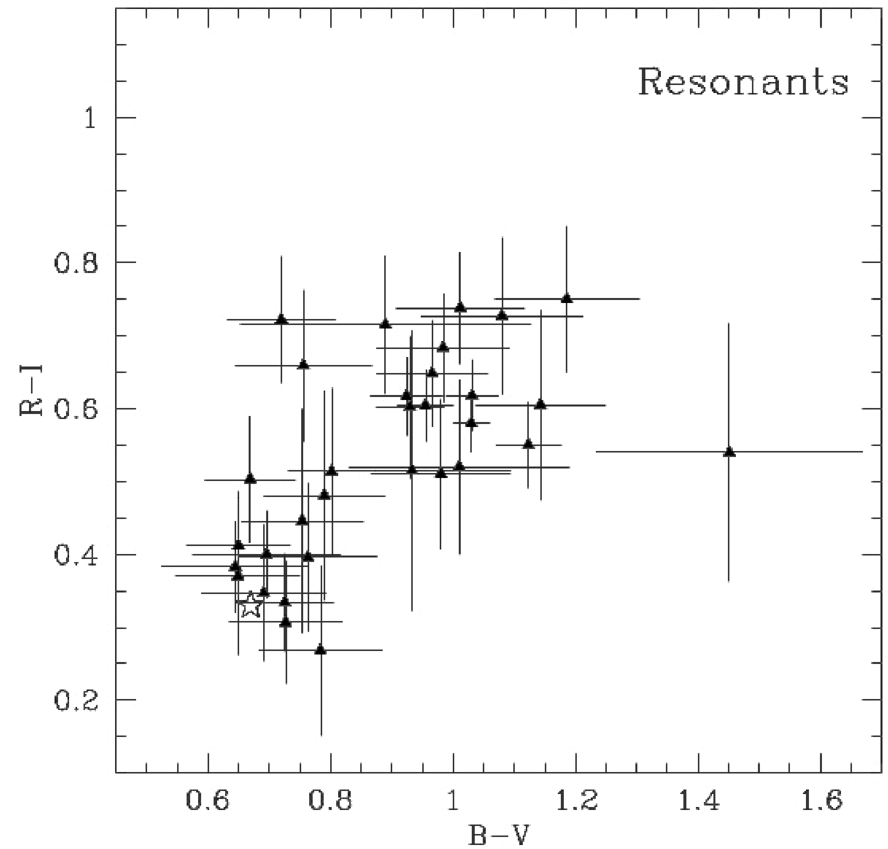
Color Distributions

Color Distributions

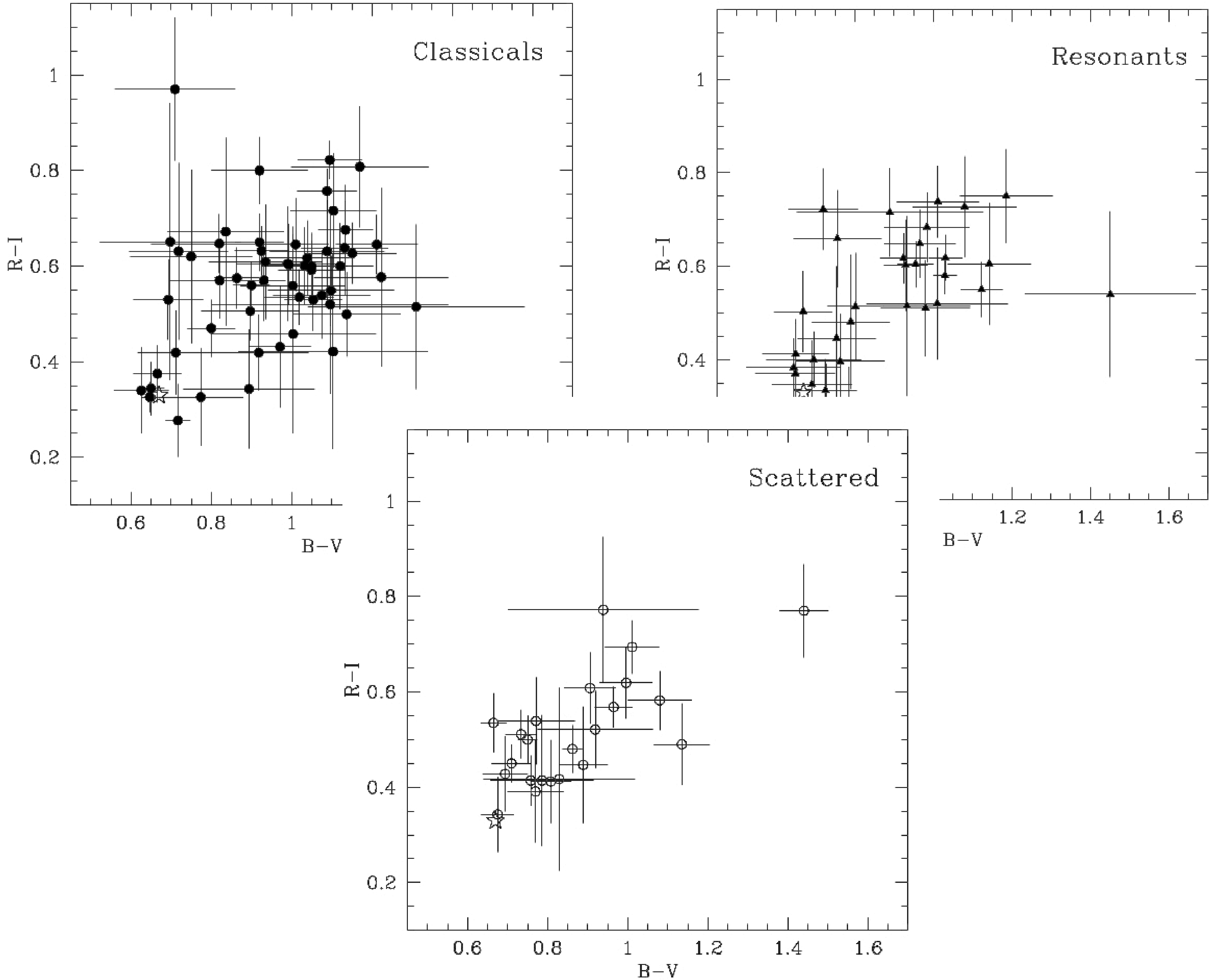


Color Distributions

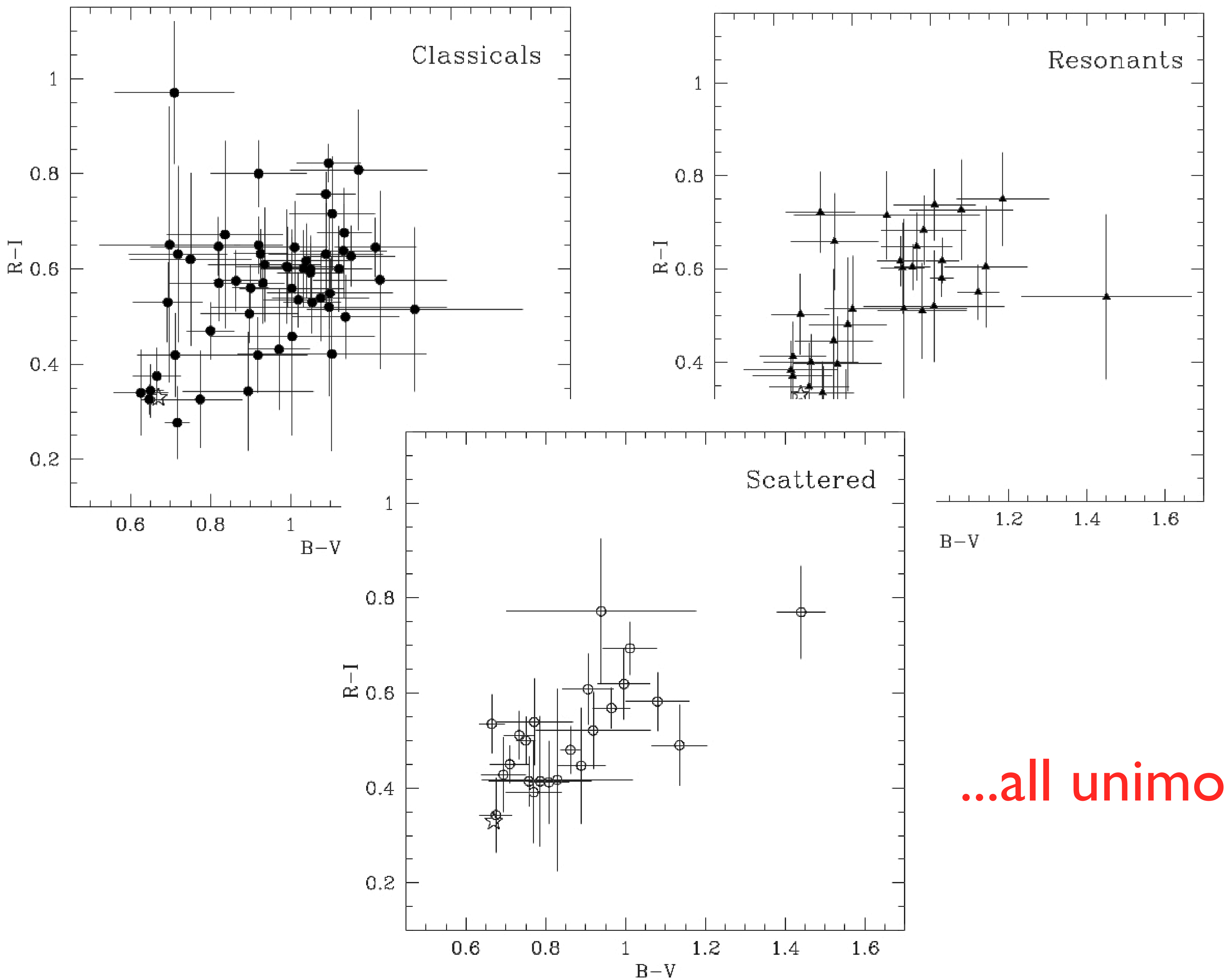




Color Distributions



Color Distributions



...all unimodal

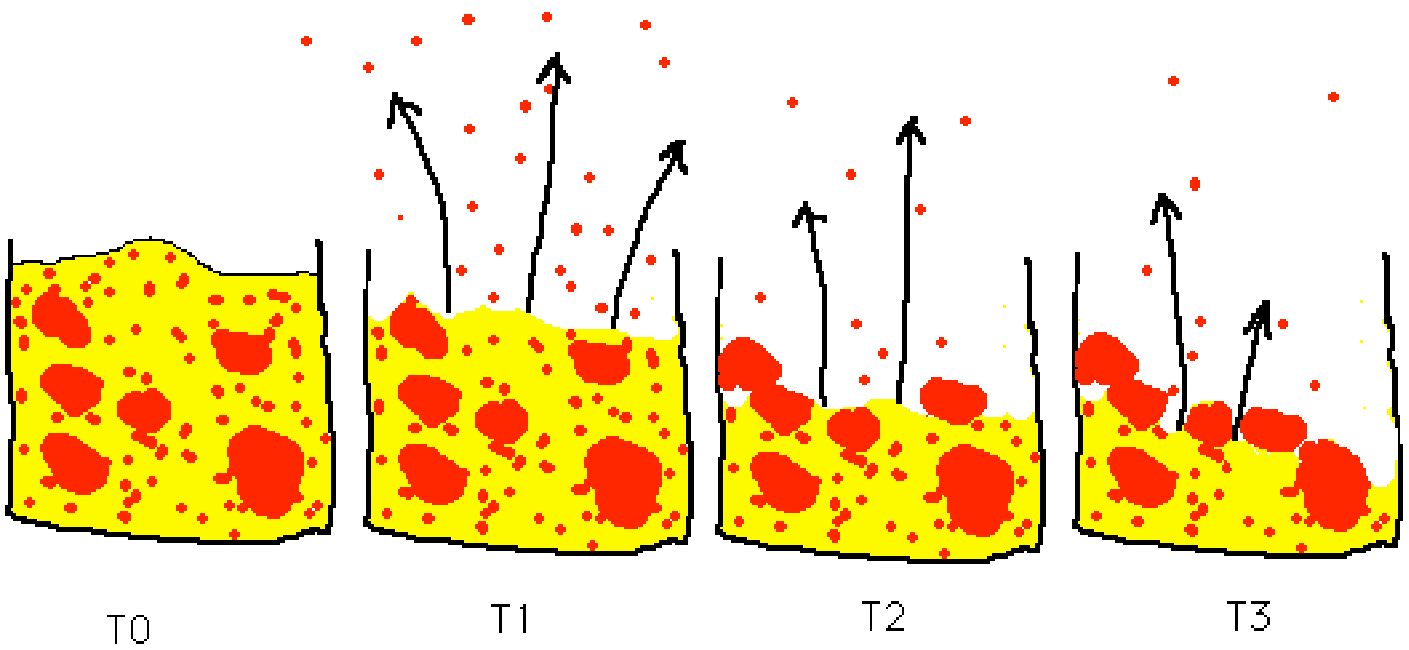
Main Result

There is a wide range of colors (meaning a wide range of surface types)

Early claims of bimodal color distribution (red KBOs and blue KBOs) were baseless and are now retracted

Why are the colors widely dispersed?

Origin of the Color Spread?



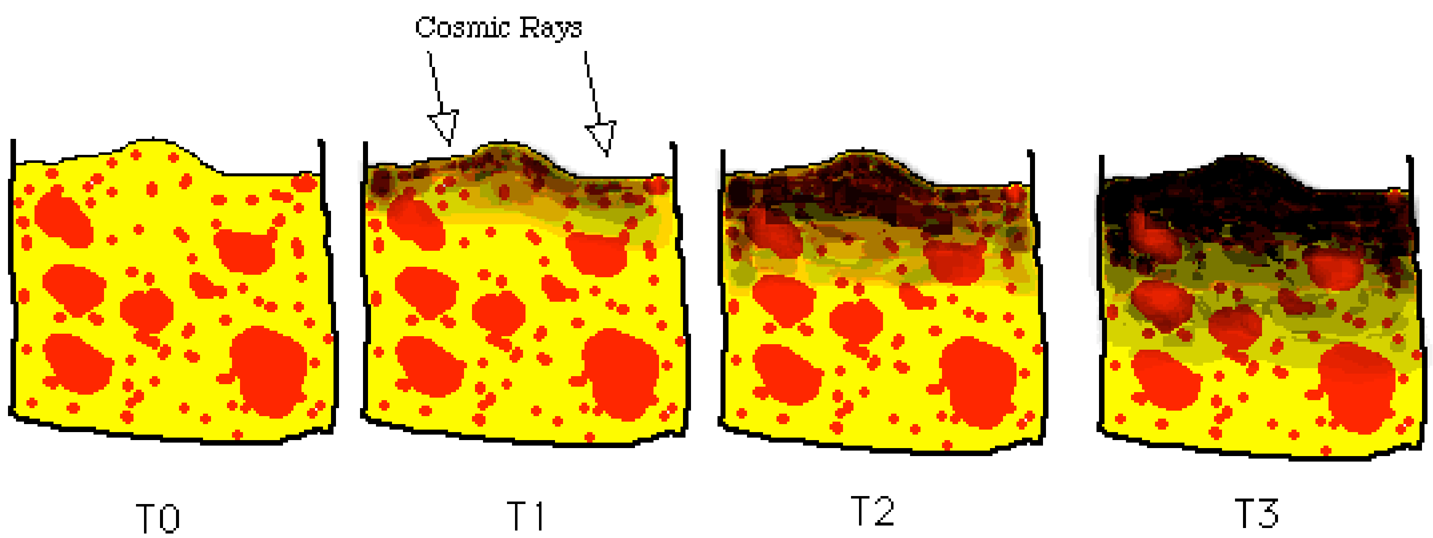
Rubble Mantle formation

Or perhaps outgassing (of supervolatiles, like CO) exposes fresh matter, resetting the color of the mantle?

- Hard to believe unless there is a deep source, because the surface depletion time is very short

Resolution: unknown.

Origin of the Color Spread?



Irradiation Mantle formation

Perhaps impact resurfacing exposes fresh matter, resetting the color of the mantle?

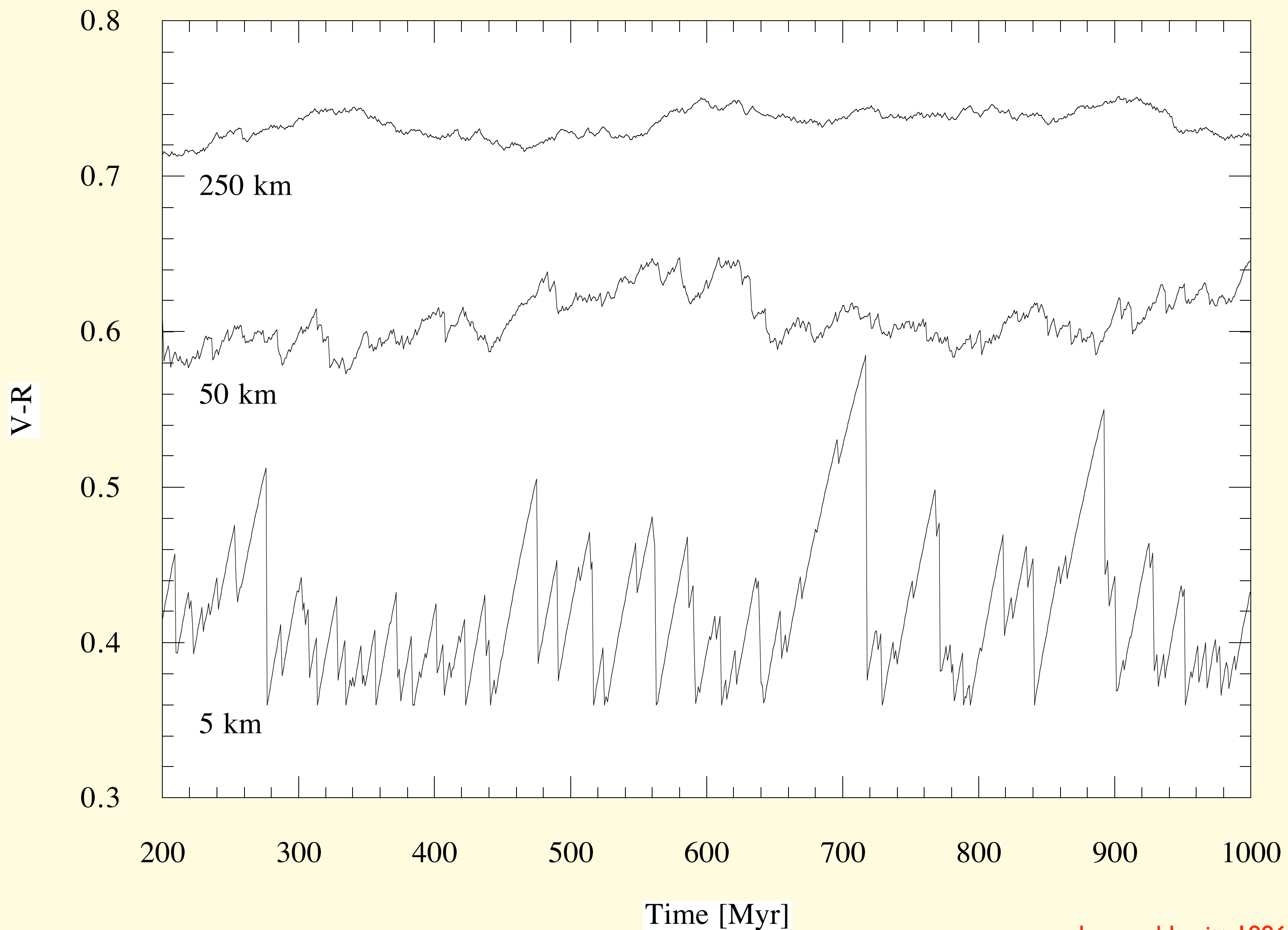
- Unlikely, given lack of rotational variation

Perhaps color differences result from real compositional differences?

-Difficult to believe given uniform conditions in the KB

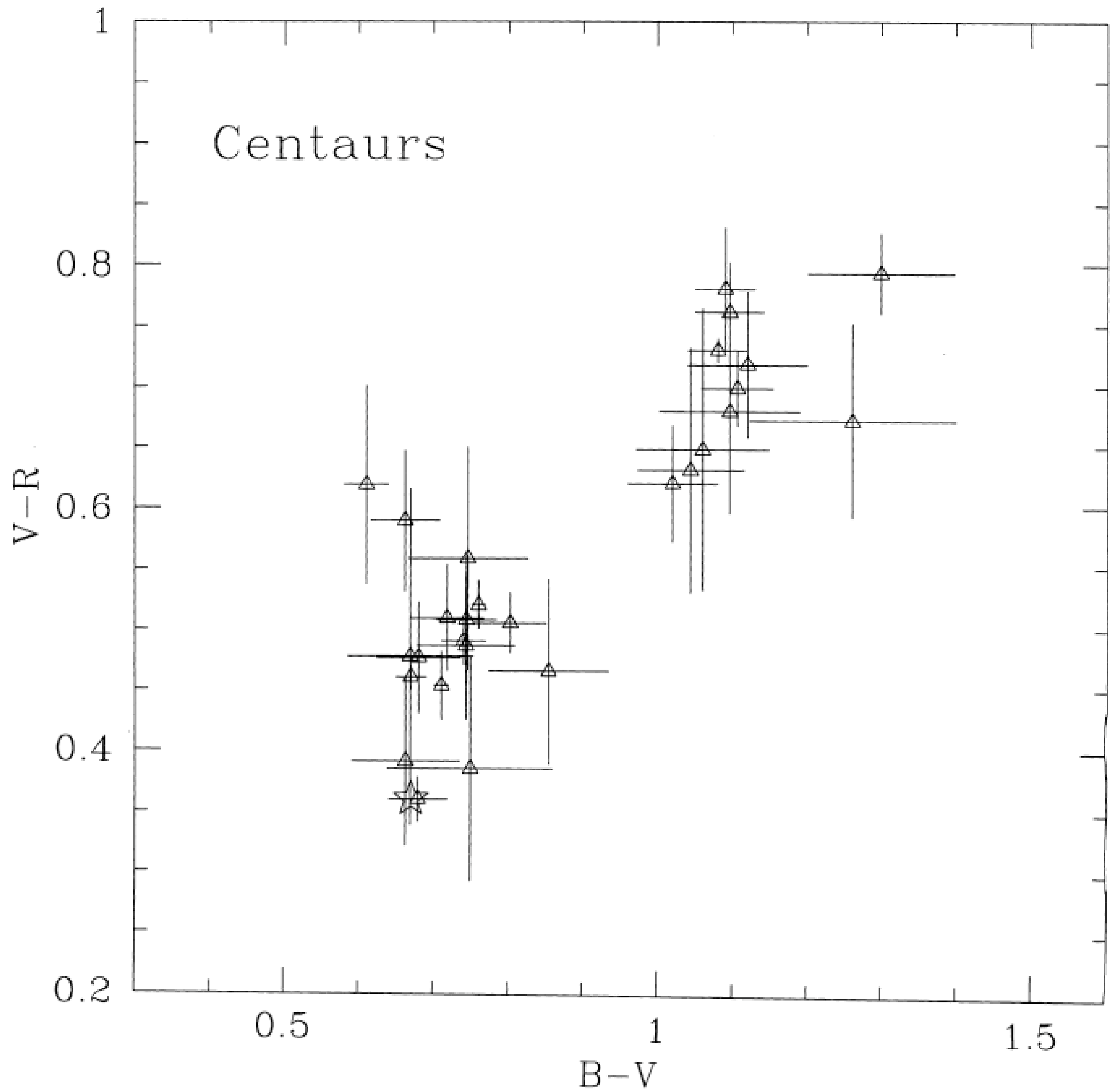
Resolution: unknown.

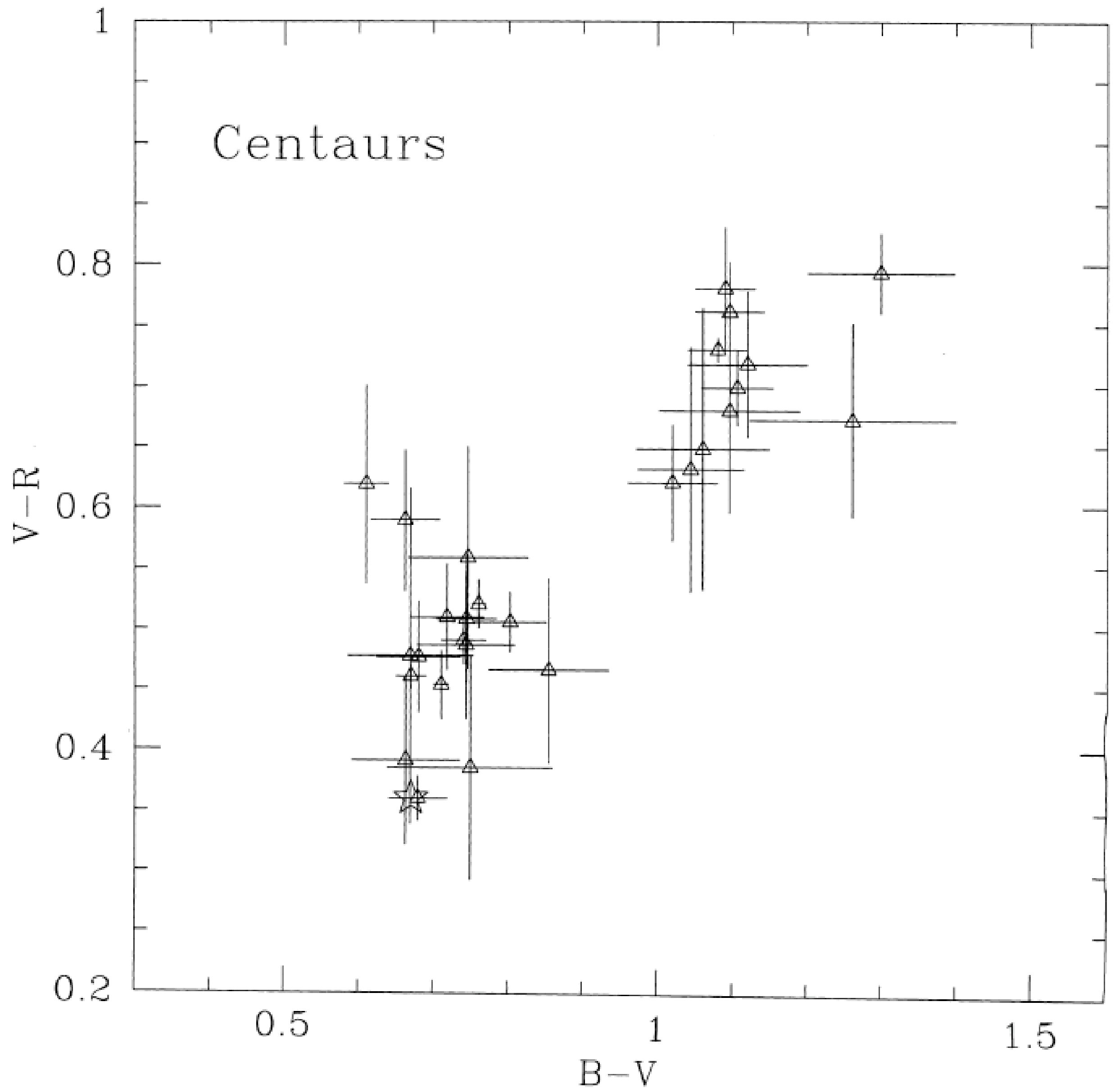
Dispersion from Competition?: Resurfacing



Luu and Jewitt 1996

Maybe. But we should see large rotational color variations. We do not.


Centaurs
V−R
B−V
1
0.8
0.6
0.4
0.2
0.5
1
1.5

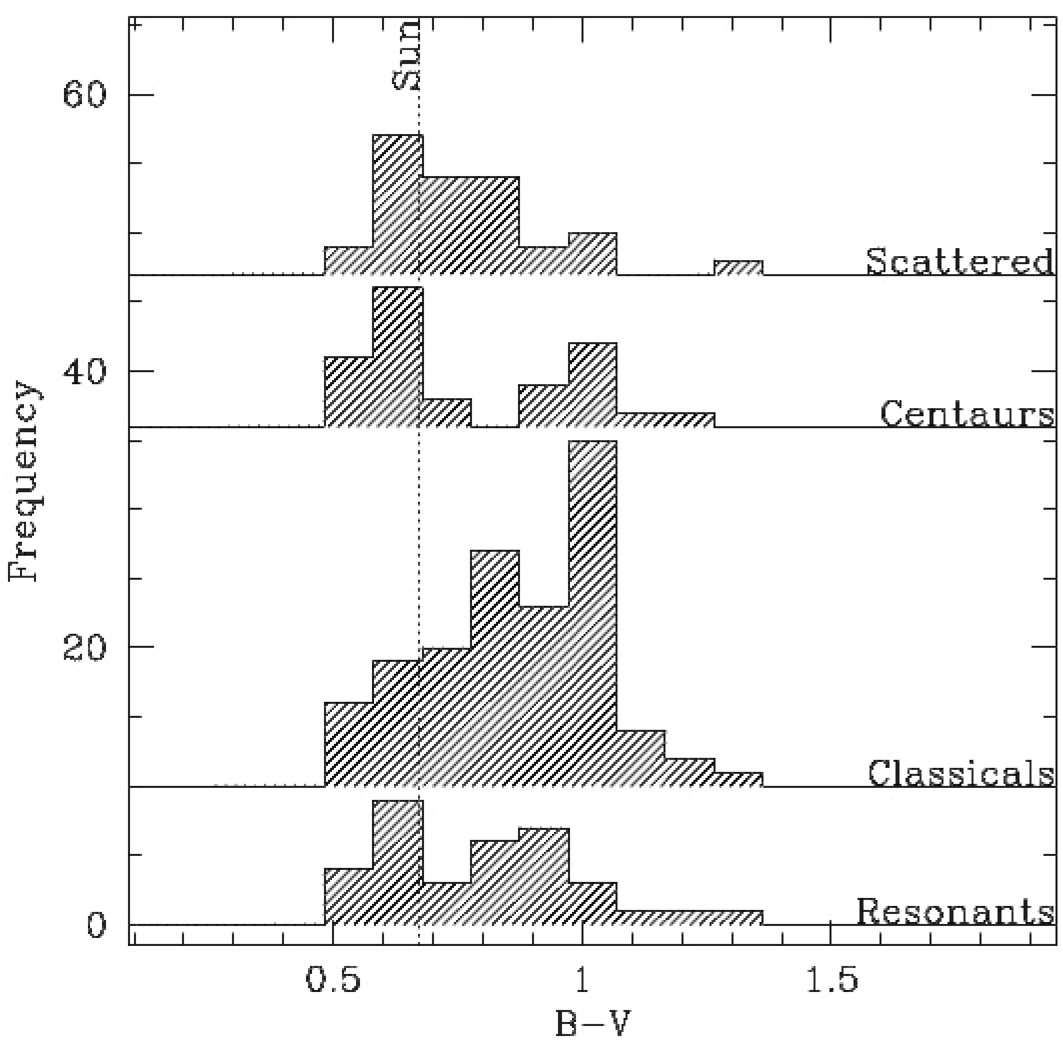


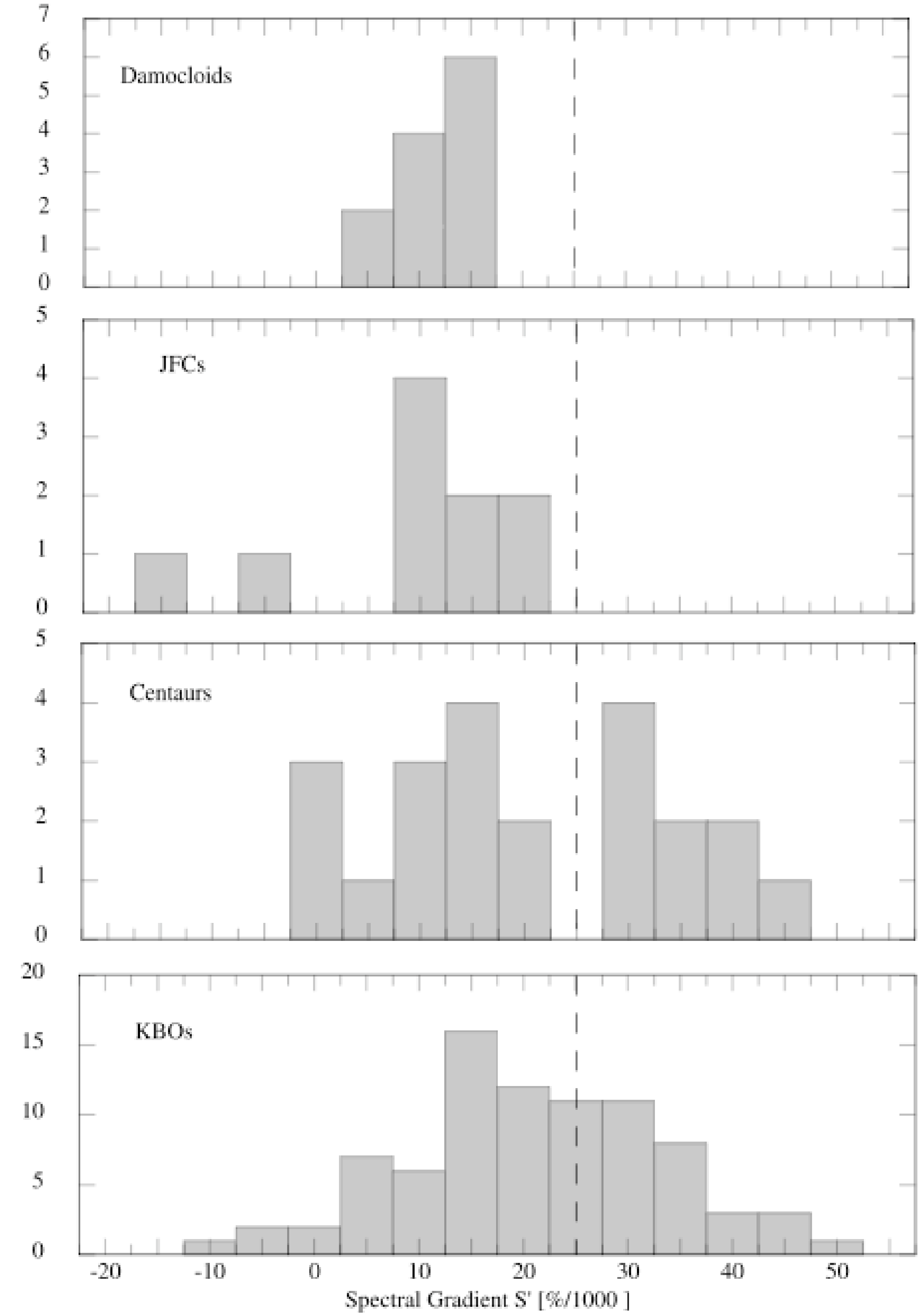
BUT

Centaur colors appear bimodal

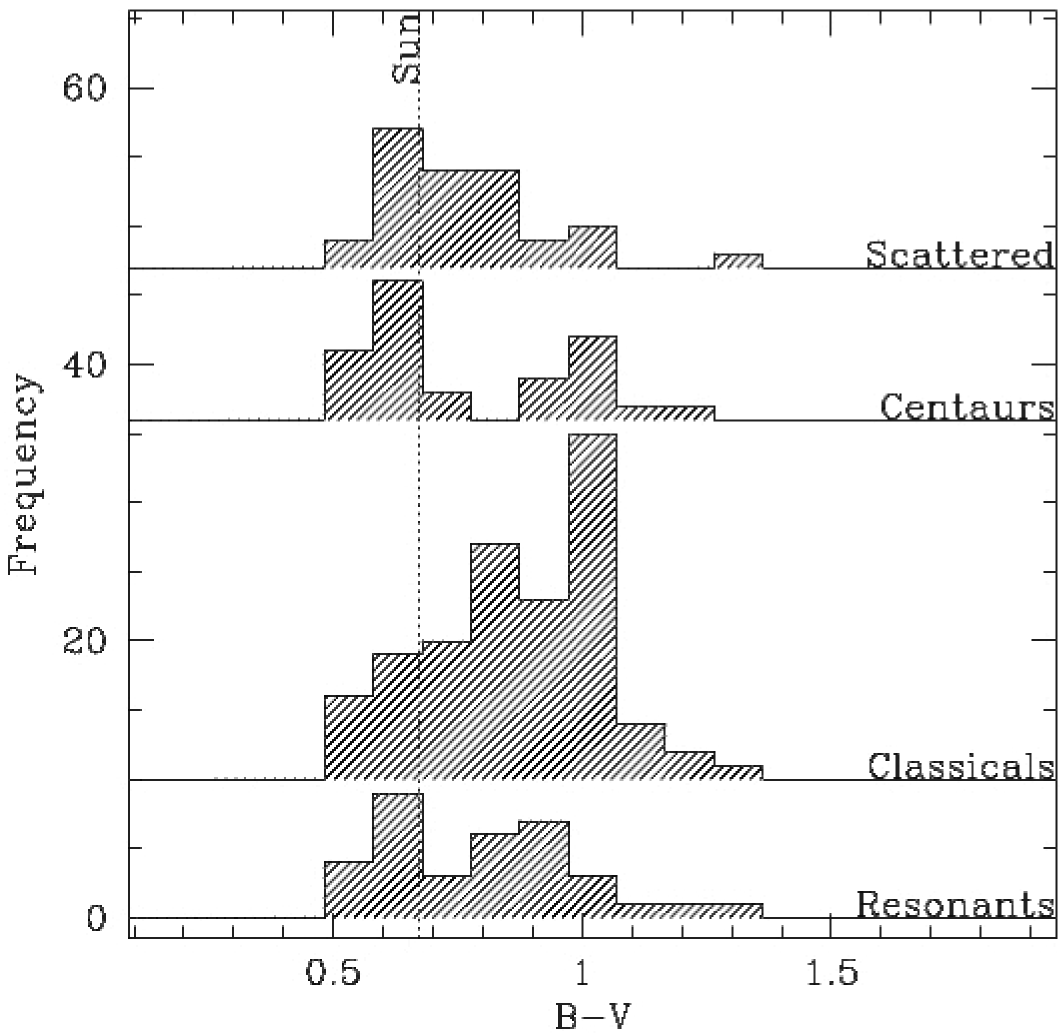
(at the ~3.5 sigma level: Peixinho et al 2004).

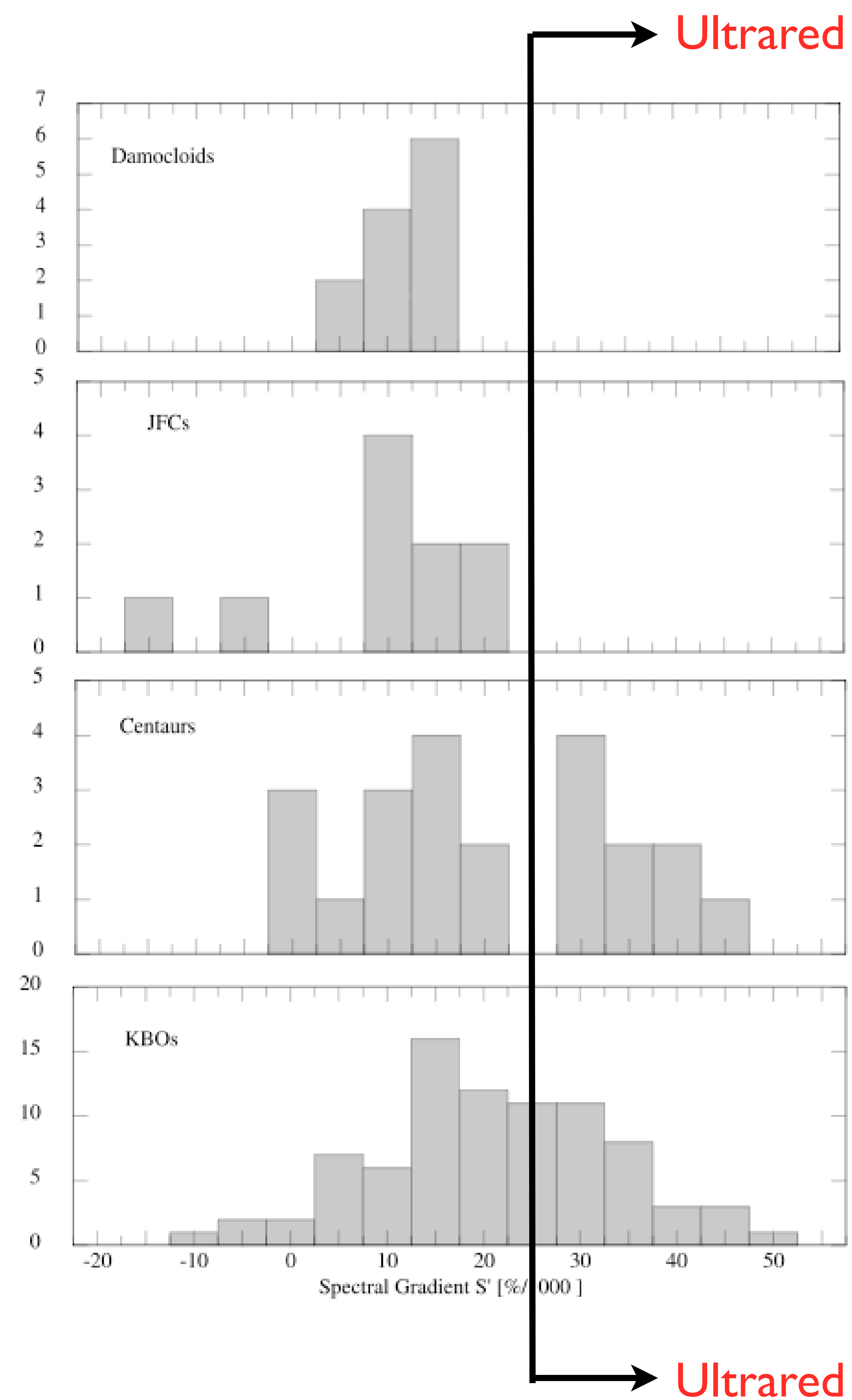
Why? Evolutionary effect? Real?





Ultra-red (organic?) matter exists only in the Kuiper belt and Centaur objects, not in the JFCs, dead-JFCs, Damocloids or Trojans





Ultra-red (organic?) matter exists only in the Kuiper belt and Centaur objects, not in the JFCs, dead-JFCs, Damocloids or Trojans

Albedos

* The really important albedo is the

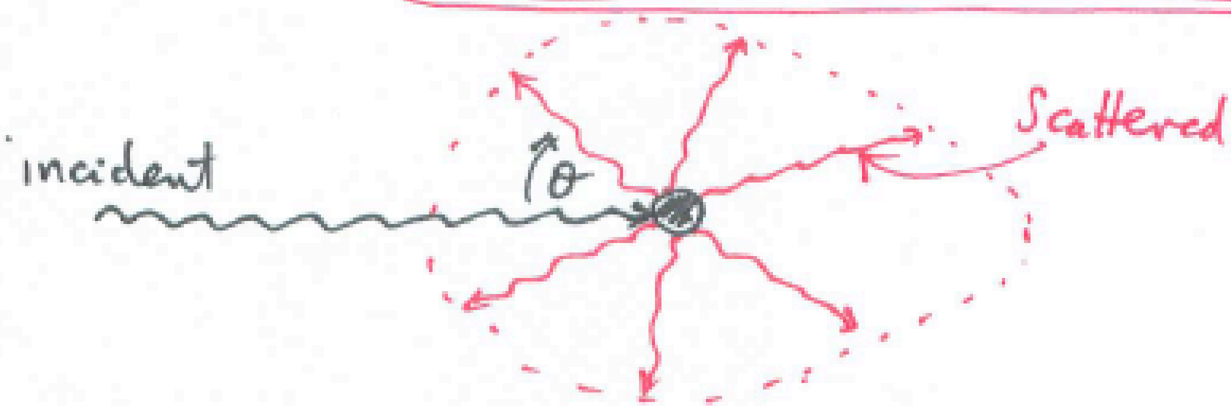
Bond Albedo
$$A = \frac{\text{scattered power}}{\text{incident power}}$$

But this is not easily measurable (need data over all λ and all directions, (θ, ϕ)).

A controls the temperature.

Measurable albedo is

Geometric Albedo
$$p = \frac{\text{flux density scattered at } \theta = 0}{\text{incident flux density}}$$



These are related by $A = p\, q$ ← "phase integral"

$$q = \frac{\int I(\theta,\phi)\, d\Omega}{\pi\, I(0)} = 2\frac{\int I(\theta,\phi) \sin\theta\, d\theta\, d\phi}{I(0)}$$

eg: Earth $p_V \sim 0.37$, $A \sim 0.29$

Very roughly, $q \sim \frac{1}{2}$ to 1, usually unknown.

Optical Flux Density $f_{optical} \propto \pi r^2 p_{optical}$

Thermal Flux Density $f_{IR} \propto \pi r^2 (1 - A)$

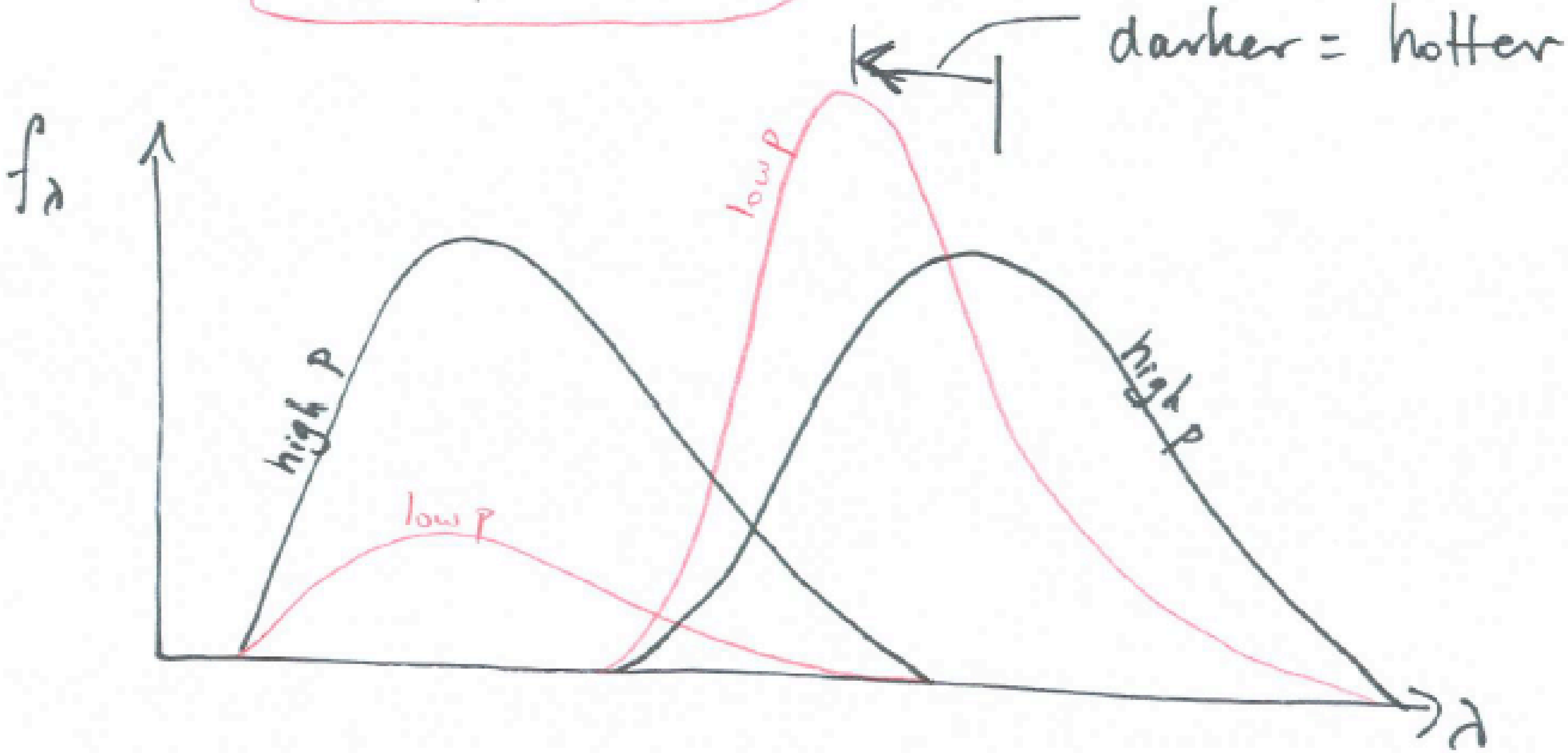
$\sim \pi r^2 (1 - p_{IR})$

So, two constraints ($f_{optical}$, f_{IR}) on two unknowns (radius r and albedo p).

