Graduate Institute of Astronomy, NCU
國立中央大學天文研究所

Census of Trans-Neptunian Population by Stellar Occultation

Wen-Ping Chen
National Central University

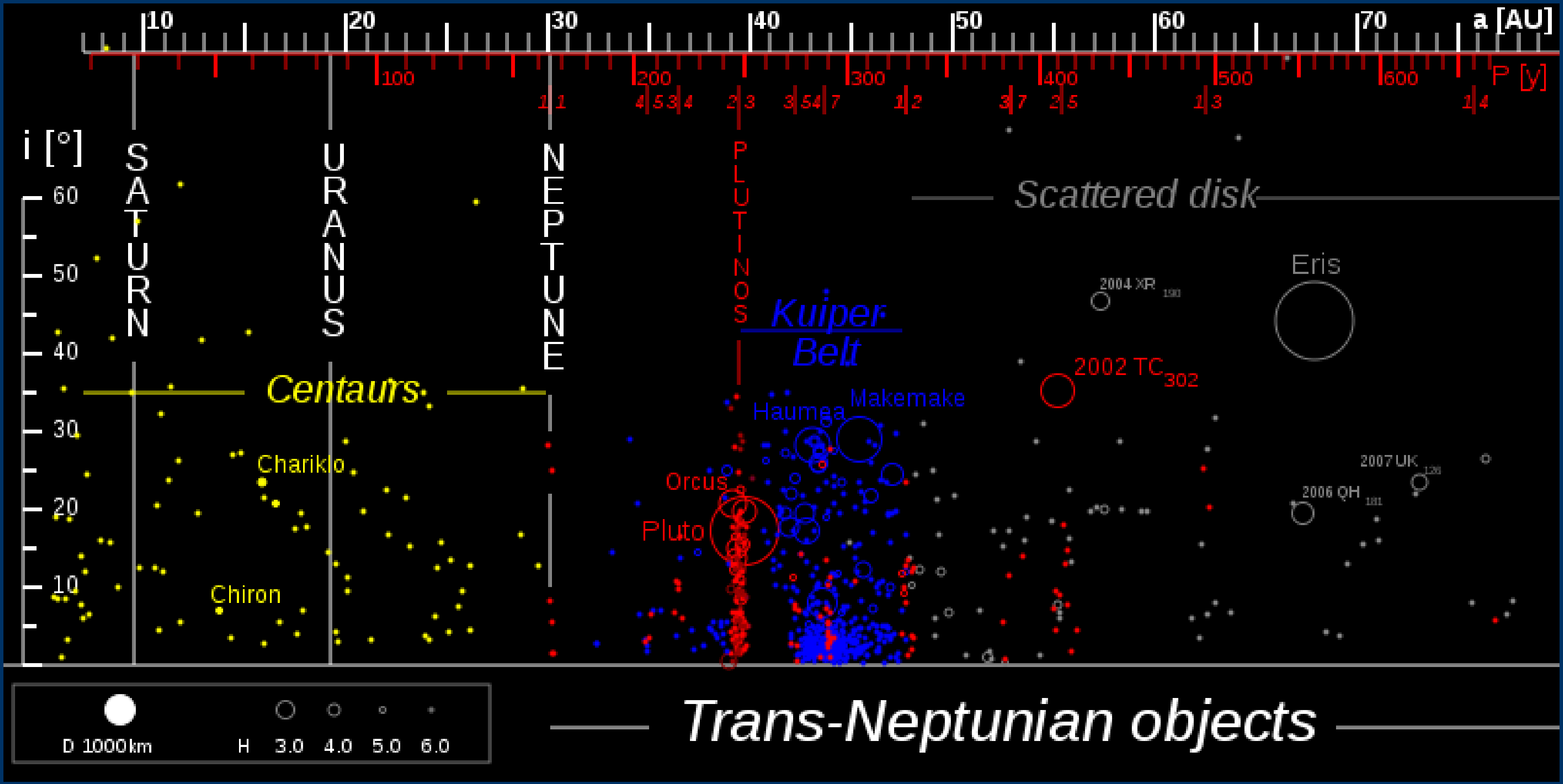
and the TAOS Team

TAOS
Taiwan-America Occultation Survey

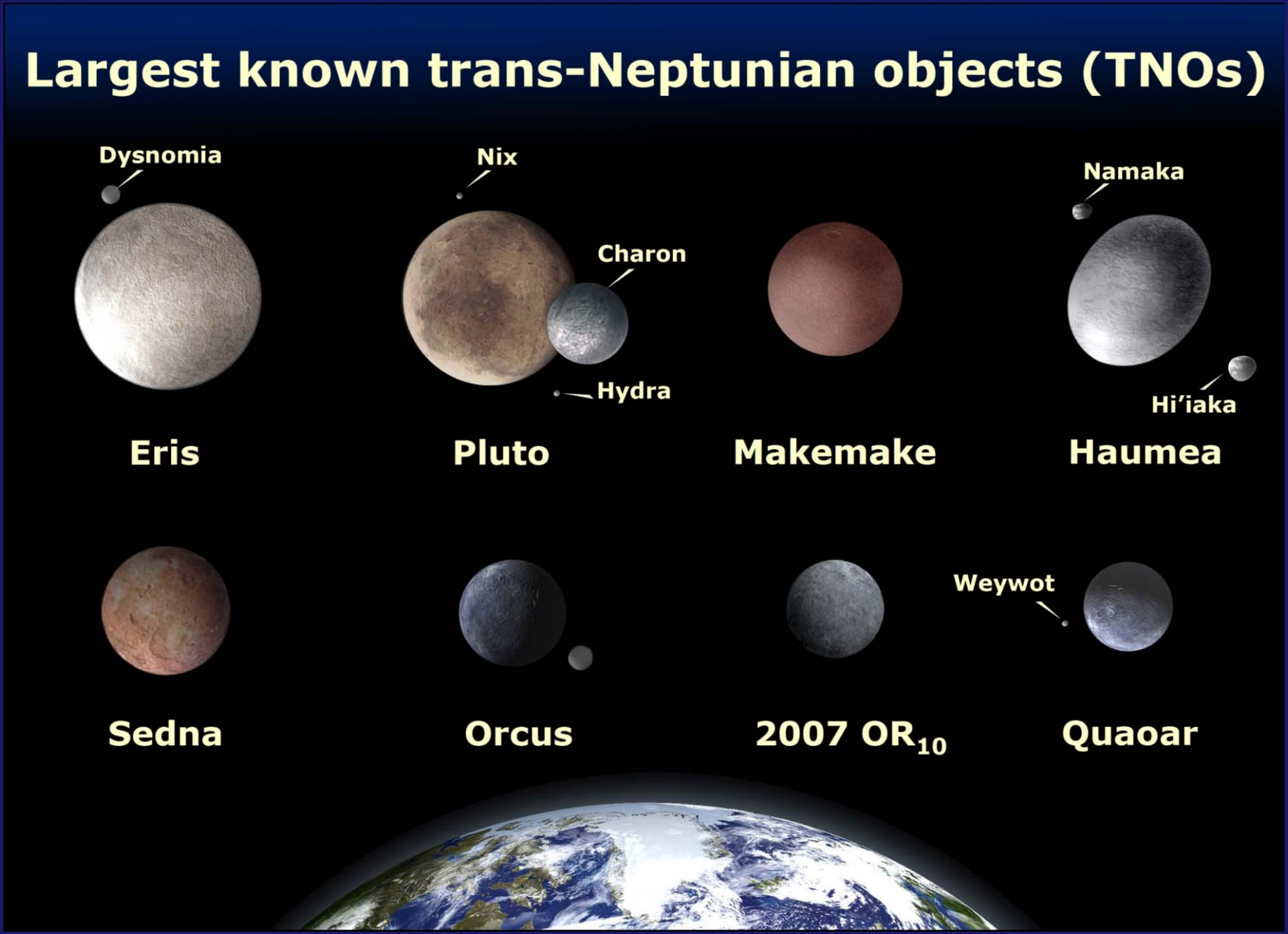
Collaborators

- **USA**
  C. Alcock, Federica Bianco ***(CfA)***
  Rahul Dave, Joe Giammarco ***(U. Penn)***
  K. Cook, Rodin Porrata ***(LLNL)***
  S. Marshall ***(SLAC)***
  Megan Schwamb ***(Caltech)***
  Tim Axelrod ***(Steward Obs)***
  I. de Pater, J. Rice ***(UC/Berkeley)***
  J. Lissauer ***(NASA/Ames)***
- **Taiwan**
  Matt Lehner, T. Lee, C.Y. Wen, S. K. King, A. Wang, S.Y. Wang, Z. W. Zhang ***(ASIAA)***
  W. P. Chen, Y. H. Chang, H. C. Lin ***(NCU)***
- **Korea** Y. I. Byun, D. W. Kim, A. ***(Yonsei U)***

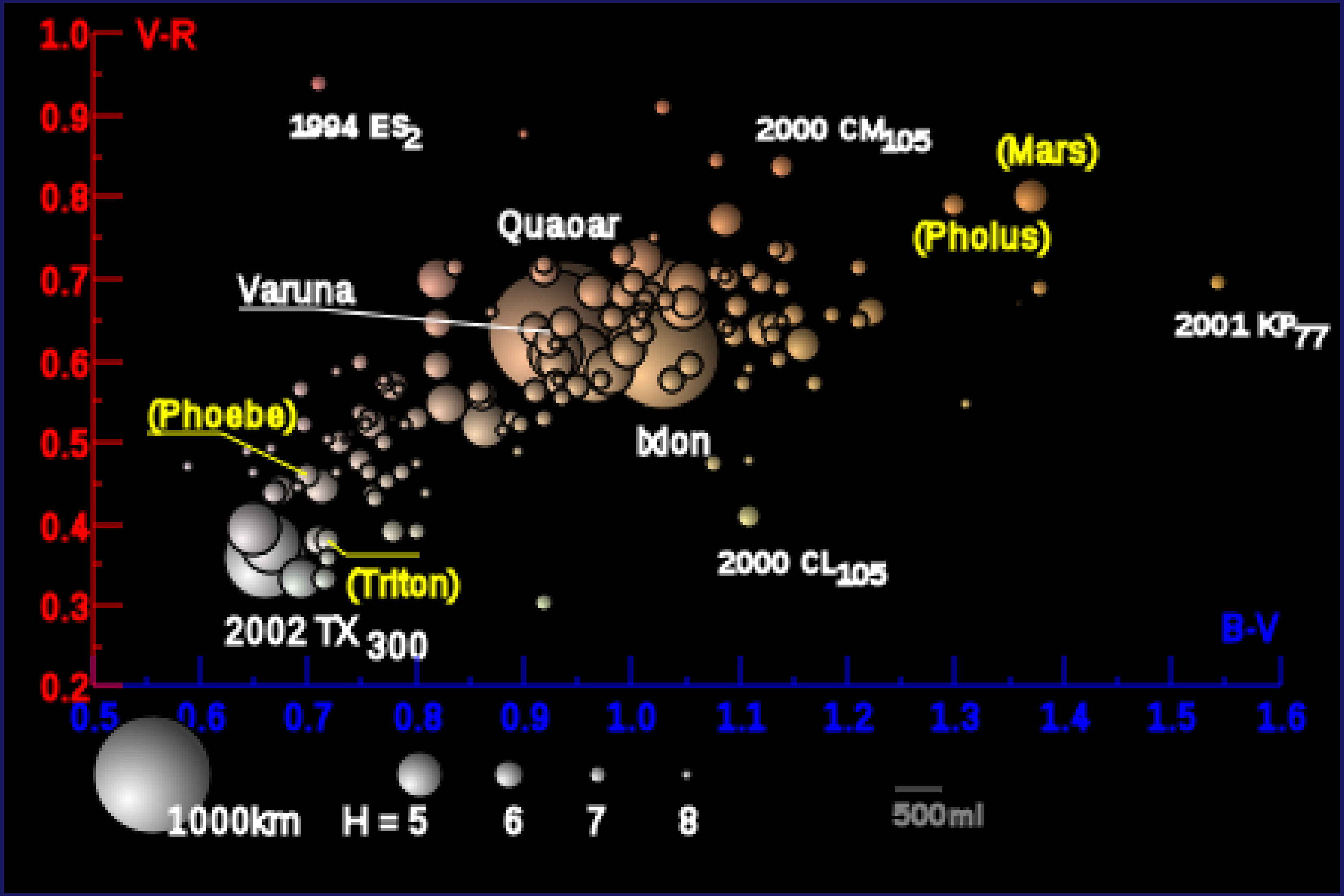
- Kuiper belt objects (KBOs): Classical and Resonant KBOs (Plutinos if 2:3)
- Scattered disk objects