There are many messy details.

eg: $p_{optical} \neq p_{ir}$, q unknown

$p_{ir} \neq A$



Rayleigh-Jeans (e.g. JCMT, IRAM. ALMA in the future)

$$D = \lambda\Delta\left(\frac{2S_\nu}{\pi k \epsilon_{\rm sm}}\right)^{1/2}\left(\frac{\sigma R^2}{F_{\rm Sun}}\right)^{1/8}\left(\frac{\epsilon_{\rm ir}\chi}{1-A}\right)^{1/8}$$

Planck Maximum (e.g. Spitzer)

$$F_{\rm vis}(\lambda_{\rm vis}) = \frac{F_\odot(\lambda_{\rm vis})}{[r/(1\ {\rm AU})]^2} R^2 p \frac{\Phi_{\rm vis}(\alpha)}{\Delta^2} ,$$

$$F_{\rm mir}(\lambda_{\rm mir}) = \epsilon \int B_\nu(T(pq, \eta, \epsilon, \theta, \phi), \lambda_{\rm mir}) d\phi\, d(\cos\theta) \times R^2 \frac{\Phi_{\rm mir}(\alpha)}{4\pi\Delta^2} ,$$

Which is better?: you be the judge.

Bottom Line: need to compare optical data (scattered flux density) with thermal data.

Problems:
1). Optical/IR data should be simultaneous to avoid complications from rotation

1). Surface temperature distribution must be modeled to calculate the emitted flux density. But latter depends on unknown thermal properties (thermal diffusivity) AND on rotational state. Model dependent.

2). Distant objects are cold: Planck maximum blocked by Earth's atmosphere (e.g. T = 50 K, Planck max ~ 60 microns).

Two solutions:
a) measure thermal Planck maximum from space (e.g. Spitzer)
b) measure the Rayleigh-Jeans tail (submillimeter)

Near Planck Maximum:

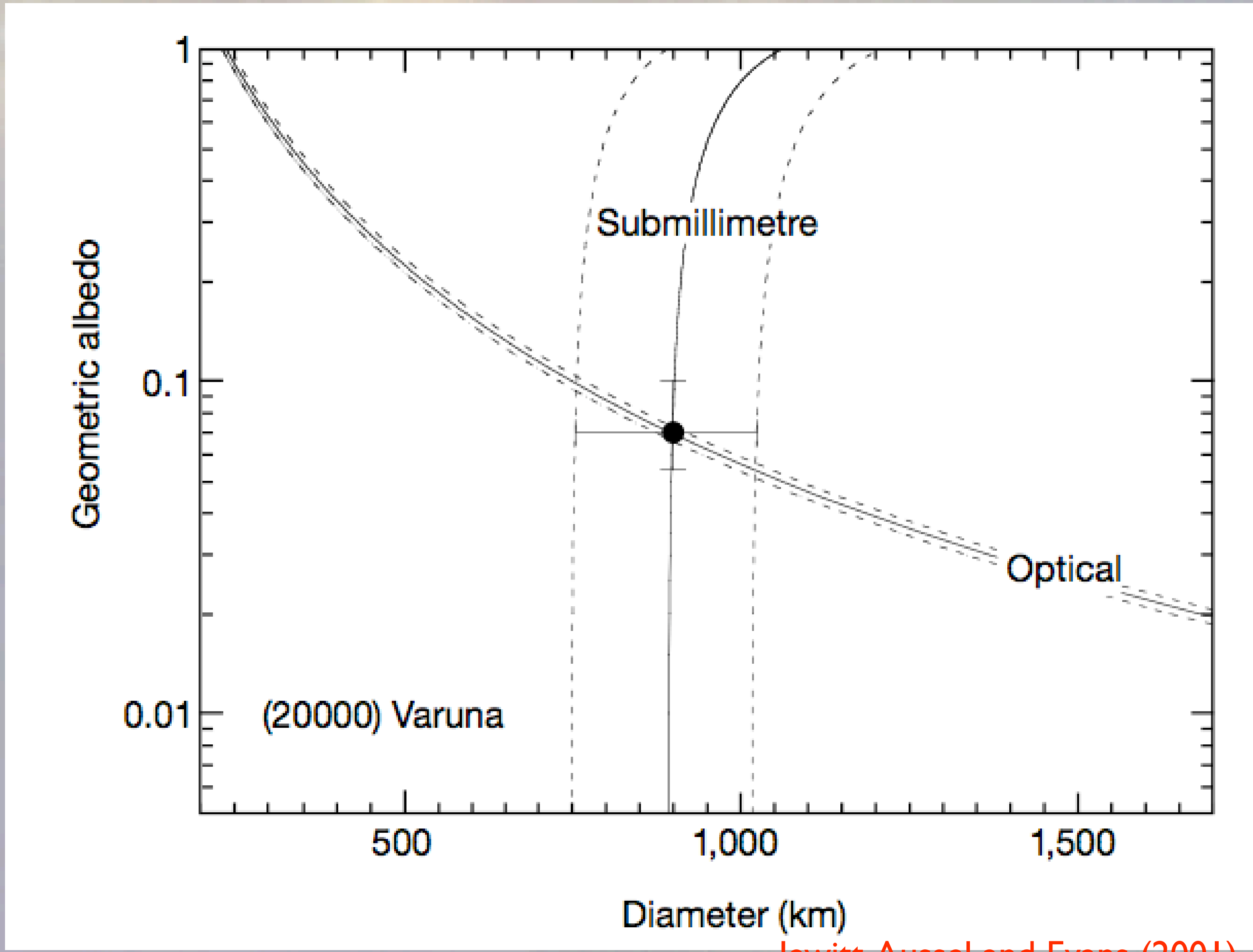
Advantage: flux density very high.
Problem: interpretation is very model-dependent. Must have 2 or more thermal wavelengths to get a good solution.

Rayleigh-Jeans Tail:
Advantage: weak model dependence
Problem: flux density very low

Of these two, the Rayleigh-Jeans approach is much more robust, when it is possible.

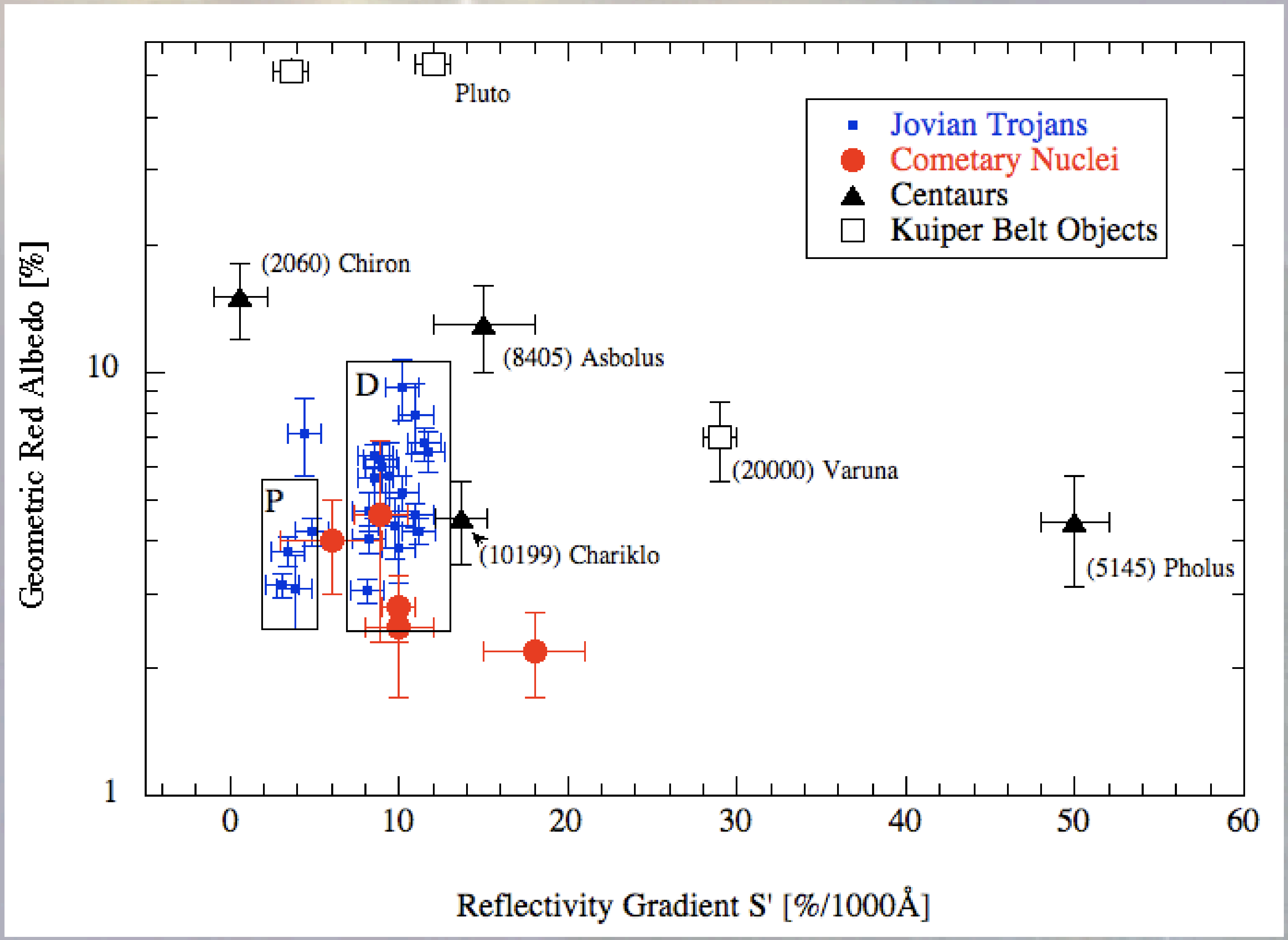
Will be a BIG application of ALMA for Kuiper Belt at ~800 μm.

$$D = \lambda\Delta\left(\frac{2S_\nu}{\pi k \epsilon_{\rm sm}}\right)^{1/2}\left(\frac{\sigma R^2}{F_{\rm Sun}}\right)^{1/8}\left(\frac{\epsilon_{\rm ir}\chi}{1-A}\right)^{1/8}$$



Jewitt, Aussel and Evans (2001)

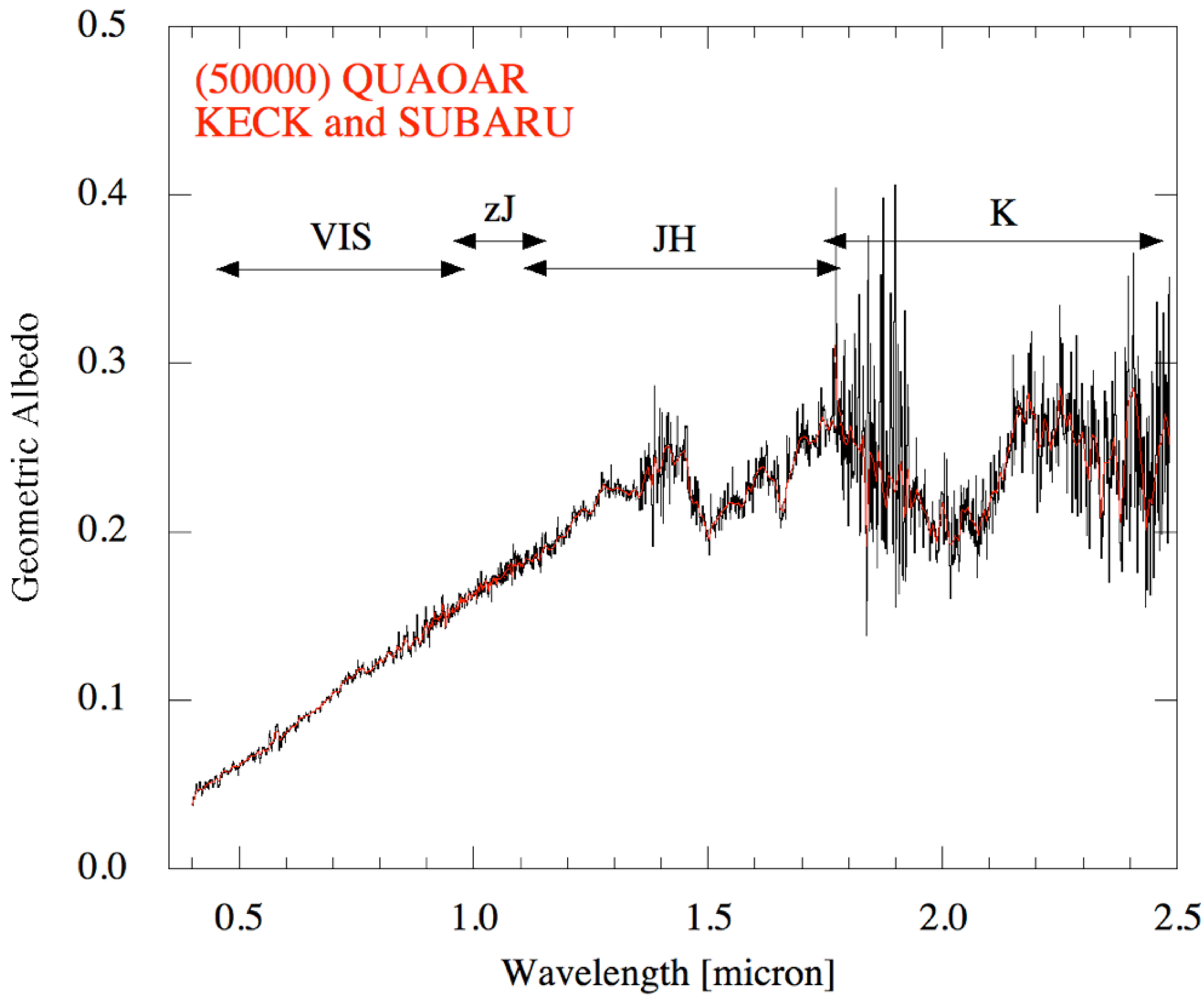
Submm advantage: very weak dependence on emissivity, albedo and other unknowns



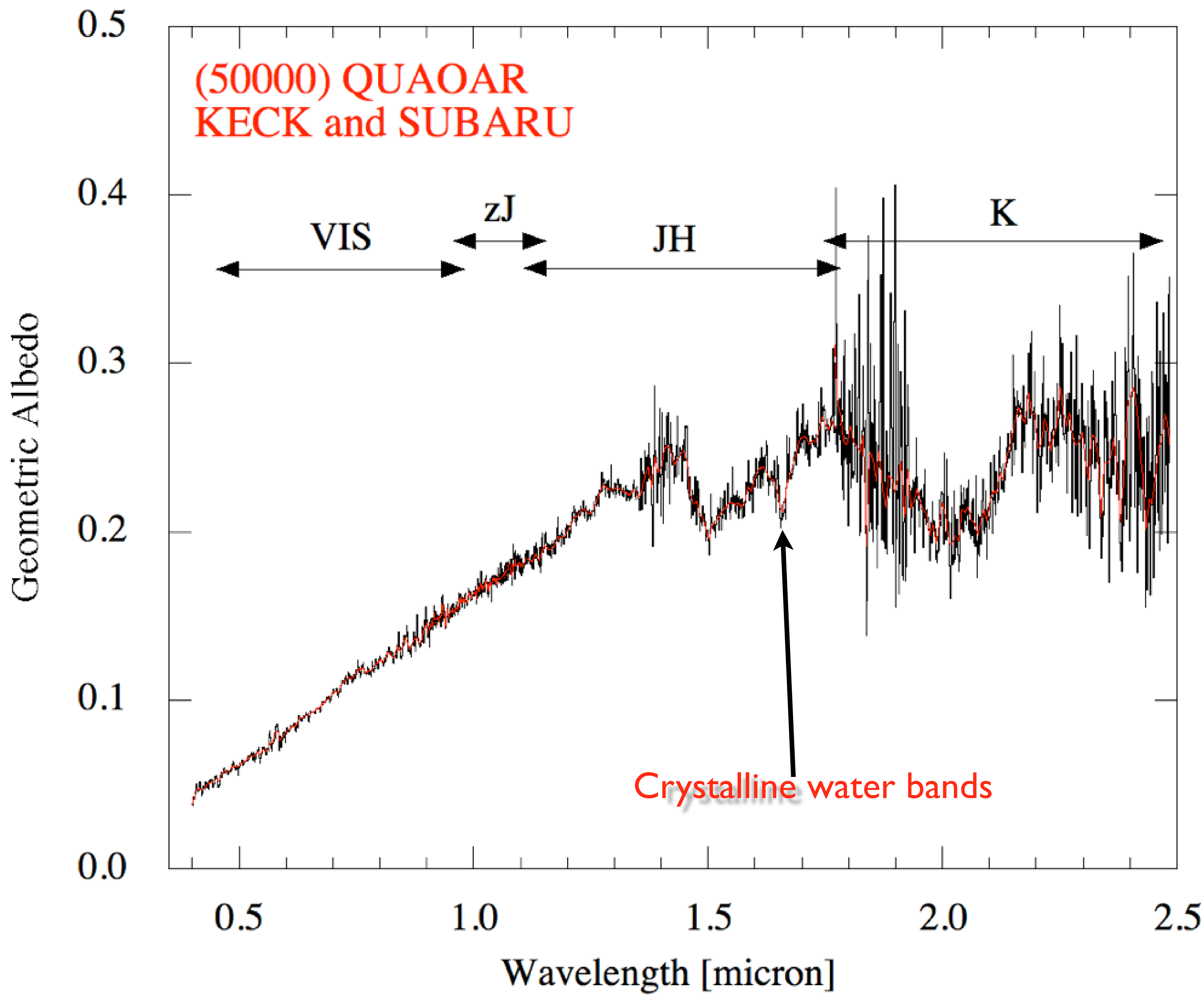
Jewitt (2007) Saas Fee Lectures

Big spread in colors AND albedos: why?

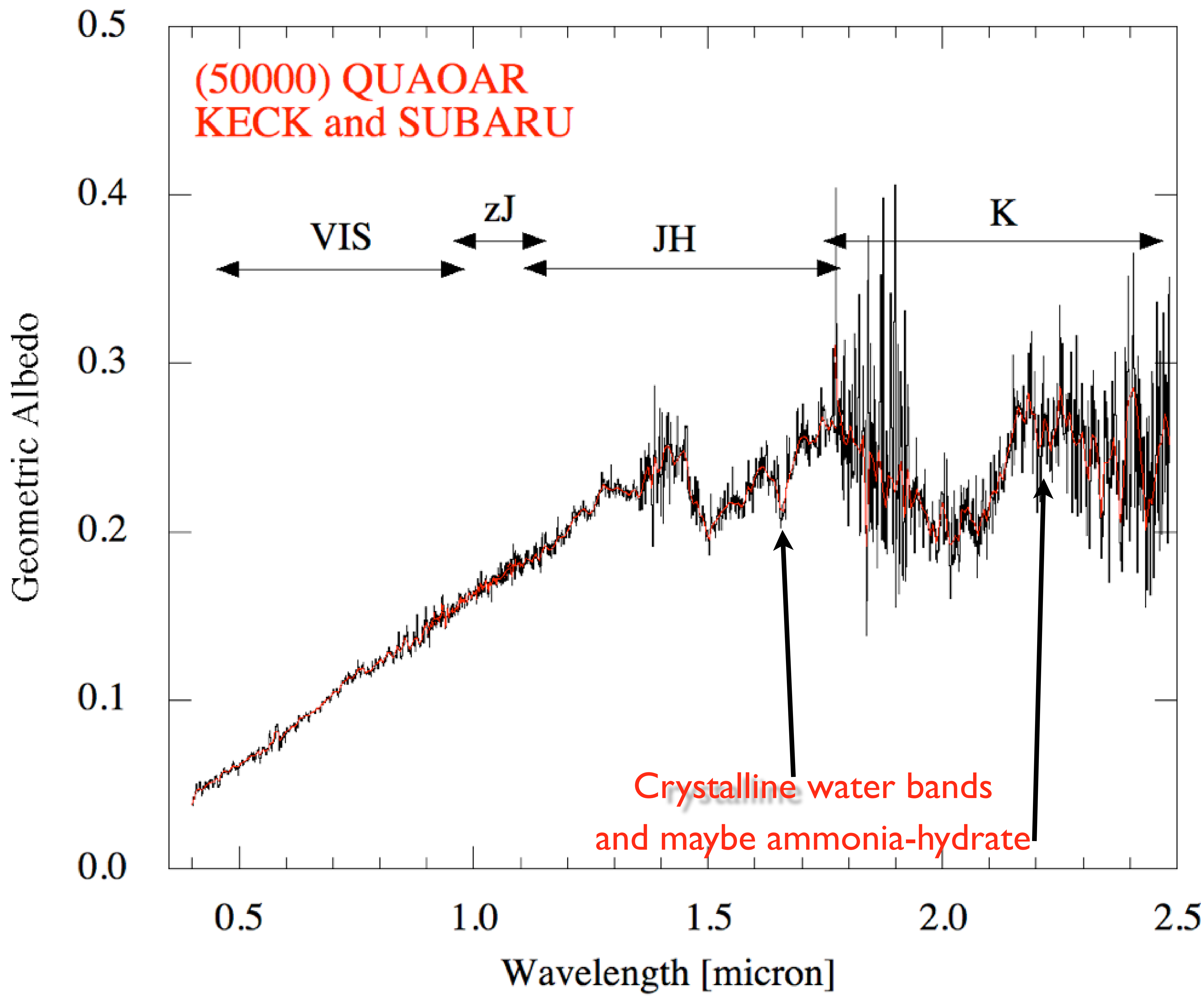
KBO Spectra



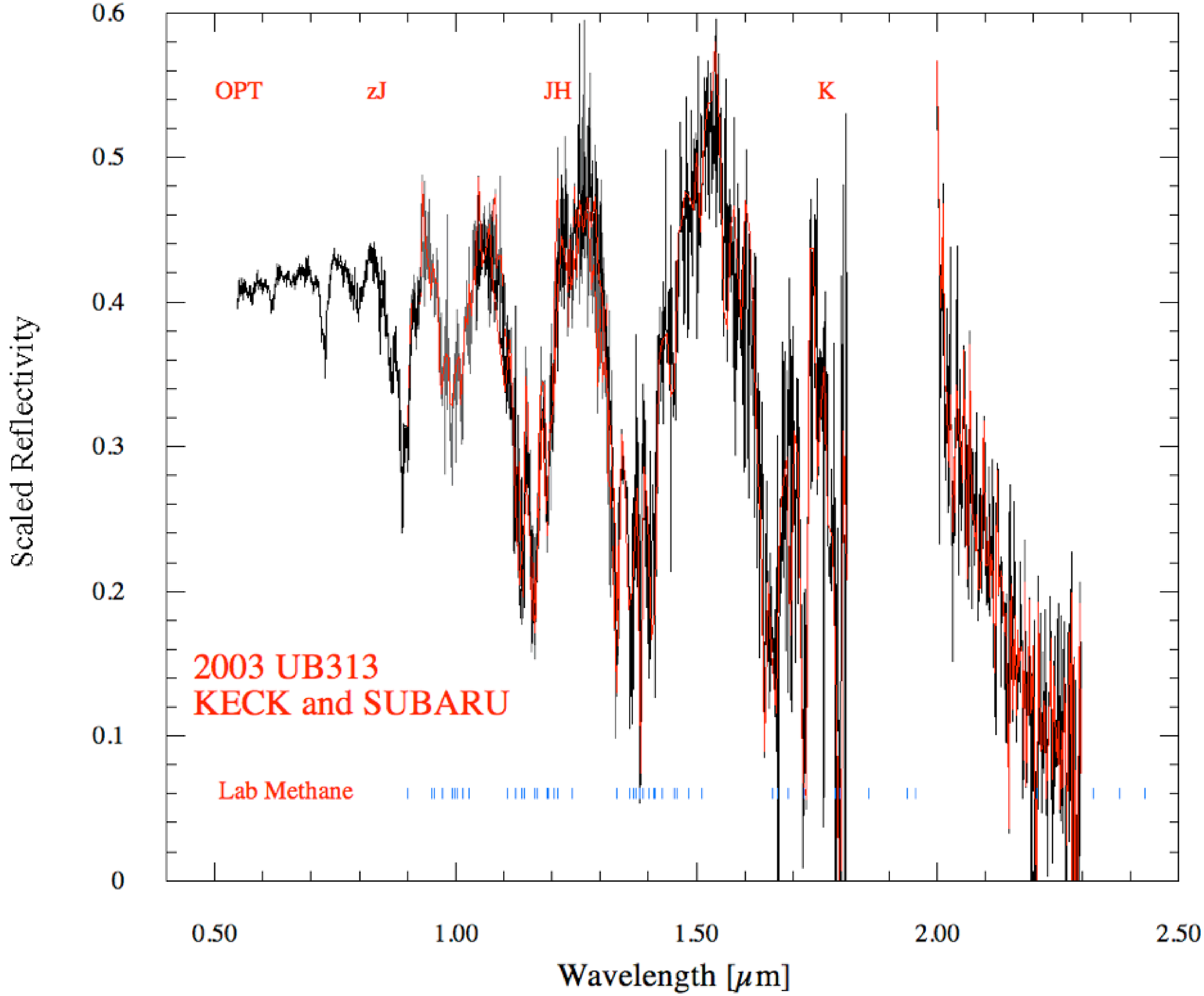
Jewitt and Luu (2004)



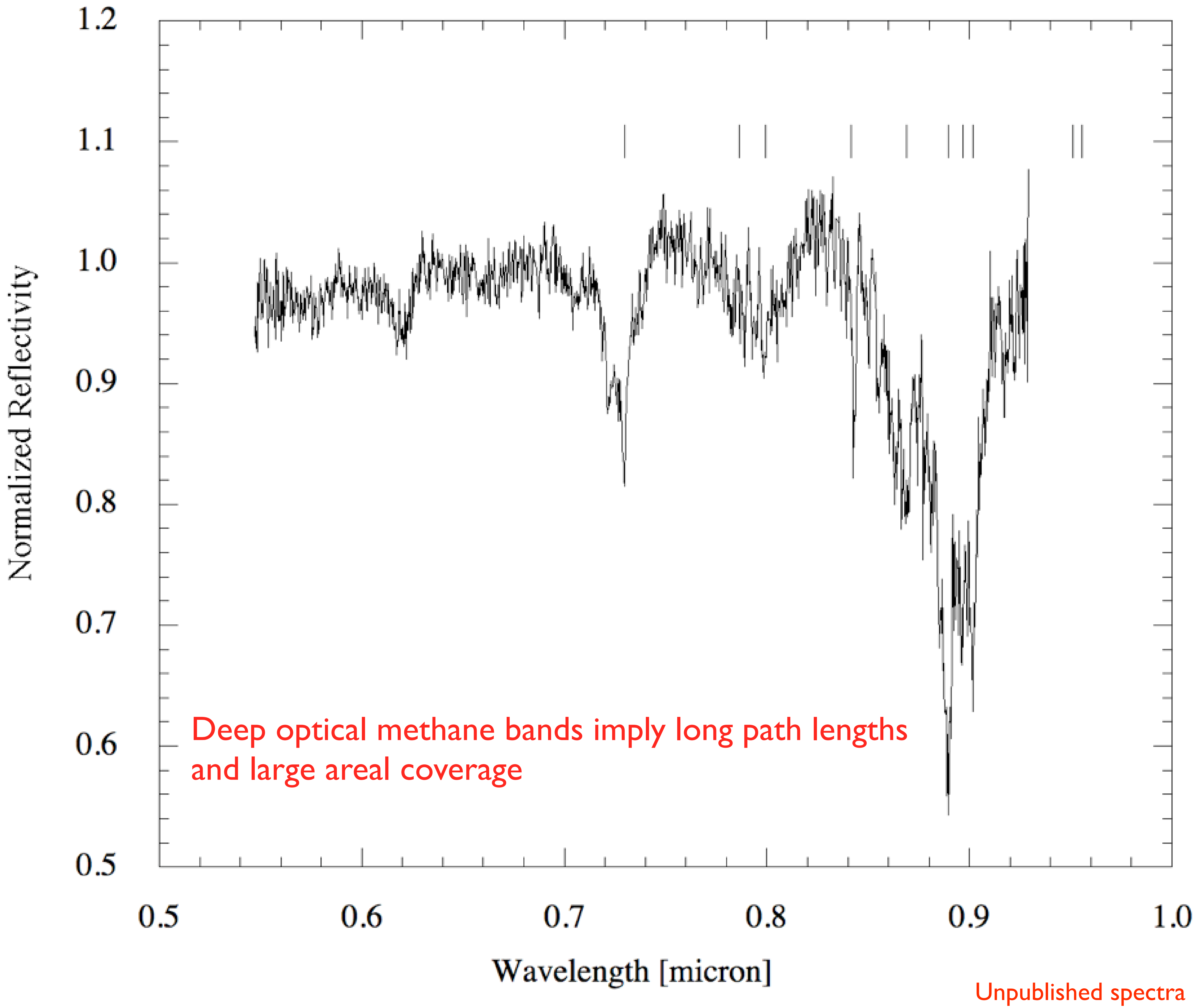
Jewitt and Luu (2004)

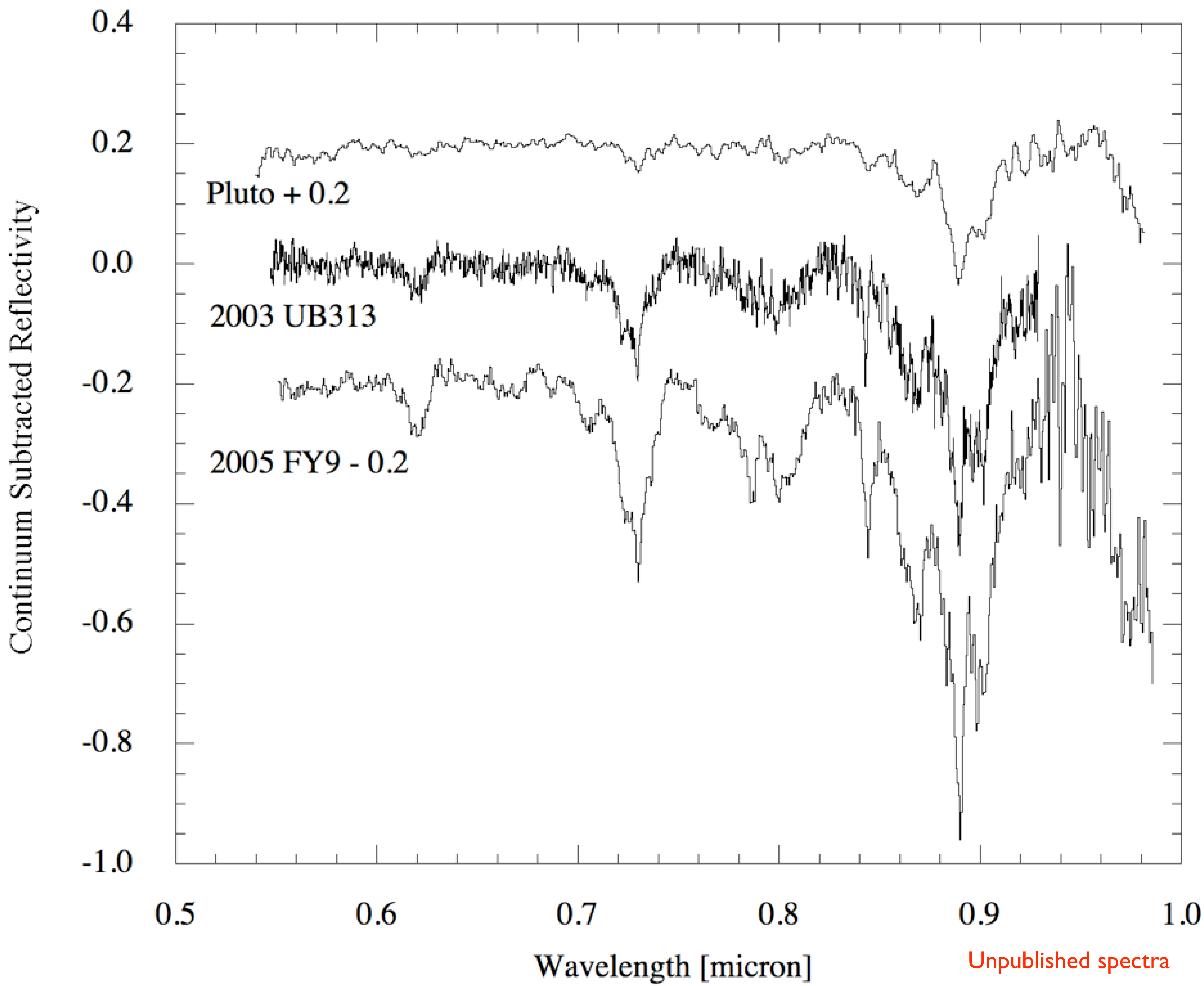


Jewitt and Luu (2004)



Unpublished spectra


Normalized Reflectivity
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.5
0.6
0.7
0.8
0.9
1.0
Wavelength [micron]
Deep optical methane bands imply long path lengths and large areal coverage
Unpublished spectra



Unpublished spectra

Compositional Diversity

1 Water-dominated objects (N ~ 7)

2 Methane-dominated objects (N = 4)

3 Featureless objects (N ~ 10 but these could be artifacts of inadequate signal-to-noise ratio, with bands yet-to-be detected).

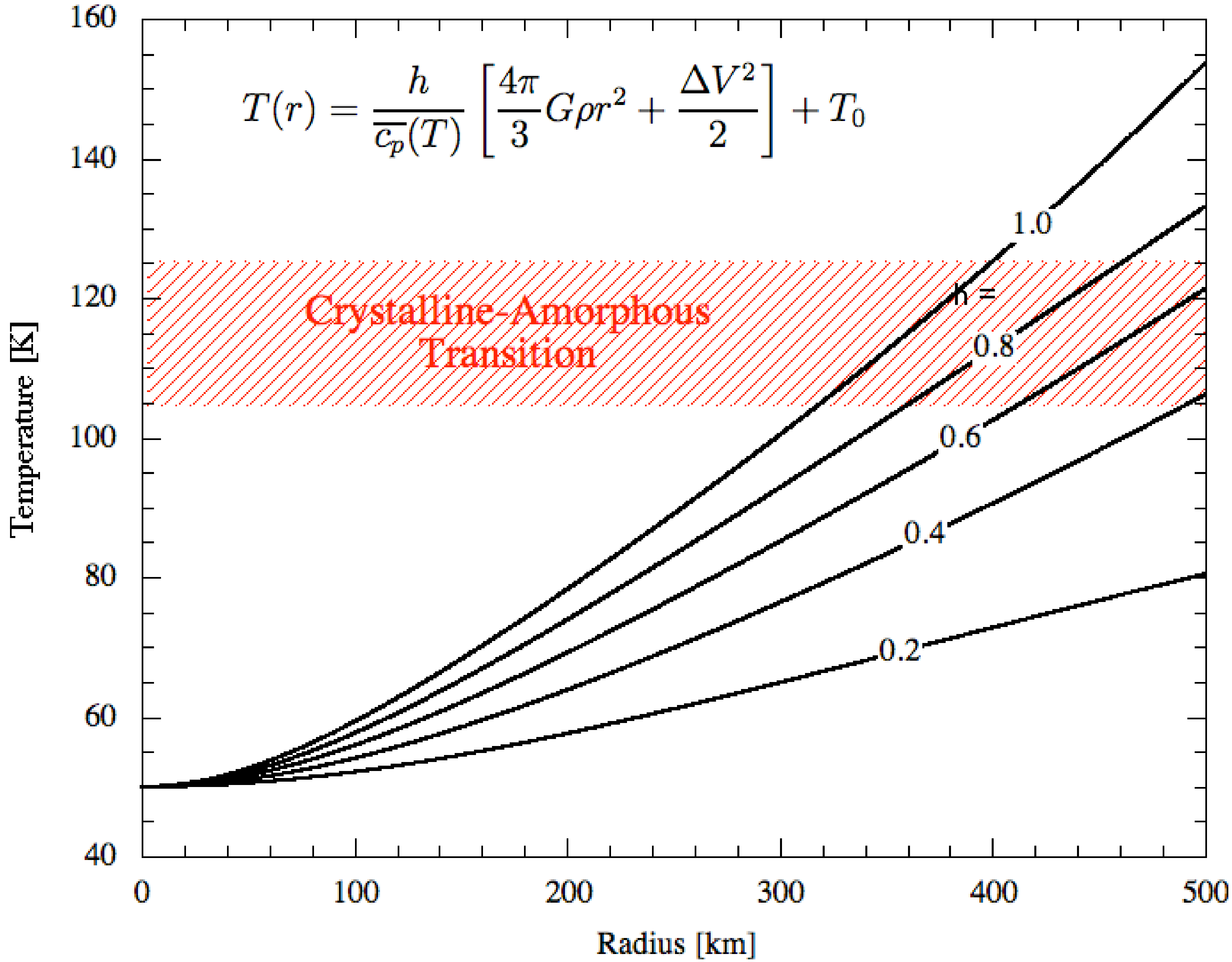
The largest KBOs seem to be methane-dominated.

Why?

What is the source of the methane? → Clathrate delivery?

→ Serpentinization + Fischer-Tropsch?

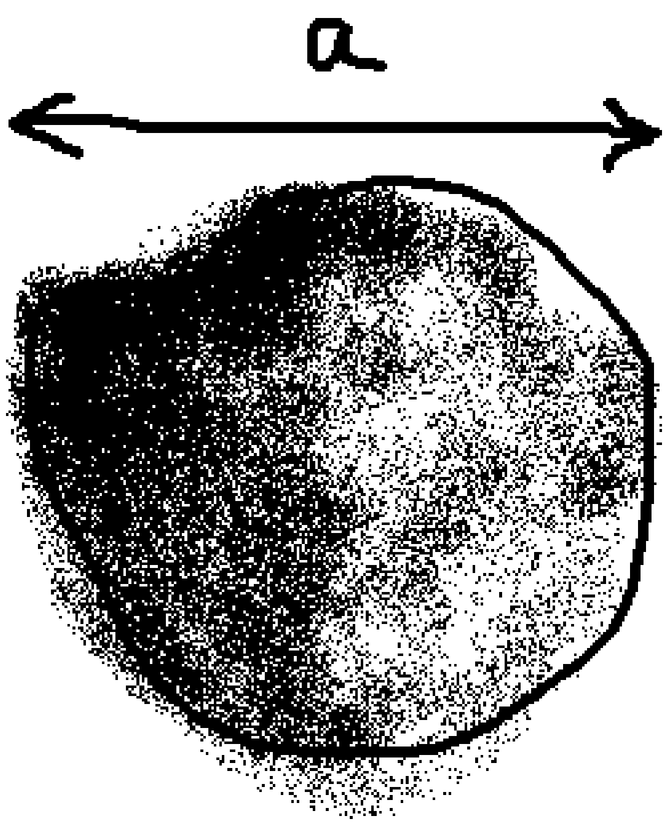
The crystalline water ice band and possible serpentinization both imply heating.



Unpublished spectra

Solid Bodies - heat transport by conduction

Conduction timescale $\sim \dfrac{\text{heat content}}{\text{heat loss rate}}$



$$\tau_c \sim \frac{m\, c_p T}{4\pi a^2 k\, dT/da}$$

Put $\dfrac{dT}{da} \sim \dfrac{T}{a}$; $m \sim \dfrac{4\pi}{3}\rho a^3$

$$\tau_c \sim \frac{\rho a^3 c_p T}{a^2 k\,(T/a)}$$

So $\boxed{\tau_c \sim \left(\dfrac{\rho c_p}{k}\right) a^2 \equiv \dfrac{a^2}{\kappa}}$

[κ = thermal diffusivity $\equiv k/(\rho c_p)$]

Dielectric solids $k \sim 1\ \mathrm{W\,m^{-1}K^{-1}}$, $\rho \sim 10^3\ \mathrm{kg\,m^{-3}}$, $c_p \sim 10^3\ \mathrm{kg\,m^{-3}}$

So $\kappa \sim 10^{-6}\ \mathrm{m^2 s^{-1}}$

Porous dielectrics $\kappa \sim 10^{-7}\ \mathrm{m^{+2} s^{-1}}$

eg: Set $\tau_c = 4.5$ Gyr (age of solar system).

$K = 10^{-7}\ m^2 s^{-1}$

Critical size $a_c \sim \sqrt{10^{-7} \times 4.5 \times 10^9 \times 3 \times 10^7} \sim 100$ km

All smaller bodies can cool primordial heat by conduction alone

eg: Set $\tau_c = 10^6 - 10^7$ yr (Centaur lifetime)

Then $a_c \sim \sqrt{10^{-7} \times (10^6 \text{ or } 10^7) \times 3 \times 10^7} \sim 2$ km to 6 km

Larger bodies cannot adjust internal T fast enough to follow local equilibrium.

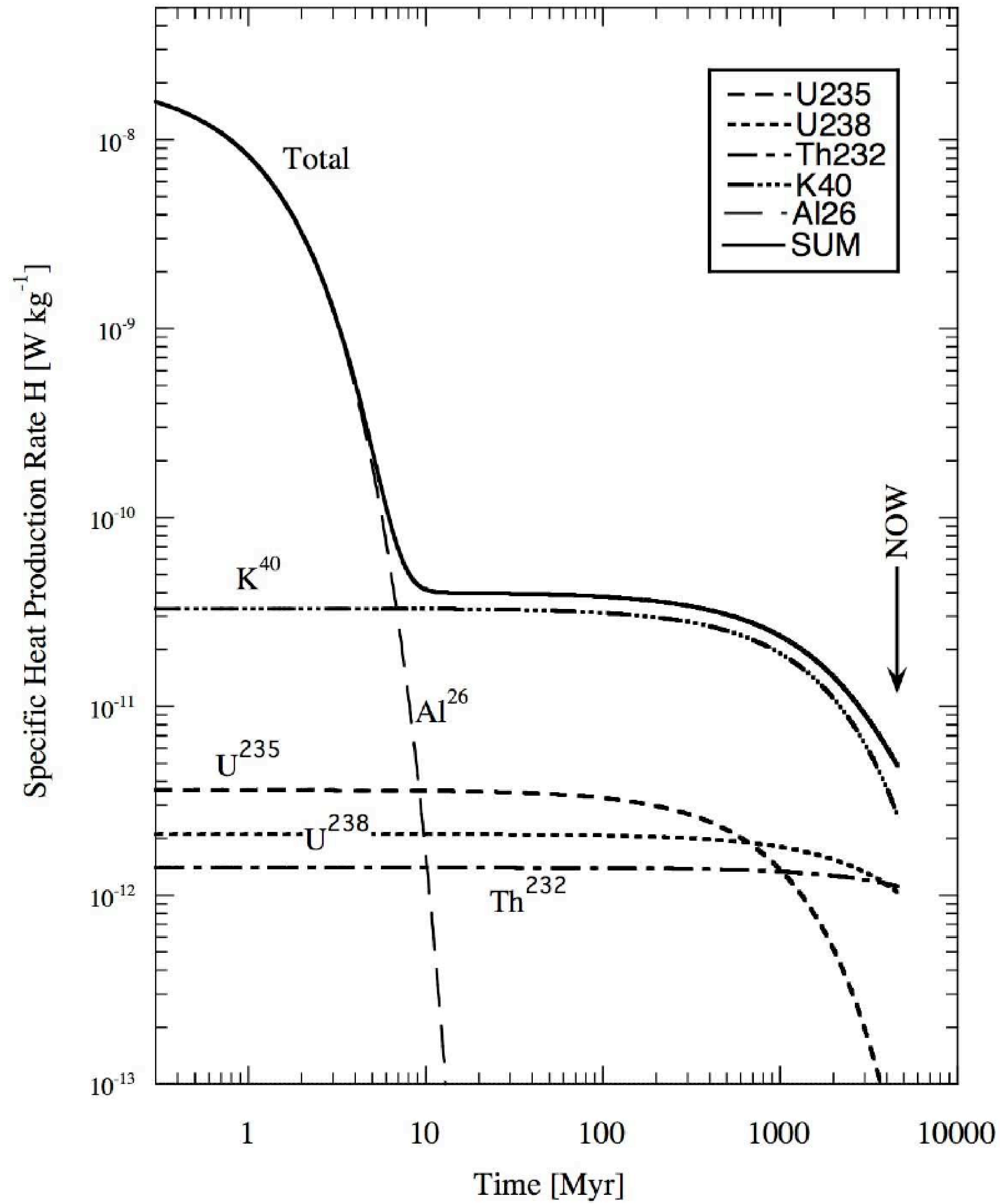
So, Centaurs/comets permanently out of thermal equilibrium

Decay Heating

Isotope	Decay[a]	τ[b]	dH/dt[c]
^{40}K	β: $^{40}\mathrm{K} \rightarrow ^{40}\mathrm{Ar}$	1.82×10^{9}	3.3×10^{-11}
^{232}Th	α: $^{232}\mathrm{Th} \rightarrow$	2.00×10^{10}	1.4×10^{-12}
^{238}U	α: $^{238}\mathrm{U} \rightarrow$	6.50×10^{9}	2.1×10^{-12}
^{235}U	α: $^{235}\mathrm{U} \rightarrow$	1.03×10^{9}	3.6×10^{-12}
^{26}Al	β: $^{26}\mathrm{Al} \rightarrow ^{26}\mathrm{Mg}$	1.06×10^{6}	2.1×10^{-8}

* $Al^{26} \rightarrow Mg^{26}$ potentially huge initial source but magnitude depends on KBO formation time c.f. ½ life of ~ 0.7 Myr.

* Longer lived U, K, Th still cook large KBOs having $\tau \sim a^2/\kappa \gg 4$ Gyr



Surface temperatures ~40 K
Crystallization of water ~110 K
Serpentinization ≥ triple point (liquid water)
Fischer Tropsch ~400 to 500 K

Radioactive decay

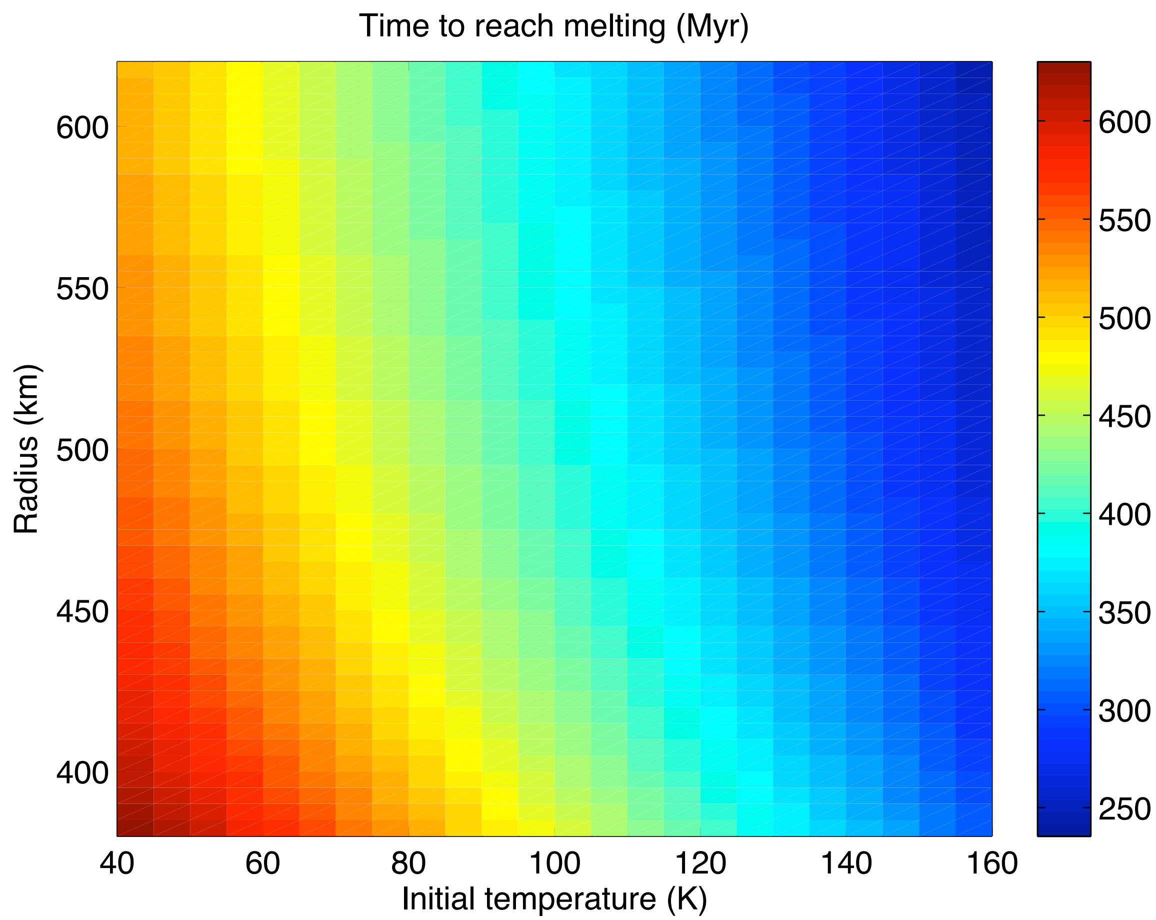
$$H(t) = \sum_i H_0^i exp\left(\frac{-t}{t_i}\right)$$

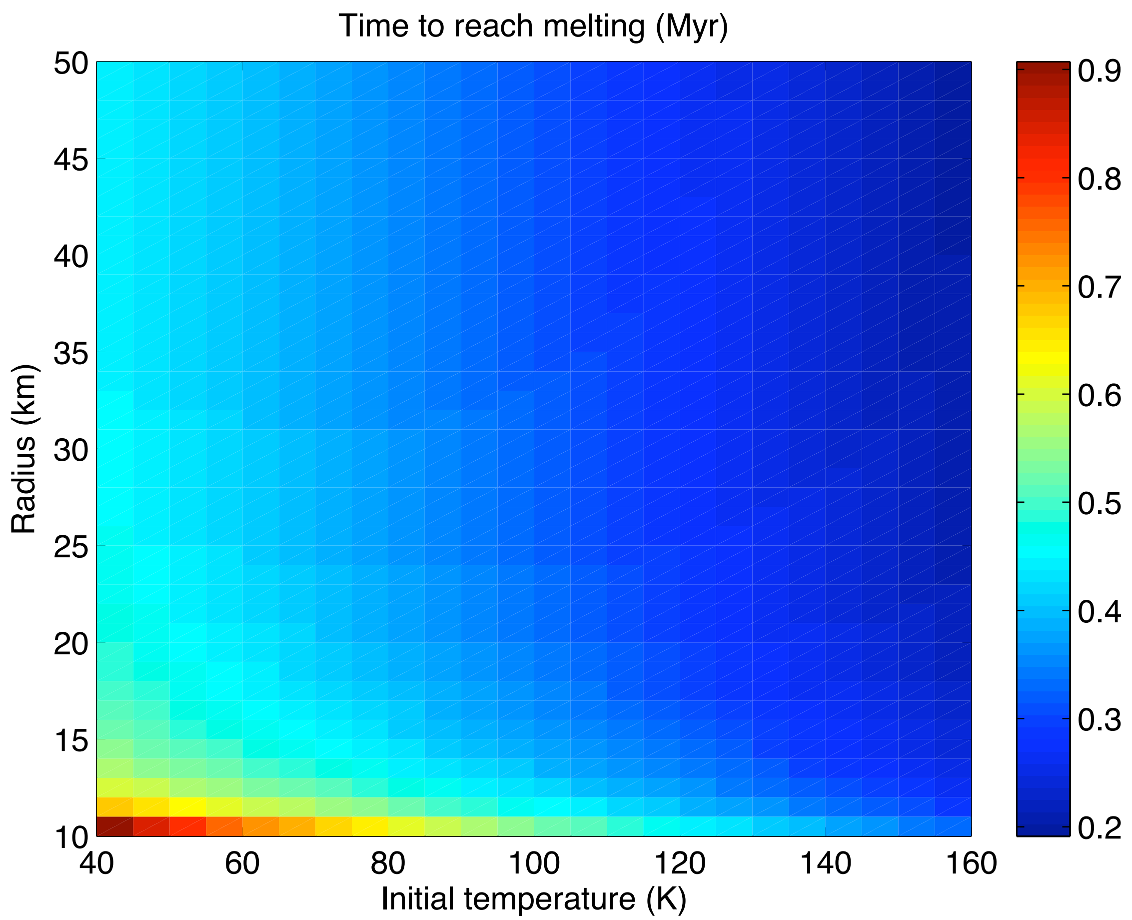
$$M\int_{t_0}^{\infty} H(t)dt = Mc_p\Delta T$$

Isotope	Half Life
Al^{26}	0.717 Myr
Th^{232}	14.05 Gyr
U^{238}	4.468 Gyr
K^{40}	1.277 Gyr

Note: $t_0 \neq 0$ because a finite time elapses between element production (in a supernova) and incorporation into a mineral.

Time to Reach Melting



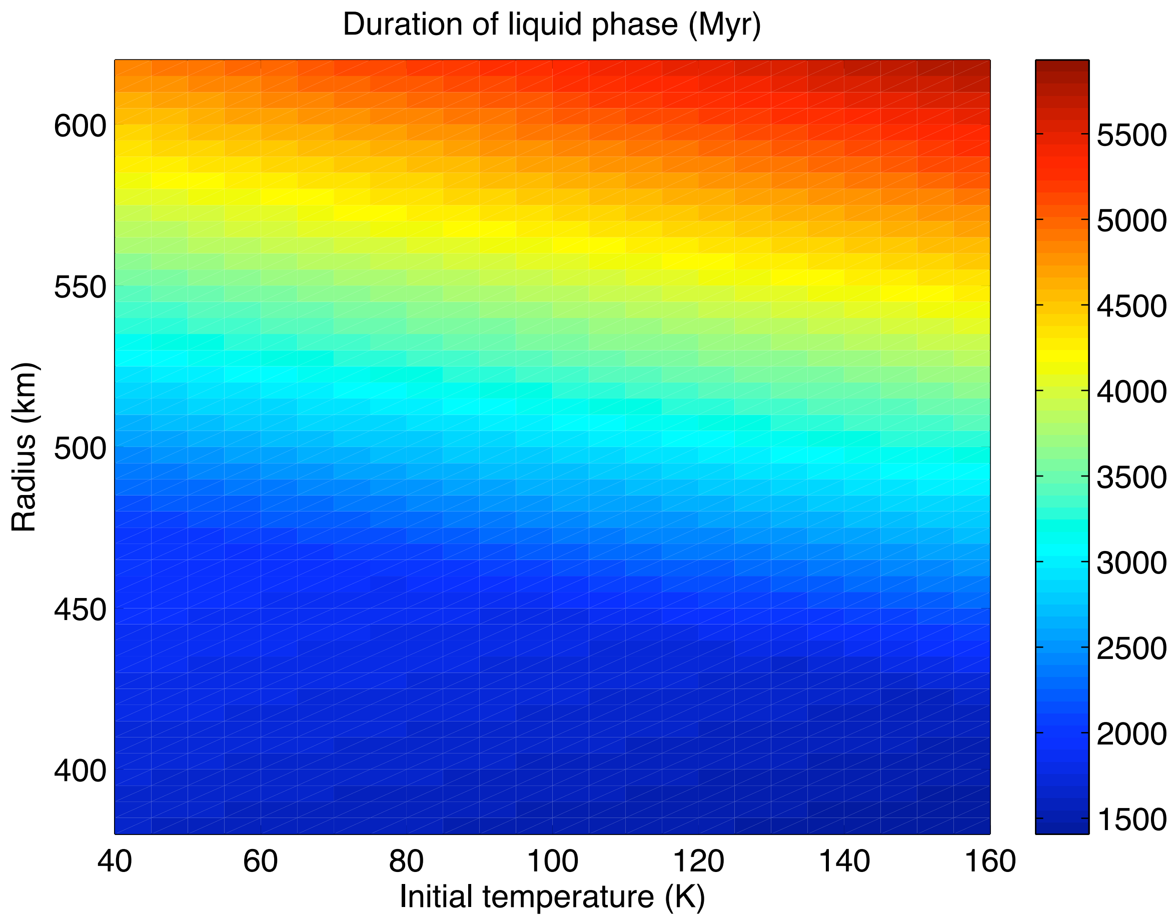


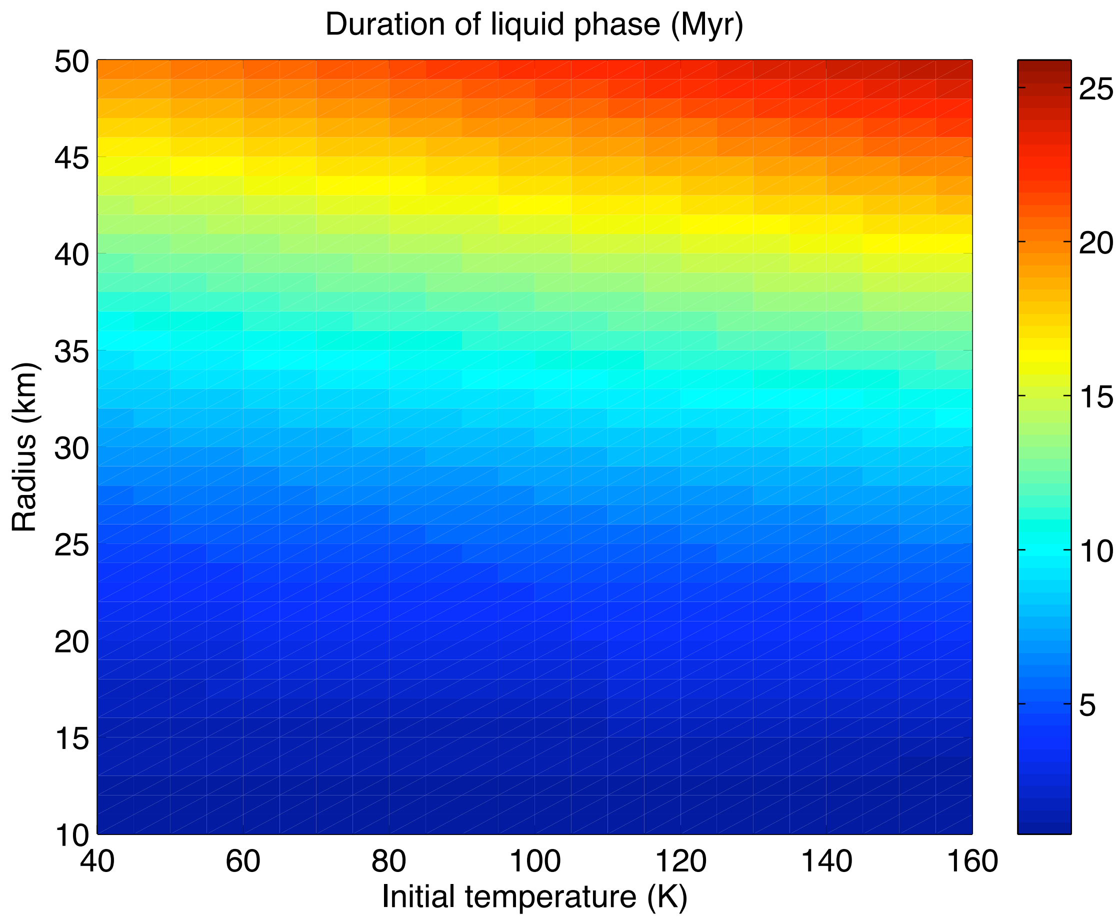
Without 26Al

With 26Al

Models by Dina Prialnik

Duration of Liquid Phase





Without 26Al

With 26Al

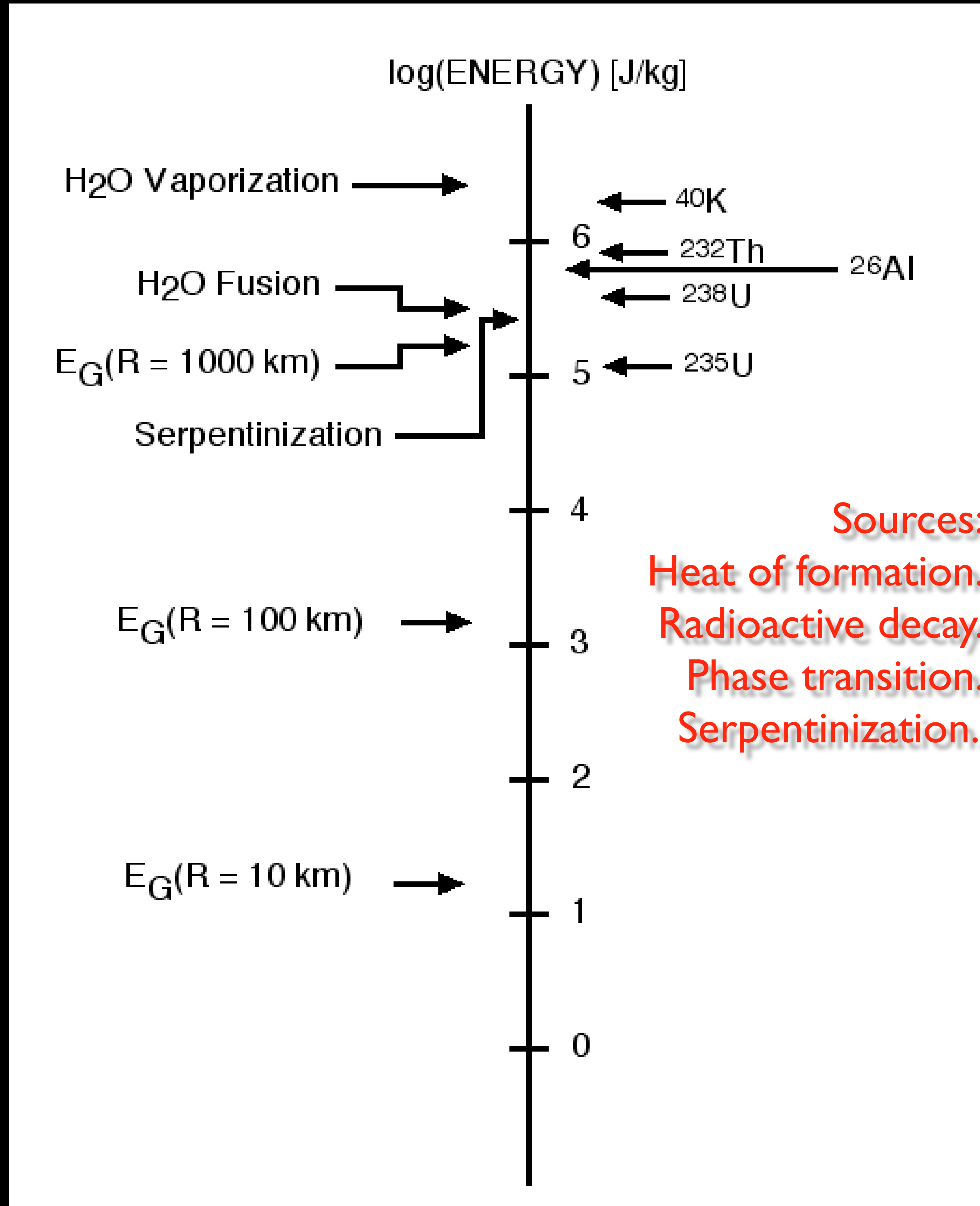
Models by Dina Prialnik

Uranus Satellite Miranda (D ~ 470 km)

i.e. << Varuna

Substantial resurfacing

NASA Voyager

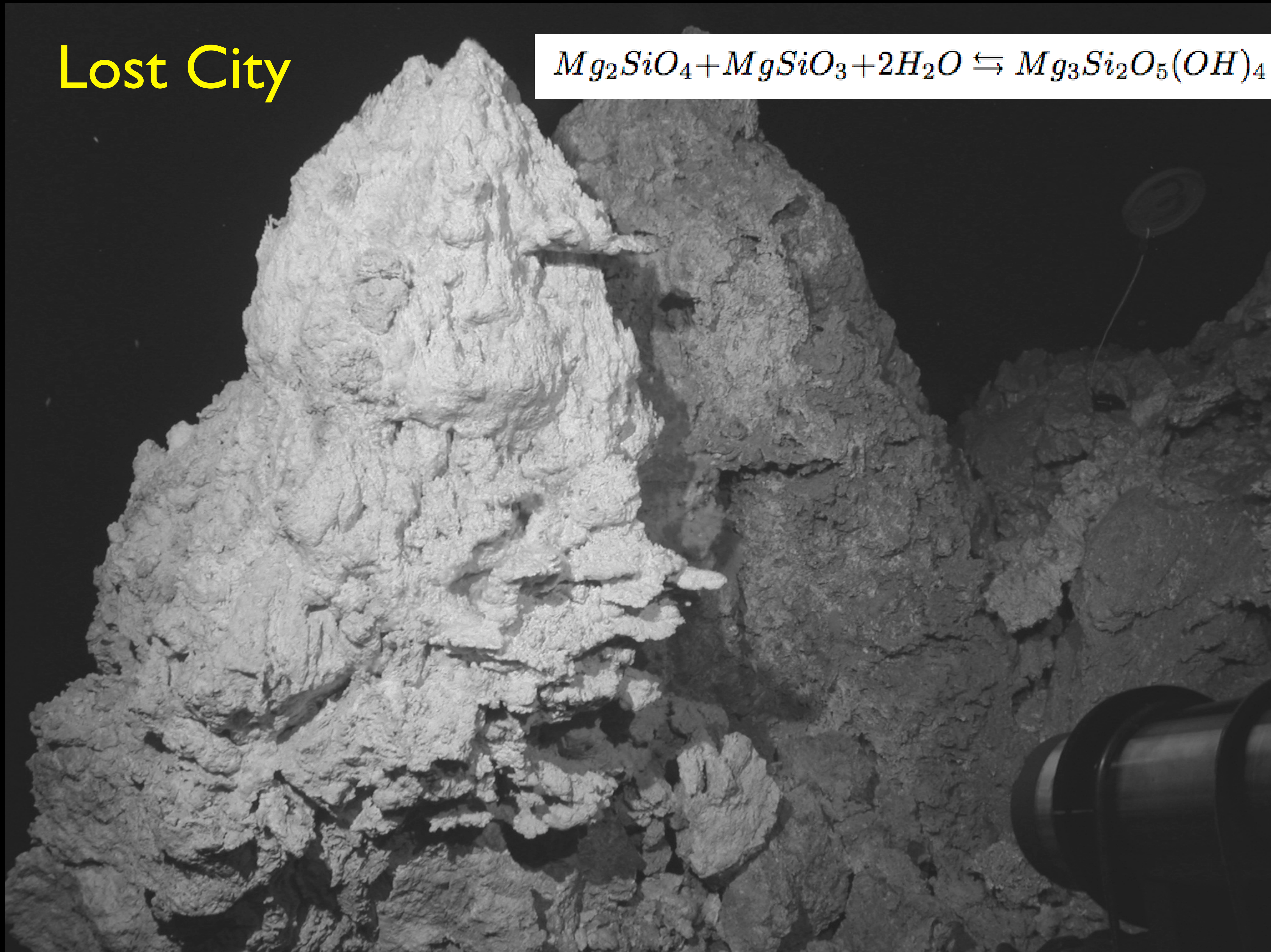


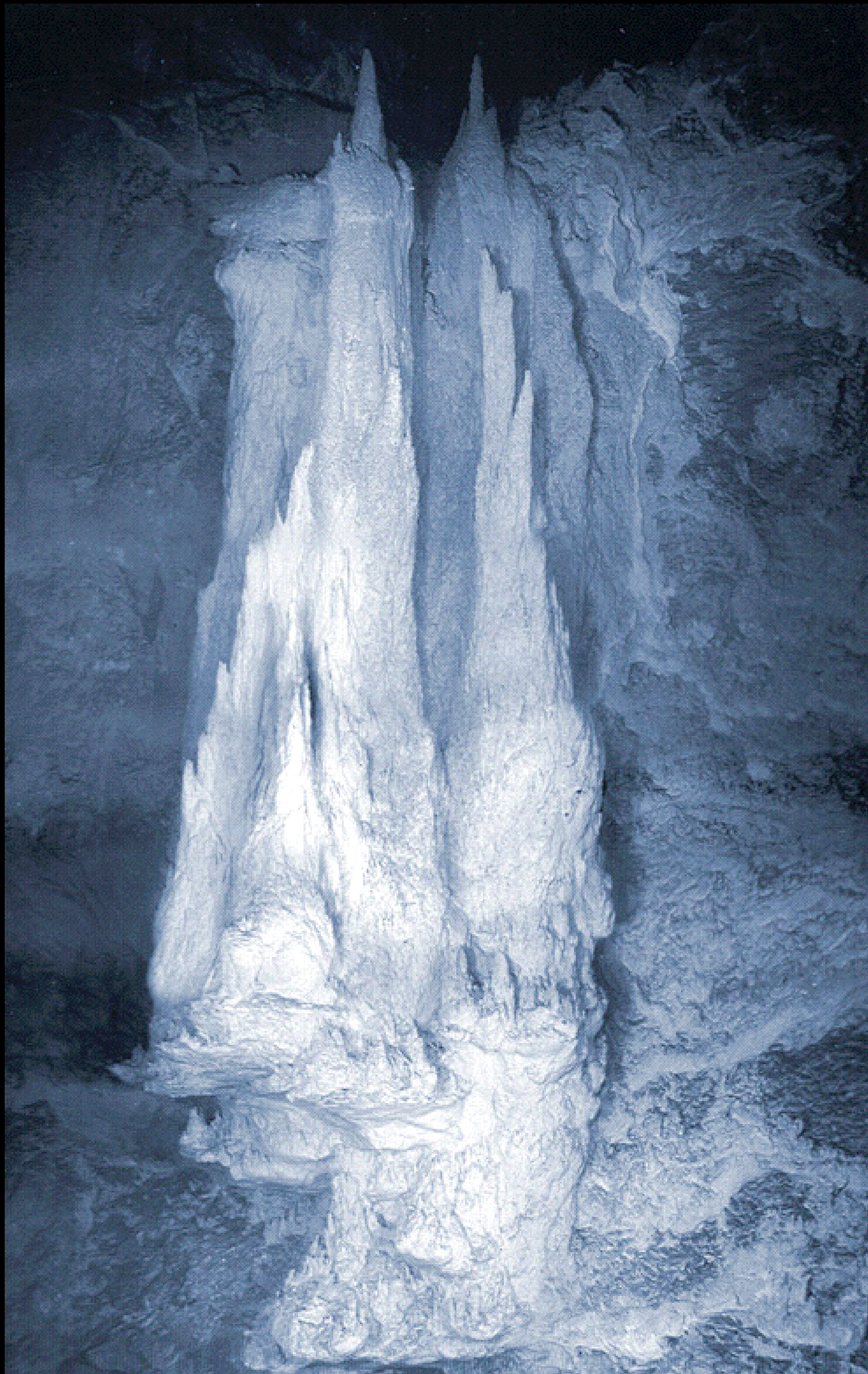
Sources:
Heat of formation.
Radioactive decay.
Phase transition.
Serpentinization.

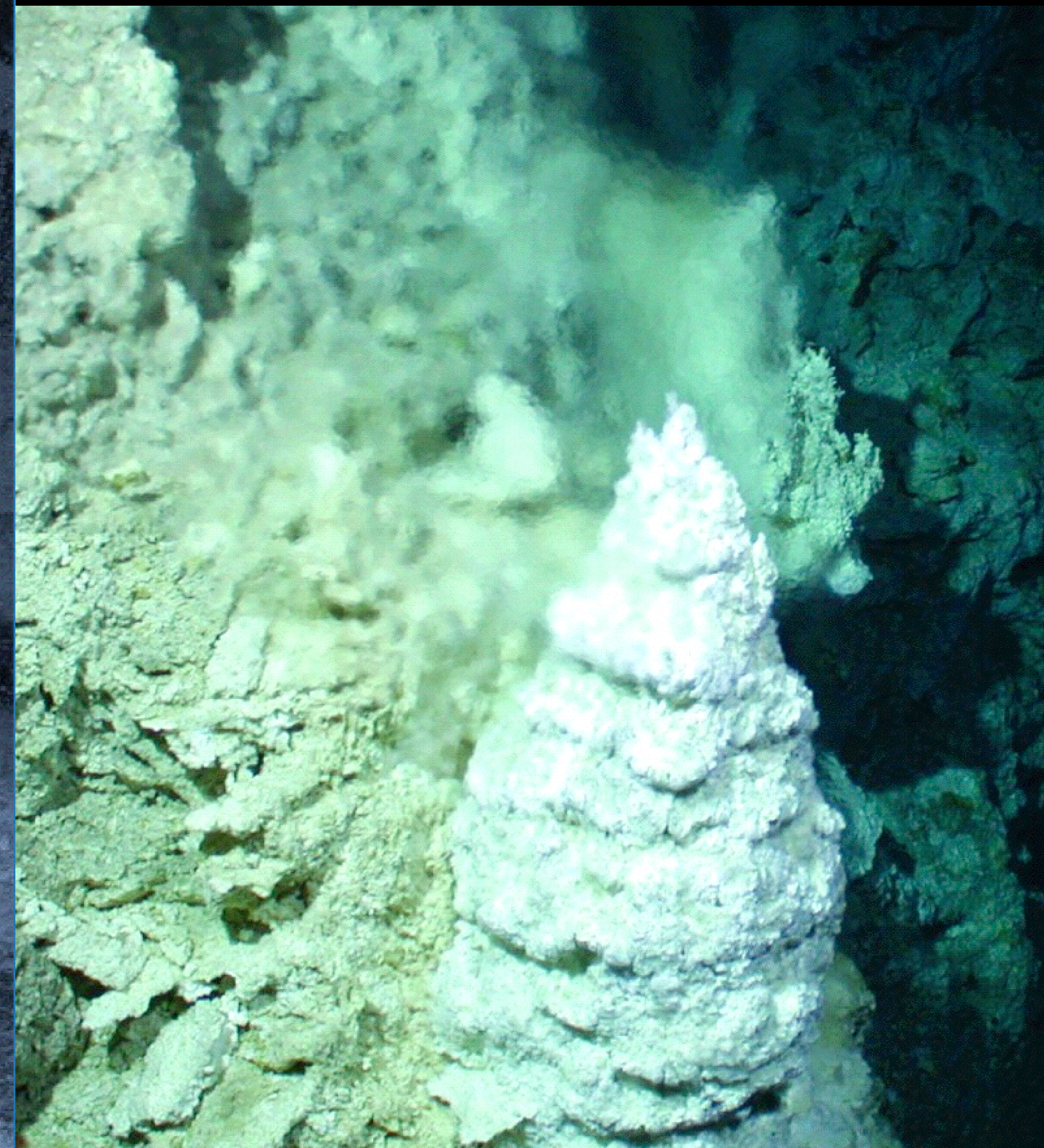
Jewitt et al. 2007 Protostars & Planets V

Lost City

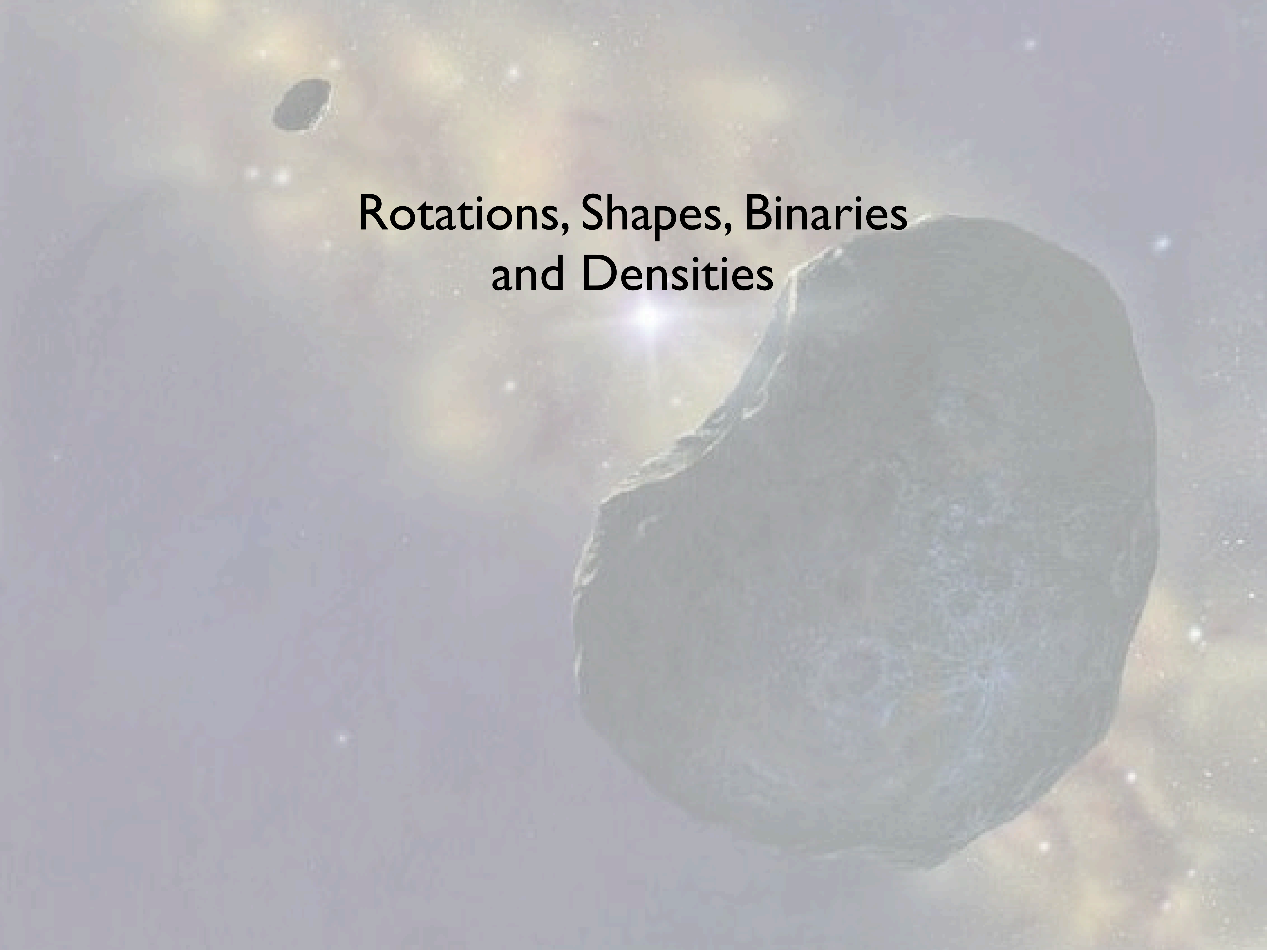
$$Mg_2SiO_4 + MgSiO_3 + 2H_2O \leftrightarrows Mg_3Si_2O_5(OH)_4$$

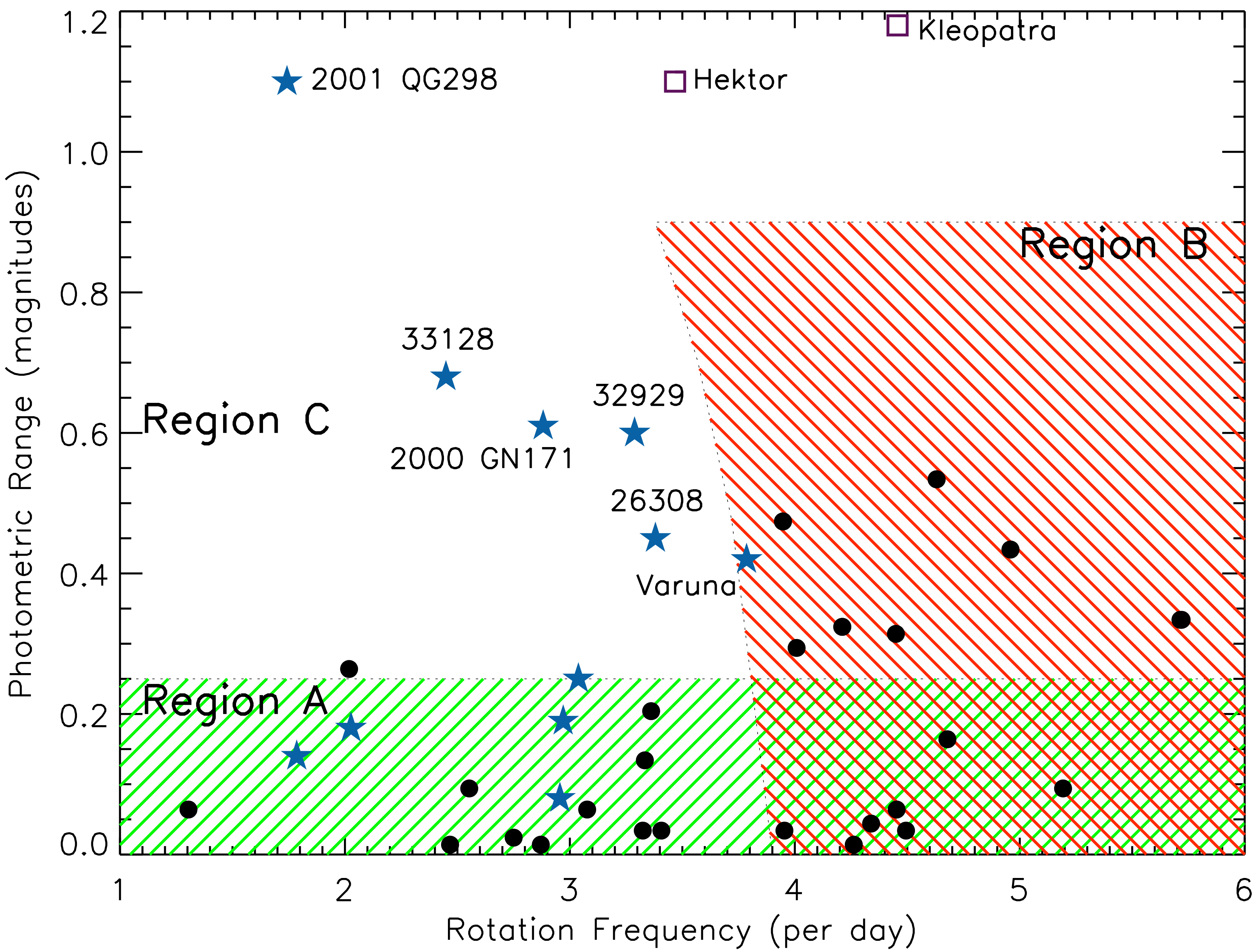






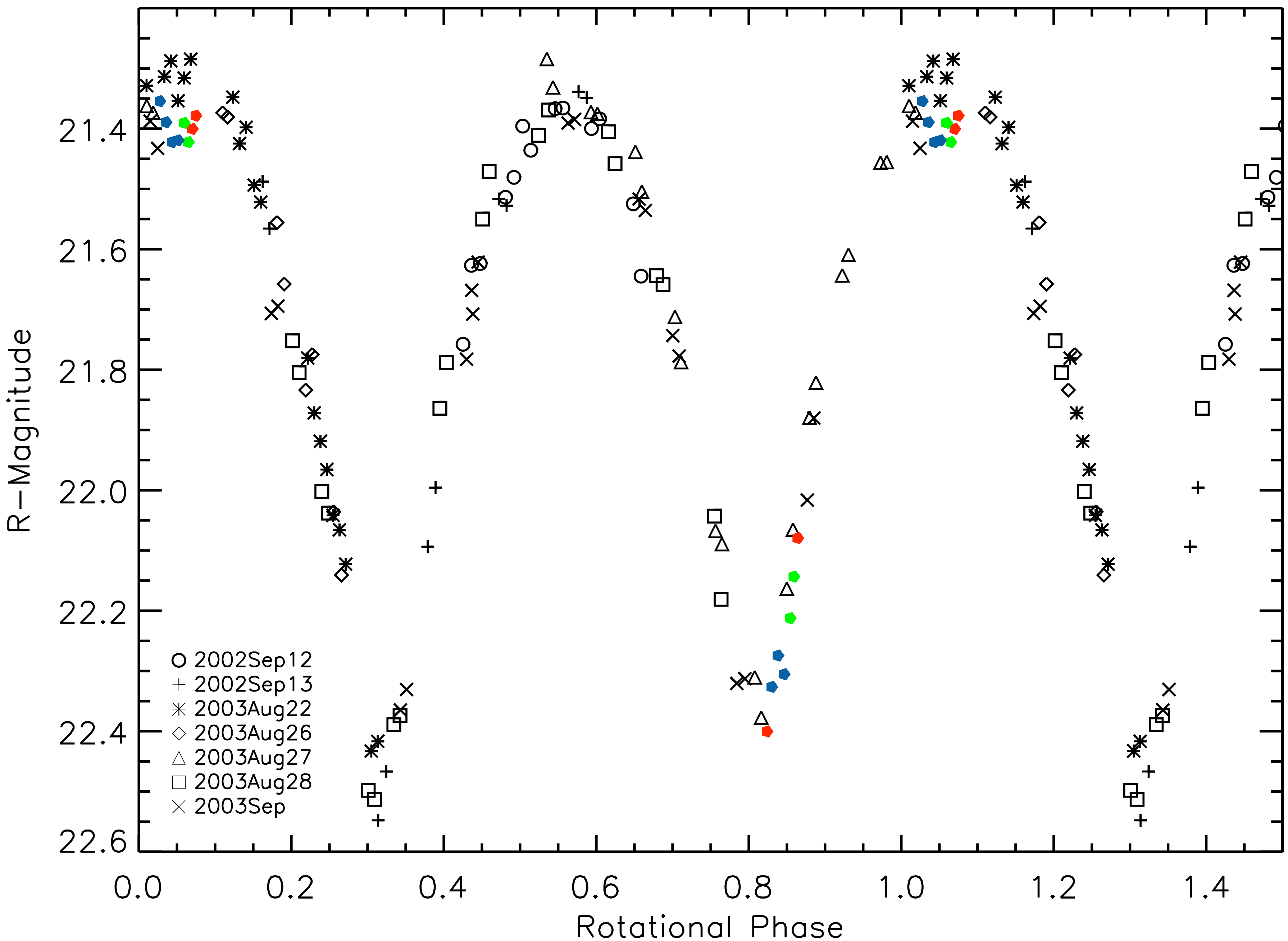
Rotations, Shapes, Binaries and Densities





Sheppard and Jewitt 2004

2001 QG298



Sheppard and Jewitt 2004

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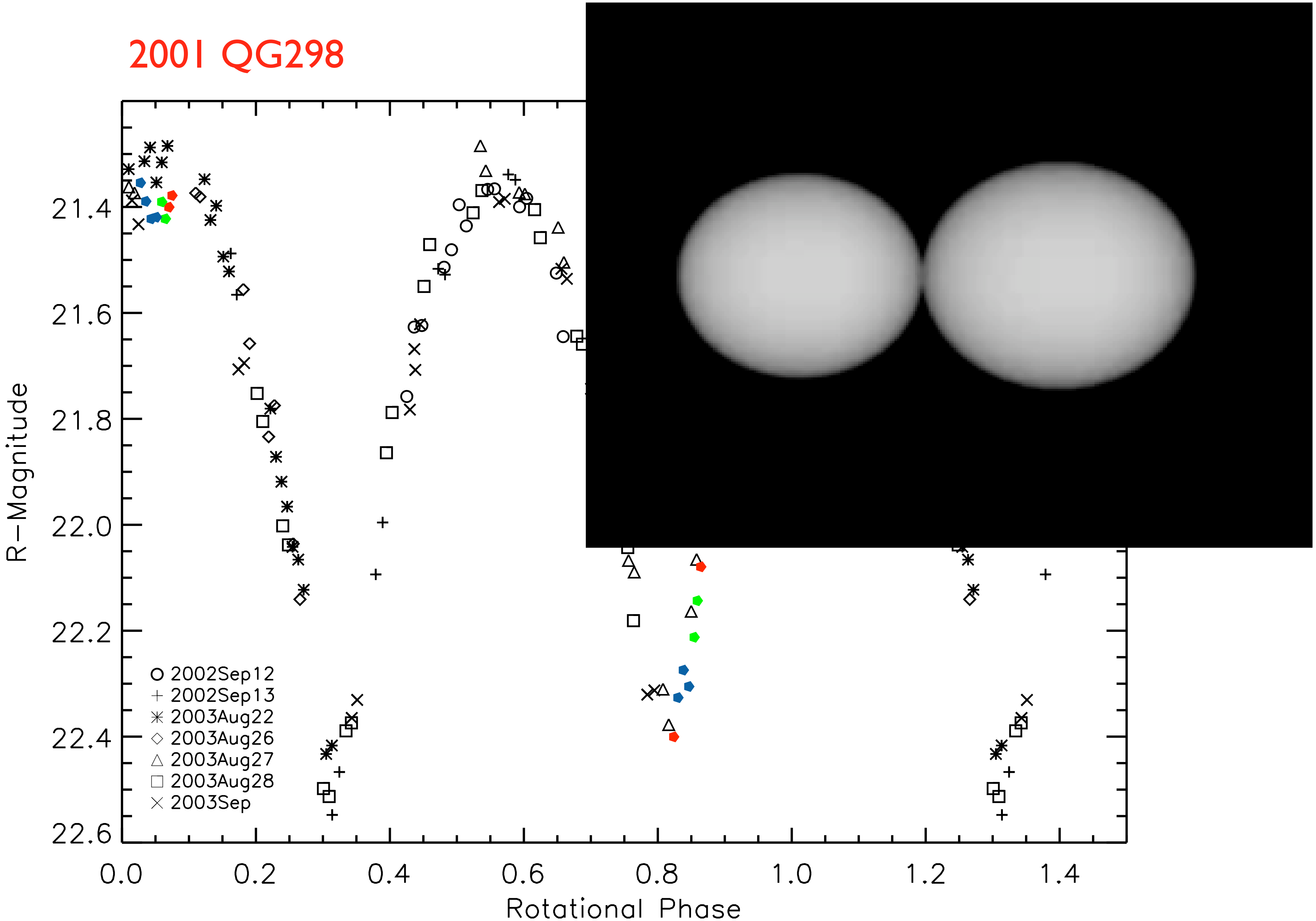
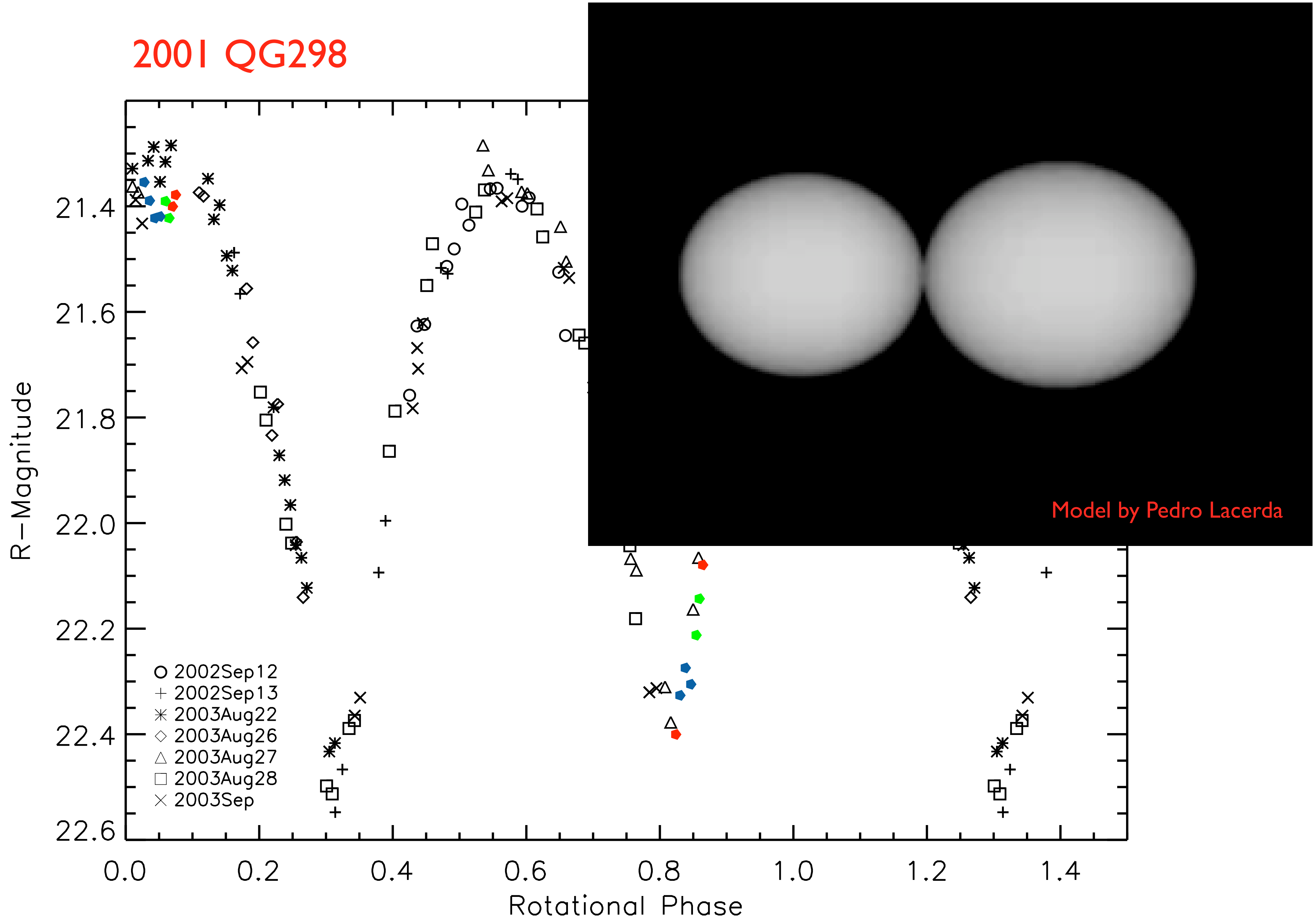
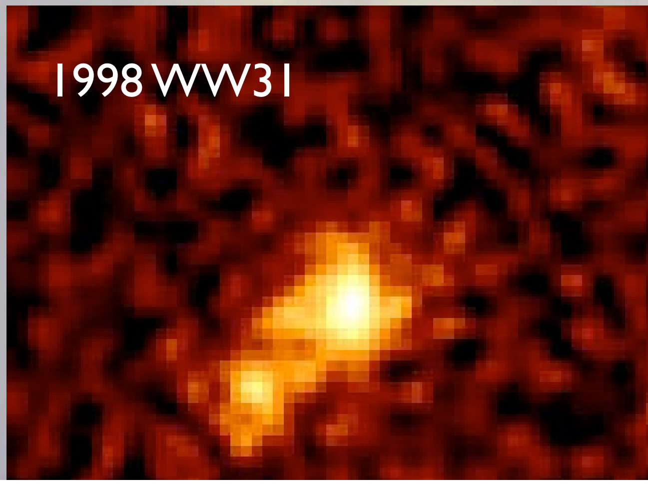


Sheppard and Jewitt 2004

2001 QG298



Sheppard and Jewitt 2004



Binary/Multiple KBOs

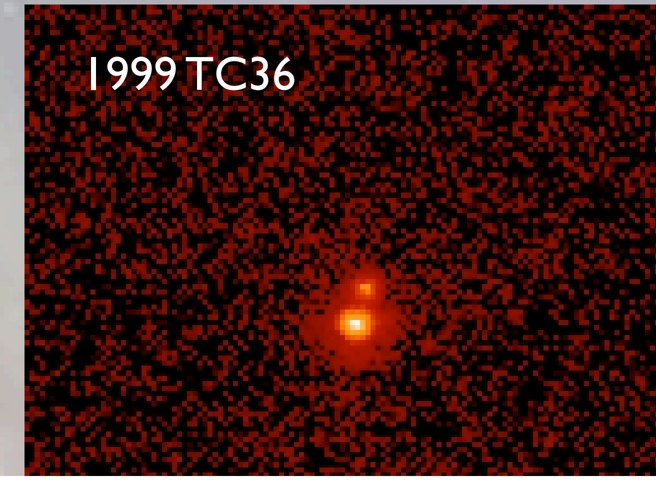
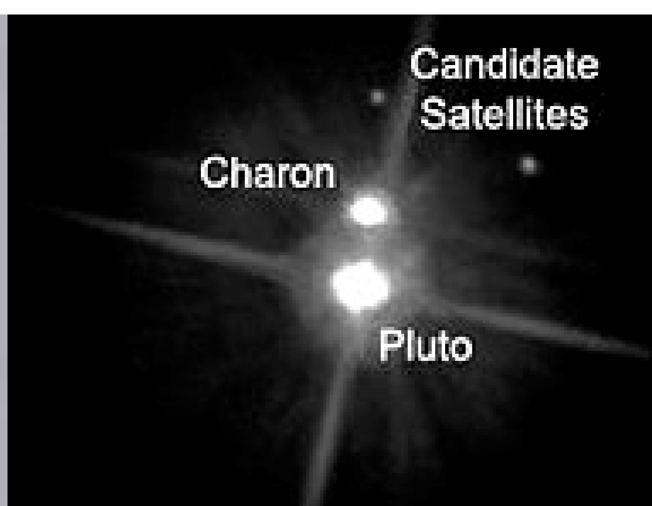


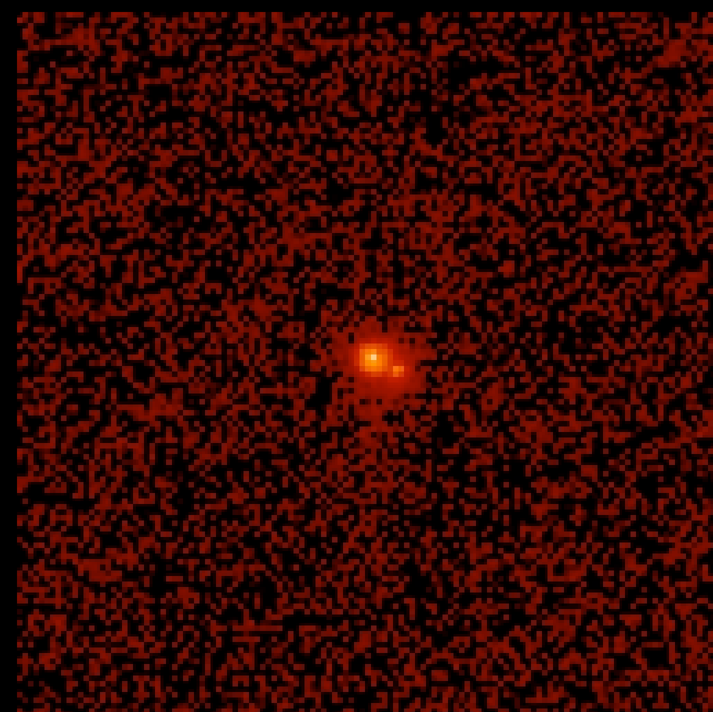
Table 4. Parameters of binary KBOs

Object	a [km][a]	e[b]	i[deg][c]	Type[d]	Q[arc-sec][e]	P[days][f]	Δmag
Pluto	19,600	0.00	96	3:2	0.9	6.4	3.2
1998 WW_{31}	22,300	0.8	42	Cla	1.2	574	0.4
(88611) 2001 QT_{297}	—	—	—	Cla	0.6	—	0.5
2001 QW_{322}	—	—	—	Cla	4.0	—	0.4
1999 TC_{36}	—	—	—	3:2	0.4	—	1.9
(26308) 1998 SM_{165}	—	—	—	2:1	0.2	—	1.9
(58534) 1997 CQ_{29}	—	—	—	Cla	0.2	—	0.3
2000 CF_{105}	—	—	—	Cla	0.8	—	0.9
2001 QC_{298}	—	—	—	Cla	0.17	—	N/A
2003 EL_{61}	49,500±400	0.050±0.003	234.8±0.3	Scat	1.5	49.12±0.03	3.3
2003 UB_{313}	36,000			Scat	0.5	14	

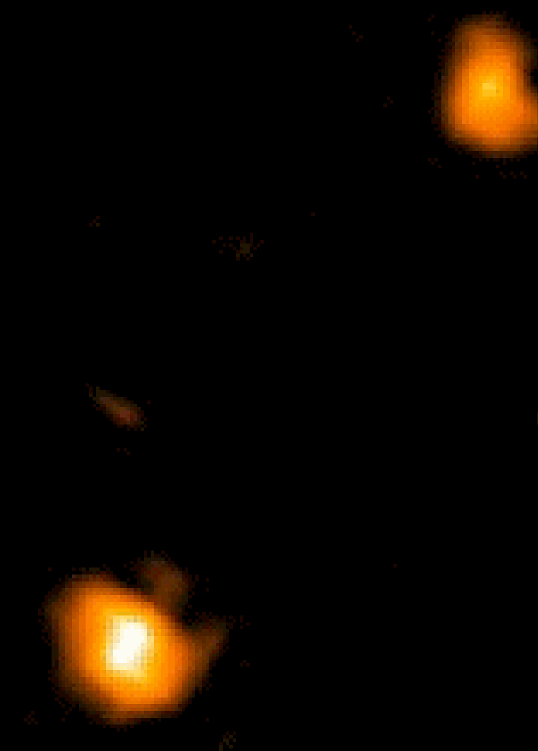


Binaries: 20+ known (fraction f ~10%?)