wikipedia


Largest known trans-Neptunian objects (TNOs)
Dysnomia
Nix
Charon
Hydra
Namaka
Hi'iaka
Eris
Pluto
Makemake
Haumea
Weywot
Sedna
Orcus
2007 OR10
Quaoar

wikipedia



V-R
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
1994 ES2
2000 CM105
(Mars)
Quaoar
(Pholus)
Varuna
2001 KP77
(Phoebe)
Ixion
2000 CL105
(Triton)
2002 TX 300
B-V
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1000km
H = 5
6
7
8
500mi

wikipedia

Distant EKOS --- *The Kuiper Belt E-Newsletter*

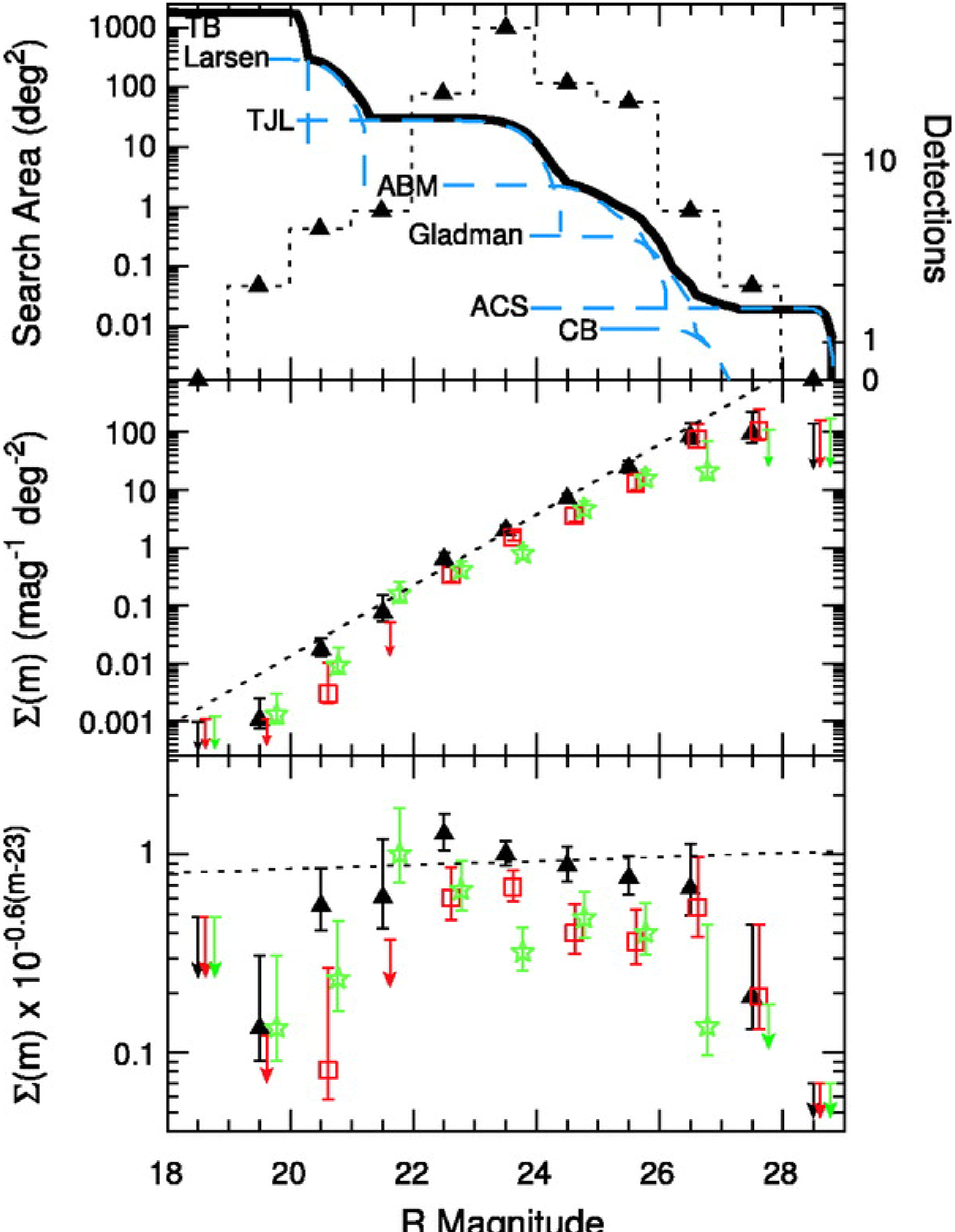
(http://www.boulder.swri.edu/ekonews/)

As of 2009/10

Current number of TNOs: 1097 (and Pluto)
Current number of Centaurs/SDOs: 248
Current number of Neptune Trojans: 6

Out of a total of 1351 objects:

- 554 have measurements from only one opposition
- 538 of those have had no measurements for more than a year
- 288 of those have arcs shorter than 10 days



HST/ACS with 22 ks per pointing found 3 KBOs, with the faintest of 28.3 mag, corresponding to a size of 25 km!