Pluto-Charon



1998 SM165

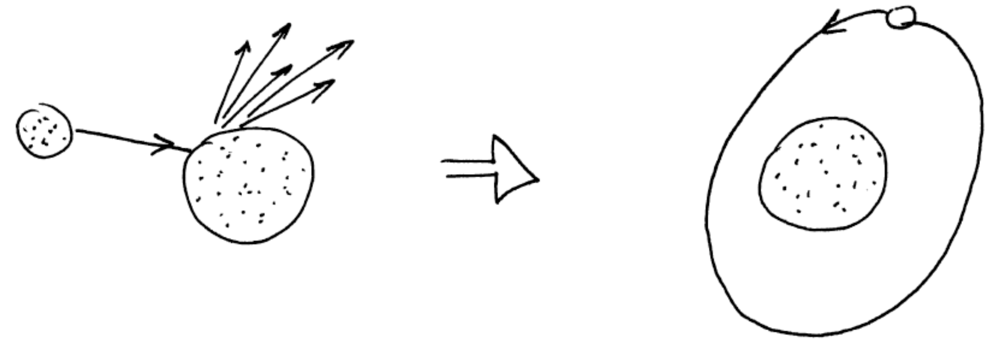


1998 WW31

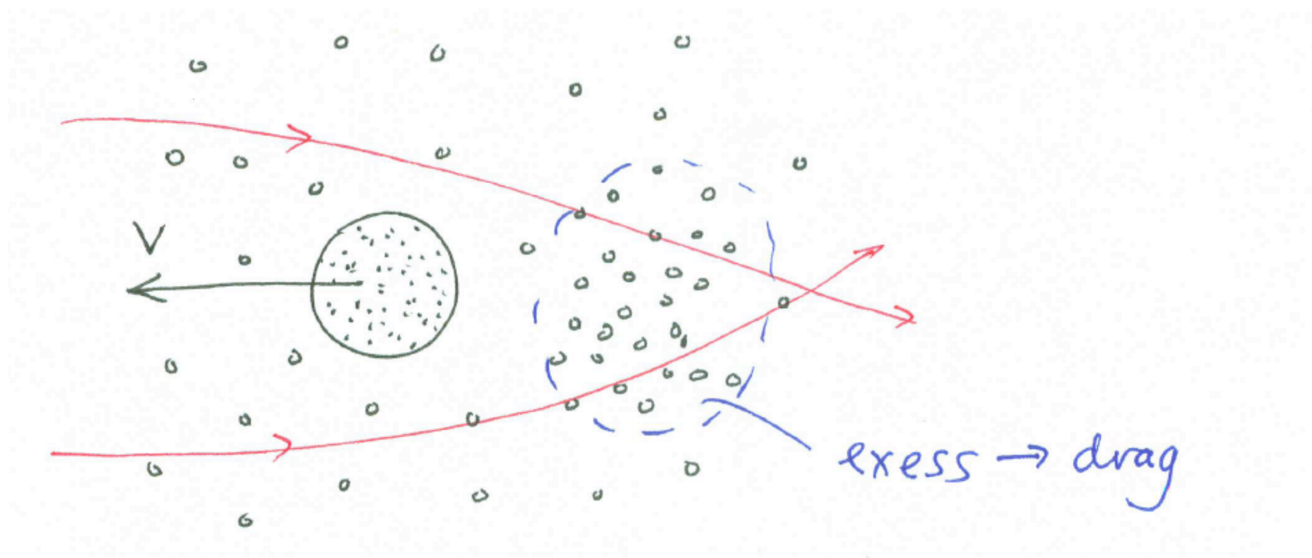
Binary Fraction: f >> 1%, certainly. But why?

Formation Mechanisms

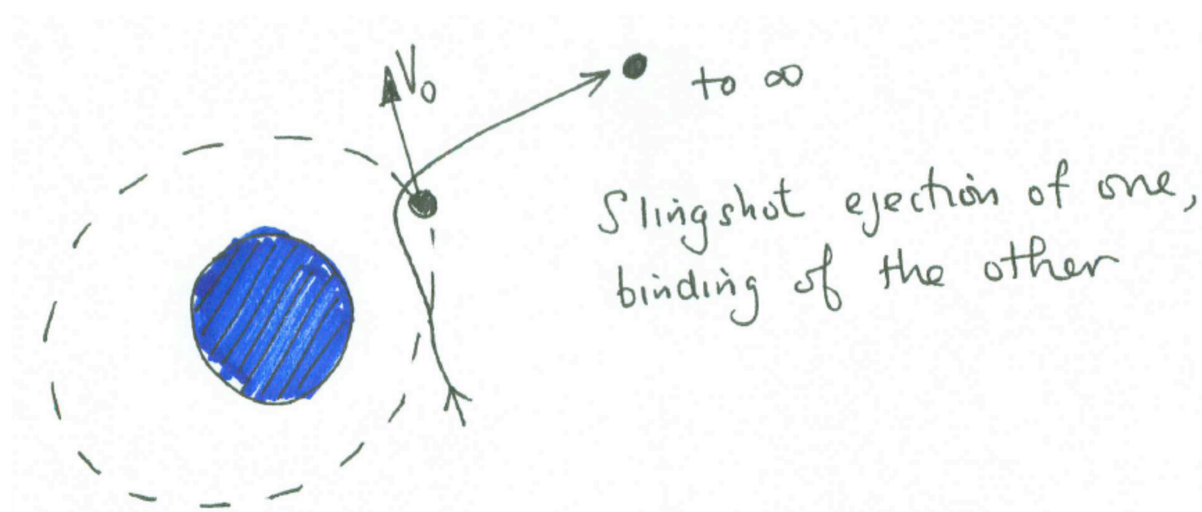
Massive collision



Dynamical Friction



Three-body interaction



Exchange and other hybrids are possible

Formation Mechanisms

Massive collision

Requires glancing impact by massive secondary. Requires 100X to 1000X higher densities than now.

Produces close, soon-circularized orbits: e.g. Pluto? (Canup 2005)

Dynamical Friction

Requires steep size distribution (total mass 100x current mass AND mass in smallest bodies).

Produces numerous, tight binaries and contact objects (e.g. 2001 QG298?)

Three-body interaction

Requires 100X to 1000X higher densities than now.
Hill spheres overlap often (Rh (100km body) ~ AU at 40 AU)!

Produces eccentric, wide binaries

Porosity

i = ice, r = rock, v = vacuum

$$\overline{\rho} = \rho_i f_i + \rho_r f_r$$

ice & rock volume fractions

$$f_i + f_r + f_v \equiv 1$$

Rock Mass Fraction →

$$\psi = \frac{\rho_r f_r}{\rho_r f_r + \rho_i f_i}$$

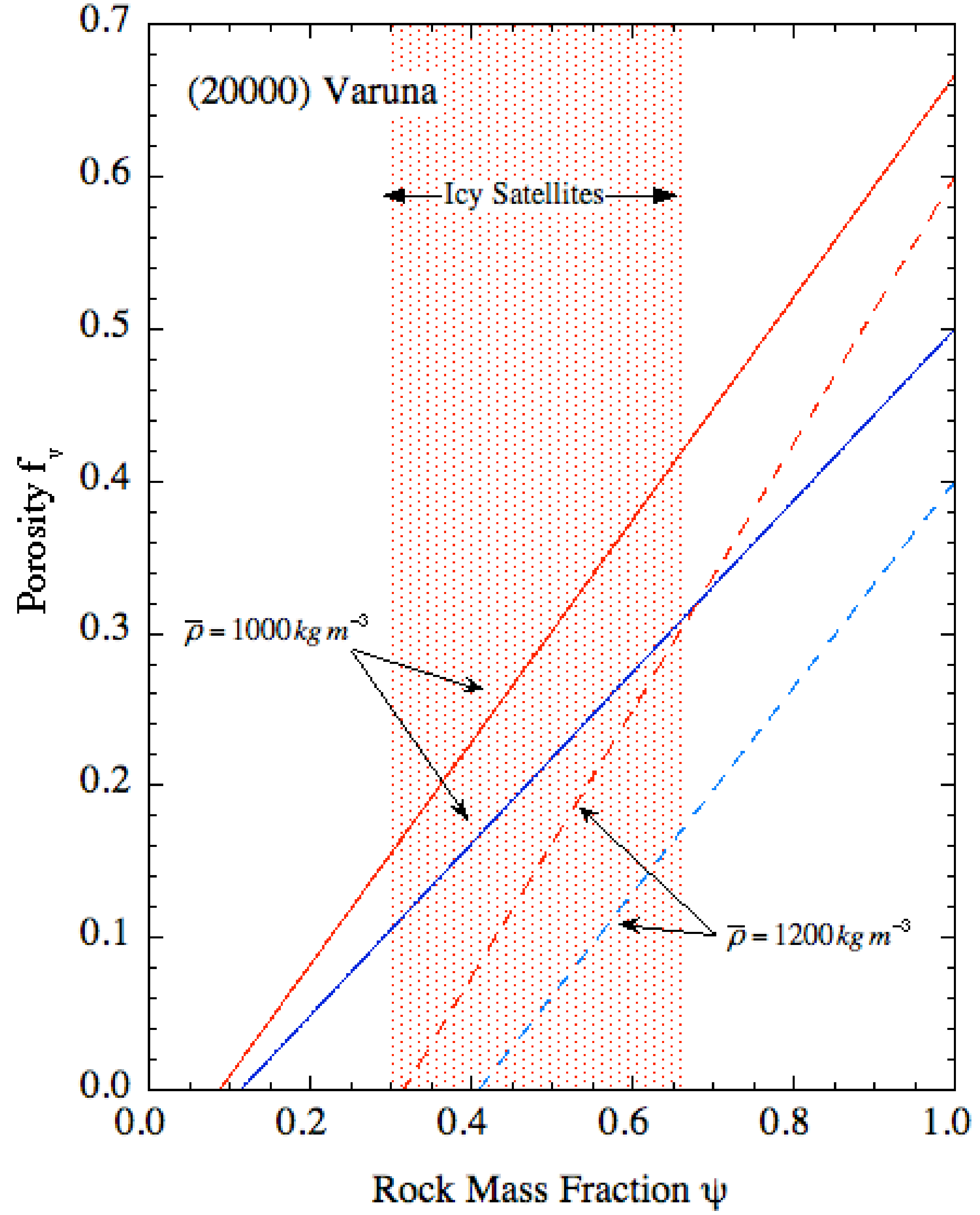
$\psi \sim 0.5$, Pollack et al 94

$$f_v = 1 - \frac{\overline{\rho}}{\rho_i}\left[1 + \psi\left(\frac{\rho_i}{\rho_r} - 1\right)\right]$$

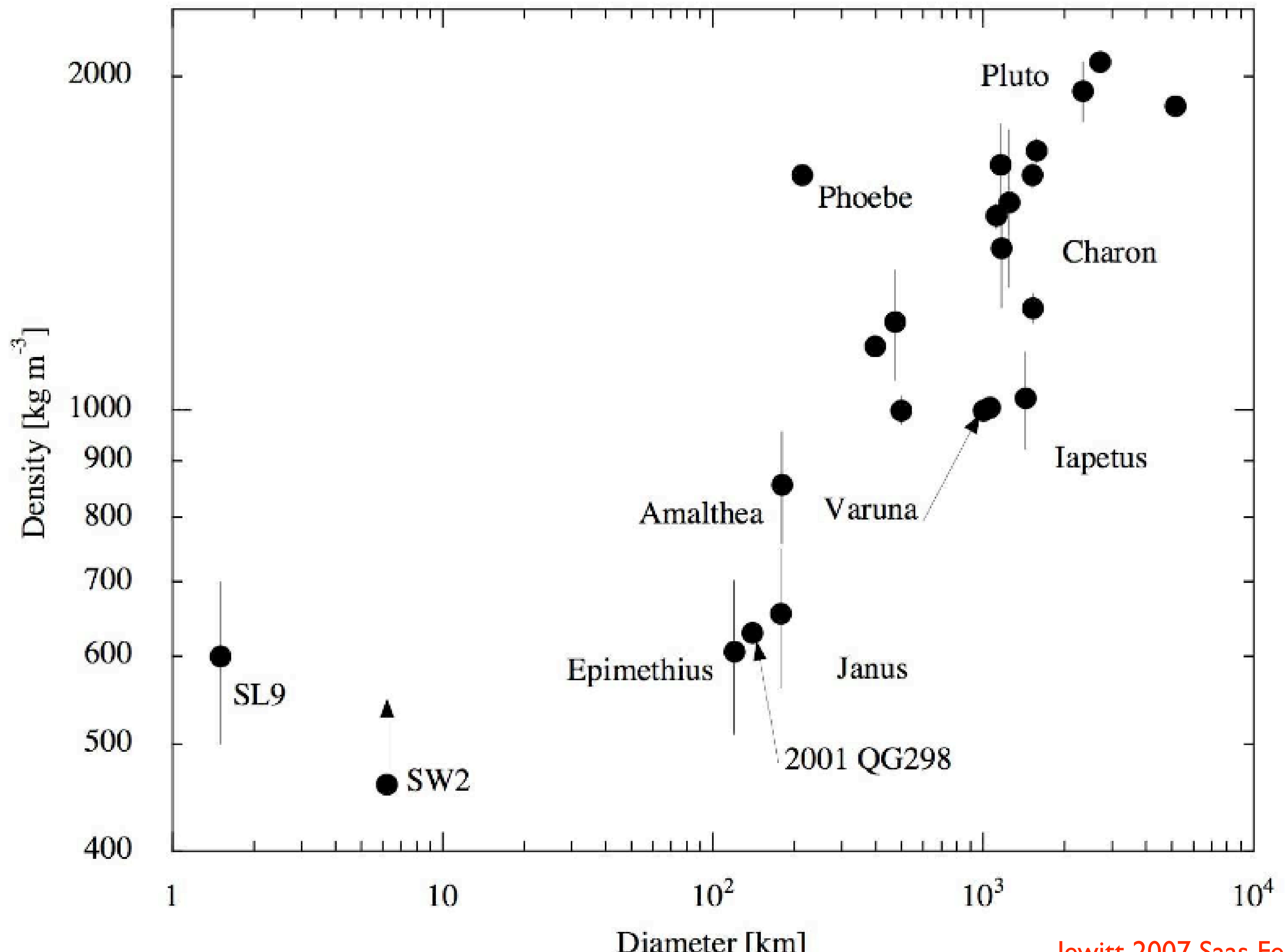
porosity

$\rho_i = 940\ kg\ m^{-3}$, $\rho_r = 2000, 3000\ kg\ m^{-3}$

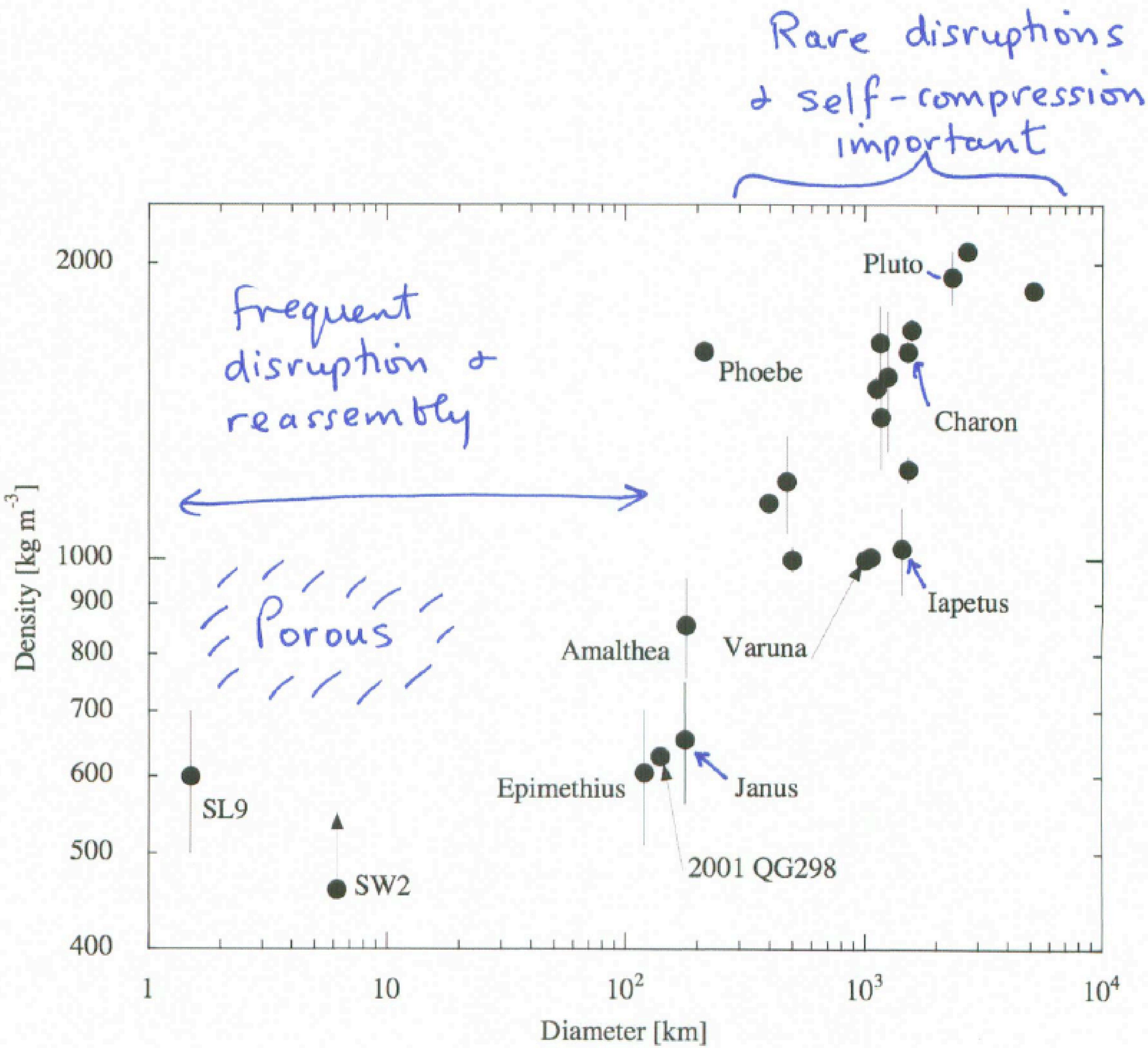
$\overline{\rho}$ from Chandrasekhar spheroid model



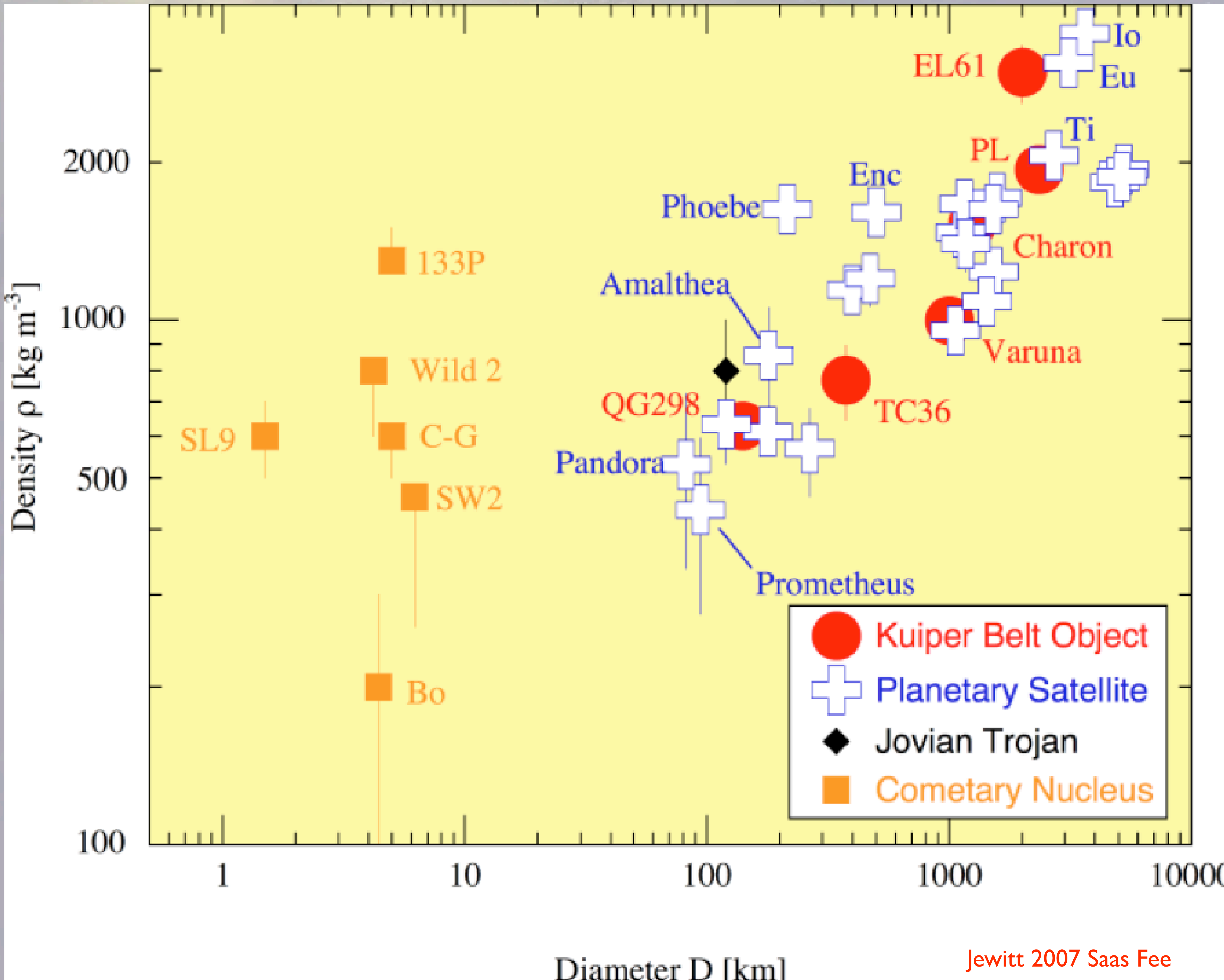
Jewitt and Sheppard (2002)



Jewitt 2007 Saas Fee



Rare disruptions & self-compression important
frequent disruption & reassembly
Porous
Pluto
Phoebe
Charon
Iapetus
Varuna
Amalthea
Epimethius
Janus
2001 QG298
SL9
SW2
2000
1000
900
800
700
600
500
400
Density [kg m^{-3}]
1
10
10^2
10^3
10^4
Diameter [km]



Jewitt 2007 Saas Fee

BREAK #2 (10 minutes)

NEXT: EXAMPLE POPULATIONS

The Irregular Satellites

Irregular Satellites

Orbits are large, eccentric, highly inclined relative to regular (disk-formed) satellites.

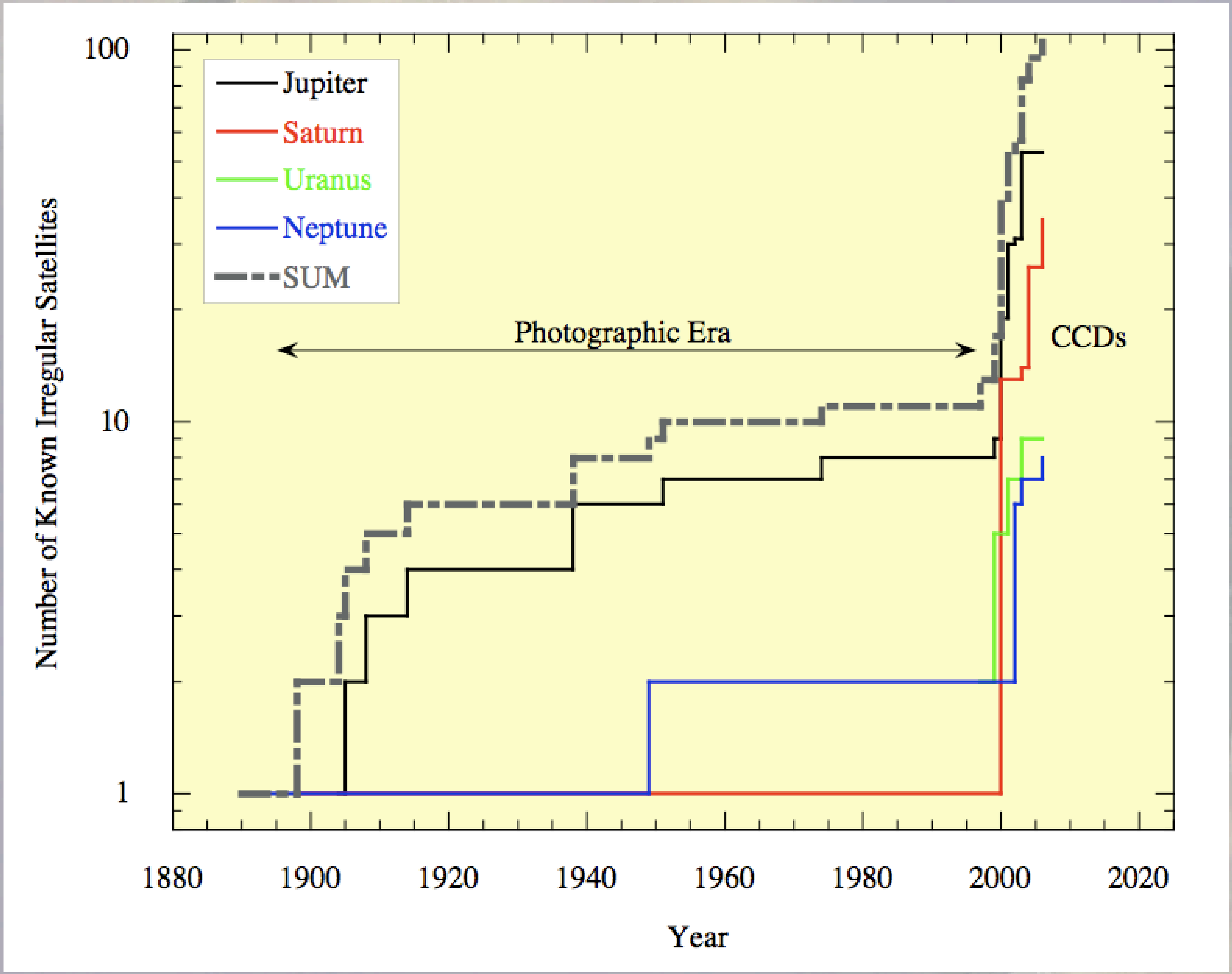
Most are retrograde and must be captured.

Capture from heliocentric orbit requires dissipation: solar system now offers no plausible source of dissipation.

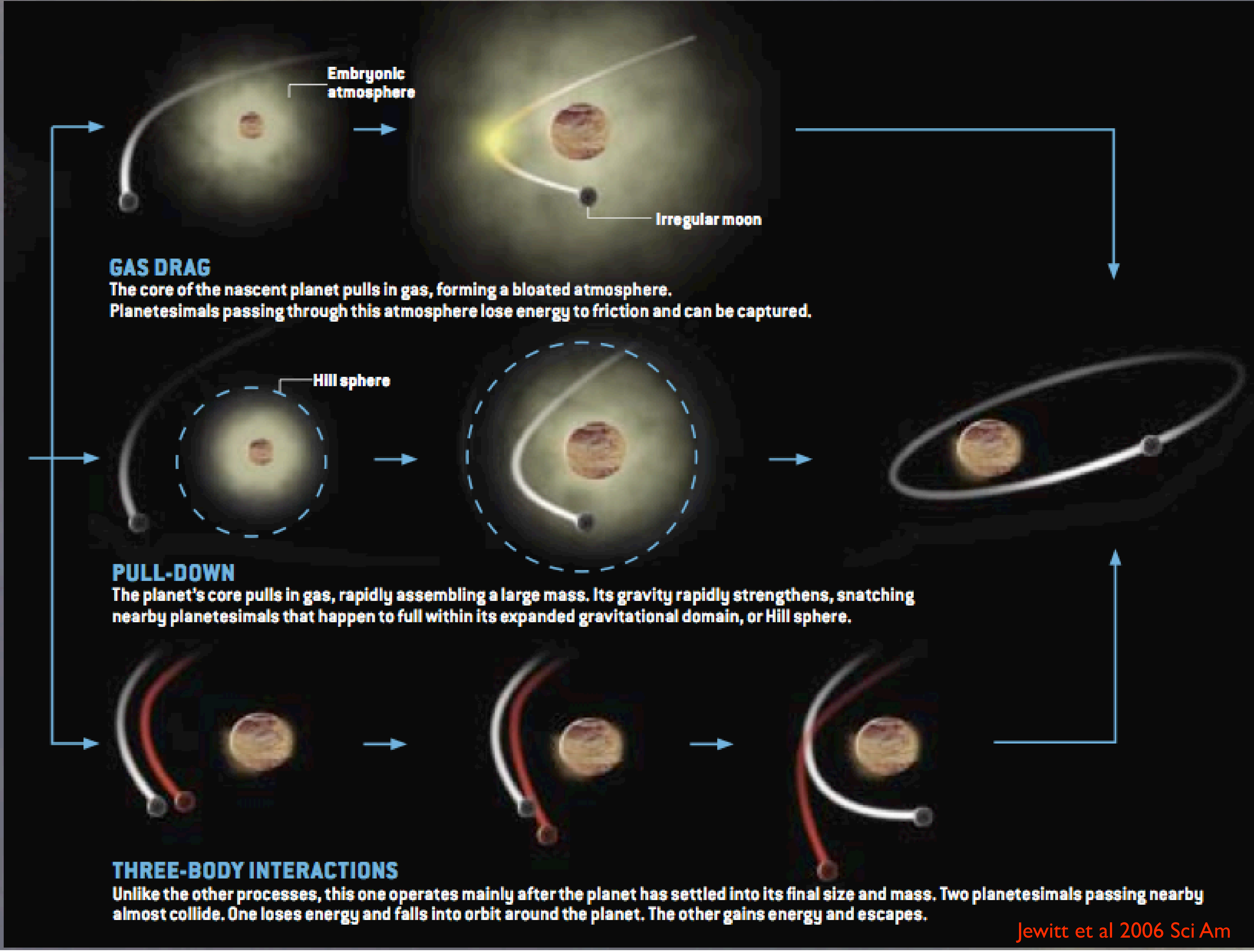
Most discussed hypotheses are

- Capture by gas-drag in the bloated phase of gas-giants
- Pull-down capture in the epoch of runaway growth by gas collapse onto the core
- Capture by 3-body interactions has also been proposed but mostly ignored

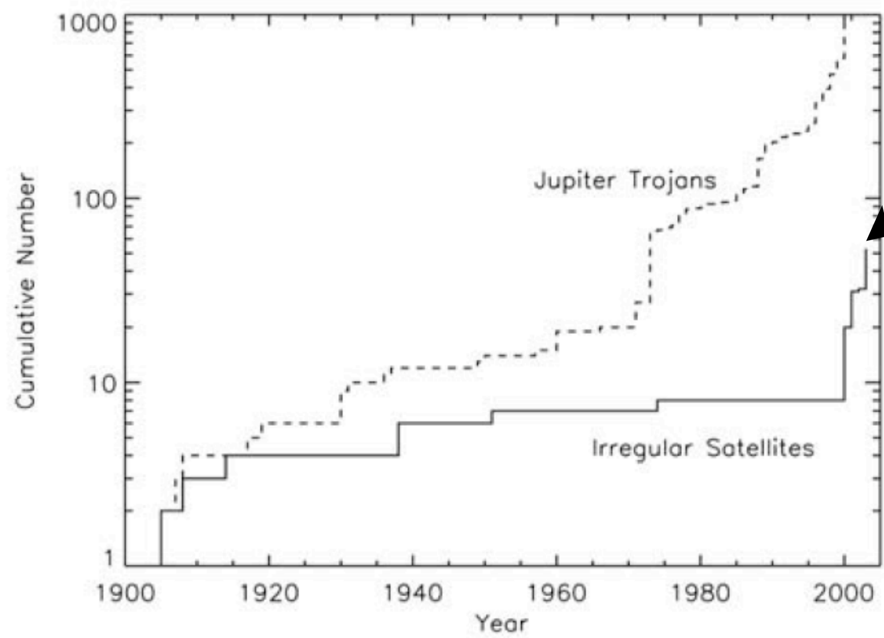
Discovery rate



Jewitt &Haghighipour (2007)



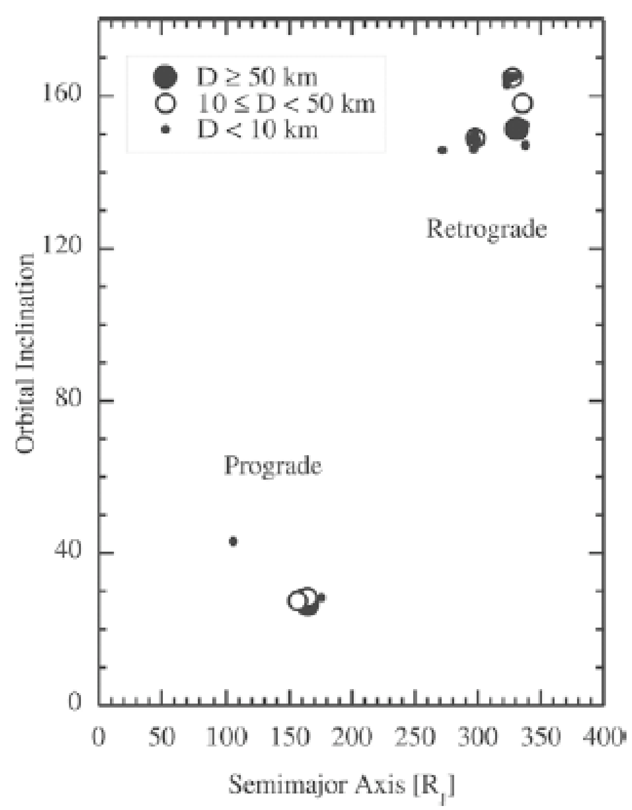
Jewitt et al 2006 Sci Am



HISS = Hawaii Irregular Satellite Survey

Discovered ~80 satellites at J, S, U and N in the last 6 years. This is doubles the known number of satellites of planets.

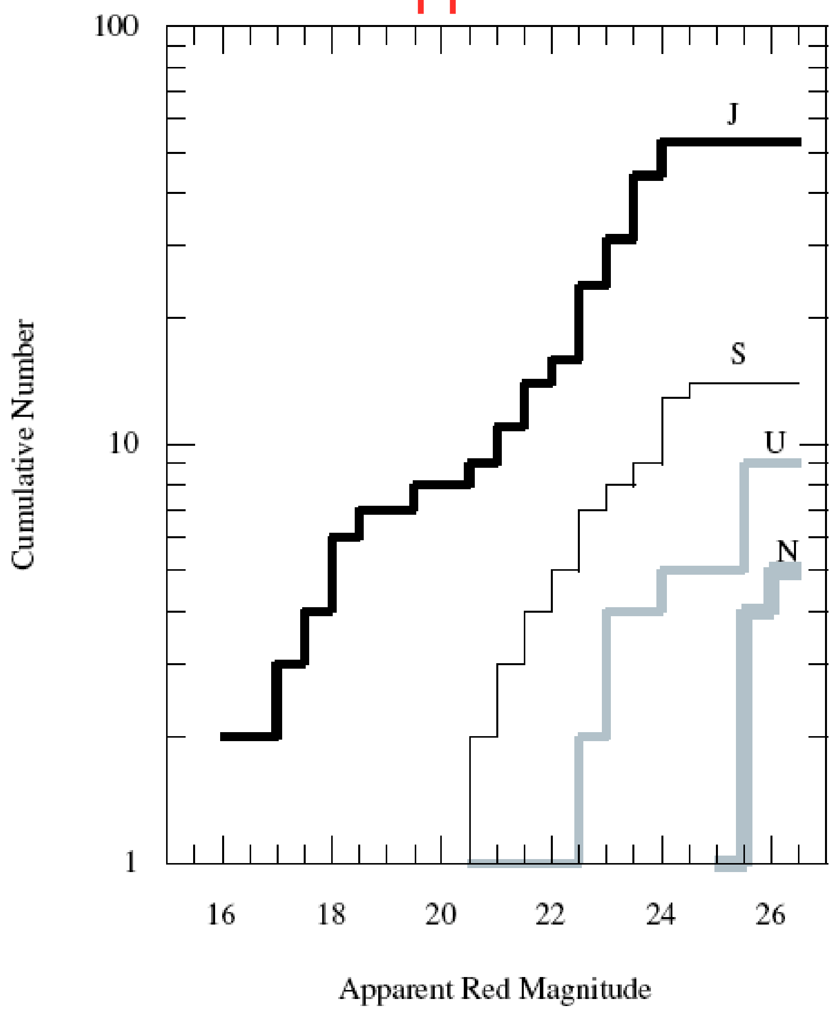
www.ifa.hawaii.edu/~jewitt/irregulars.html



Sheppard and Jewitt 2004

- Orbits are clustered in a-e-i space.
- Polar orbits are not found (Kozai instability)
- Retrogrades outnumber progrades
- Orbits lie within central ~1/2 Hill Sphere

Apparent



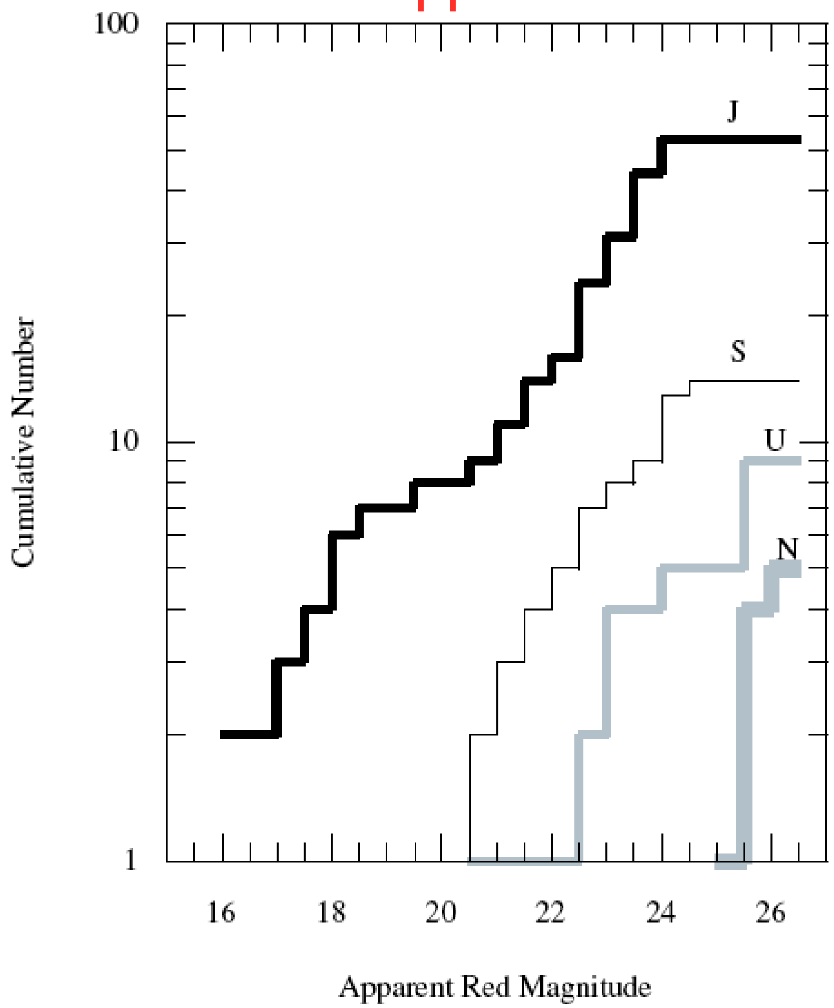
Number of iSats ~ invariant at J, S, U, N

Observation is incompatible with gas drag and pull down capture since U,N are ice giants not gas giants and formed by a different process, with little gas and no mass runaway.

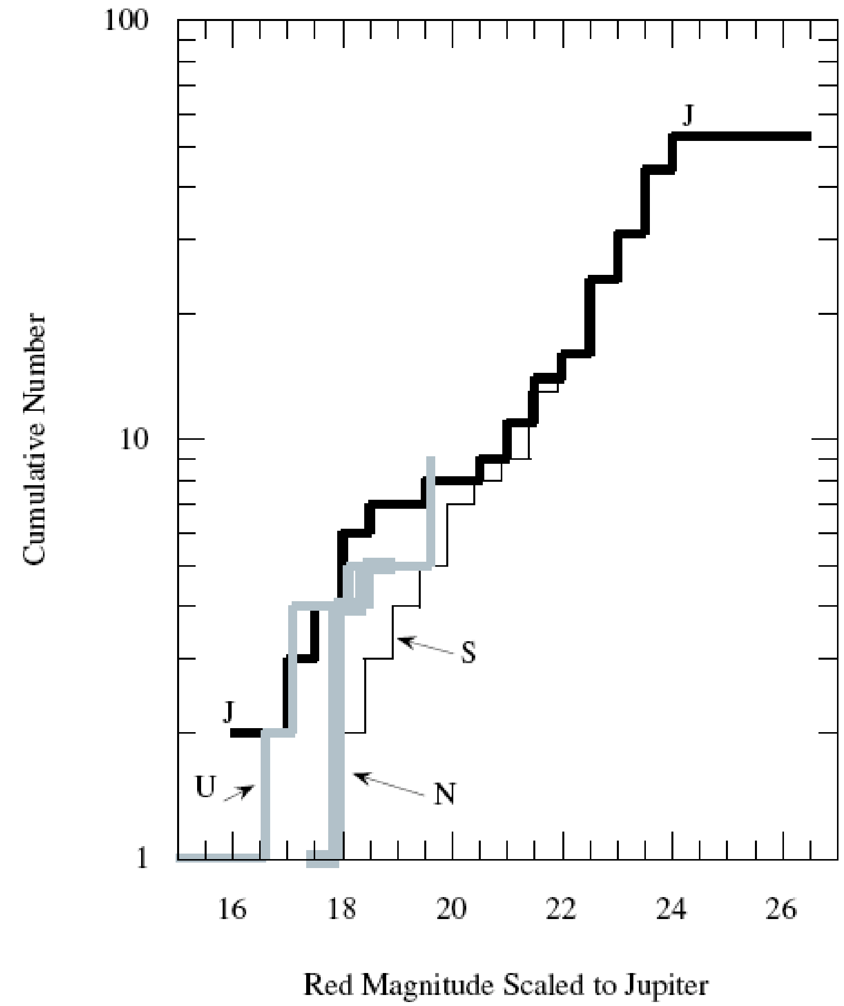
3-body interactions remain viable.

Jewitt and Sheppard (2005)

Apparent



Distance-corrected



Number of iSats ~ invariant at J, S, U, N

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3-body interactions remain viable.

Jewitt and Sheppard (2005)

Phoebe

Source

LOCAL - in association with planet formation. Then the iSats (and the Trojans) are correctly seen as survivors of core accretion at the giant planets.

DISTANT - maybe from the Kuiper Belt in a late clearing stage (late-heavy bombardment)

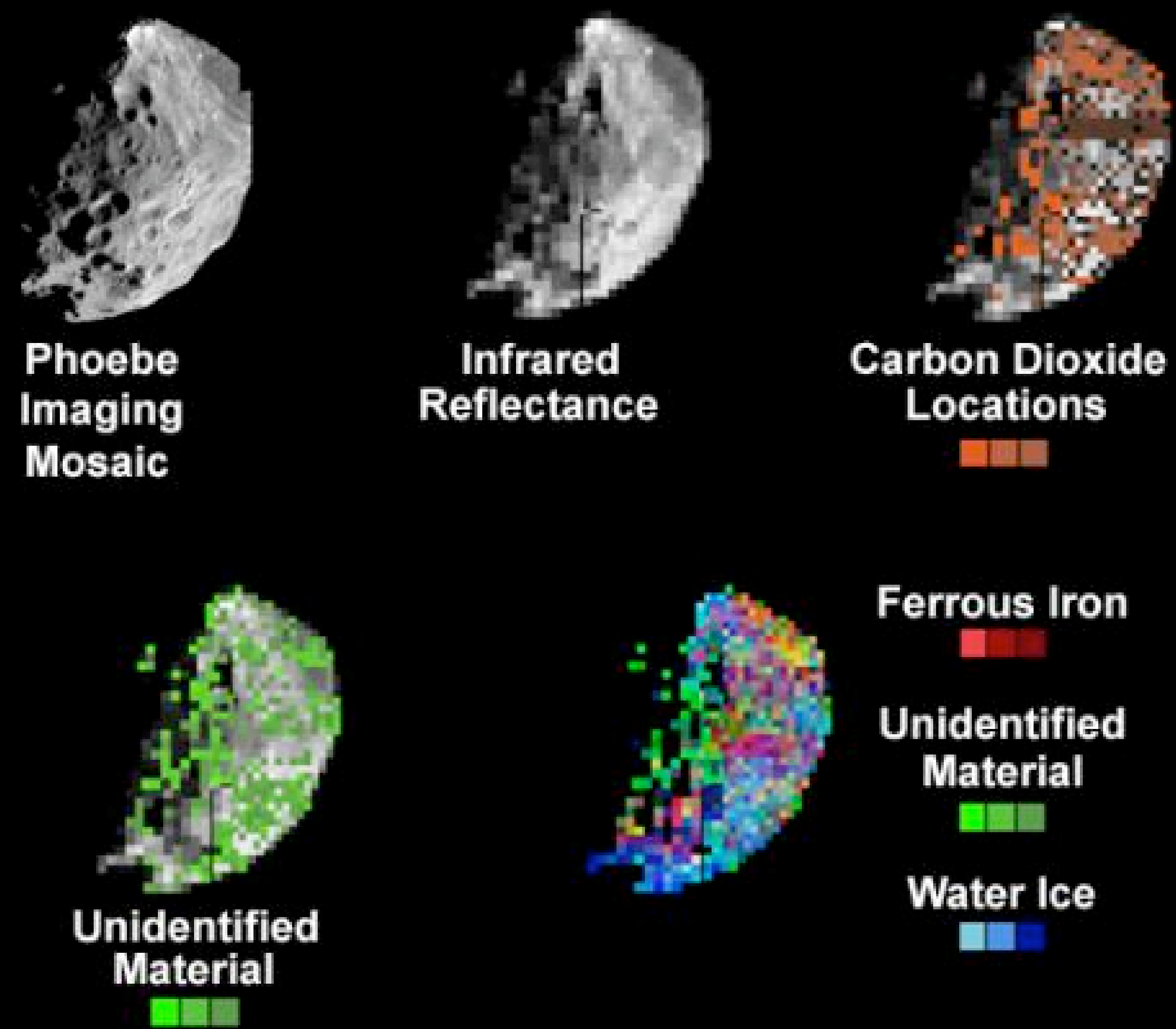
EVIDENCE - no compelling evidence yet.

Johnson argues that Phoebe's 1.7 g/cm3 density supports KB source (highly non-unique)

Cassini spectra show diverse ices on Phoebe that may be compatible with KB source (unique?)

Volatiles

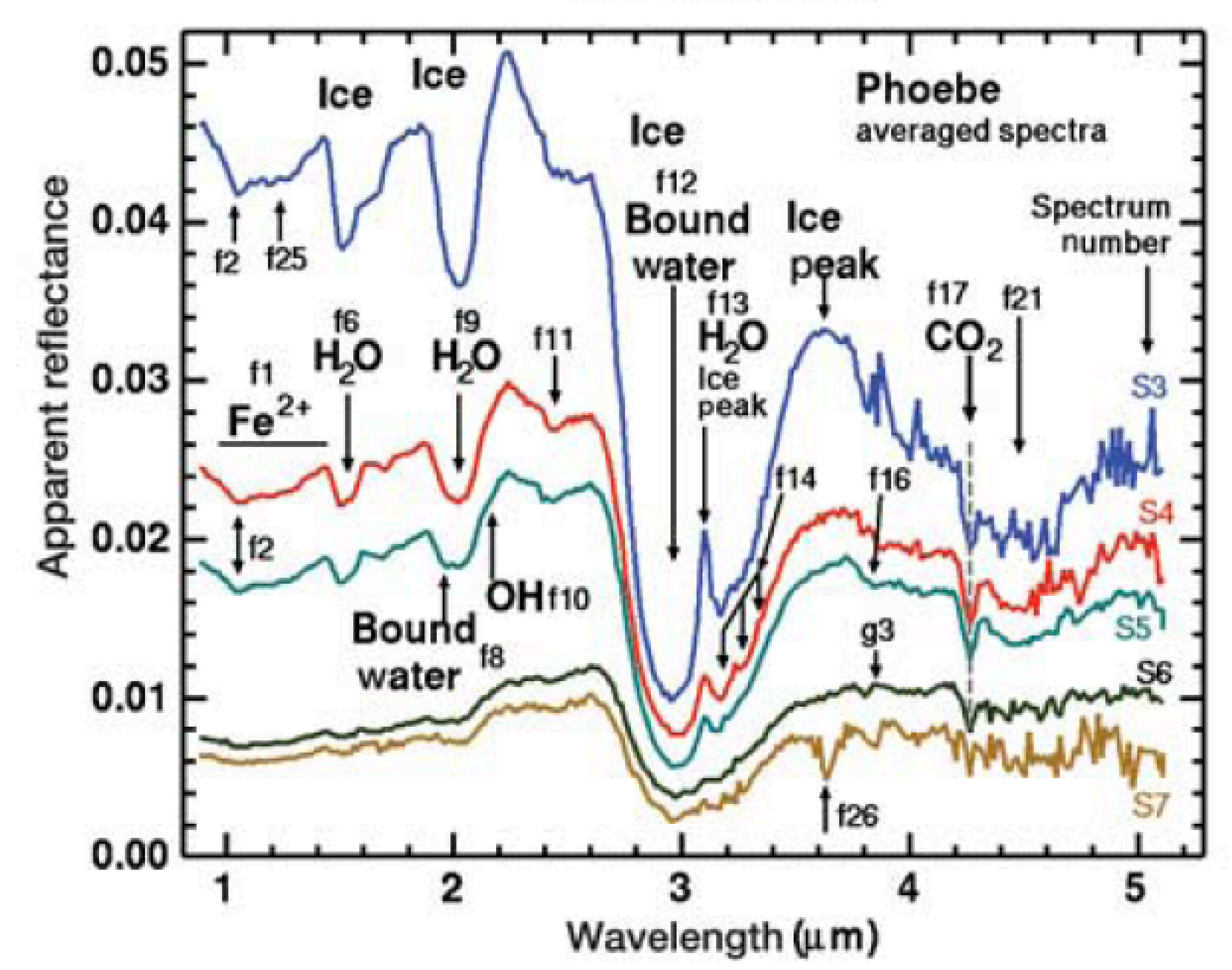
Phoebe



Clark et al 2005

Volatiles

Phoebe



Clark et al 2005

The Centaurs

Centaurs

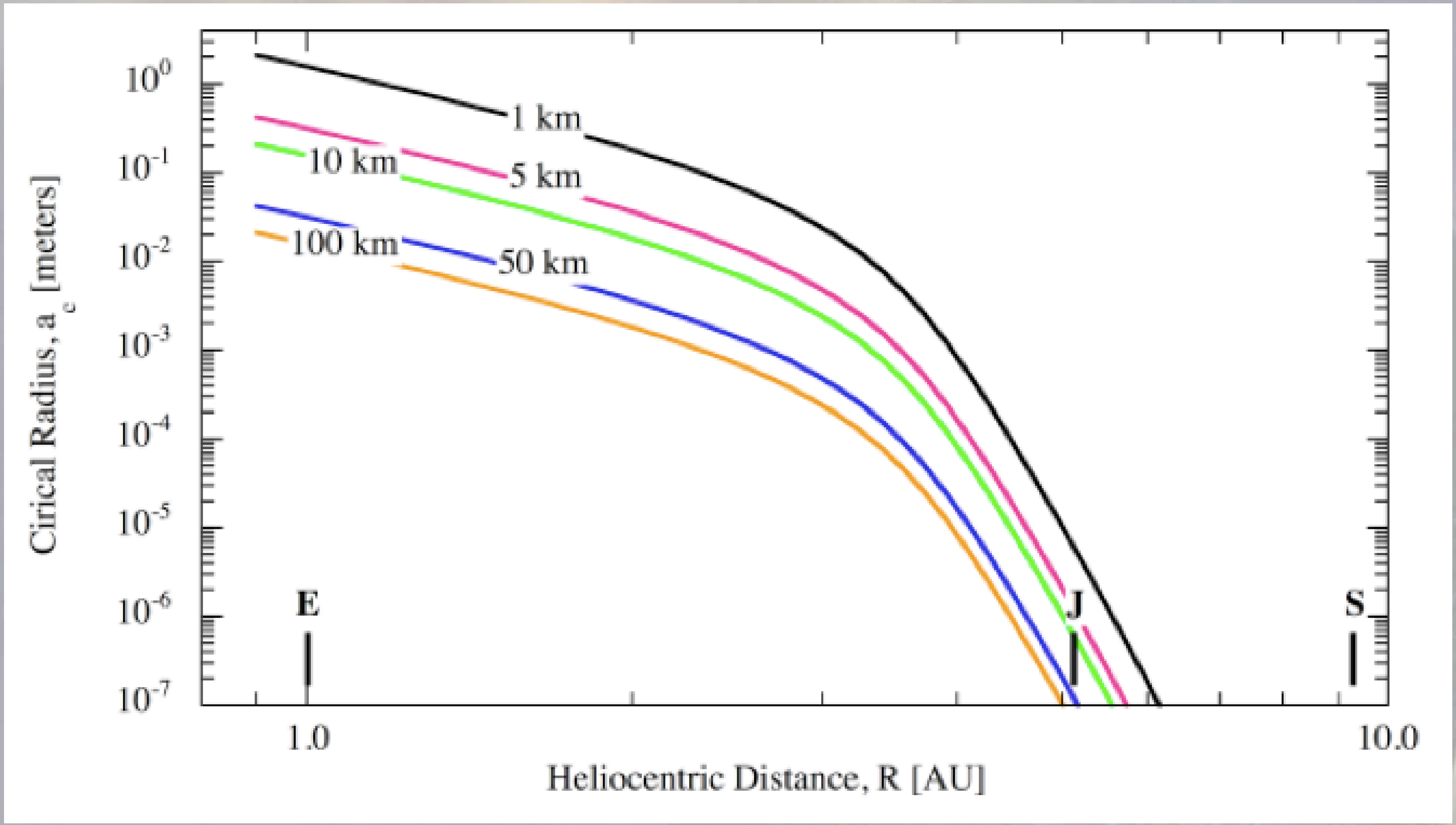
(define by $5 \leq a \leq 30$ AU AND $5 \leq q \leq 30$ AU)

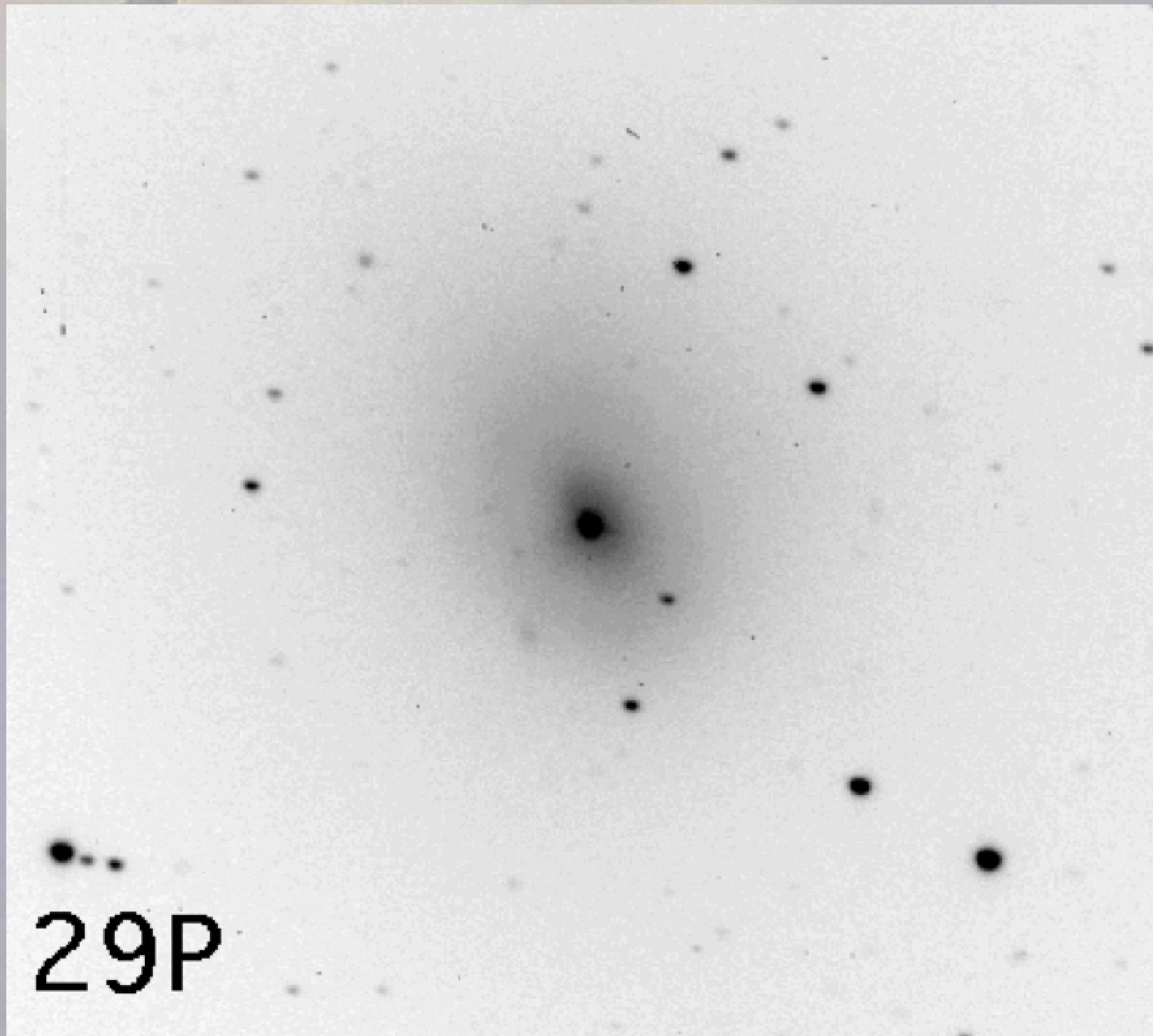
Known sample ≈ 70

$N(D \geq 100 \text{ km}) \approx 100$

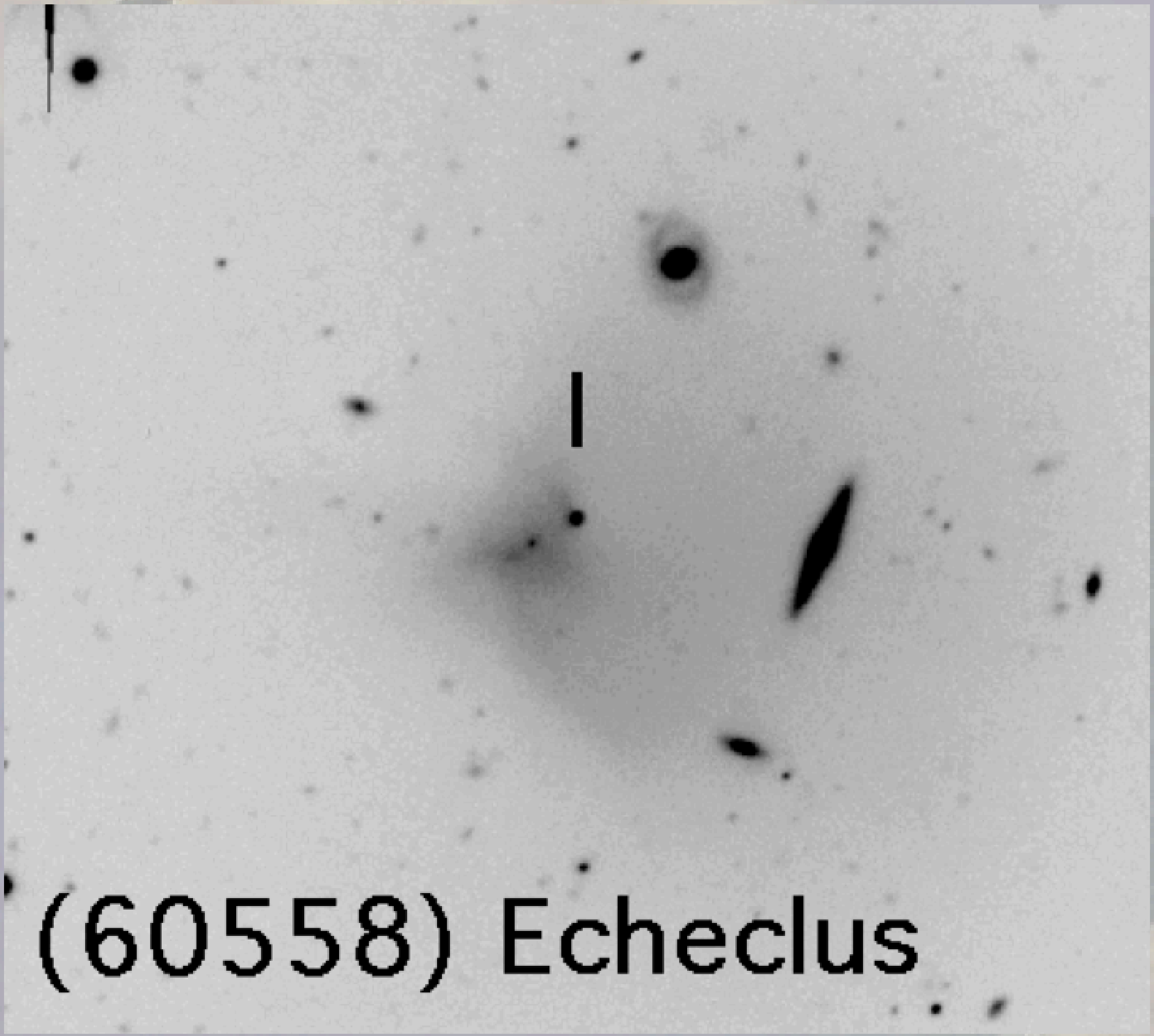
Size index $q \approx 4$ (differential)

Water ice sublimation

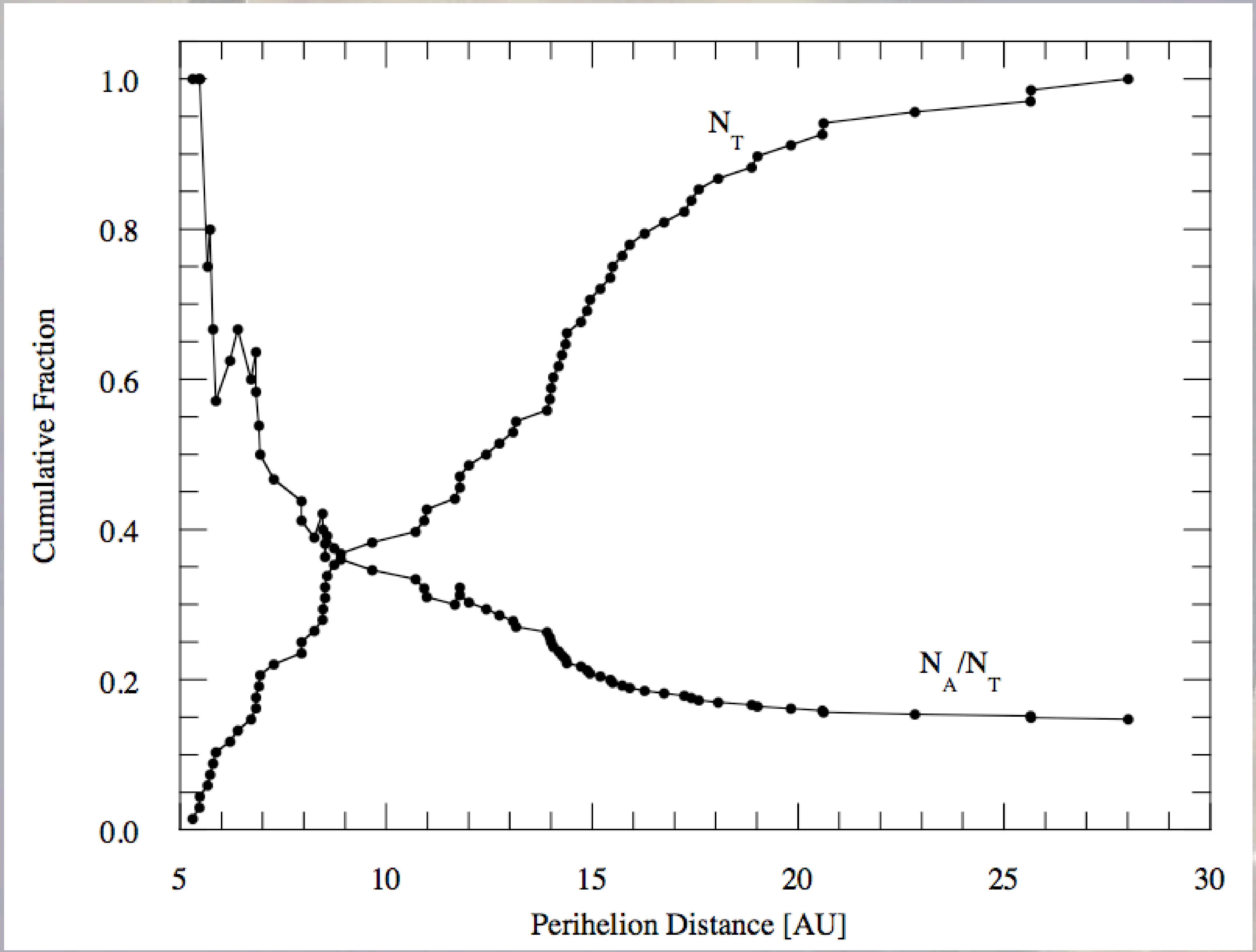




Jewitt 2007 in press



Jewitt 2007 in press



Jewitt 2007 in press

Crystallization

Crystallization timescale

$$\tau_{cr} = 3.0 \times 10^{-21} e^{\left[\frac{E_A}{kT}\right]}$$

Kepler timescale

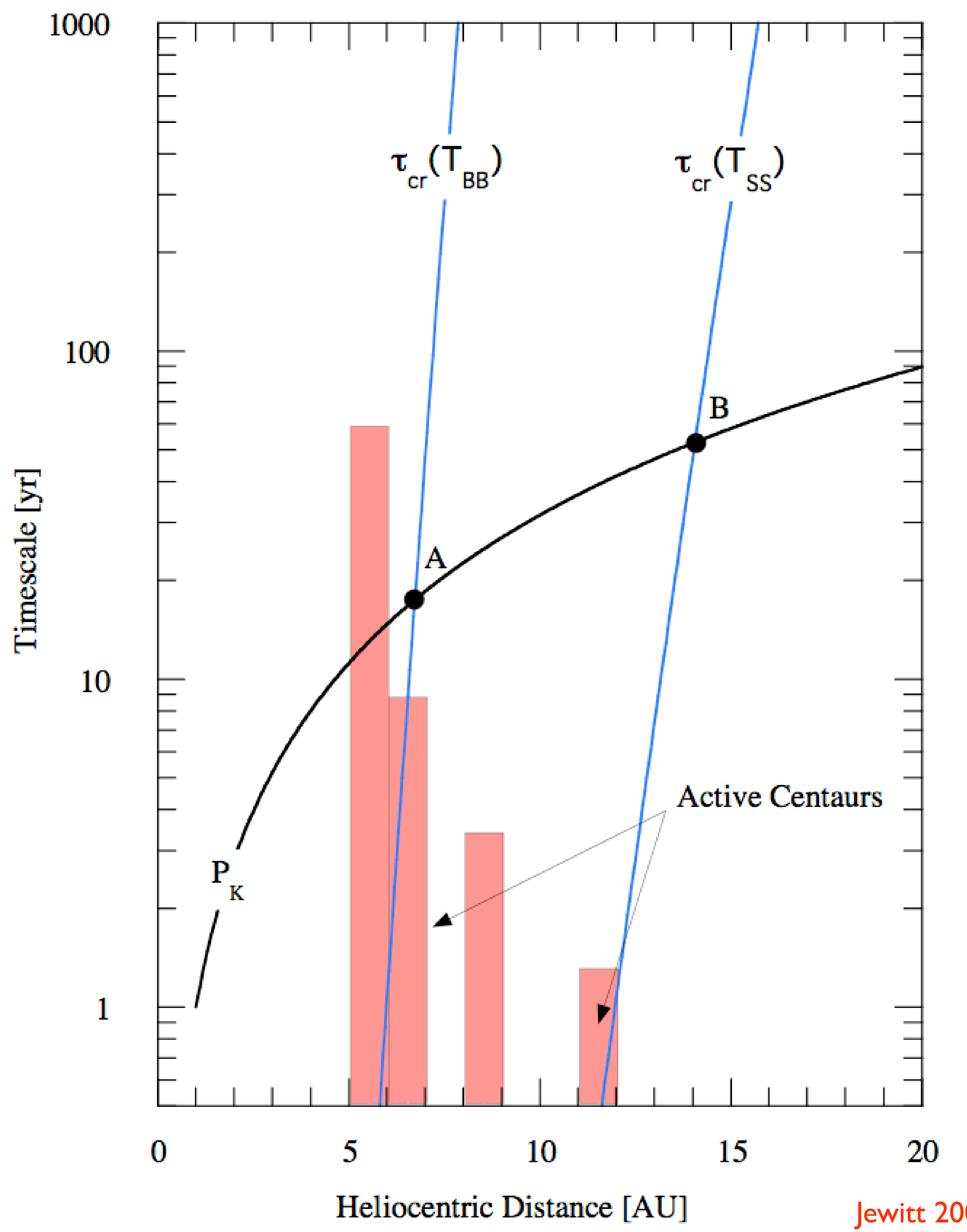
$$t_k = a_{AU}^{3/2}$$

Temperature

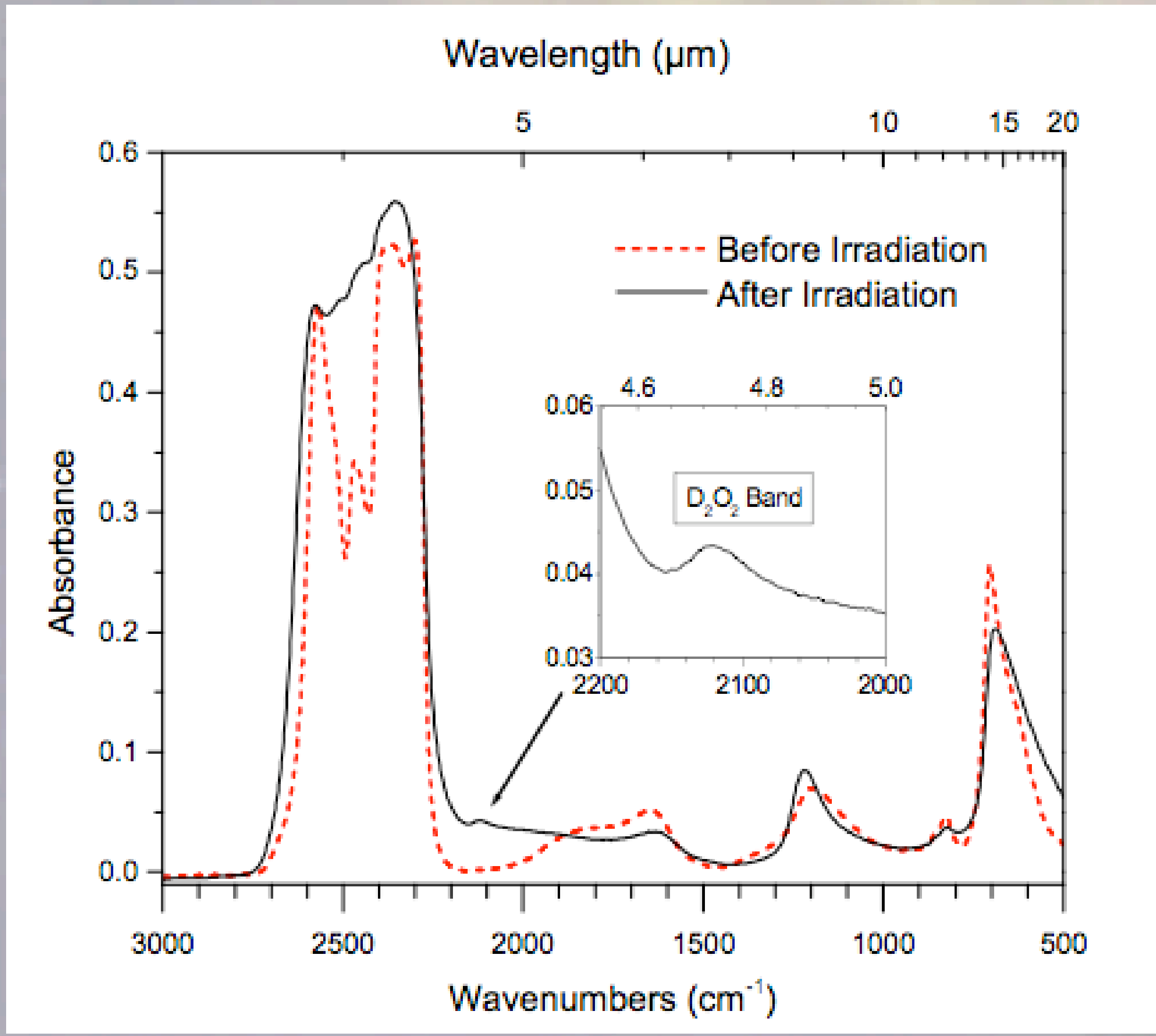
$$T_\chi = \left[\frac{L_\odot(1-A)}{4\pi\chi\epsilon\sigma R^2}\right]^{1/4}$$

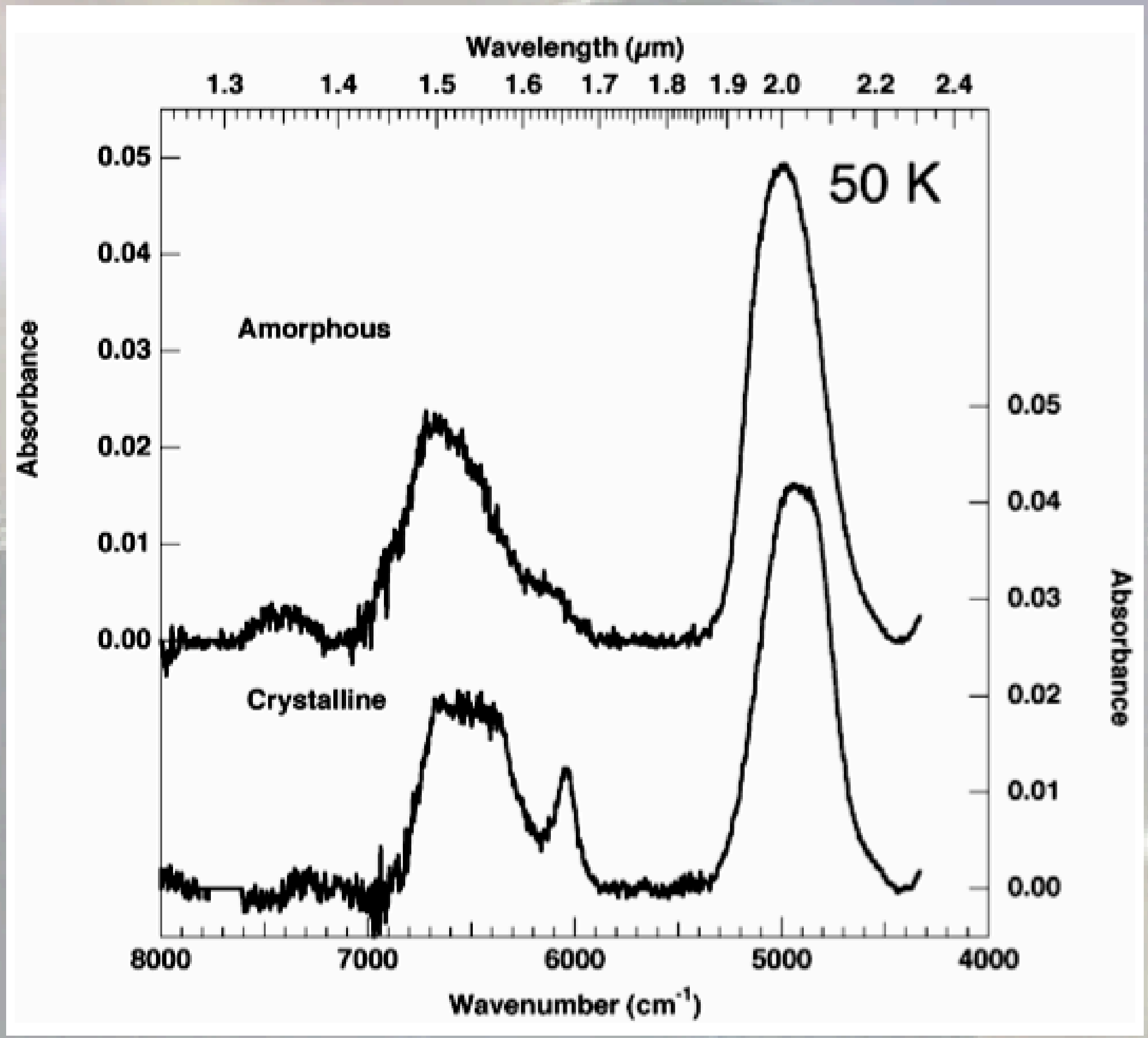
Critical distance

$$a_{AU} = \left[3.0 \times 10^{-21} e^{\left[\frac{E_A}{kT}\right]}\right]^{2/3}$$



Jewitt 2007 in press



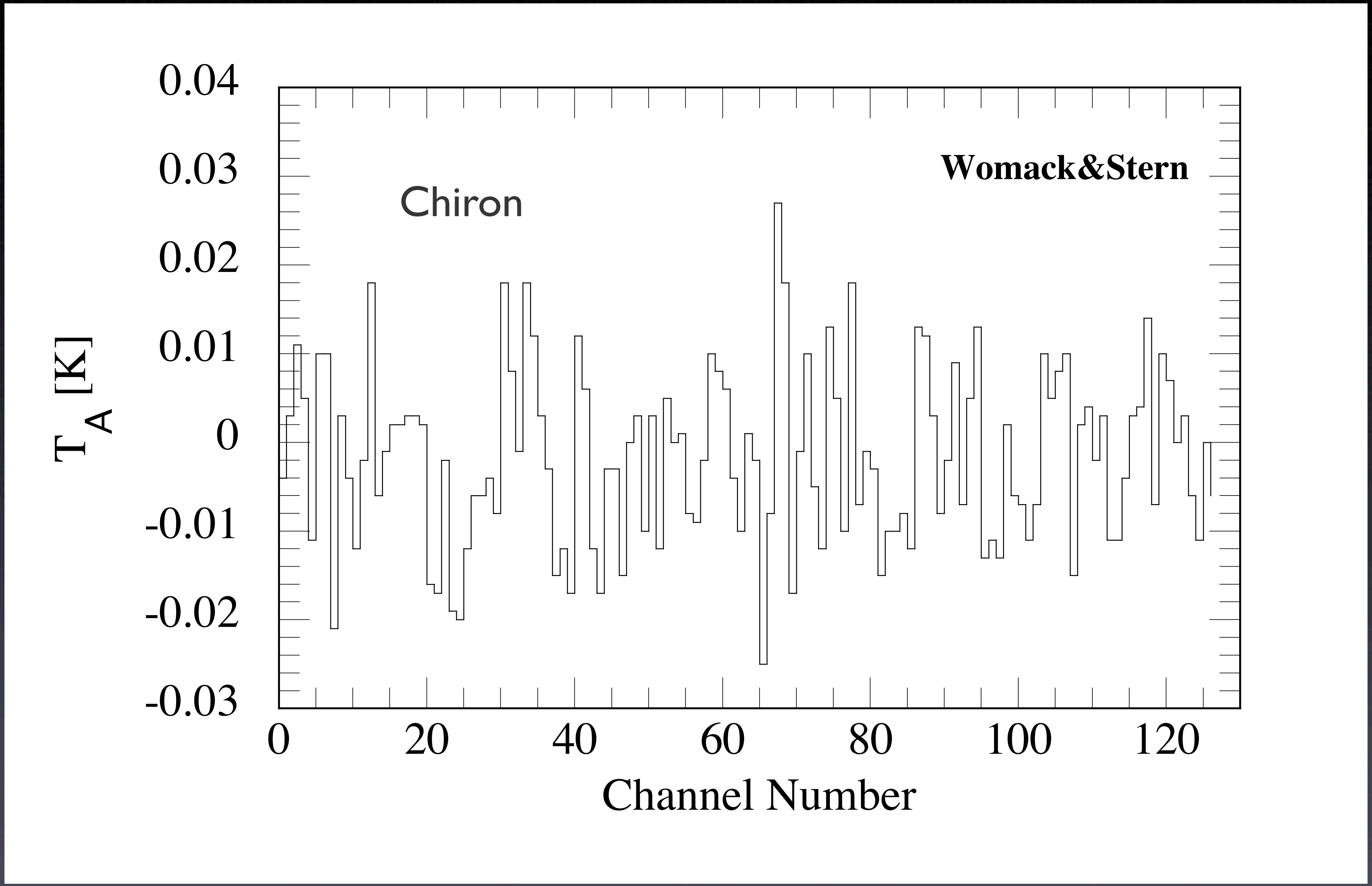


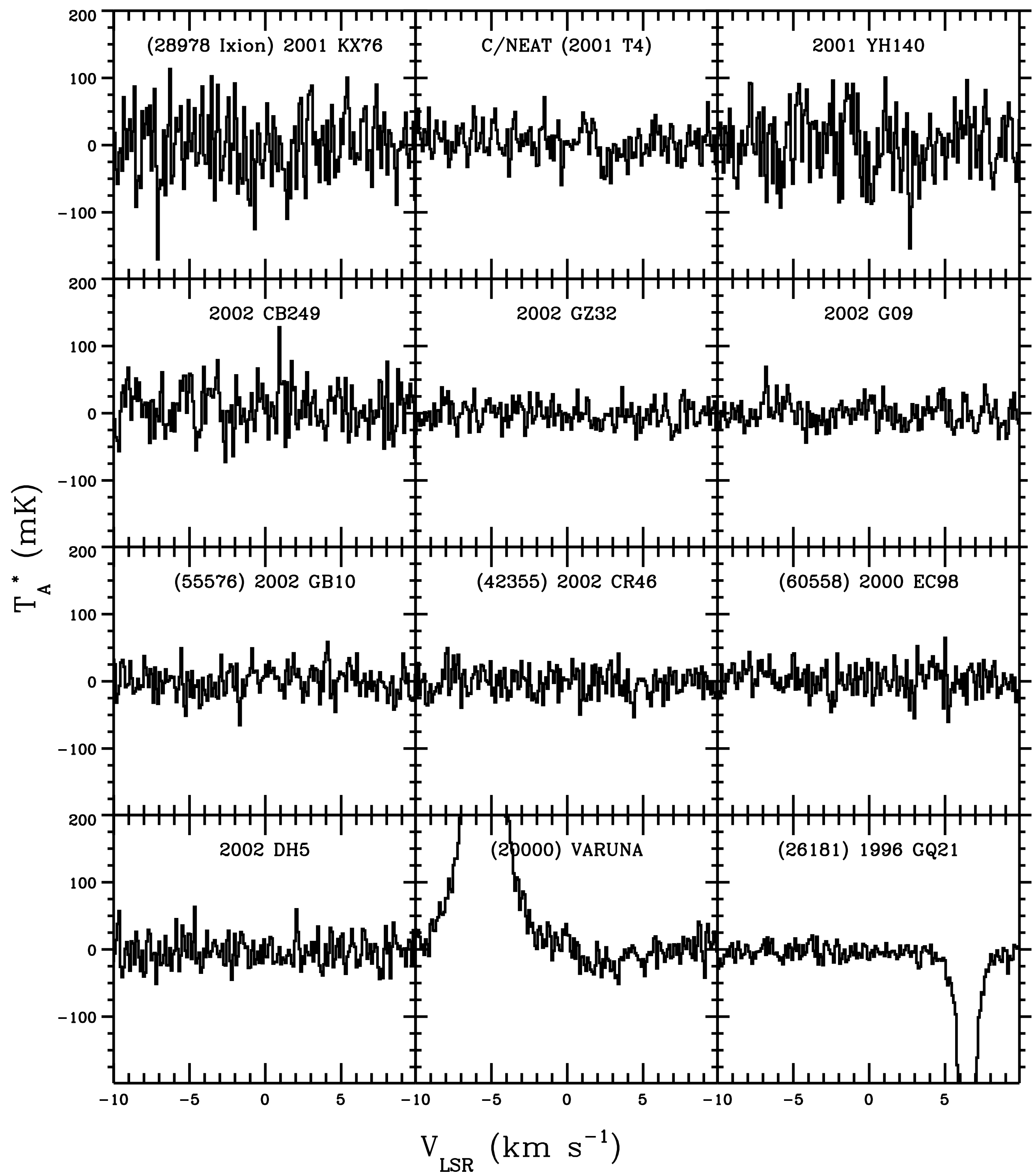
Zheng et al. (2006) Ap. J., 639, 534-548

Mastrapa and Brown (2006) Icarus 183, 207

- Comets are CO-rich
- Comets are from the Kuiper Belt
- Centaurs are an intermediate stage
- CO is very volatile
- Maybe we can detect CO in Centaurs too?

PS: One 5-sigma detection of Centaur CO has been claimed





$$f_J = \frac{(2J+1)e^{-\chi_J/kT}}{\Sigma_i(2i+1)e^{-\chi_J/kT}}.$$

Table 2. Journal of Observations

Object	UT 2002[a]	t [b]	R[c]	Δ [AU] [d]	α[e]	τ_{230}[f]	$\int T_A dv$[g]
(60558) 2000 EC98	May 27, 29, 31	21040	14.826	14.527	3.8	0.15 - 0.20	0.017
C/NEAT (2001 T4)	Aug 22, 24	13200	8.571	8.144	6.3	0.15 - 0.18	0.021
2002 CB249	Apr 23	8580	13.901	13.269	3.3	0.16 - 0.22	0.028
2002 DH5	May 30, 31	16800	14.523	14.614	4.0	0.14 - 0.18	0.023
2002 GO9	May 22, 23	20100	14.038	13.201	2.4	0.15 - 0.20	0.016
(55576) 2002 GB10	May 24, 25	25200	15.201	14.650	3.2	0.17 - 0.25	0.020
(42355) 2002 CR46	May 27, 29, 30	16210	18.051	18.586	2.7	0.15 - 0.20	0.019
2002 GZ32	May 21, 22, 23	27160	21.123	20.641	2.4	0.13 - 0.20	0.016
(28978) Ixion	Mar 13	4200	43.150	42.870	1.3	0.17 - 0.23	0.045
2001 YH140	Apr 23	4170	36.405	6.690	1.5	0.18 - 0.20	0.041
(26181) 1996 GQ21	Jan 10, 11, 12, 13	54000	39.408	39.620	1.4	0.13 - 0.18	0.010
(20000) Varuna	Jan 9, 10	20400	43.208	42.810	1.2	0.13 - 0.18	0.015

[a] UT Dates of observation

[b] Total integration time in seconds

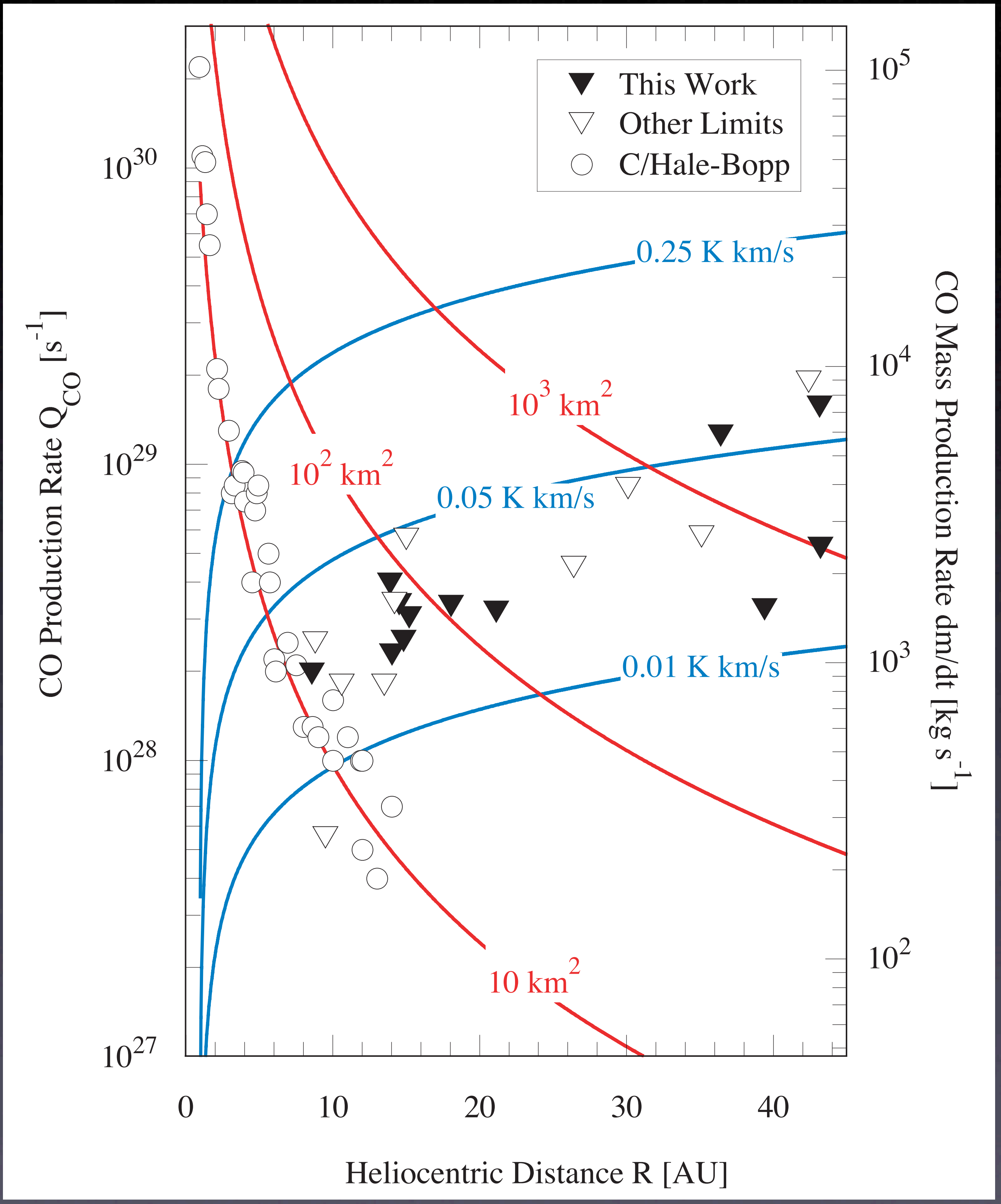
[c] Average heliocentric distance in AU

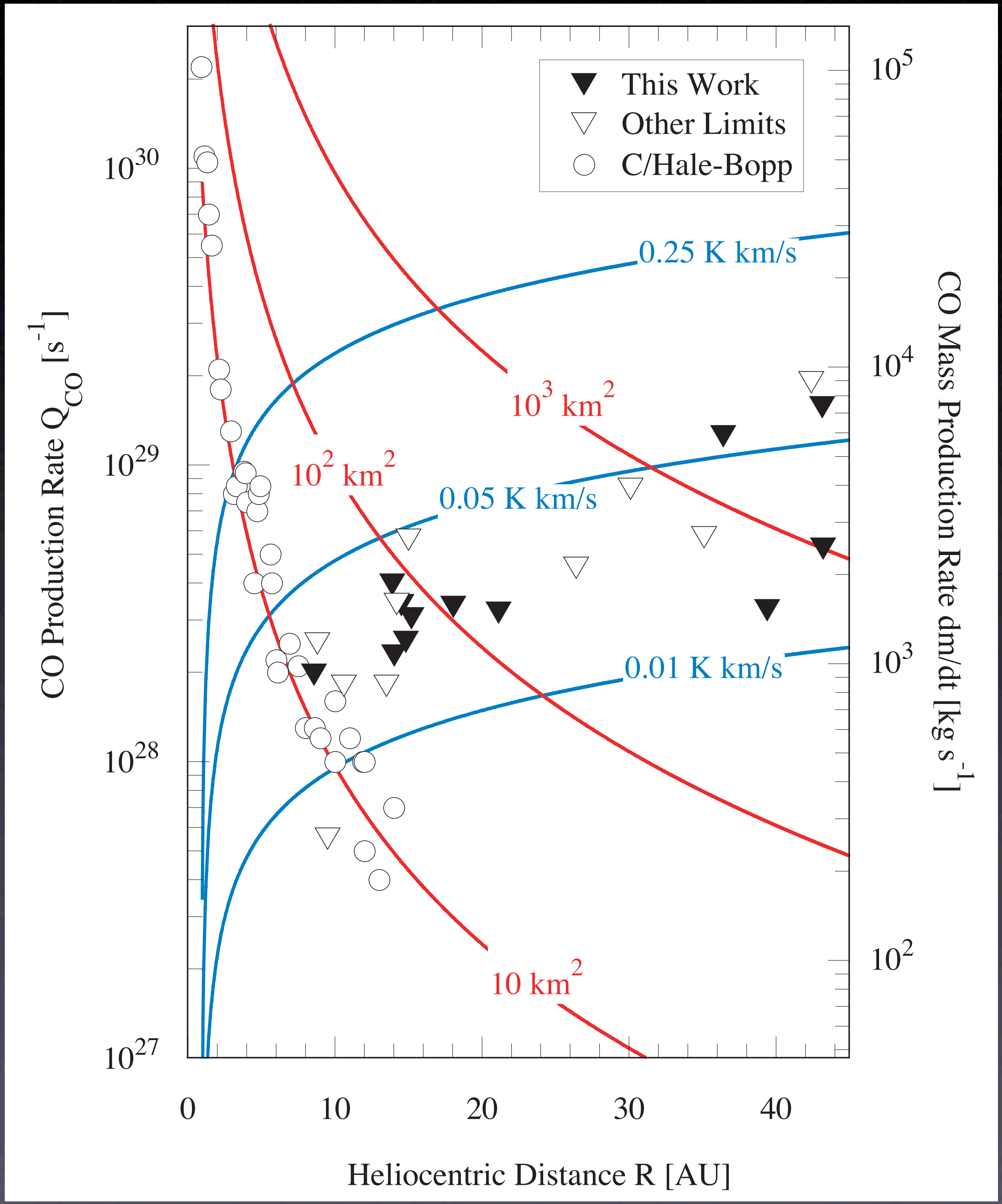
[d] Average geocentric distance in AU

[e] Phase angle in degrees

[f] Atmospheric optical depth at 230 GHz

[g] 3σ upper limit to the line area in K km s^{-1} in a 1 km s^{-1} band


This Work
Other Limits
C/Hale-Bopp
0.25 K km/s
0.05 K km/s
0.01 K km/s
10 km²
10² km²
10³ km²
CO Production Rate Q_CO [s⁻¹]
CO Mass Production Rate dm/dt [kg s⁻¹]
Heliocentric Distance R [AU]
10^30
10^29
10^28
10^27
10^5
10^4
10^3
10^2
0
10
20
30
40