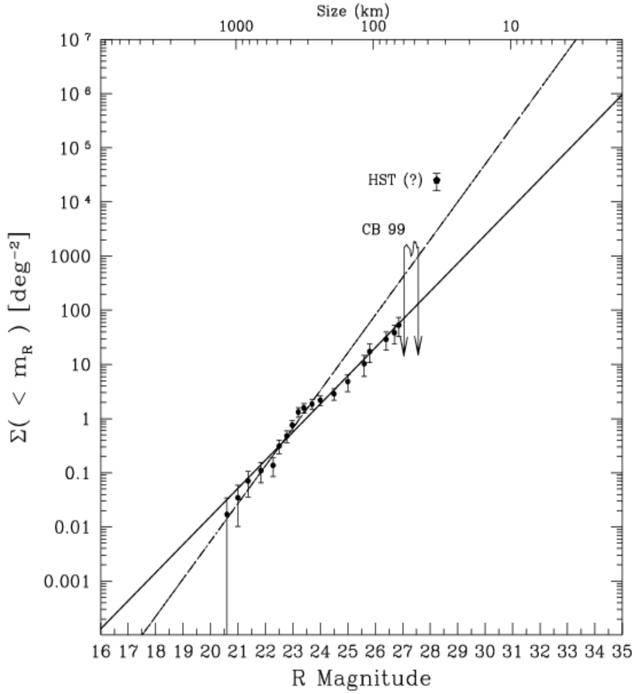
Deficit in both large and small bodies

Classical KB and Excited KB are different

CKBOs mostly 100 km bodies with a second peak <10 km

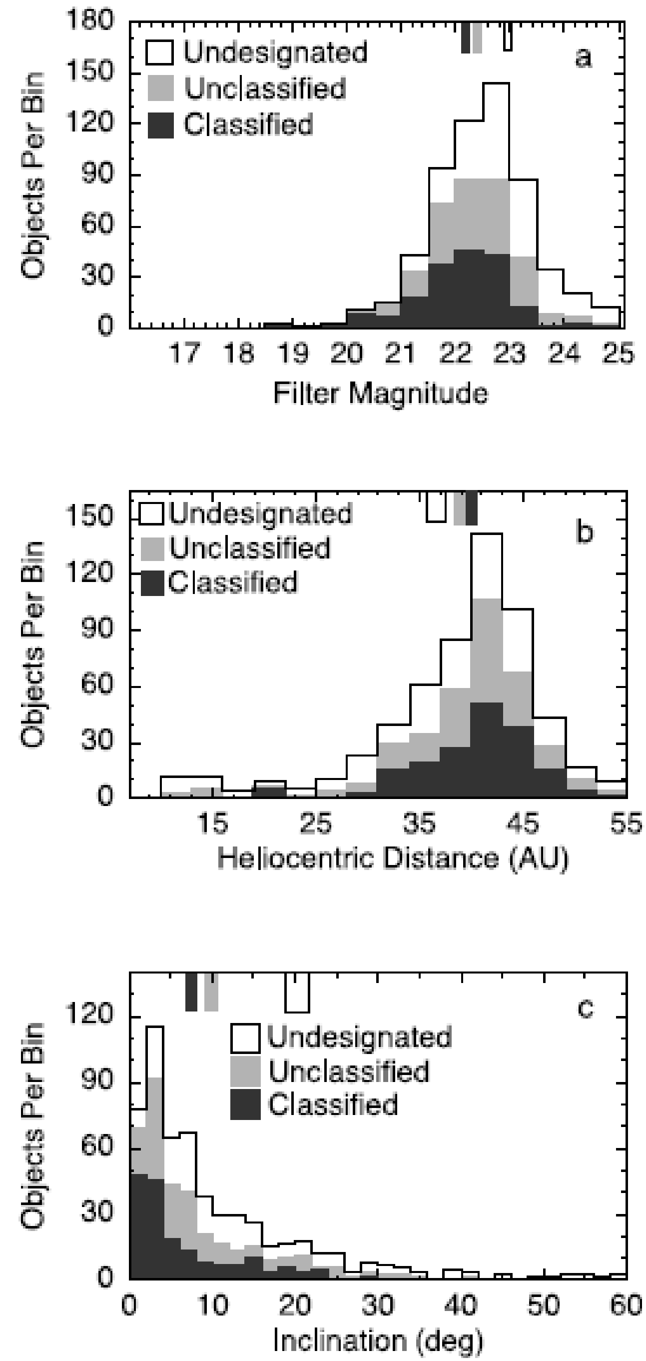
Largest EKBOs=Pluto

Burnstein et al. (2004)



Statistical studies now become possible

A deficit at small-size end?



Distinctly different populations!