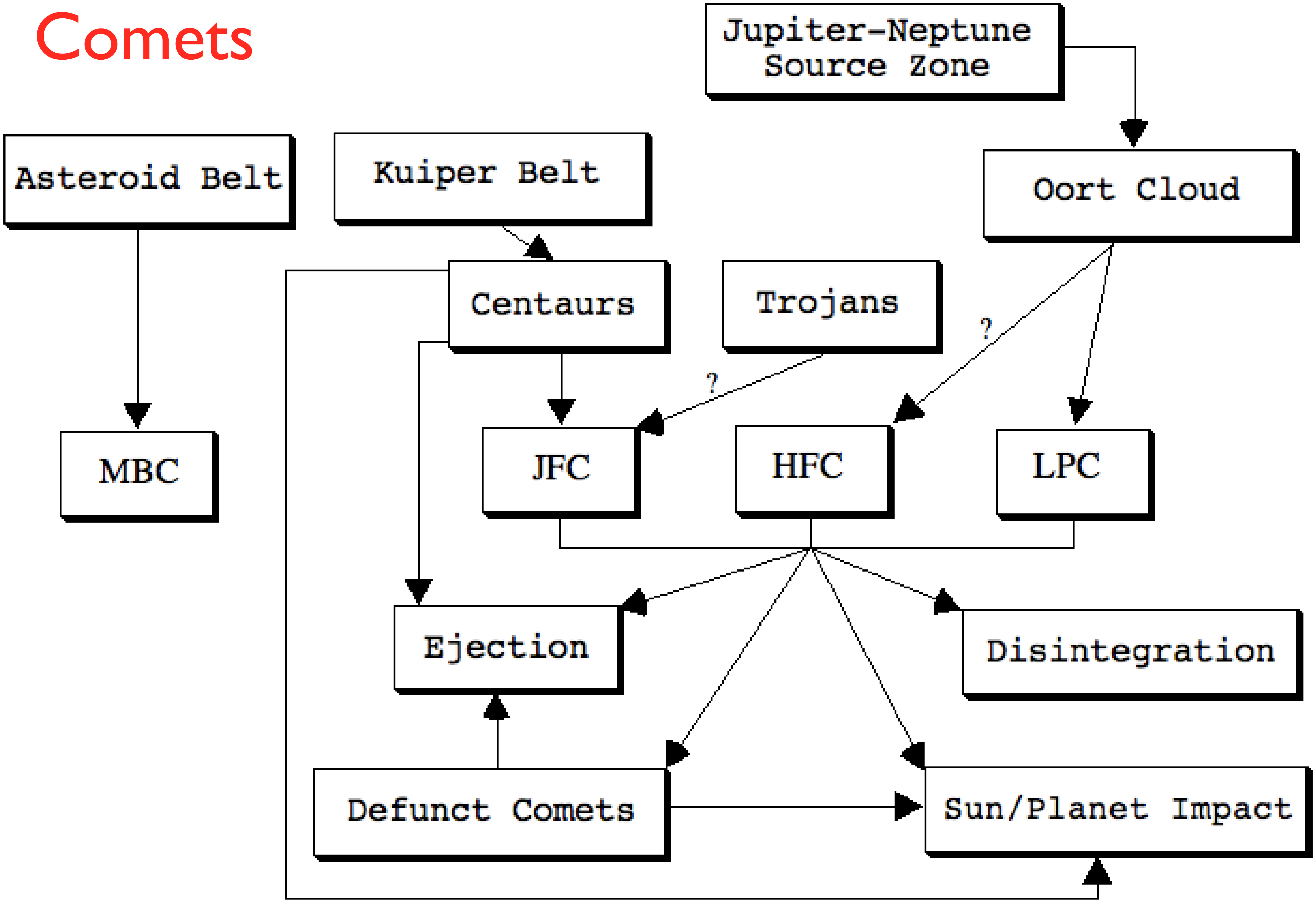
ALMA can do better

Summary

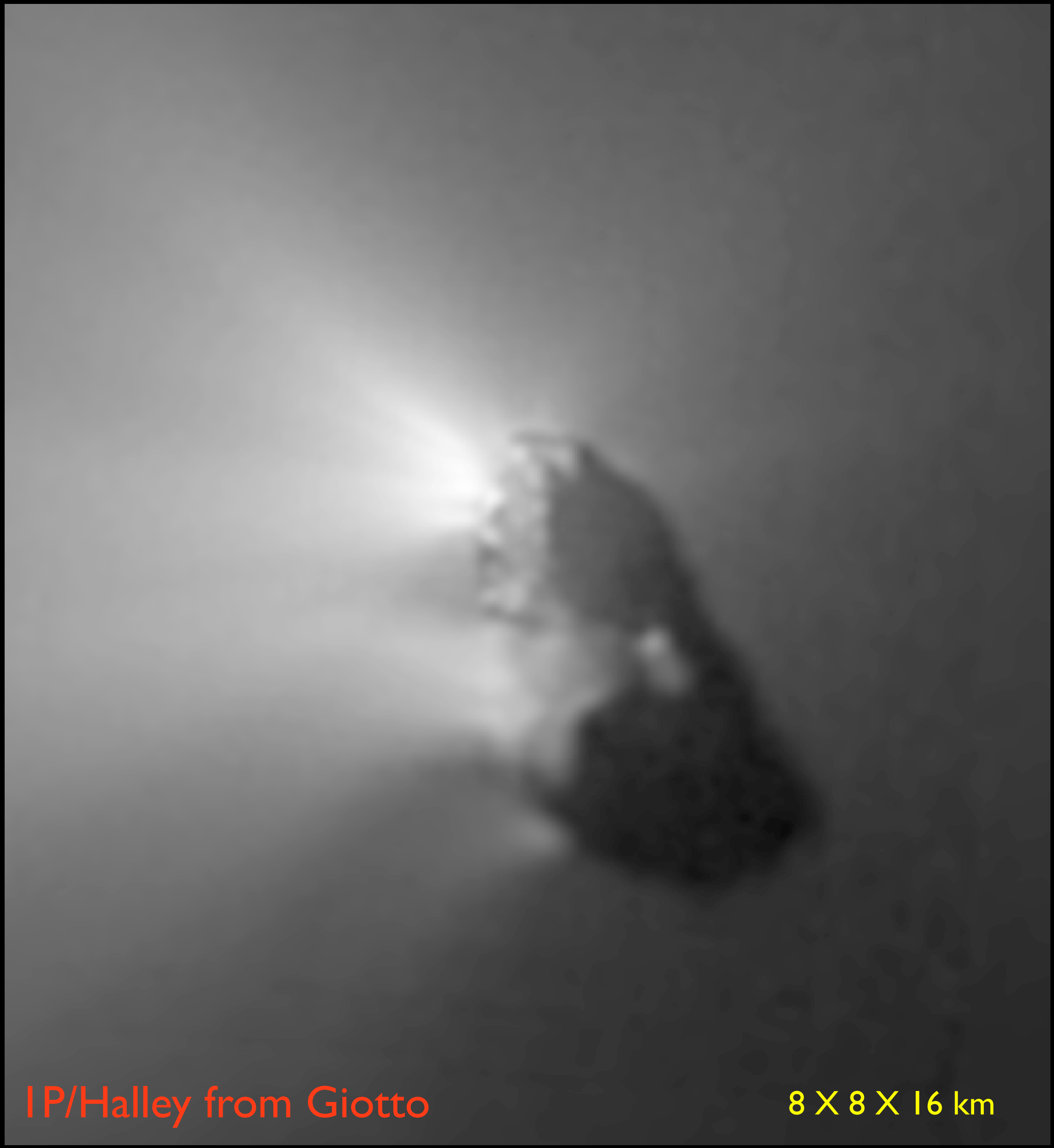
- CO 2-1 is not detected in the Centaurs
- Limits to the active fraction < 0.01 are obtained
- Surface CO is depleted, presumably by sublimation, even before the main on-set of cometary activity
- If CO is there, it is out of thermal contact with the surface most of the time

The Comets

Comets

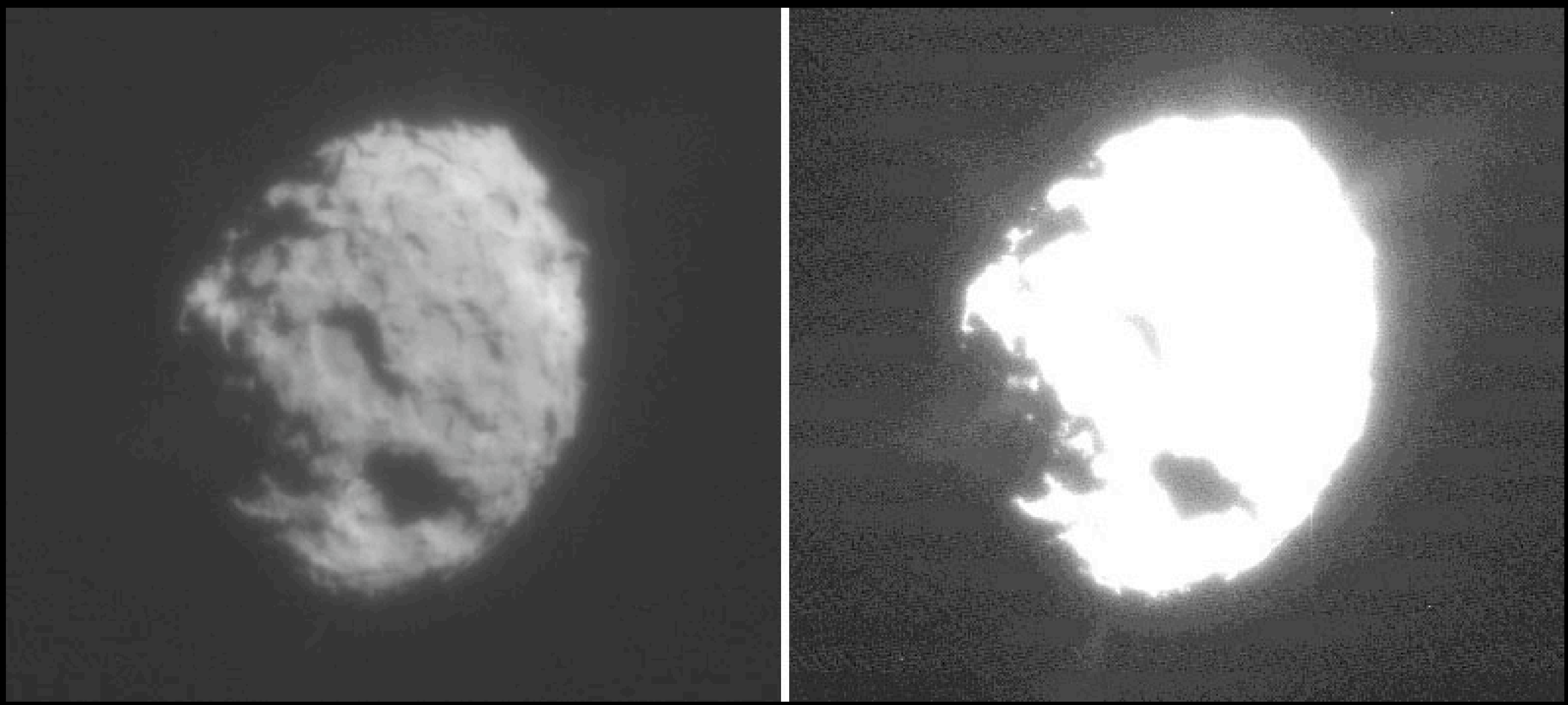


Jupiter–Neptune Source Zone
Asteroid Belt
Kuiper Belt
Oort Cloud
Centaurs
Trojans
?
?
MBC
JFC
HFC
LPC
Ejection
Disintegration
Defunct Comets
Sun/Planet Impact


1P/Halley from Giotto
8 X 8 X 16 km

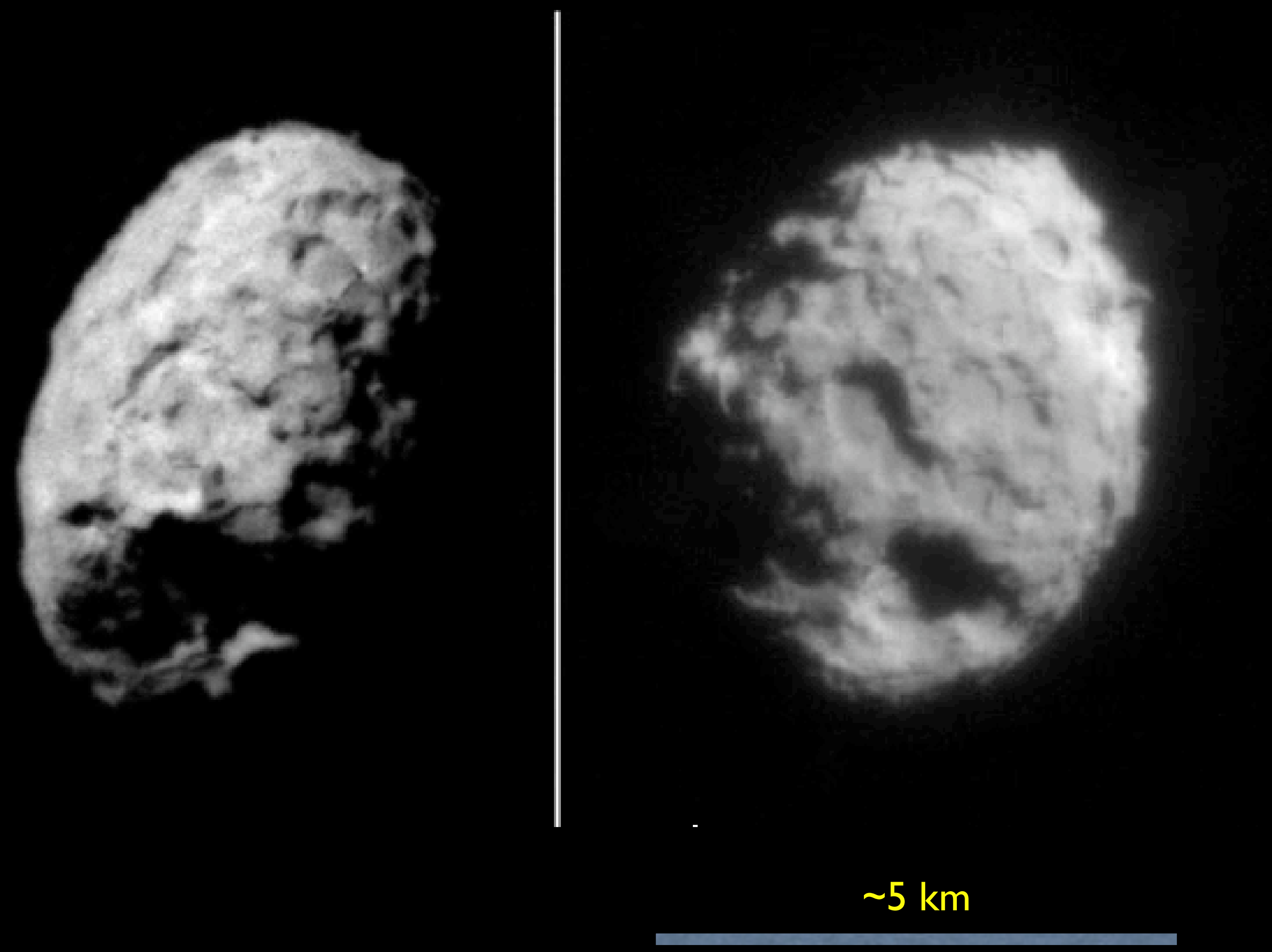
4 X 4 X 8 km

19P/Borrelly from Deep Space 1



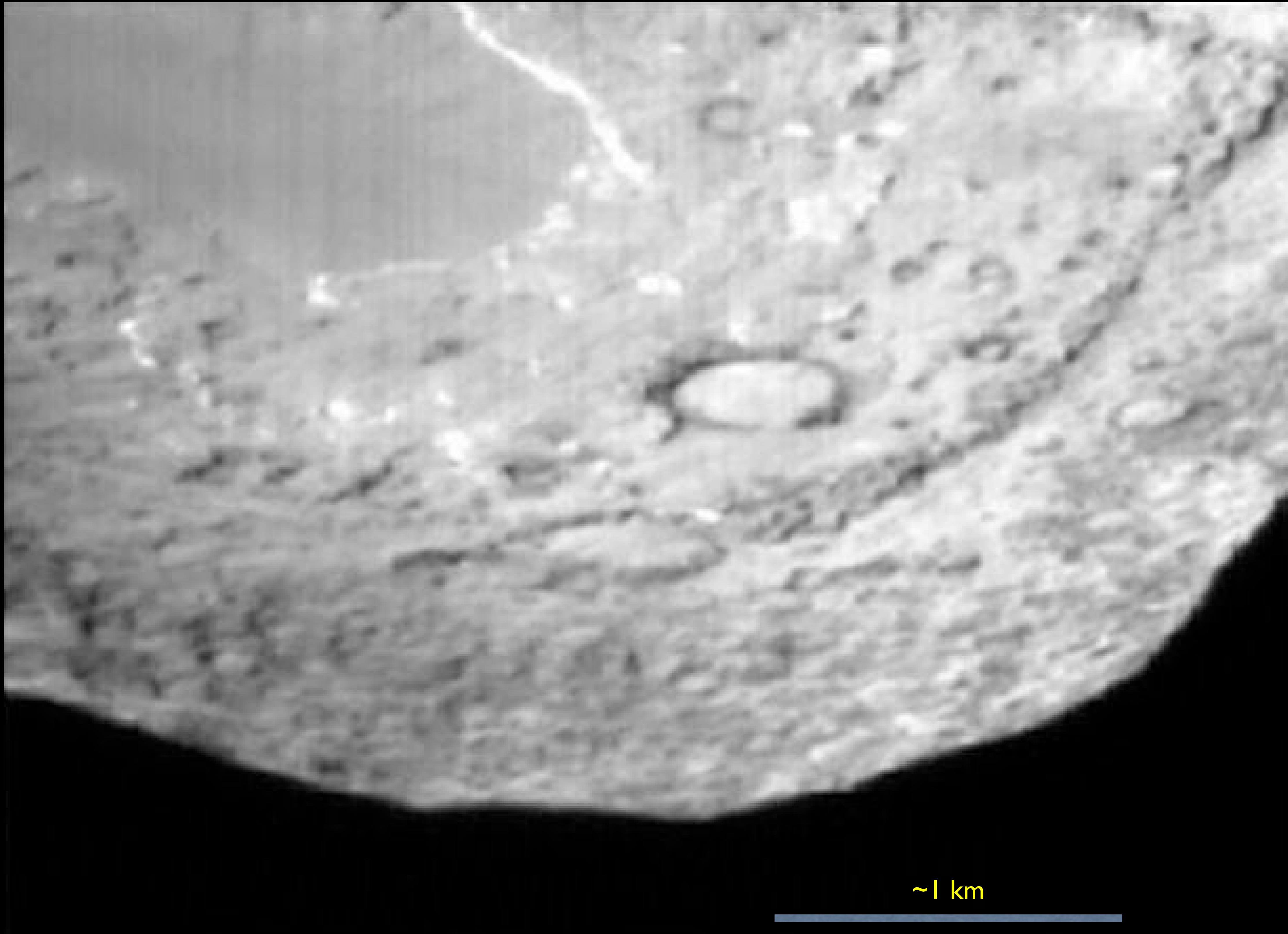
81P/Wild 2 from Stardust


81P/Wild 2



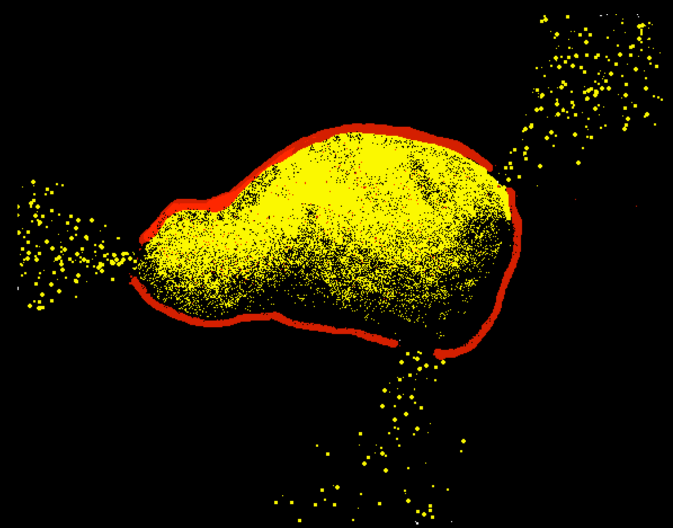
81P/Wild 2

9P/Tempel 1



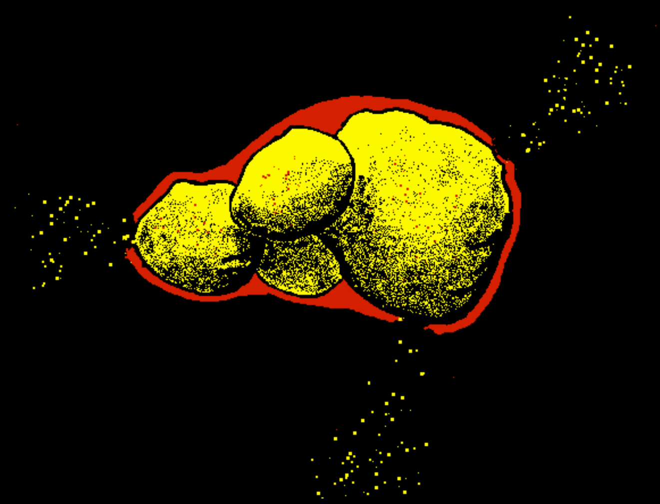
9P/Tempel 1

Nucleus Internal Structure



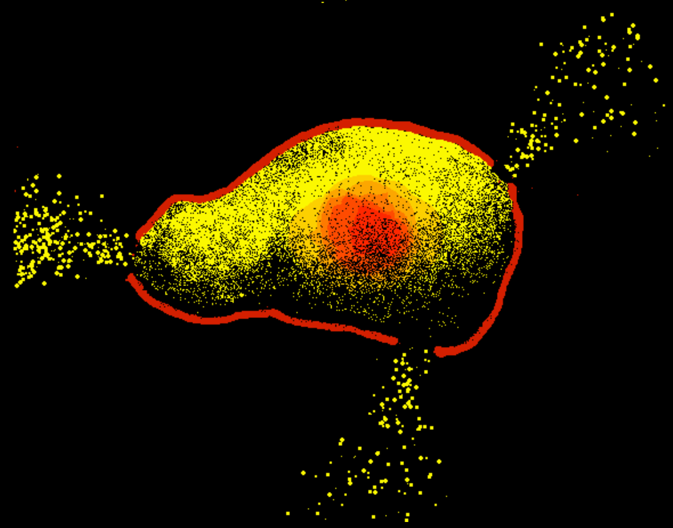
Monolithic Nucleus

Solid ice-rich body overlain by refractory mantle (red) through which outgassing occurs



Multi-component Nucleus

Weakly bonded aggregate structure (is suggested by the disaggregation of Shoemaker-Levy 9)

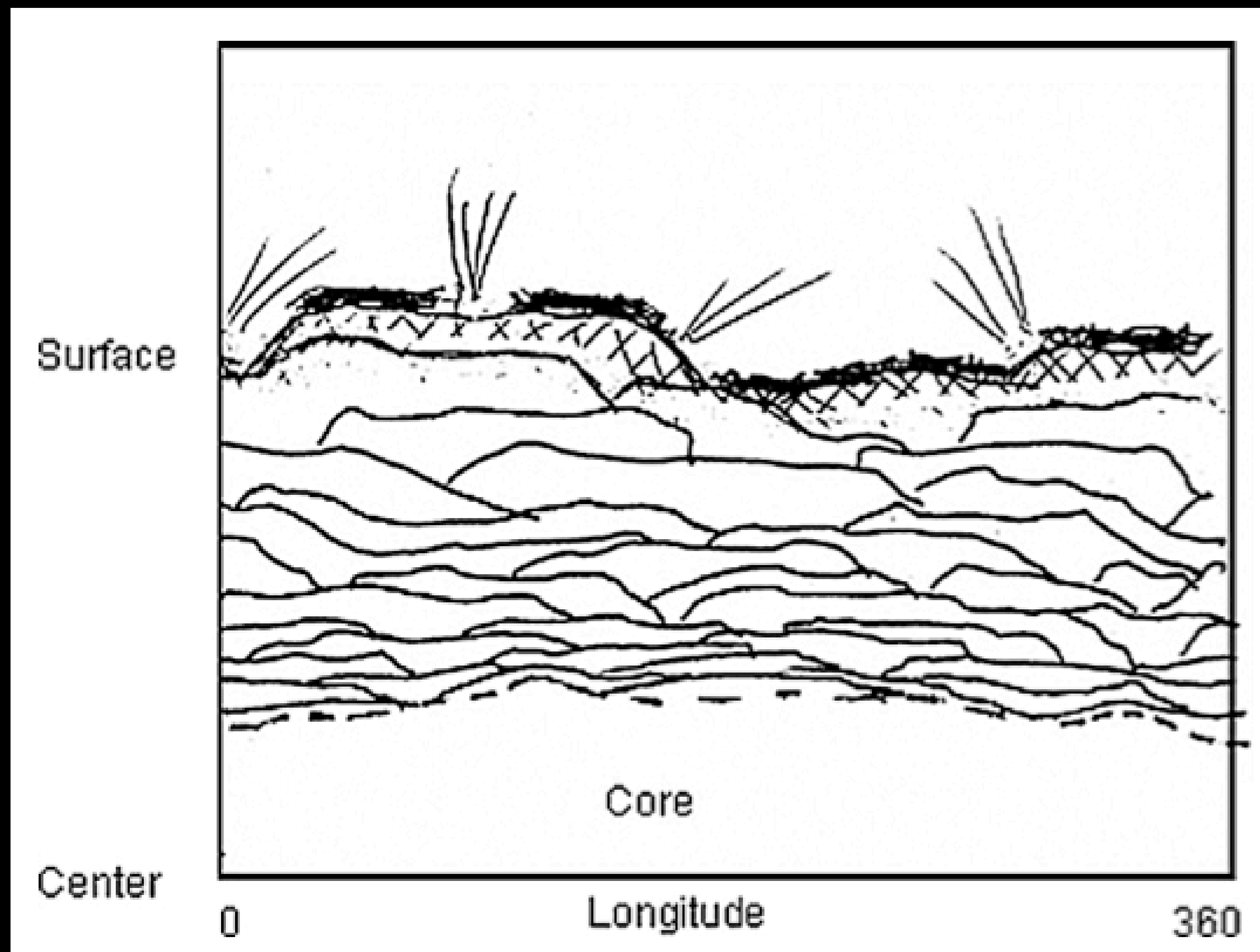


Differentiated Nucleus

Radial compositional variation due to impressed temperature gradient and resulting volatile migration

Jewitt

TALPS model (Belton et al 2007)



Dynamical Time $\tau_{dyn} \sim 4 \times 10^5 yr$

Conduction Time $\tau_c \sim \left(\frac{r_n^2}{\kappa}\right)$ $\tau_c \sim 3 \times 10^5 r_n^2$ yr

Specific sublimation rate (kg/m2/s) $\dot{m} = \frac{S_\odot}{LR^2}$

Devolatilization Time (no mantle) $\tau_{dv} \sim \frac{\rho_n r_n}{f\dot{m}}$ $\tau_{dv} \sim 2 \times 10^5 r_n$ yr

Mantling Time $\tau_M \sim \frac{\rho_n L_D}{\dot{m} f_M}$

Vent Lifetime

$\dot{r} \sim \frac{\dot{m}}{\rho}$ $\tau_v \sim \frac{2f^{1/2}\rho R^2 L r_n}{S_\odot}$ $\tau_v \sim 5r_n$ yr

Torques - spin up

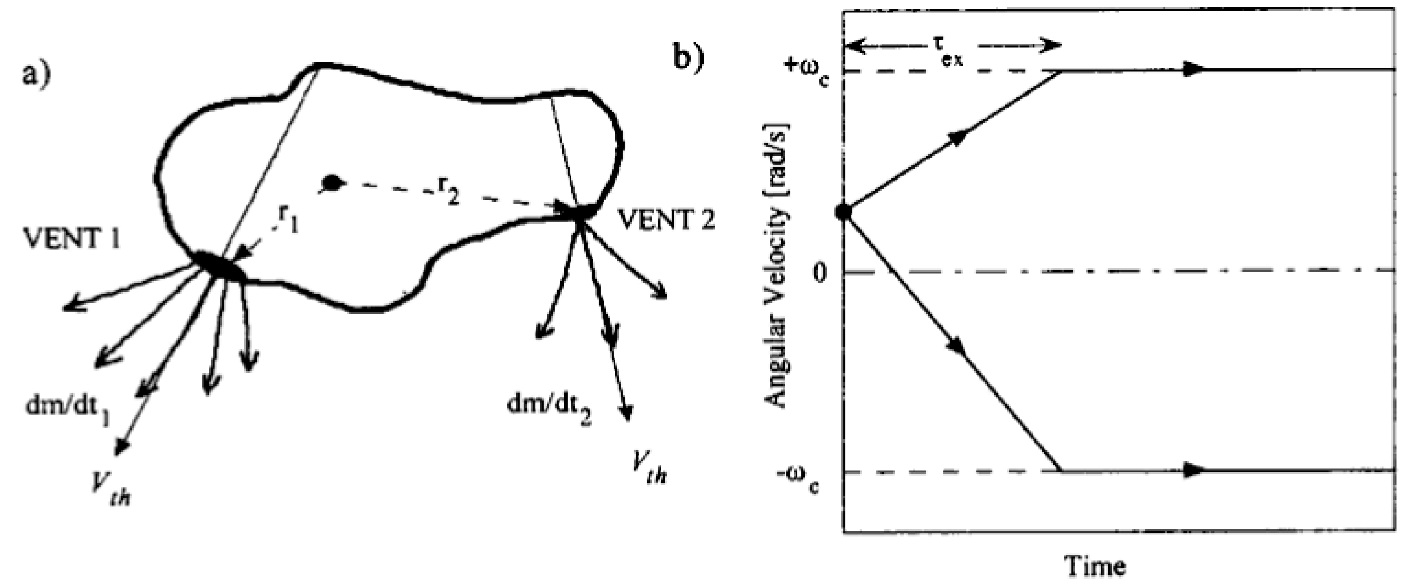


Figure 1. (a) Two vents on an irregular nucleus losing mass towards the sun (bottom of the figure). Recoil forces on the nucleus about the center of mass (black circle) exert a torque. The net torque on the nucleus is the sum of torques from all vents. (b) In response to the net torque, the spin of the nucleus evolves towards the critical frequency, ω_c (Equation (1)).

For relevant sizes and mass loss rates

$$\tau_{ex} \ll \tau_{damp}$$

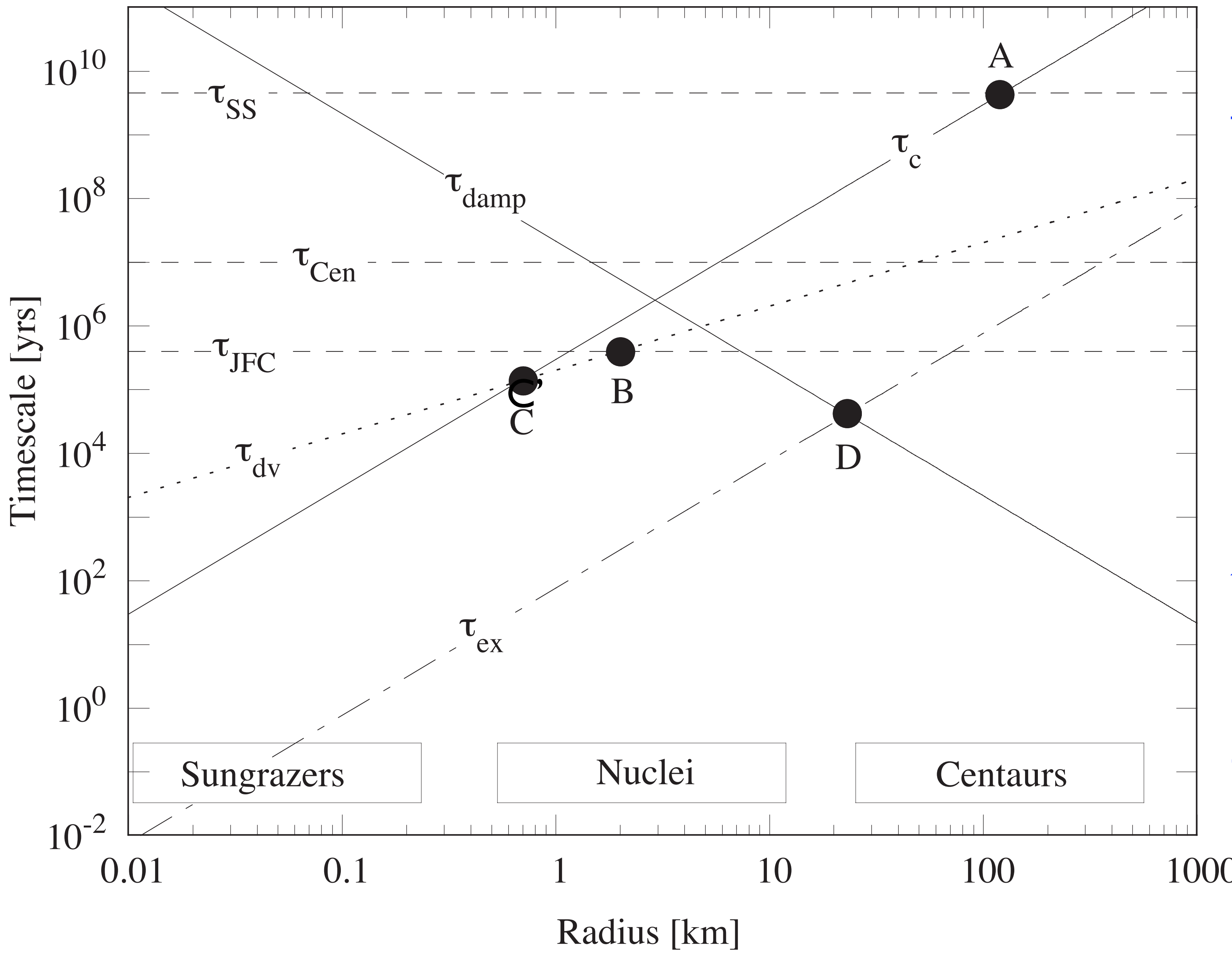
$$\tau_{ex} \sim \left[\frac{\omega \rho r_n^4}{V_{th} k_T \dot{M}} \right]$$

$$\tau_{ex} = 0.1 \ (r_n/1 \ \mathrm{km})^2 \ (\mathrm{yr})$$

$$\tau_{damp} \sim \frac{\mu Q}{\rho K_3^2 r_n^2 \omega^3}$$

$$\tau_{damp} \sim 1.0 \times 10^5 \left(\frac{P^3}{r_n^2} \right)$$

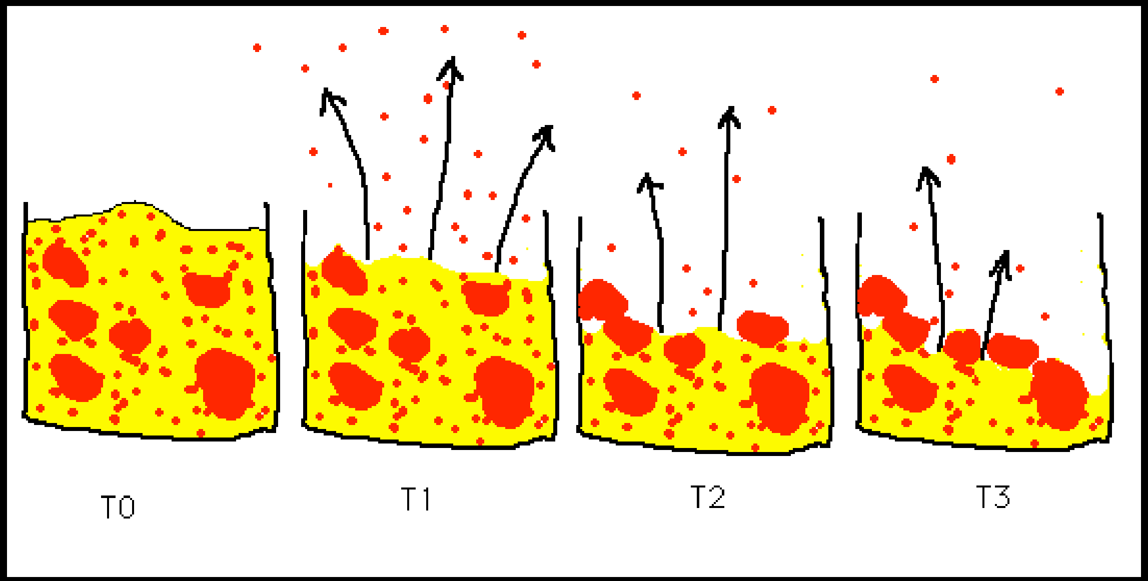
The Timescales Plot



- A: conduction time = age of solar system (only large objects can retain heat of formation)
- B: devolatilization time = dynamical lifetime (small nuclei could lose all volatiles)
- C: conduction time = devolatilization time (heat reaches core before volatiles depleted. Explosion?)
- C': conduction time = JFC dynamical time (objects a > 1 km are perpetually out of thermal equilibrium)
- D: excitation time = damping time (objects < 20 km should be in excited spin states)

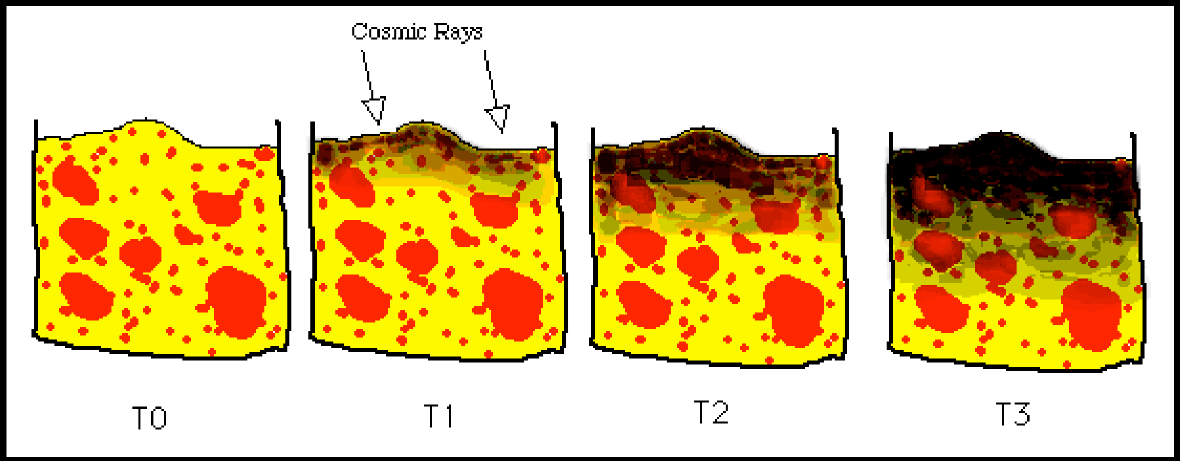
Jewitt 2005 Comets II book

Mantles



Rubble Mantle

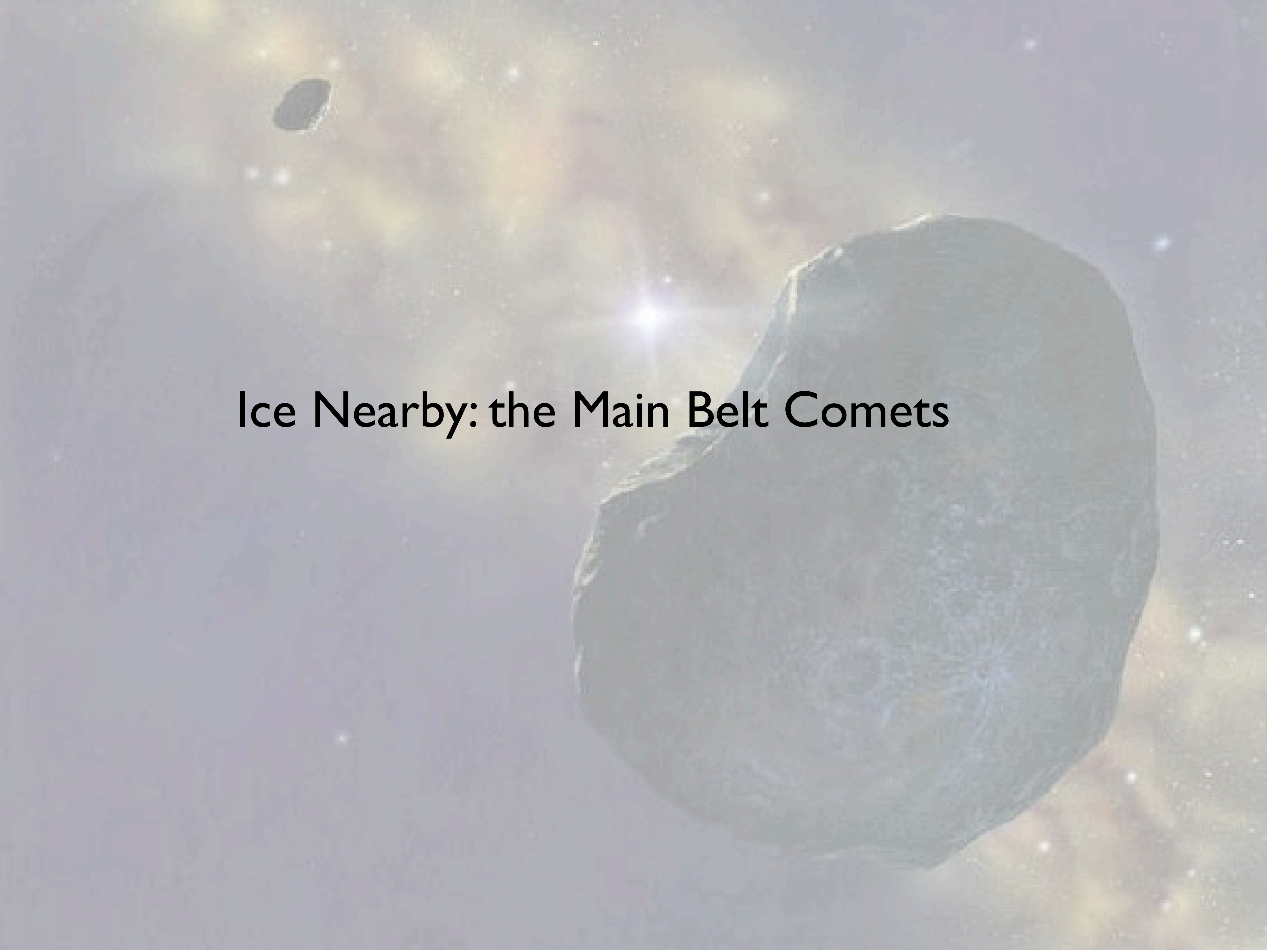
At initial time T0, the comet nucleus consists of a mixture of ices (yellow) and rocks (red). At later time T1, sunlight from above heats the nucleus surface and sublimates the ice. Dust particles and the smaller rocks are entrained in the gas flow (arrows) and are ejected from the nucleus. Large rocks are too heavy to be lifted. By time T3, about half the surface is covered by large rocks left behind as a lag deposit. In the final time step T4, the surface is almost completely sealed by the rubble mantle. The time difference T4 - T0 is uncertain but probably very short. Rubble mantles could form within a single orbit.



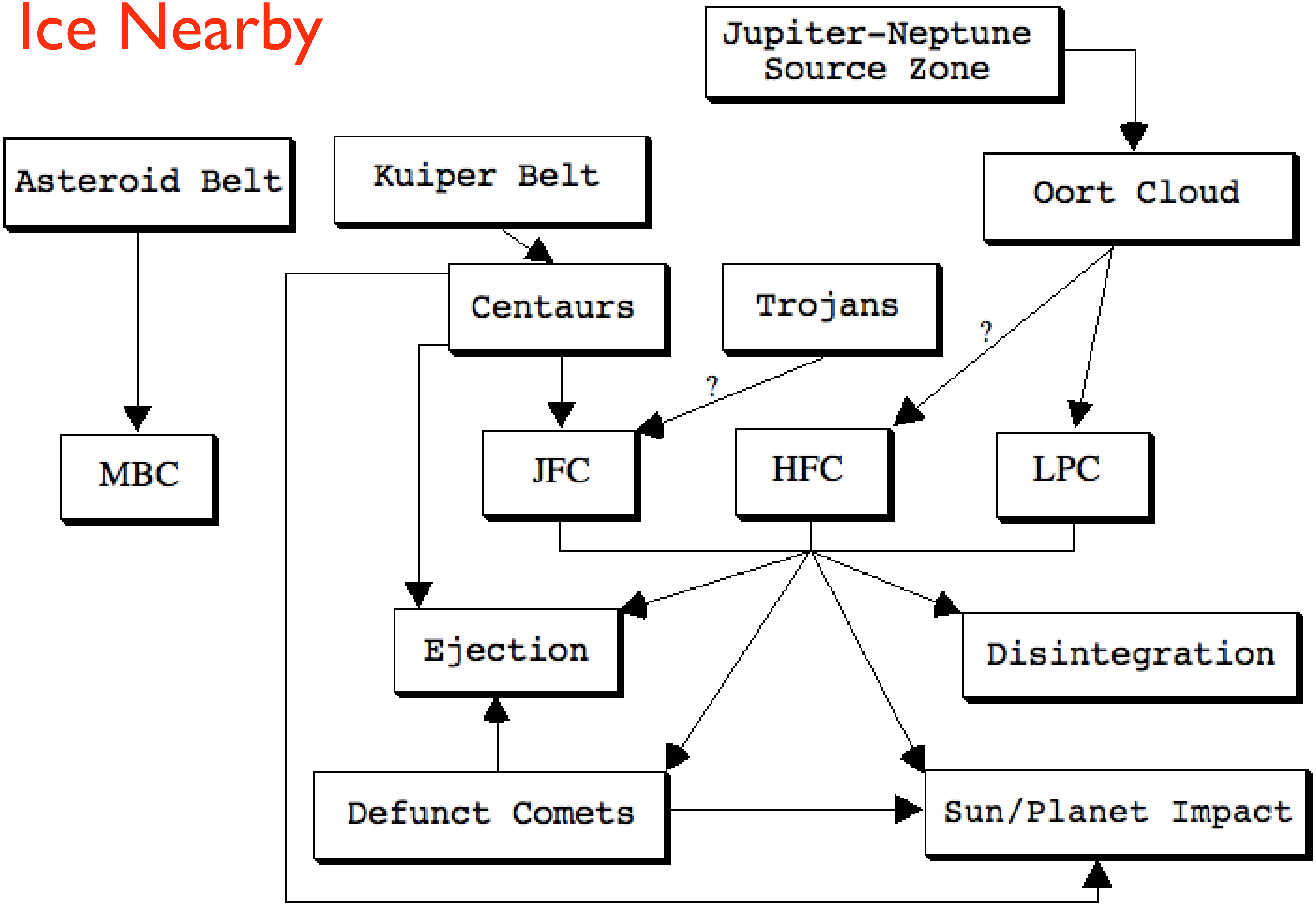
Irradiation Mantle

At initial time T0, the comet nucleus consists of a mixture of ices (yellow) and rocks (red). At later time T1, cosmic rays irradiate the nucleus surface and begin to damage molecular bonds in the icy material. As time increases (step T2) the degree of damage done by the cosmic rays increases. Laboratory experiments with particle accelerators show that during irradiation there is preferential escape of hydrogen and an increase in the chemical complexity of the irradiated material. Many complex carbon compounds may be formed, resulting in a surface mantle that is dark (like charcoal) and neutral to red in color. By the final time step (T3), the process is saturated. The MeV cosmic rays responsible for most damage have a penetration depth of roughly 1 meter in ice, so the irradiation layer would be about this thick. The time difference T3 - T0 is thought to be about 100 million years.