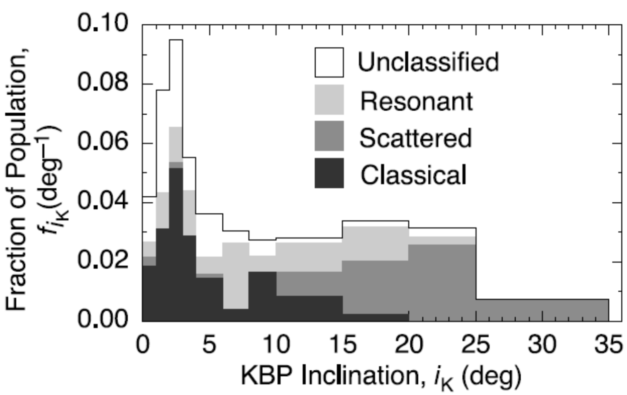
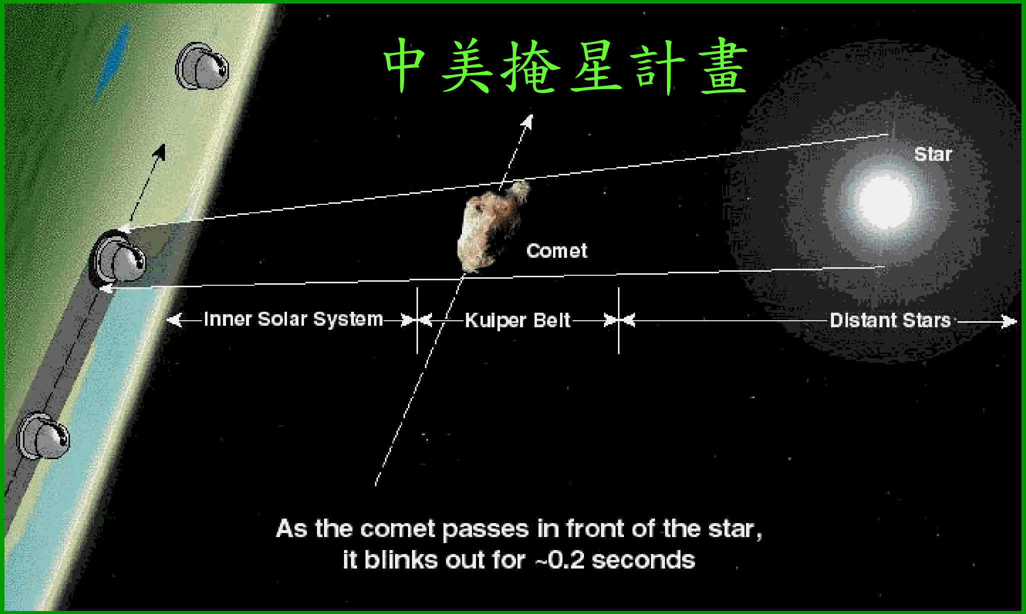


FIG. 17.—The unbiased KBP inclination distribution as a function of KBO classification. The fraction of objects in the sample per degree of inclination is the same as Fig. 16, with each bin shaded to reflect the proportion of objects by classification. Unclassified objects are represented by open areas, Resonant objects are light gray, Scattered (Near and Extended) objects are dark gray, and Classical objects are black. The low-inclination "core" is primarily composed of Classical objects, while the higher inclination "halo" is primarily Scattered objects. Along the KBP inclination axis, the boundary between Classical and Scattered objects is not distinct.

← Elliot et al. 2005 →

The **TAOS** (Taiwan-America Occultation Survey) project, a novel telescope array set up by groups from Taiwan, US and Korea, began routine observations in early 2005 and has the potential to make unique contribution to the knowledge of our Solar System.

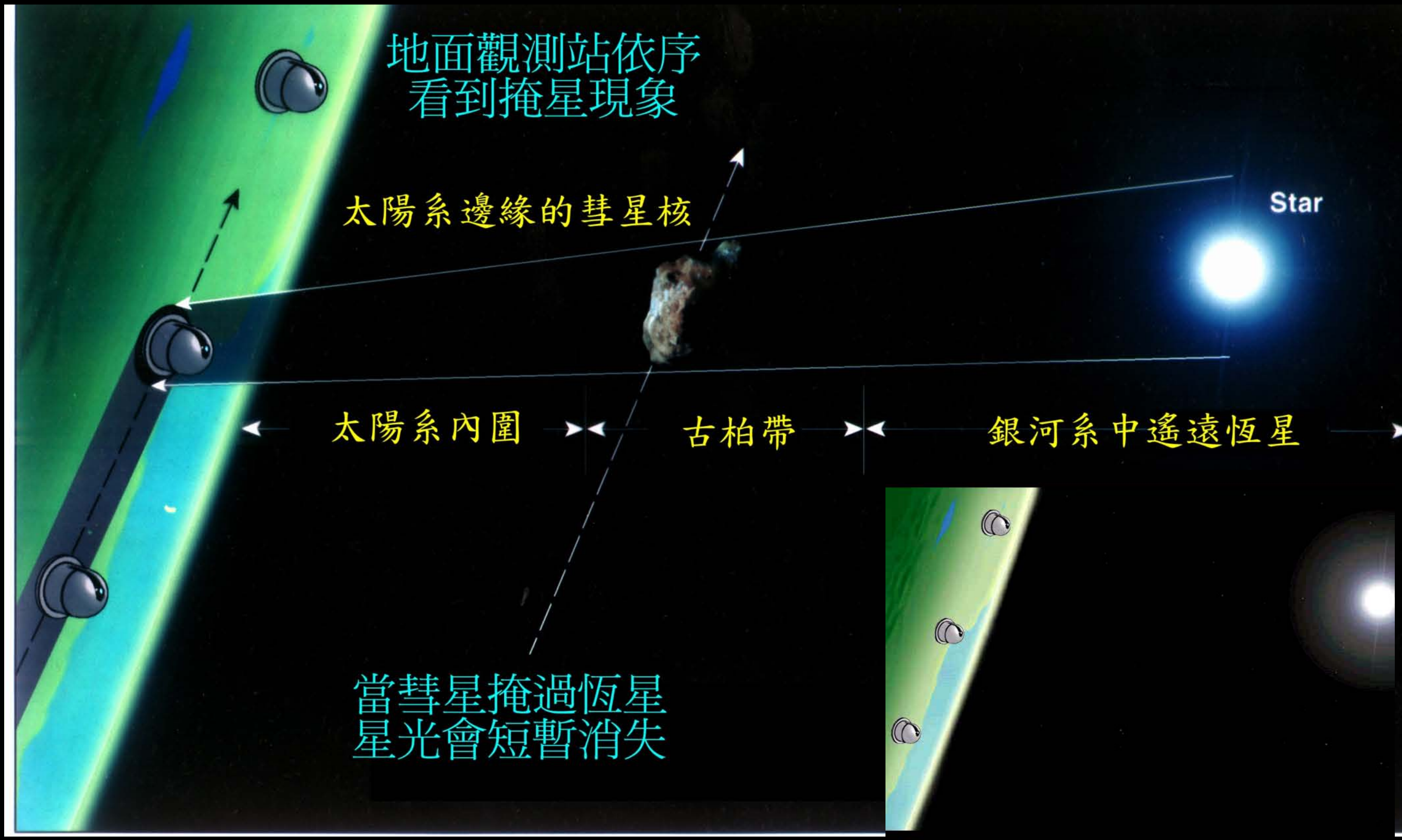
Comet nuclei too faint to be detected by direct imaging may be “seen” when they move in front of a background star --- a stellar occultation event.