Ice Nearby: the Main Belt Comets

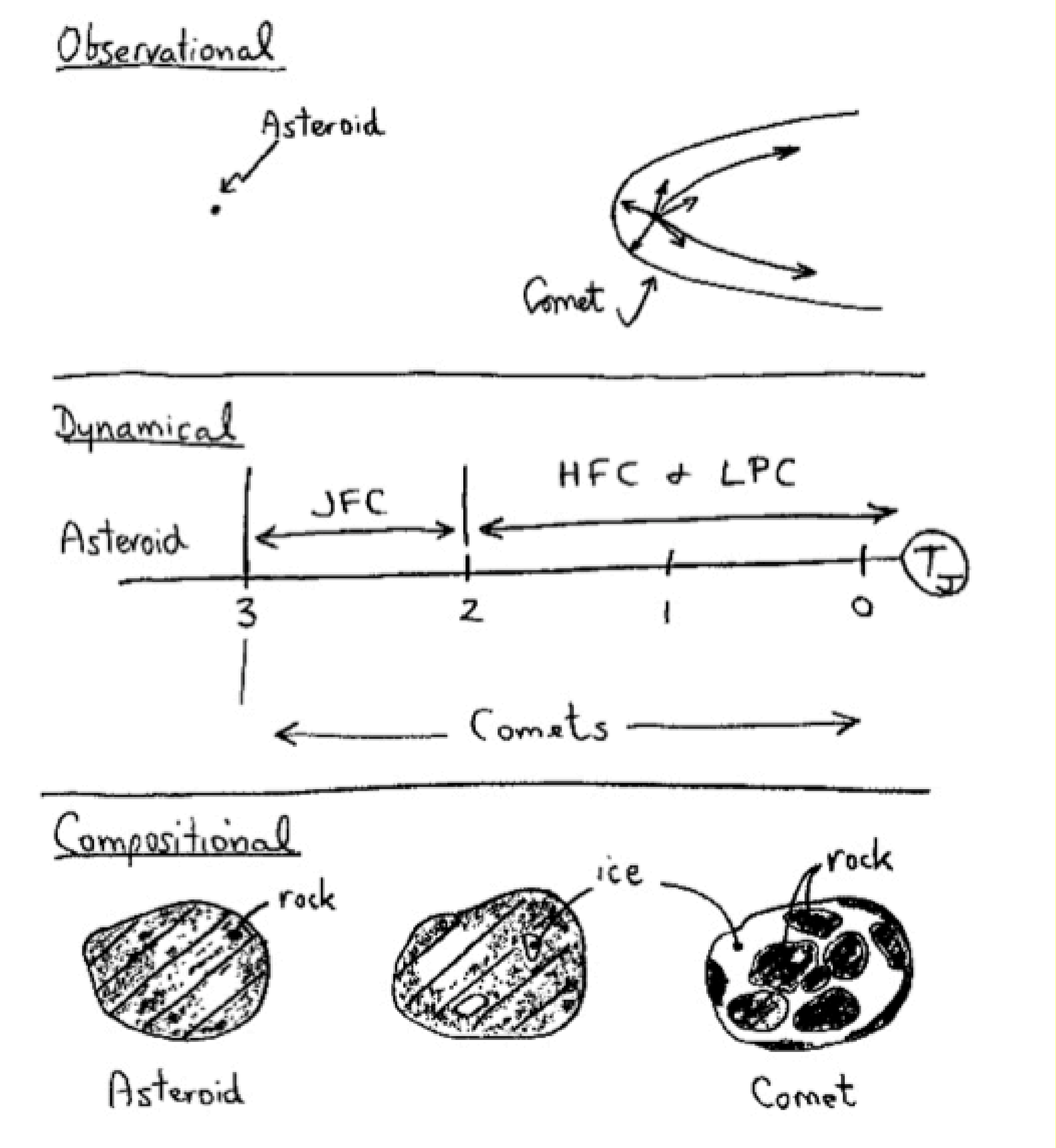


Ice Nearby


Jupiter-Neptune Source Zone
Asteroid Belt
Kuiper Belt
Oort Cloud
Centaurs
Trojans
?
?
MBC
JFC
HFC
LPC
Ejection
Disintegration
Defunct Comets
Sun/Planet Impact

Comet vs Asteroid

$$T_J = \frac{a_J}{a} + 2\left[(1-e^2)\frac{a}{a_J}\right]^{1/2} cos(i)$$



Comet vs Asteroid

- Observational: Coma = comet, no coma = asteroid
  (depends on instrument used)

- Dynamical: $T_J \leq 3$ - Comet, $T_J > 3$ - Asteroid
  (simplistic, obvious exceptions)

- Physical: comet contains substantial bulk ice
  (fundamental but unrealizable)

Origin of Earth's Water

• Earth probably formed dry because it formed hot.

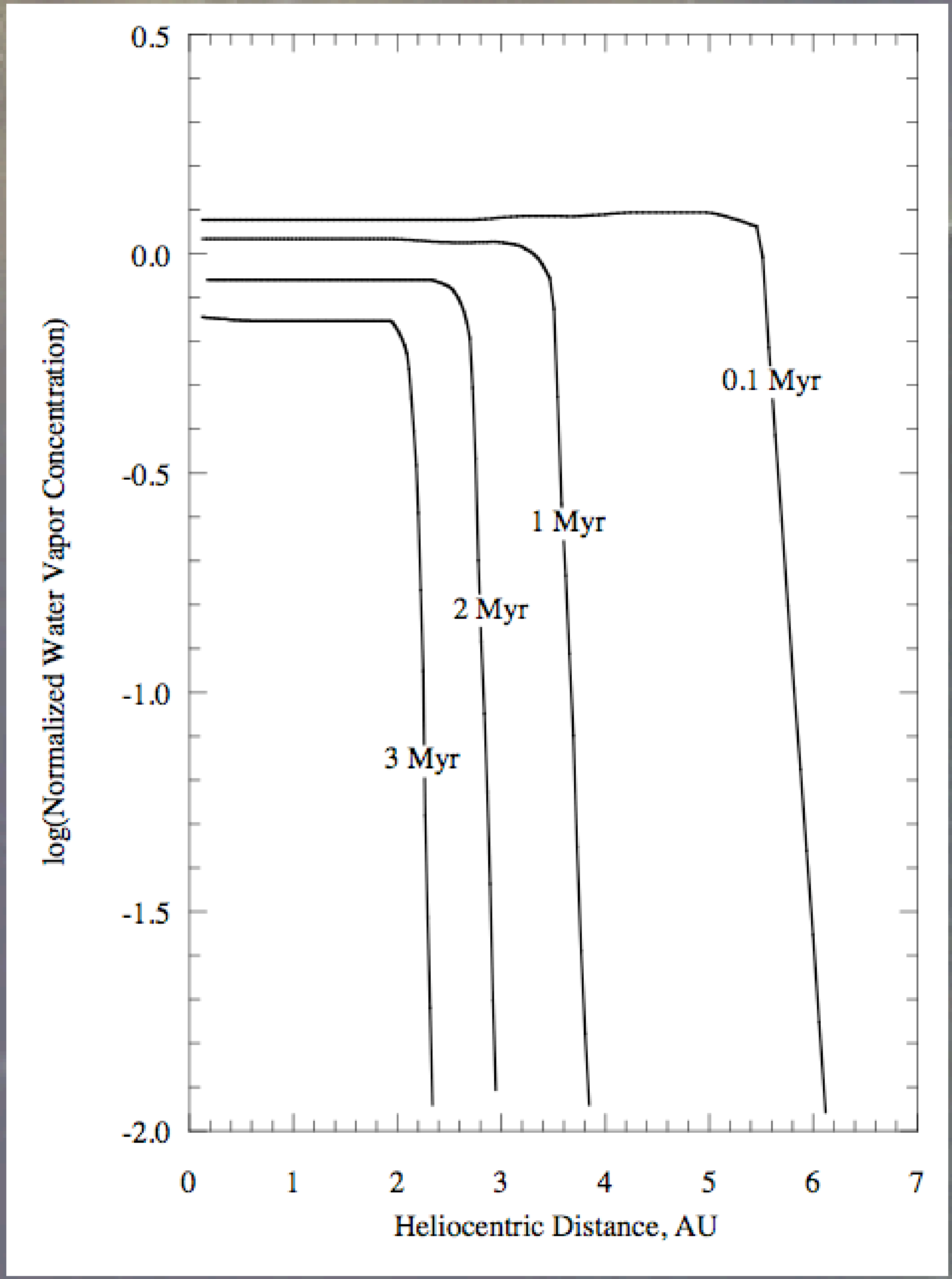
• Water was accreted later.

• Plausible sources are comets and icy asteroids.

• Comets seem to have the wrong D/H ratio.

• Icy asteroids have just been discovered from Mauna Kea (the Main Belt Comets): they may be the source of the oceans.

Where is the Ice?



"Snow Line"

Ciesla and Cuzzi 2006

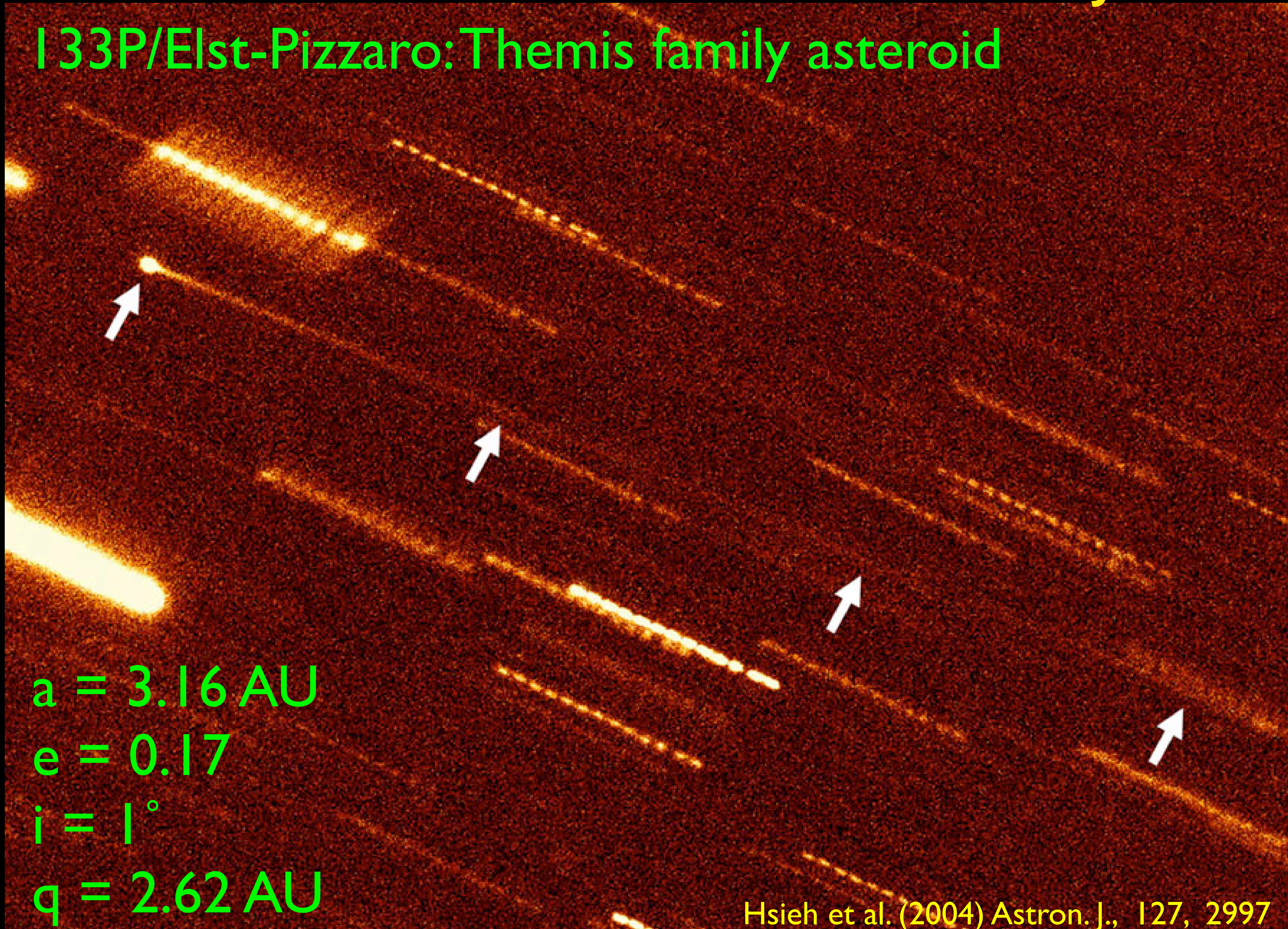
Art by Michael Carroll

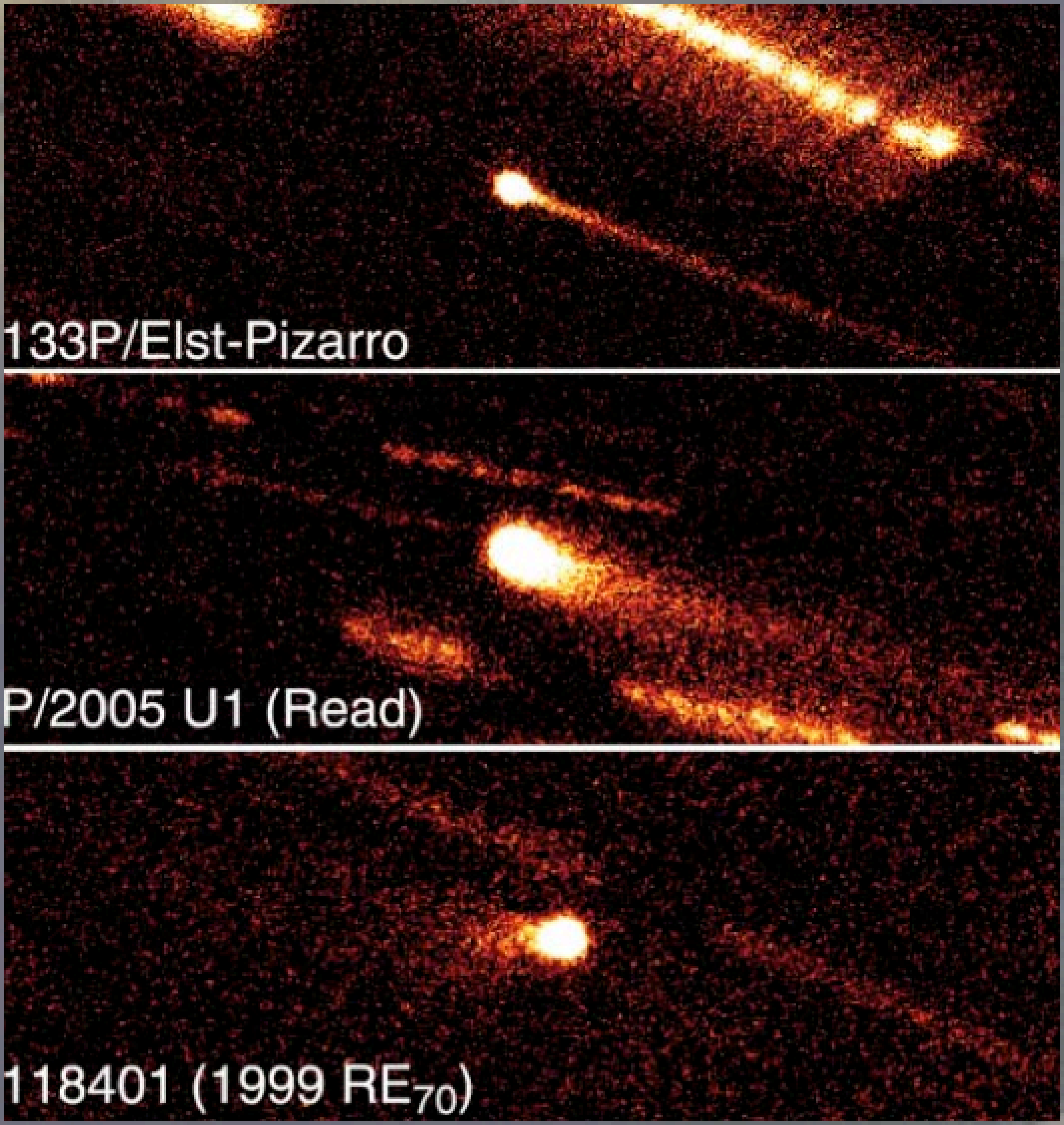
Comet: Observational Constraints

- Ortho/Para ratio -> T ~ 30 K
- $0.01 \leq CO/H_2O \leq 0.2$ -> T ~ 30 - 50 K
- HDO and DCN -> T ~ 30 K
- Kuiper Belt Source -> T ~ 40 K

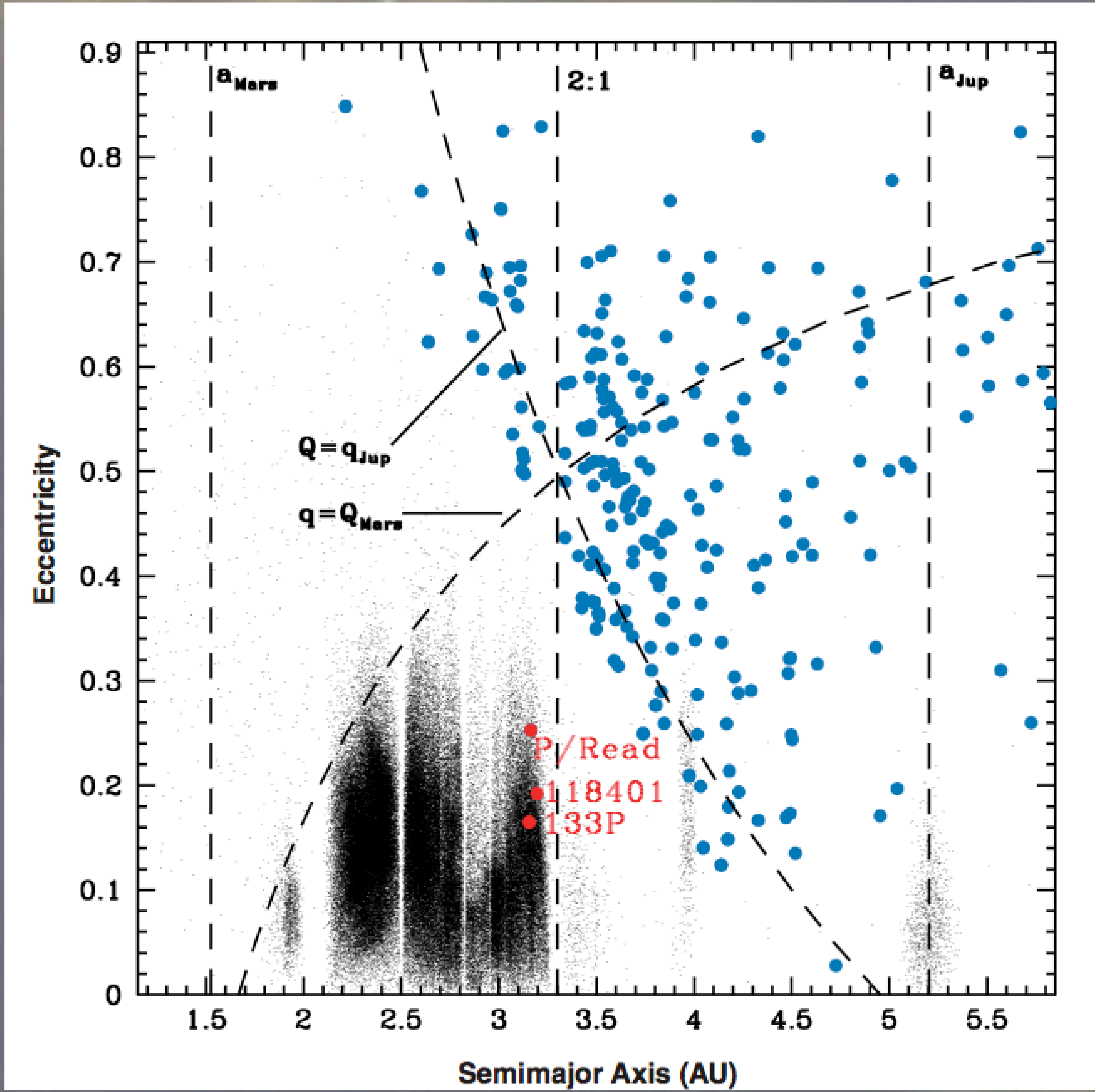
Formation at very low tempertures is indicated

TJ = 3.18

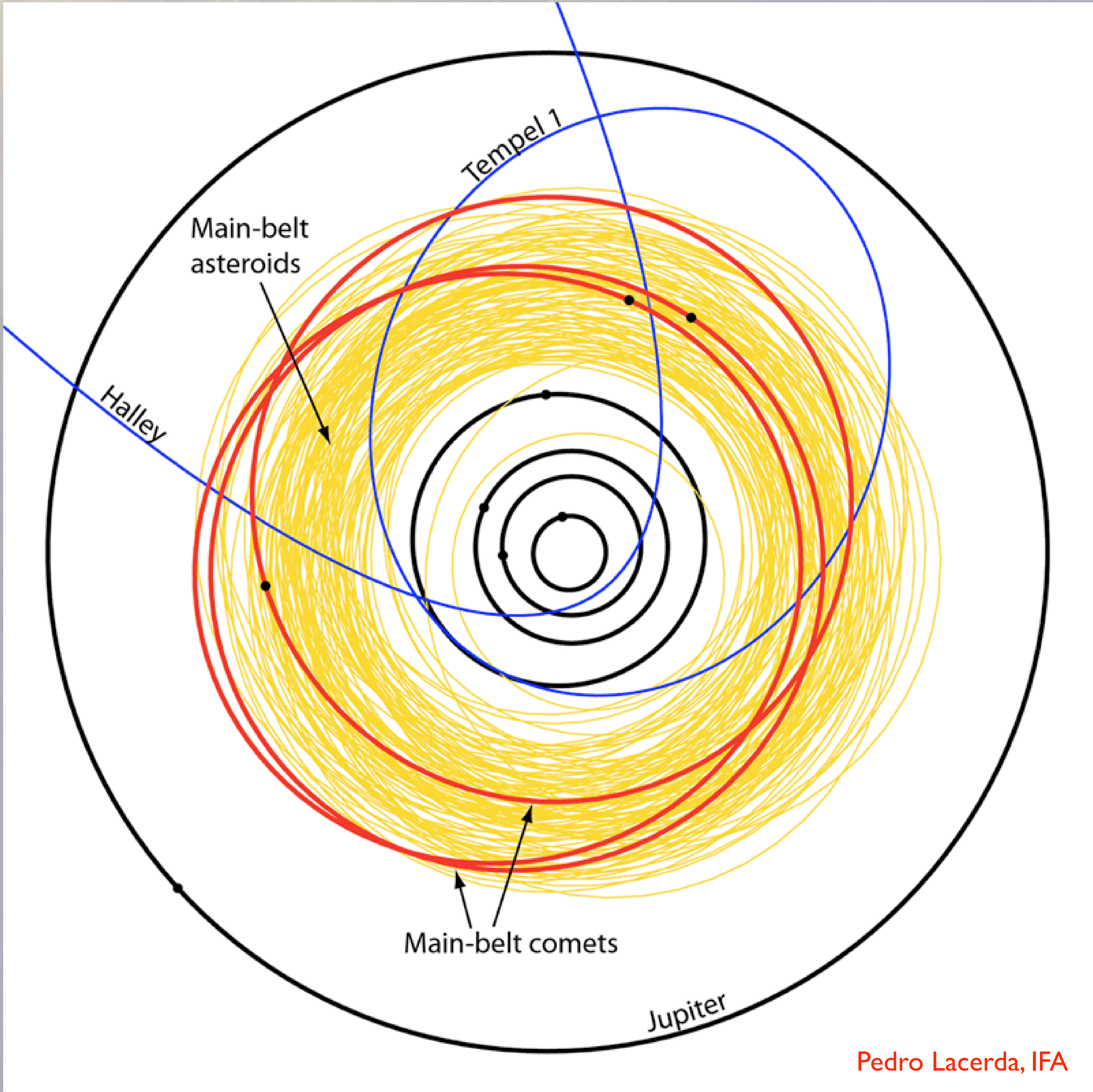

133P/Elst-Pizzaro: Themis family asteroid
a = 3.16 AU
e = 0.17
i = 1°
q = 2.62 AU
Hsieh et al. (2004) Astron. J., 127, 2997



Hsieh and Jewitt (2006) Science, 312, 561-563

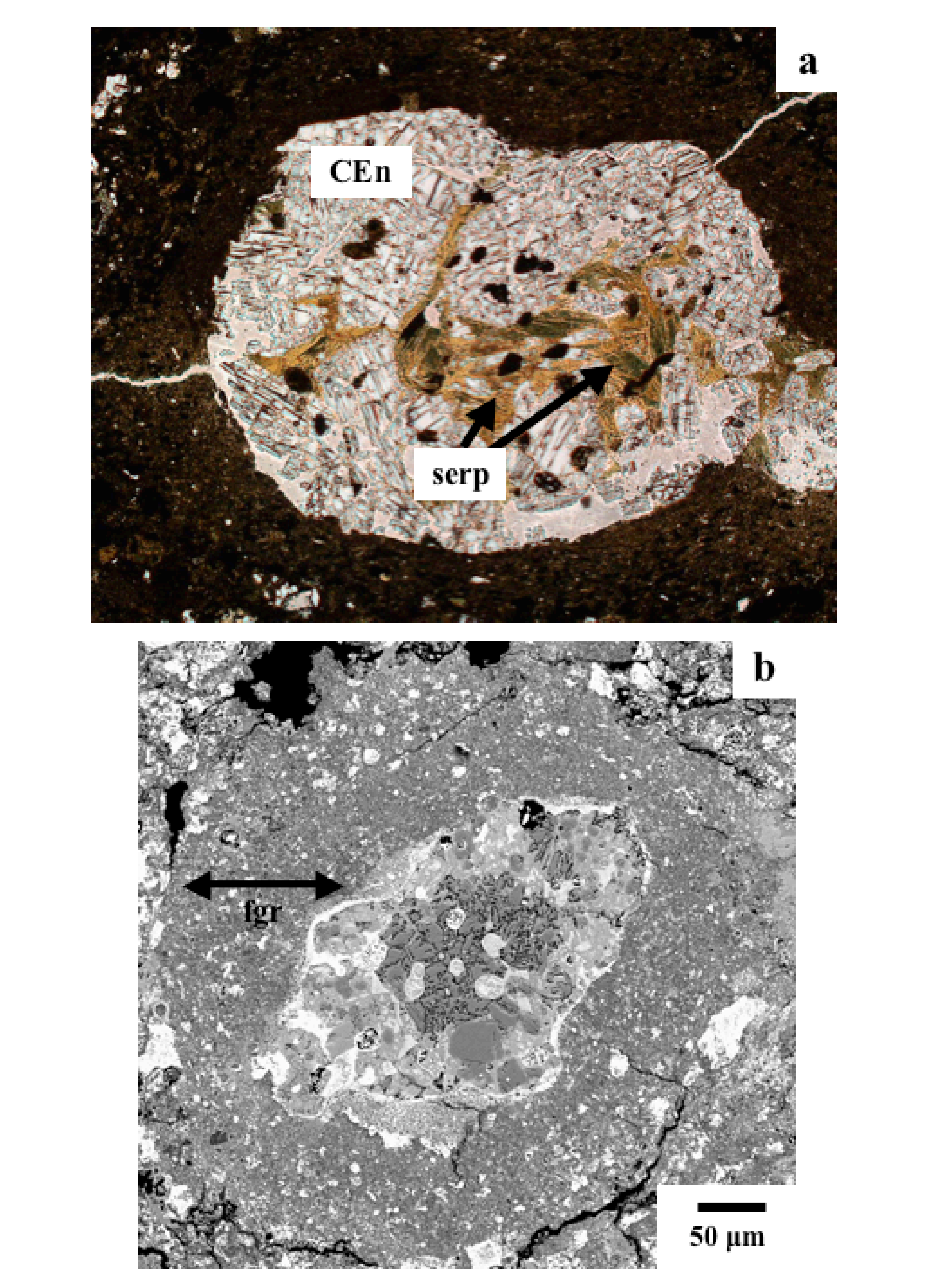


Hsieh and Jewitt (2006) Science, 312, 561-563


Tempel 1
Main-belt
asteroids
Halley
Main-belt comets
Jupiter
Pedro Lacerda, IFA

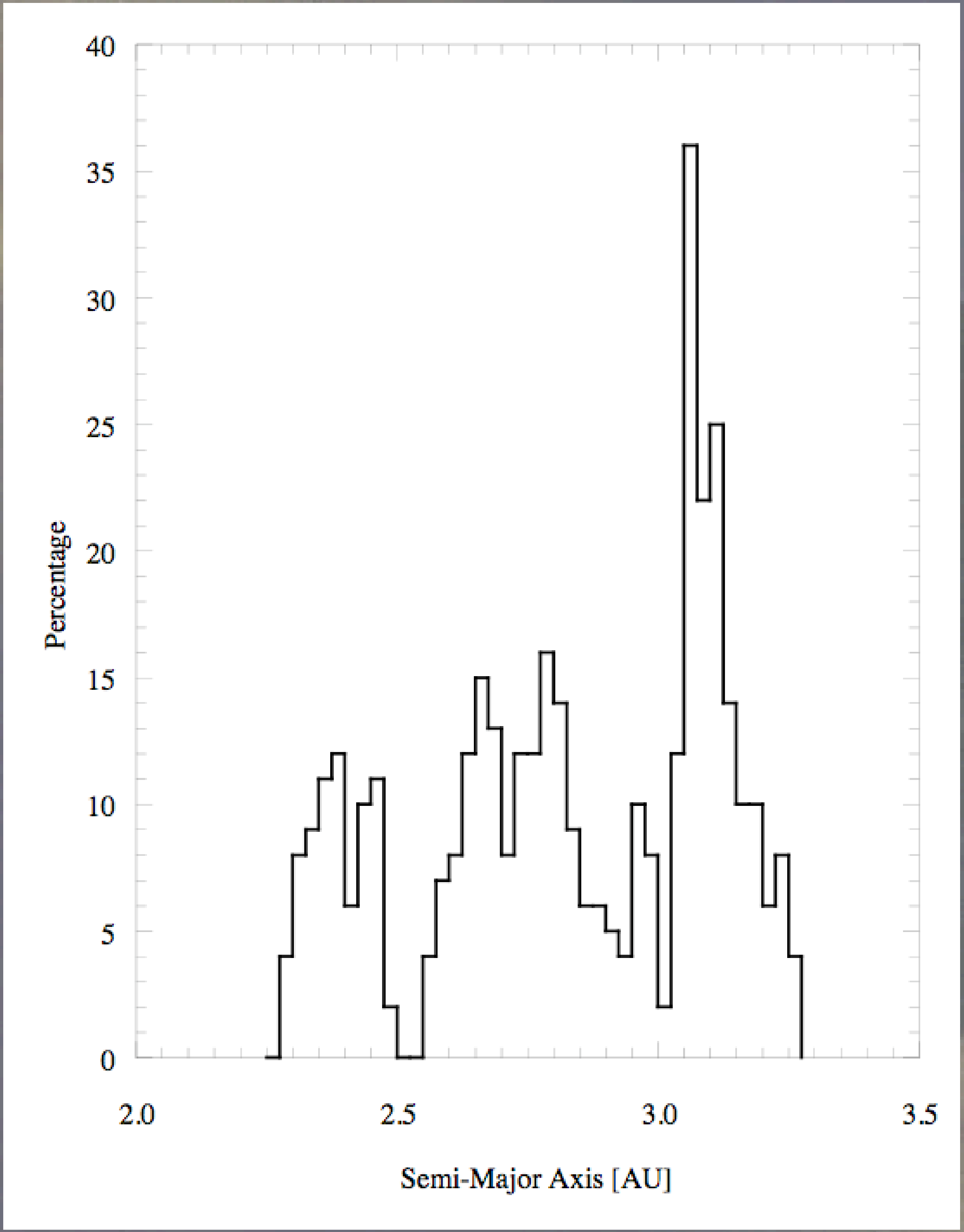

Melted main-belt comets?

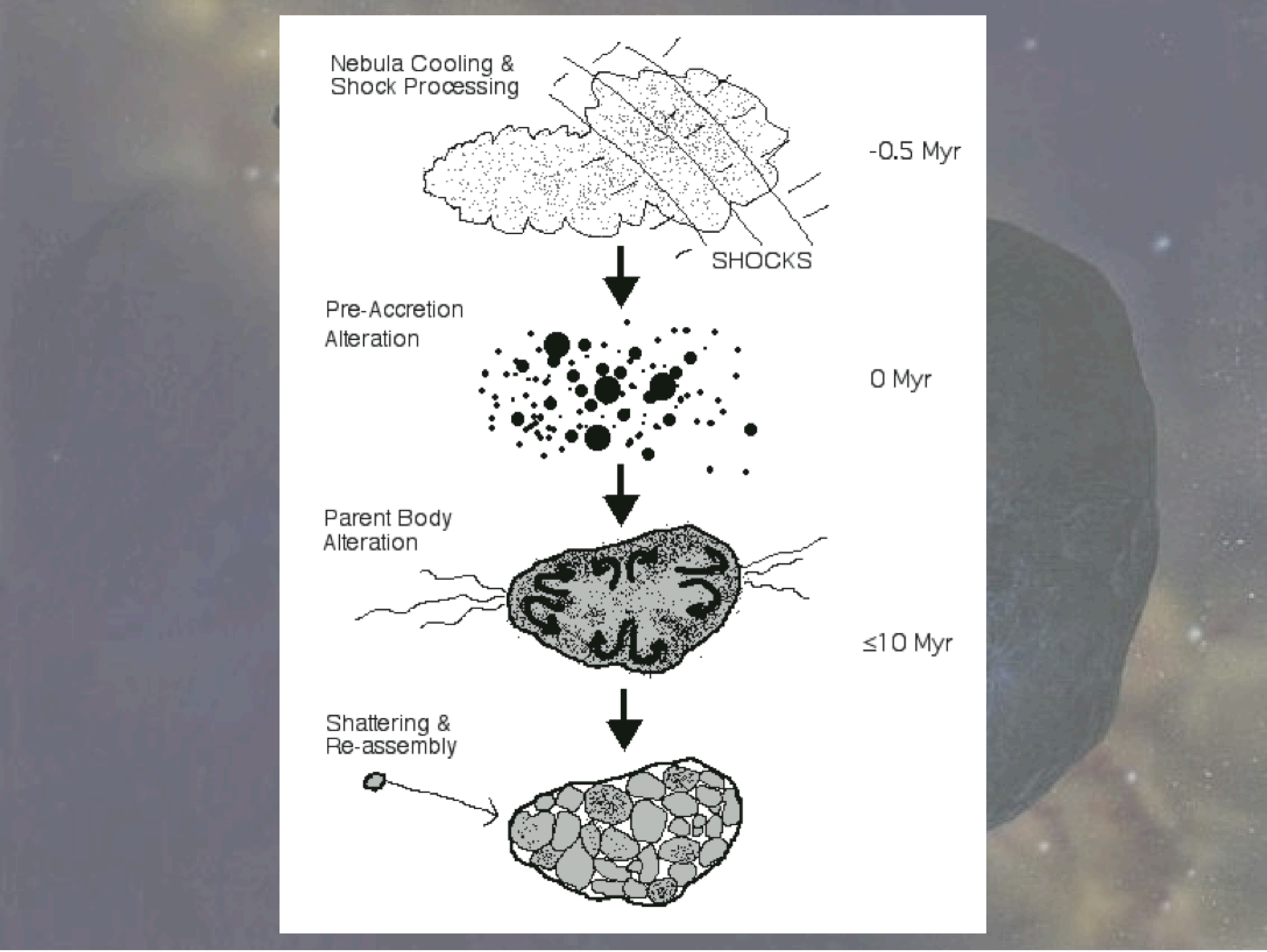
Ice Nearby

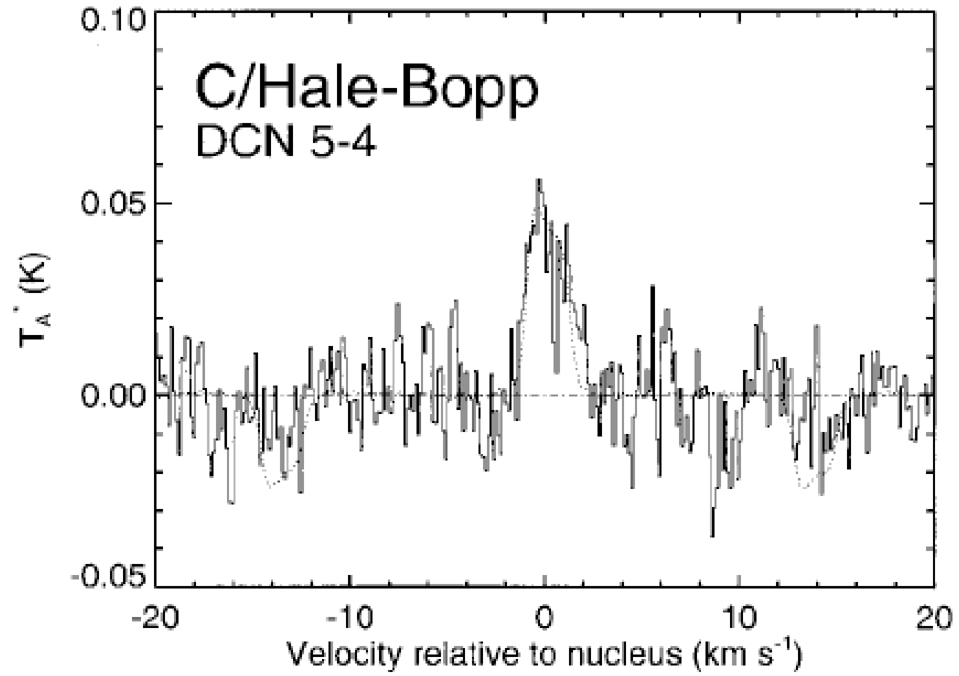


Following figures are from sources identified in
Jewitt et al 2007, Protostars and Planets V book, U Z Press

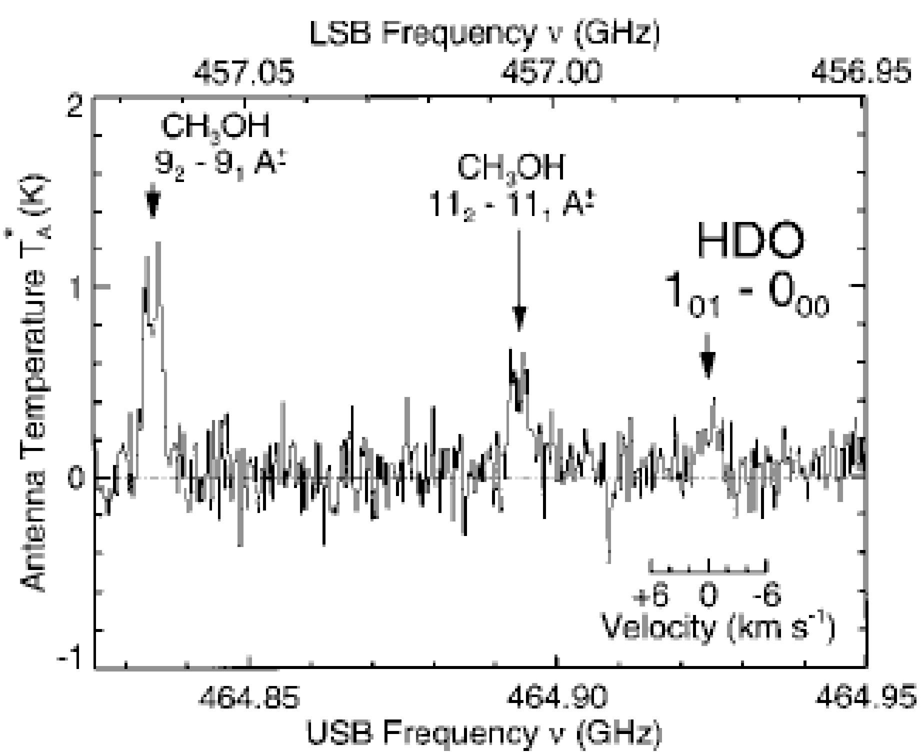
Ice Nearby




Nebula Cooling &
Shock Processing
SHOCKS
-0.5 Myr
Pre-Accretion
Alteration
0 Myr
Parent Body
Alteration
≤10 Myr
Shattering &
Re-assembly



Meier et al (1998) Science, 279, 1707



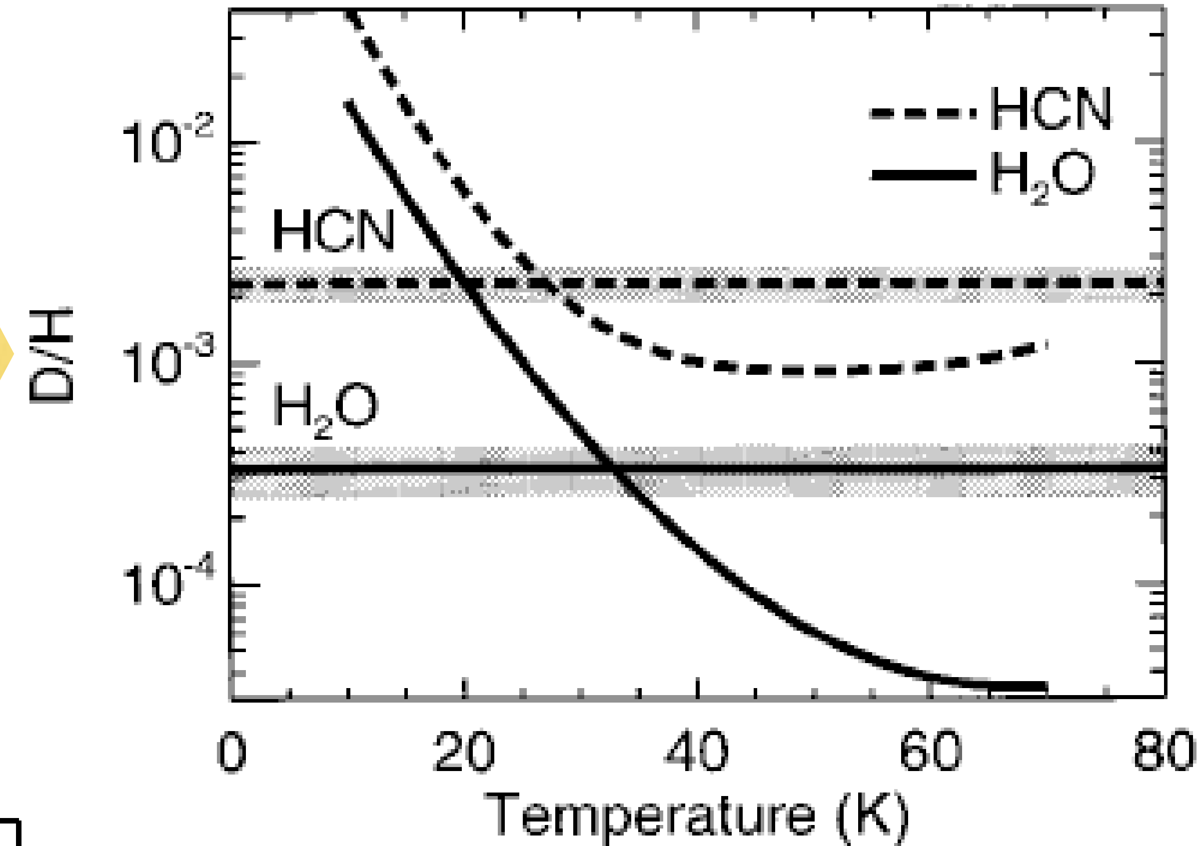
Meier et al (1998) Science, 279, 842

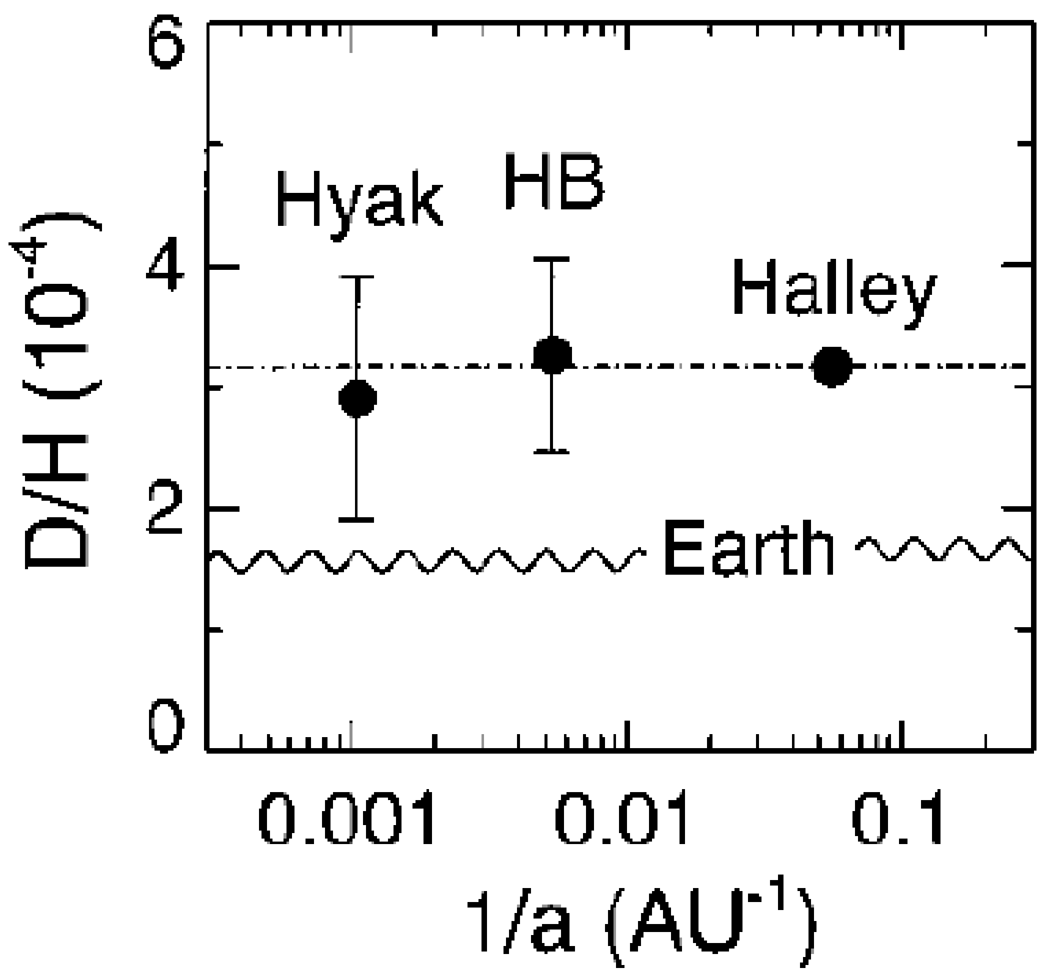
This kind of isotopic work requires a dry site, a large telescope (we used the 15-m JCMT), and a Hale-Bopp class comet.

Comparable HDO data exist only for 3 comets, none of them short-period comets.

HDO and DCN abundances are consistent with ion-molecule reactions at T ~ 30 K.