Project Overview

- Census of the small objects in the solar-system family
- An array of wide-field telescopes (D=50 cm, f/1.9, FOV=3 sq. deg) to monitor brightness changes of ~1,000 stars at 5 Hz rate
- Looking for a 'blink' of starlight (occultation) when an object (> 2 km) moves in front of a distant star
  Frequency of events ➔ population of "interveners"
- Data rate a few 100 GB per night; only "interesting" data downloaded via the dedicated E1 connection
- Real-time data analysis (light curves, statistics)
- Requiring coincidence detection of the same event by all telescopes to guard against false positive

TAOS will detect KBOs by stellar occultation

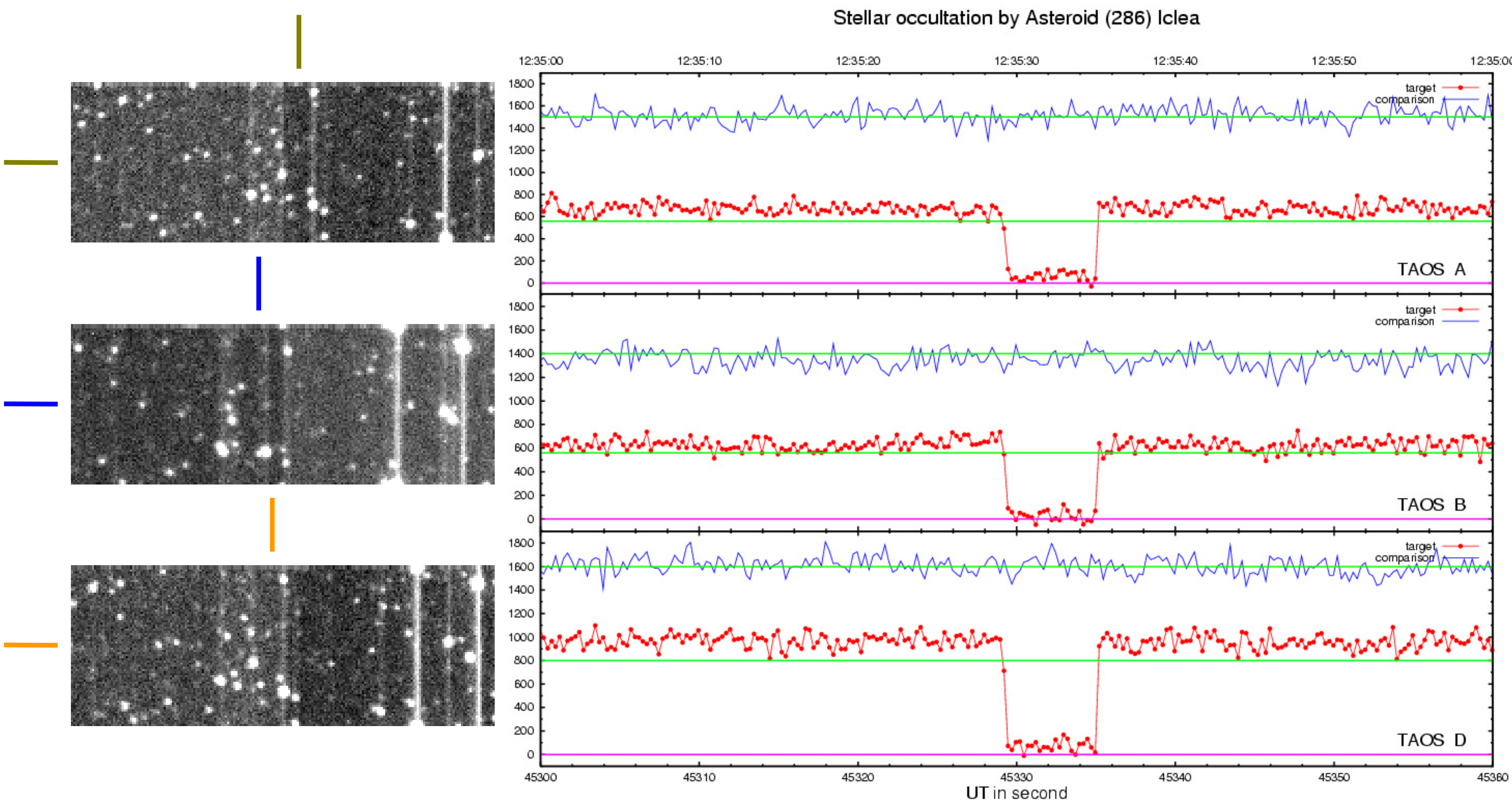


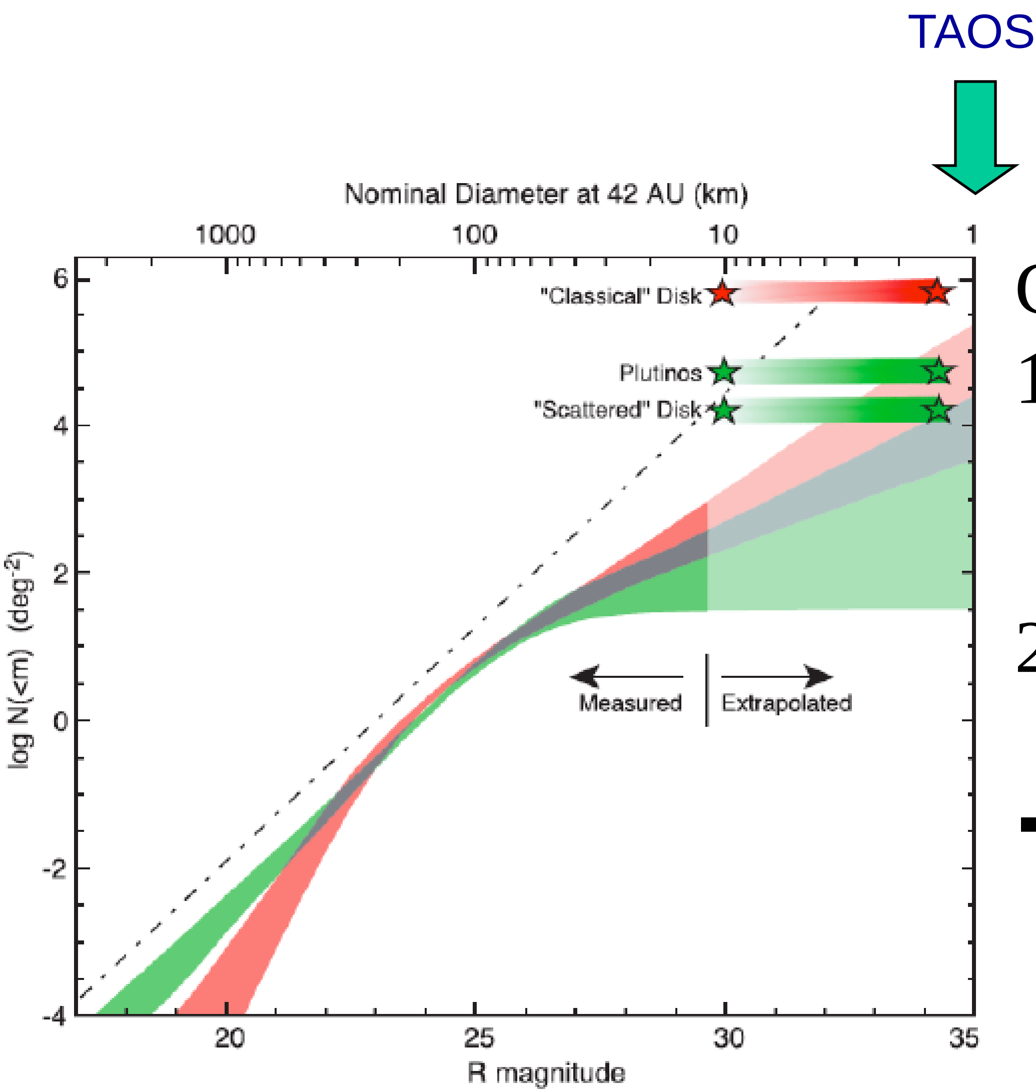
TAOS Telescopes

Four telescope systems: 50 cm f/1.9 Cassegrain by Torus, each equipped with an SI800 camera (2K x 2K EEV) by Spectral Instruments

On a predicted event by an asteroid

2006 Feb 06 three TAOS telescopes detected a suspected occultation of TYC 076200961 (m_V ~ 11.83) by **(286) Iclea** (m_V ~ 14.0 mag, D~ 97 km)





Competing mechanisms

1. accretion of planetesimals to form larger bodies,
2. grinding destruction to smaller sizes

➔ Size distribution

KBO Population (Bernstein & Trilling 2004)

Event Detection ---
Rank Statistics

- Use the rank, instead of the flux, to quantify the light curve

$$\eta_i = -\ln\left(r_i^A r_i^B r_i^D / N_P^3\right)$$

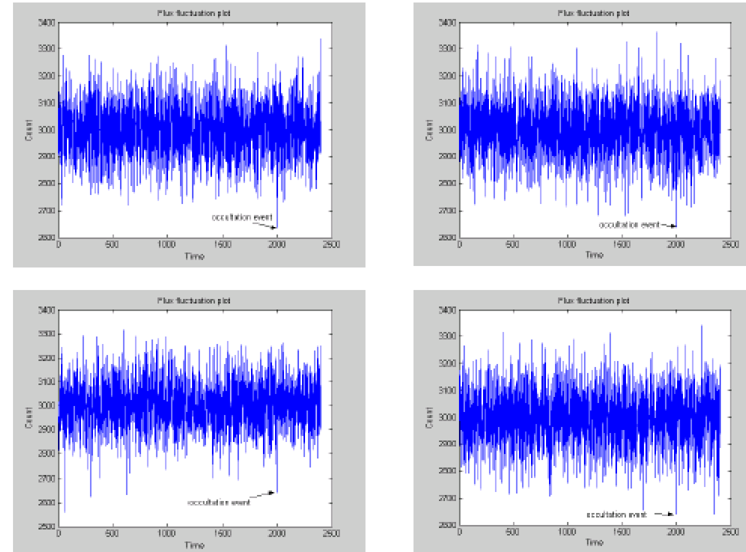
- A true occultation event should have the lowest rank in **all** telescopes