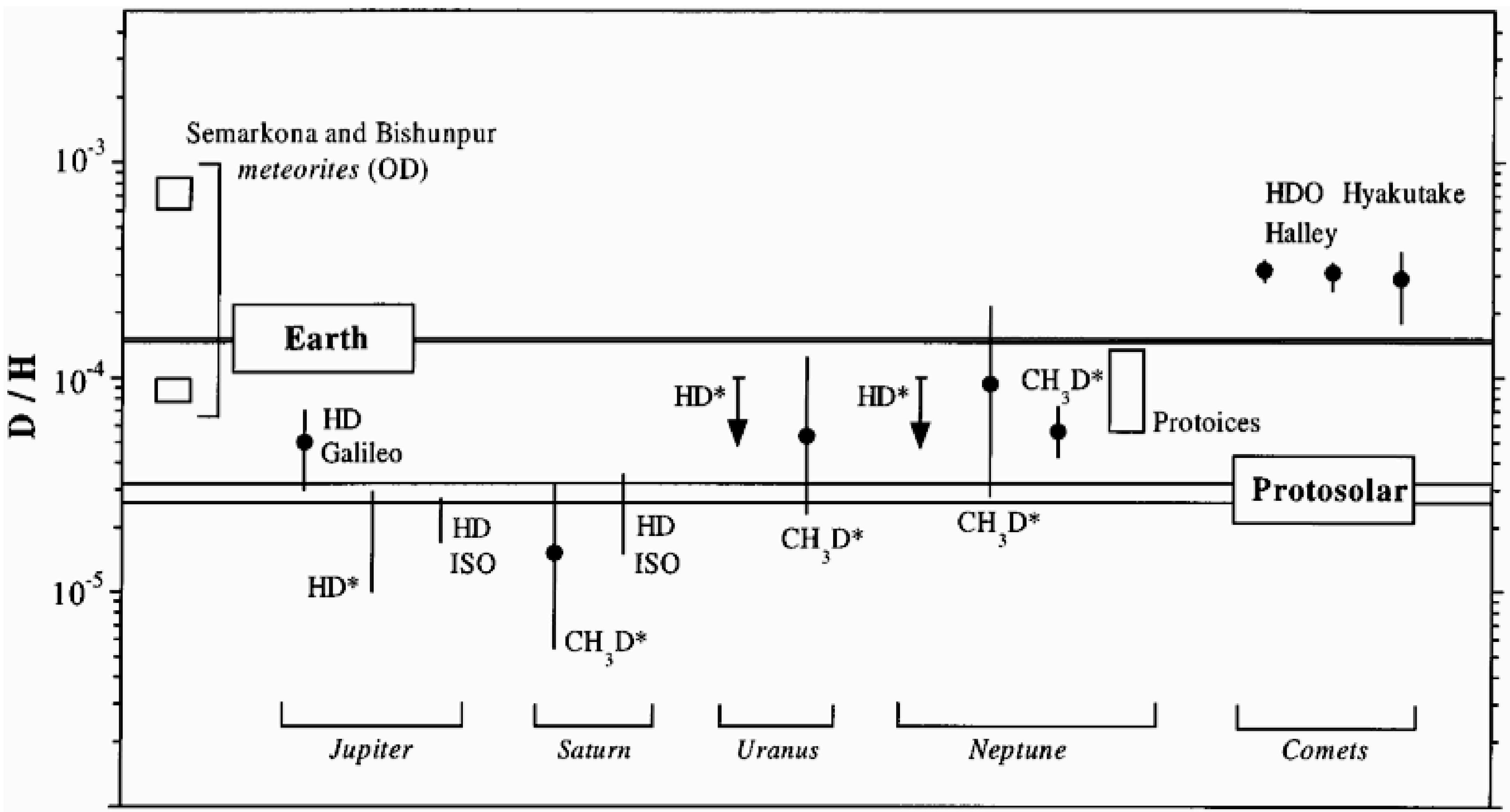
These comets may preserve products of interstellar or early nebular (low density, low temperature) chemistry.





HDO/H2O is about 3 X higher in comets than in Standard Mean Ocean Water.

Earth's oceans do not consist of melted comets alone.



D / H
10^{-3}
10^{-4}
10^{-5}
Semarkona and Bishunpur
meteorites (OD)
Earth
HD
Galileo
HD*
HD
ISO
CH3D*
HD
ISO
HD*
CH3D*
HD*
CH3D*
CH3D*
Protoices
Protosolar
HDO Hyakutake
Halley
Jupiter
Saturn
Uranus
Neptune
Comets

Other (non-cometary) sources of water:

- The local raw materials (too hot, dry?)
- Asteroid belt sources (too few?)
- Jovian Trojan asteroids (too far?)
- Jupiter family comets (unknown D/H, high noble gas content?)

Resolution is unclear: outer belt asteroids may have the "right" HDO/H2O ratio but they do not carry the noble gases. Comets seem to have HDO/H2O too high, but may be better carriers of noble gases.

Source of Terrestrial Water?

D/H SMOW ~ 1.6 x 10(-4)

D/H Comets ~ 3.3 x 10(-4)

(but these are 3 HFC/LPC comets, not short-period comets, and so may not be representative)

Conclude: Oceans are not just melted HFC/LPC comets

Dynamical simulations favor main-belt asteroid source: the MBCs might fit the bill

Go there with a spacecraft to find out

Mission to MBCs

Objectives: Measure chemical and isotopic nature of the ice in the MBCs with a view to understanding the relation, if any, to terrestrial volatiles.

Strategy: Multiple rendezvous spacecraft (ion drive?) with mass spectrometer and cameras. Discovery mission.

Necessary First Steps:

1) Map distribution of MBCs with Pan STARRS

2) Obtain or prove that we cannot obtain useful gas spectra of MBCs from the ground

3) Establish that we can secure a mass spec of high enough resolution and low enough mass

The Immediate Future

TAOS Project in Taiwan

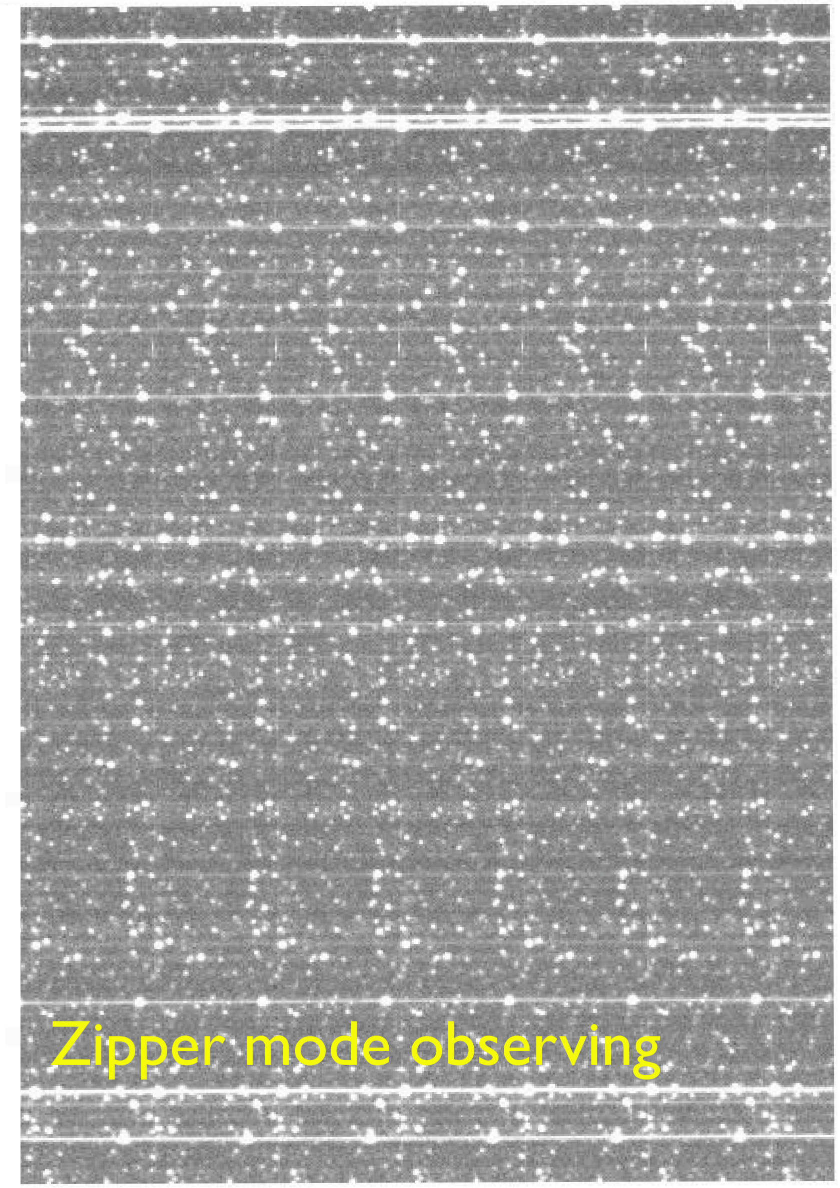
Occultation Method

- Motion is parallactic
- Duration $\Delta t \sim \frac{D}{v} \lesssim$ second

- Fresnel scale $\ell \simeq \sqrt{\lambda \Delta} \sim$ 2 km @ 40 AU

- Rate – depends on $n(D)dD$ at smallest sizes
  - could be few to few $\times 100\ yr^{-1}$
  - is the key measurable

- Advantage – utility scales slowly w/. $\Delta^{1/2}$
  - c.f. scattered light $\propto \Delta^{-4}$



Occultation

Motion is p

Duration

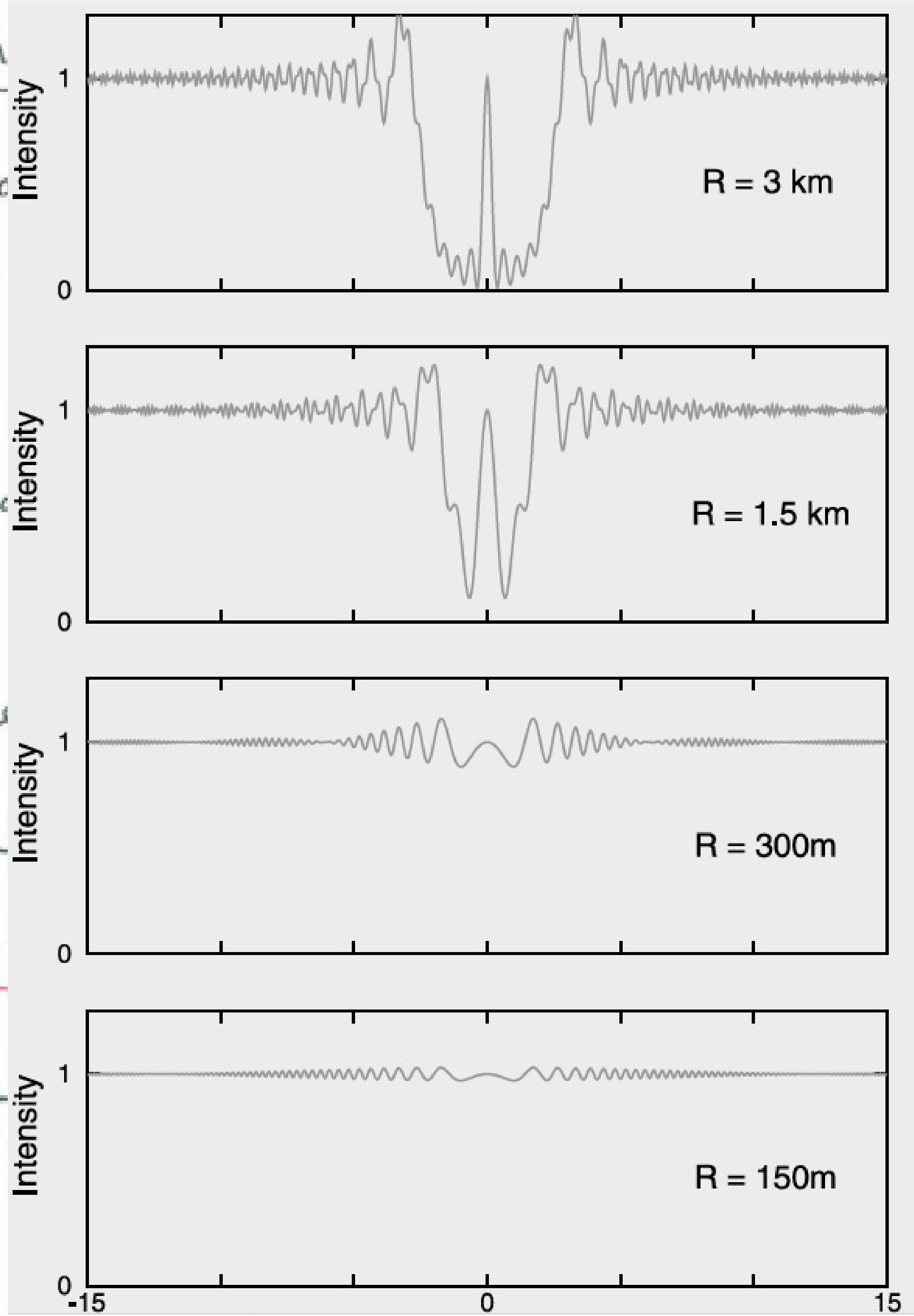
Fresnel sc

Rate – dep

– cou

– is

Advantage –



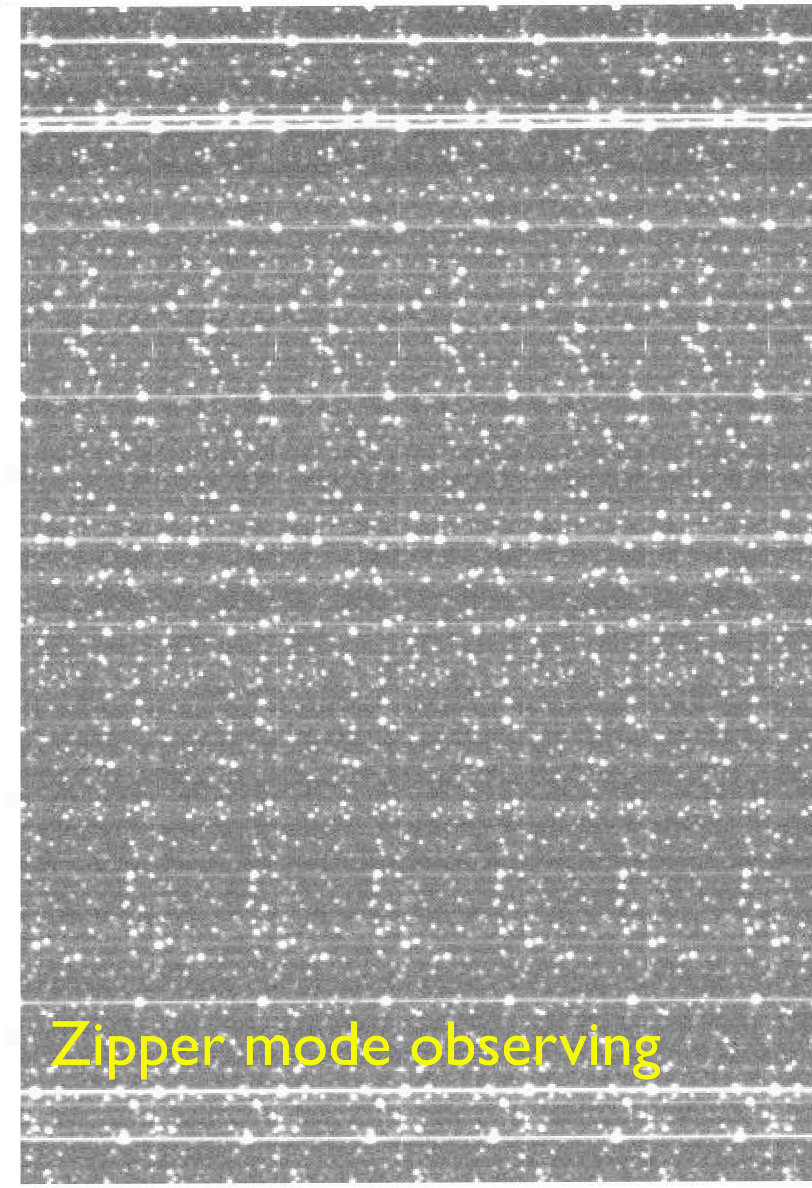
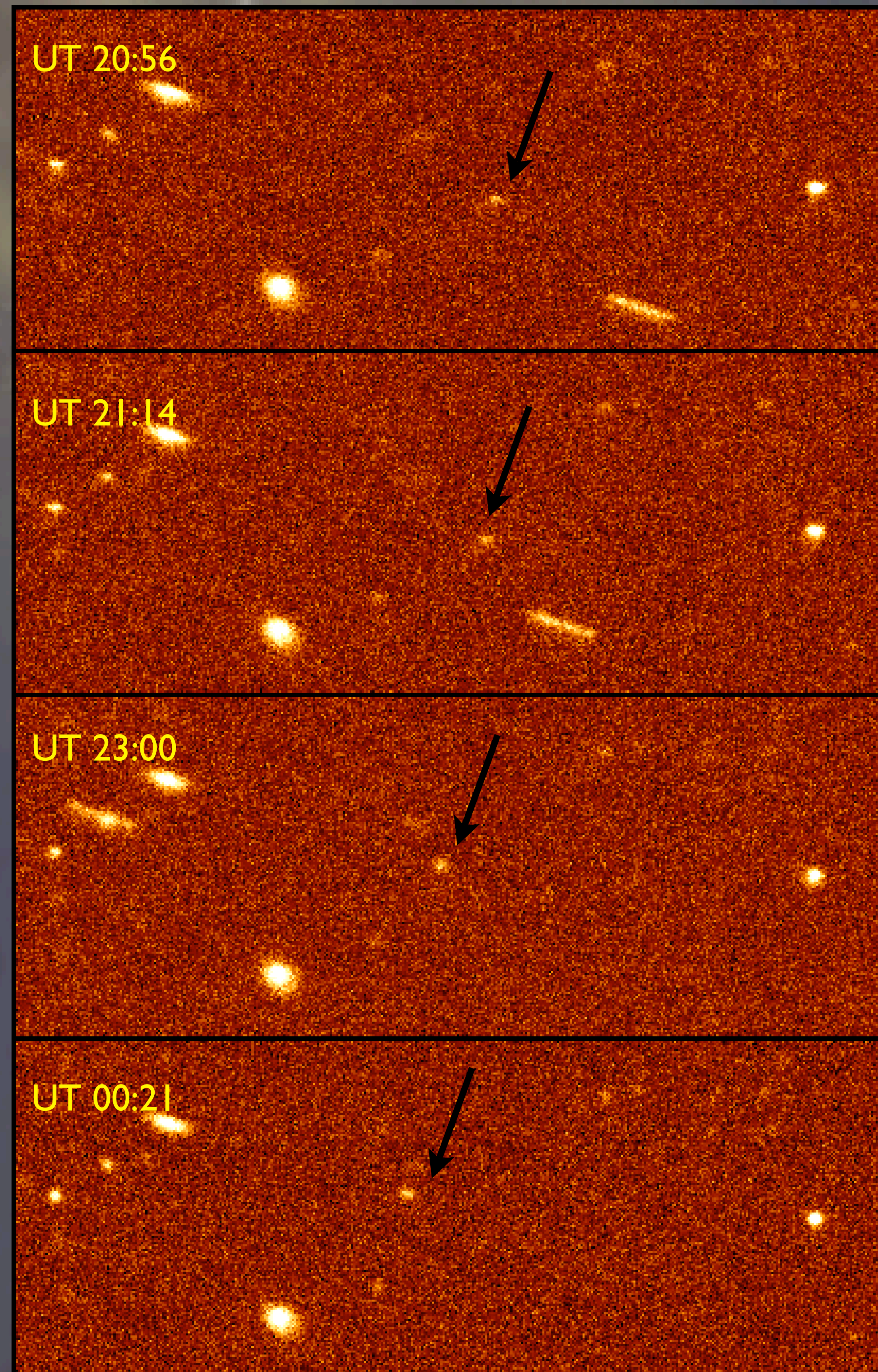


Image Differencing

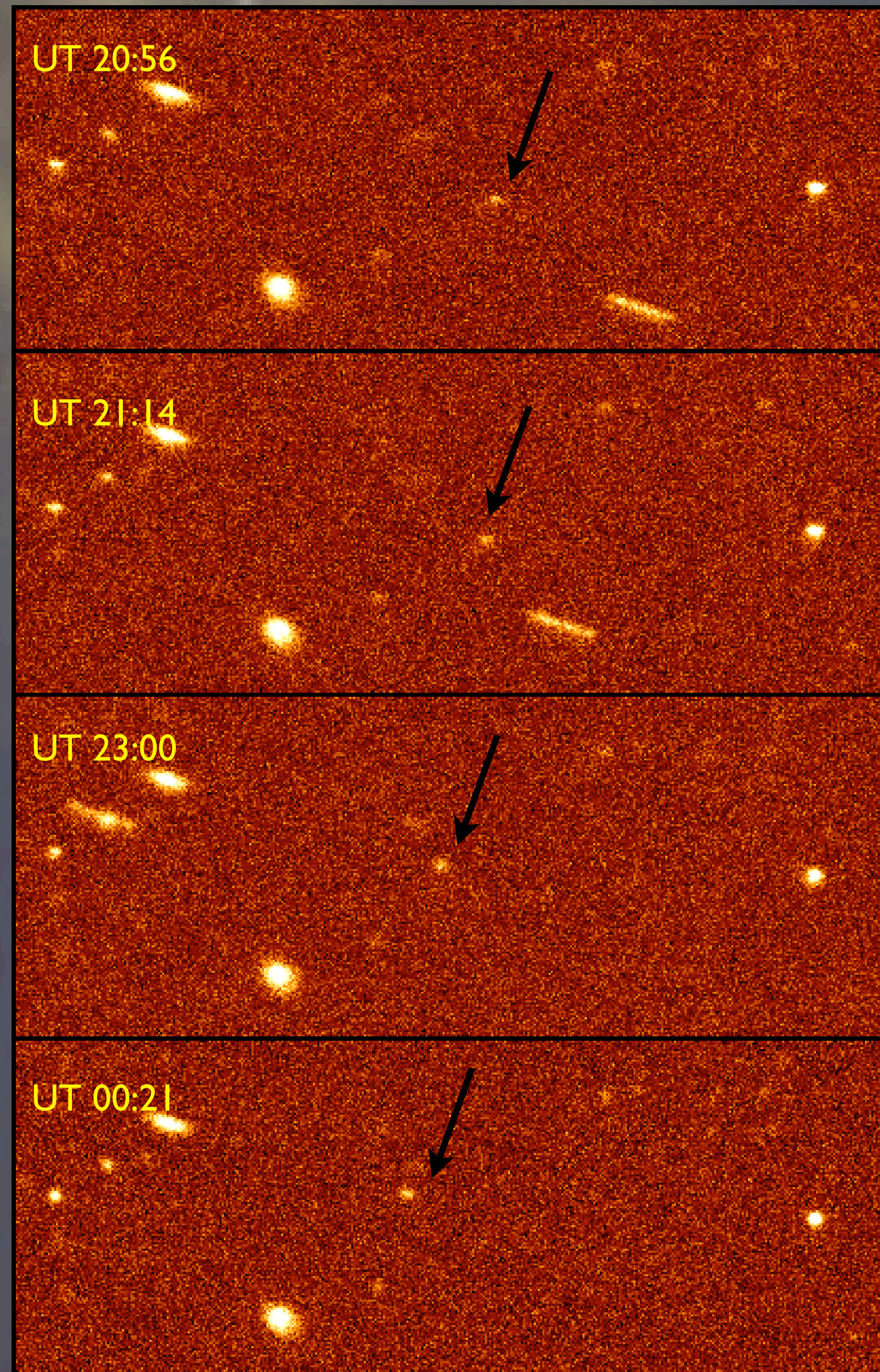
1992 QB1



Art by Michael Carroll

Image Differencing

1992 QB1



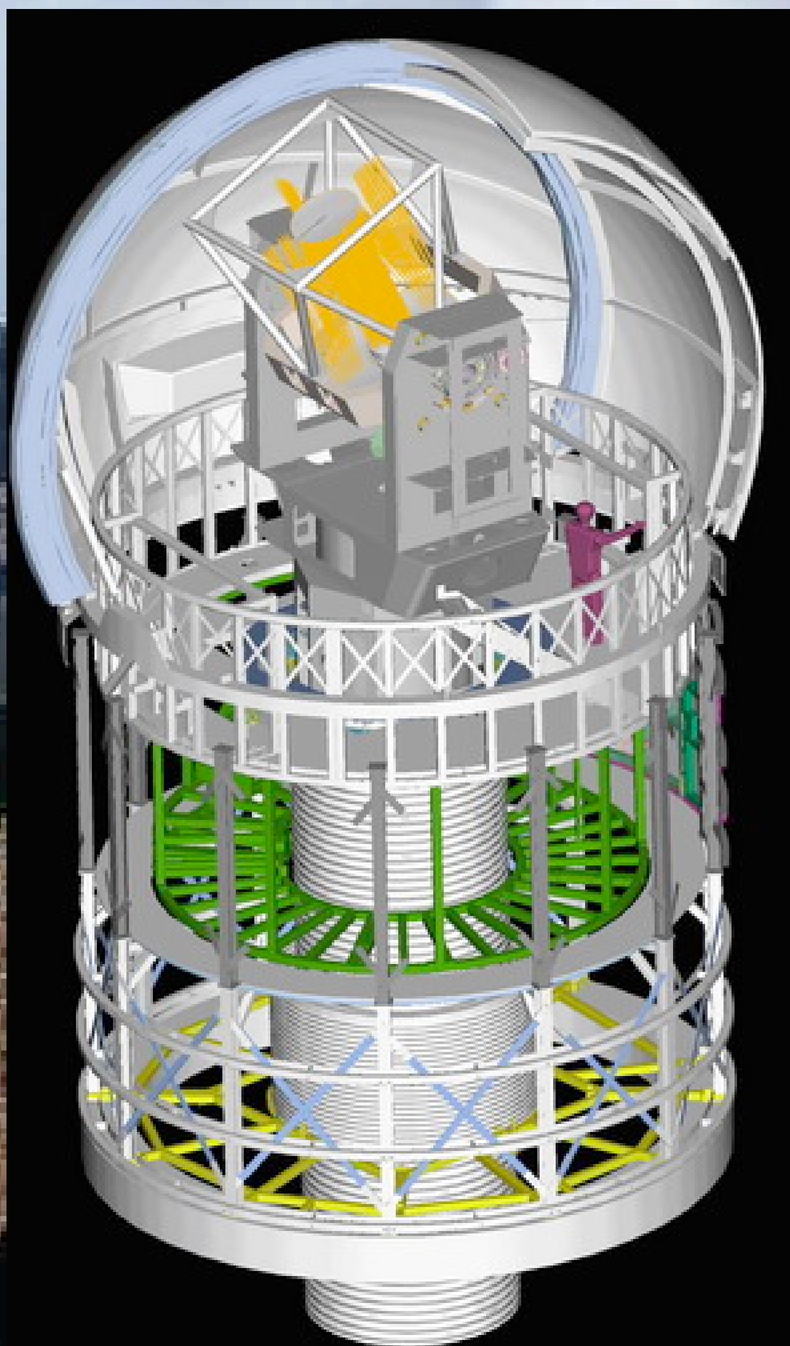
Pan STARRS

- Everything so-far detected by (essentially) image-differencing.
- Big new advance will be all-sky surveying with Pan STARRS.
- Limiting red mag ~ 24.
- Expect ~20,000 KBOs in Year 1.
- All will be re-imaged many times per year: perfect astrometric follow-up.
- Astrometry 0.2” shrinking to 0.05” with time.
- Minimal sky-plane bias = improved orbital element mapping capability.

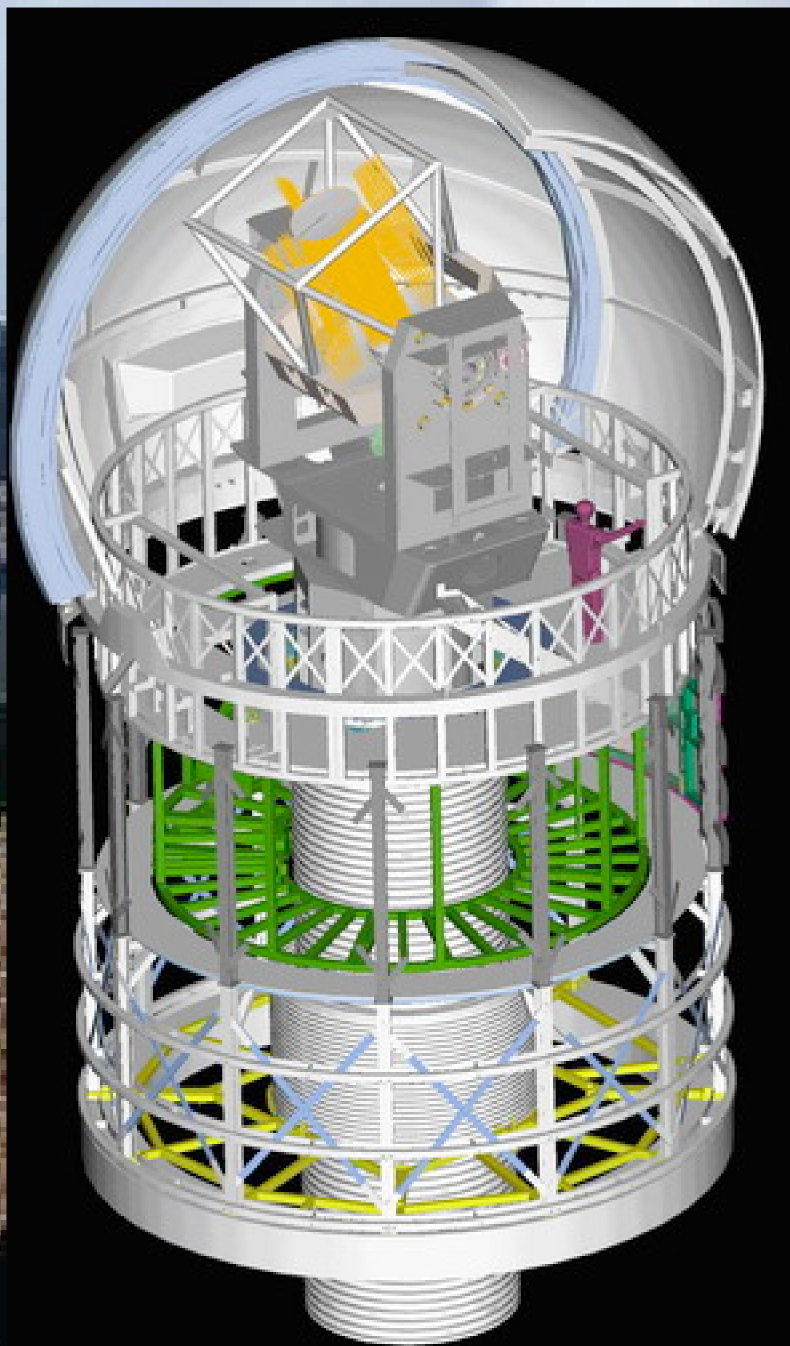
Art by Michael Carroll

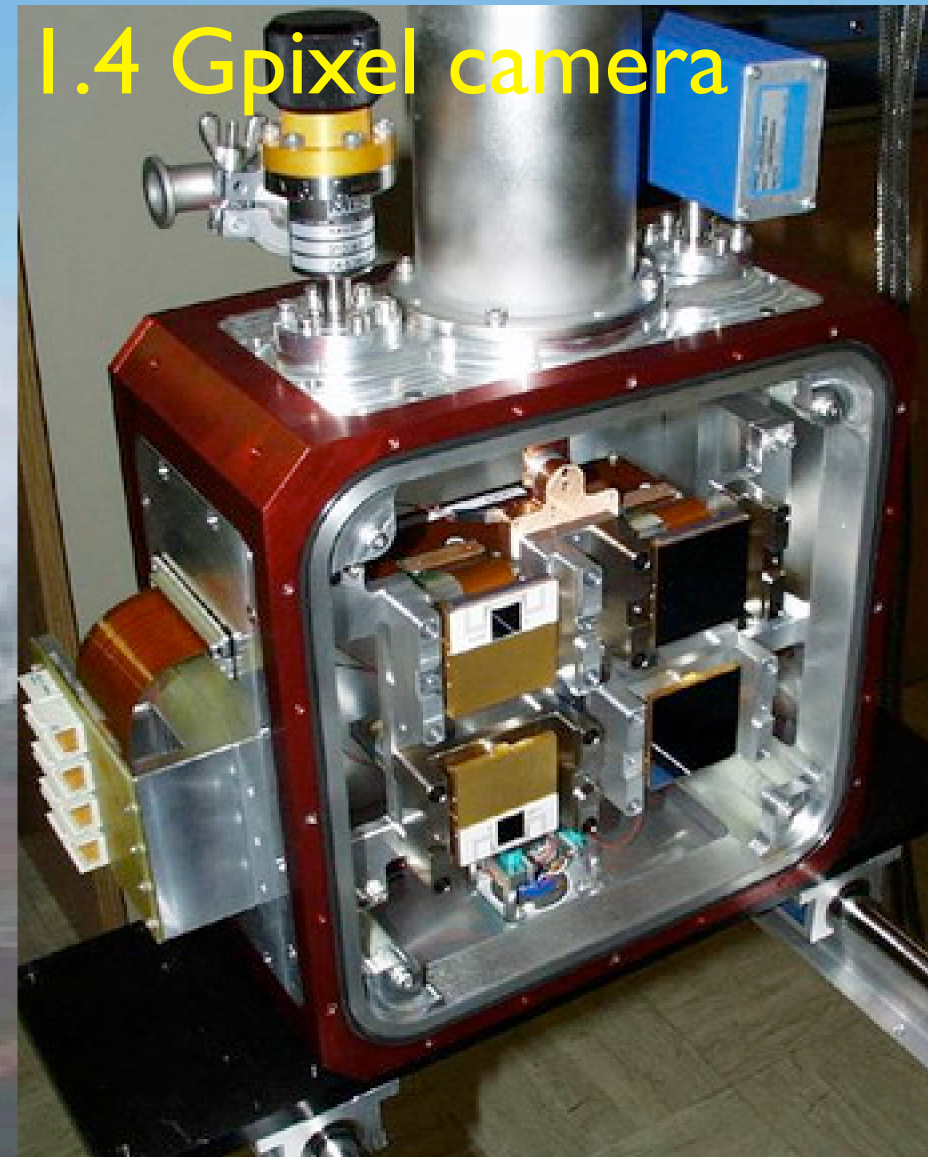
Pan STARRS 1
Haleakala

Pan STARRS 1
Haleakala

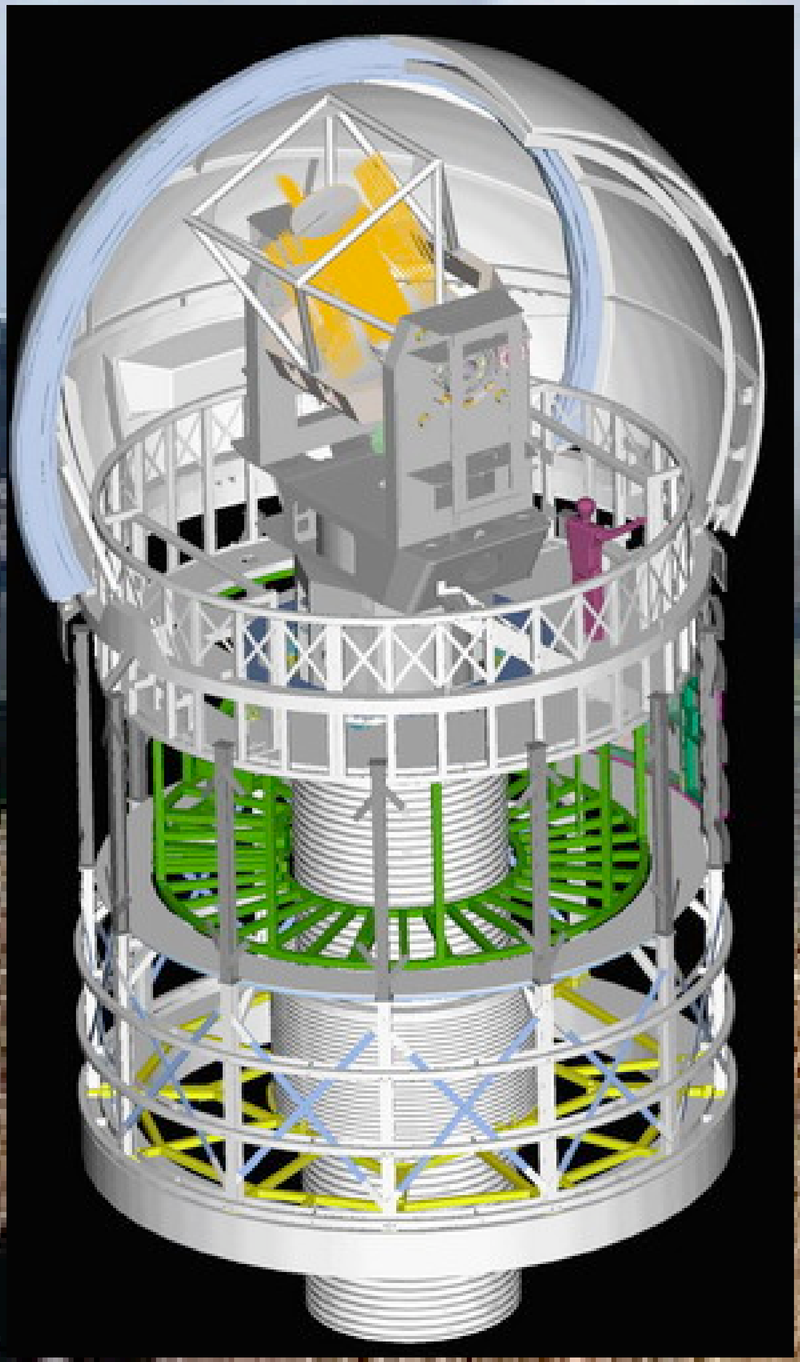


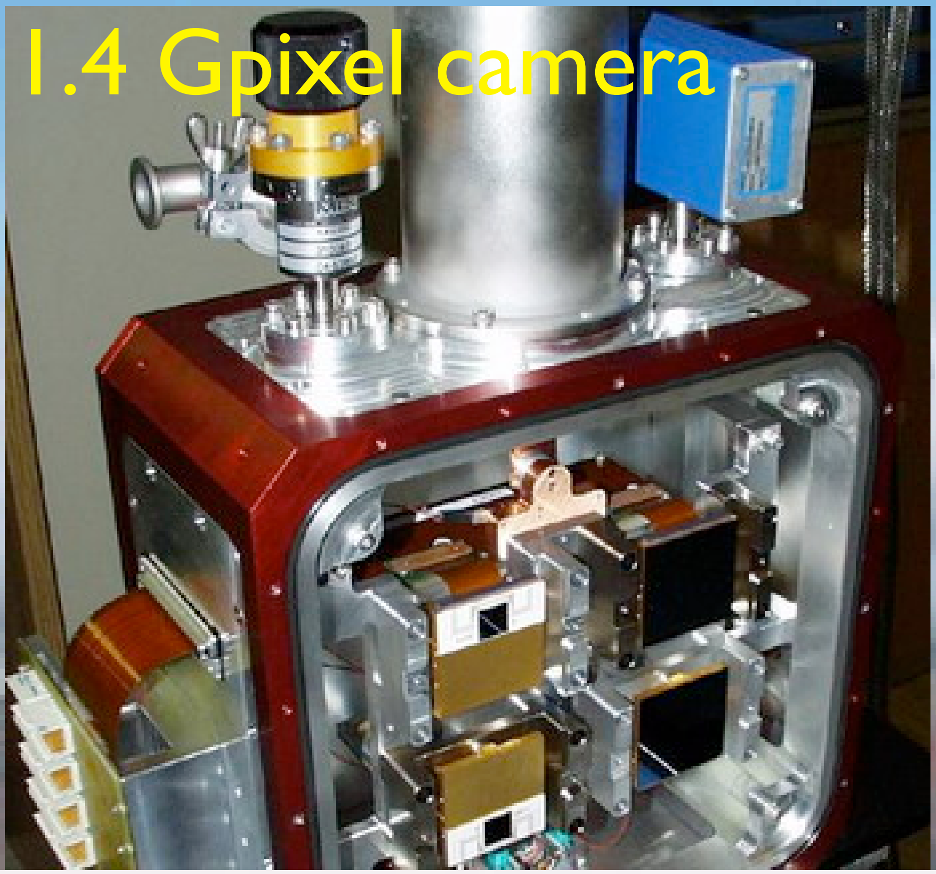
Pan STARRS 1
Haleakala

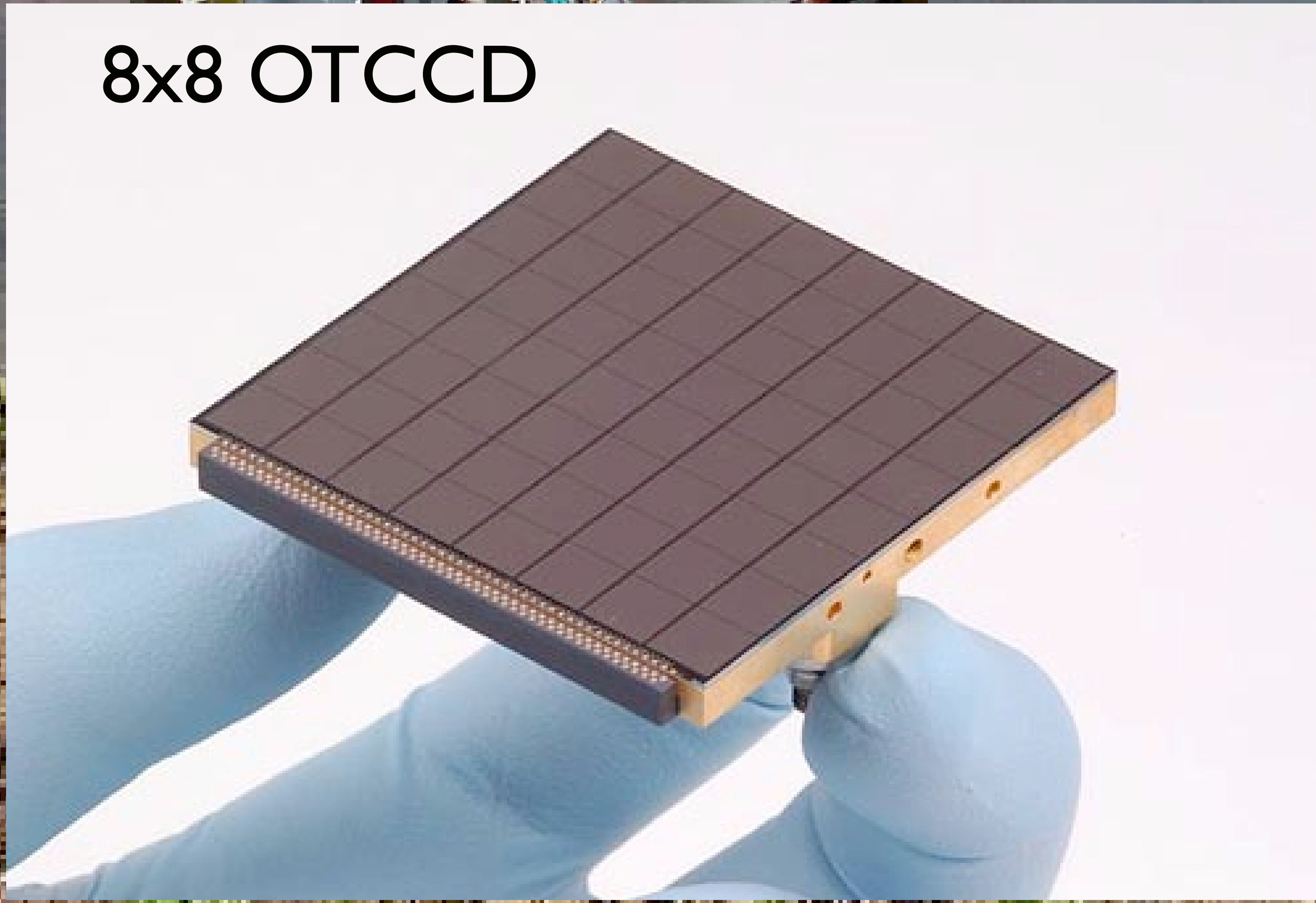




Pan STARRS 1
Haleakala

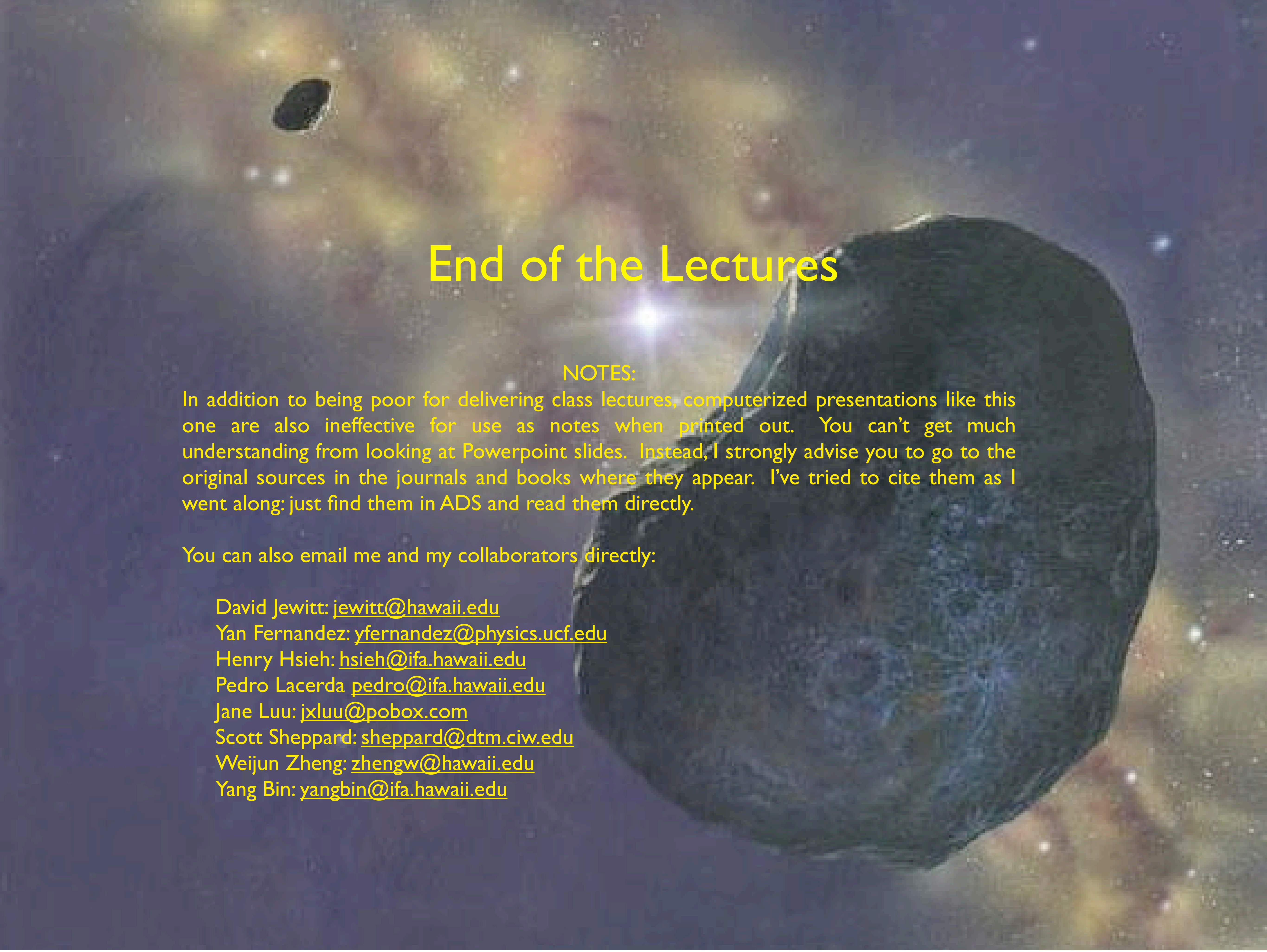






HOW DOES PAN-STARRS COMPARE WITH EXISTING WIDE-FIELD SURVEYS?

Telescope	Diam(m)	$\Omega(deg^2)$	$A\Omega$
USAF Linear	1.0	2.0	1.5
SDSS	2.5	3.9	6.0
CFHT	3.6	1	8.0
SUBARU	8.1	0.2	8.8
Pan-STARRS	3.6	7	60
Nominal LSST	6.5	7	190



End of the Lectures

NOTES:

In addition to being poor for delivering class lectures, computerized presentations like this one are also ineffective for use as notes when printed out. You can't get much understanding from looking at Powerpoint slides. Instead, I strongly advise you to go to the original sources in the journals and books where they appear. I've tried to cite them as I went along: just find them in ADS and read them directly.

You can also email me and my collaborators directly:

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