no need for highly accurate flux

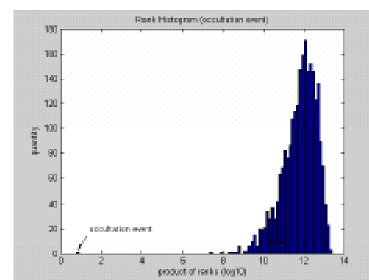
➔ speed

conditional probability

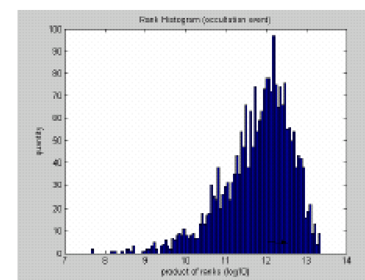
➔ low false rates



Simulated light curves by each of the four telescopes

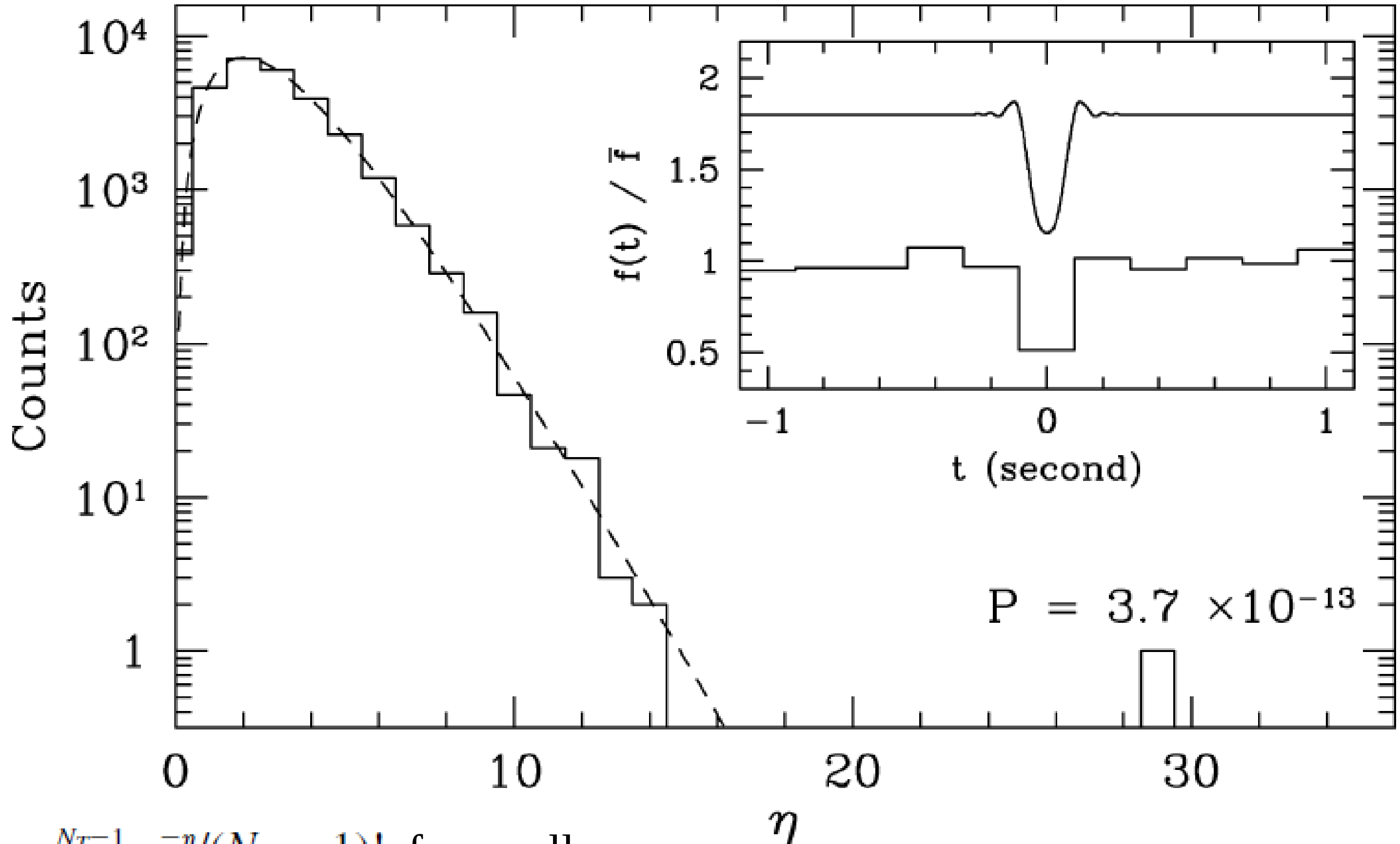


With occultation



Without

Ranking statistics



$P(\eta) = \eta^{N_T - 1} e^{-\eta}/(N_T - 1)!$ for small η

FIG. 3.—Histogram of η for a light curve set implanted with a *simulated* occultation by a 3 km KBO. Each light curve comprises 26,637 points and the ranks from the three telescopes are found to be 1, 3, and 1. The event is clearly visible at $\eta = 29.47$, and the probability of a rank product of 3 or lower from random chance is $P = 3.7 \times 10^{-13}$. The overlaid dashed line is the theoretical distribution of η. The theoretical and implanted light curves are shown in the inset, offset vertically for clarity.

Zhang et al. (2008)

Results by TAOS

- In 2005-2006 more than several billion stellar photometric measurements have been collected.
- Of 2.4×10^9 rank triplets, no events were found.
- This sets a stringent upper limit to the number and size distribution of TNOs.
- The limit can be estimated by the efficiency of the survey, i.e., by the fraction of ***recovered*** events artificially injected into observed light curves (same noise, processed by the same analysis pipelines).

Effective solid angle of the survey

$$\Omega_e(D) = w_D^{-1} \sum_j [E_j v_{\text{rel}_j} H_j(D)/\Delta^2]$$

where D: KBO diameter

Ej: duration of a light curve set

$v_{\text{rel}j}$: relative speed between KBO and Earth

Hj: event cross section

Δ: geocentric distance (≡ 43 AU, not sensitive)

*w*D: weight (fraction of injects in simulations)

The expected number of ***detected*** events by KBOs with sizes ranging from D_1 to D_2 then is

$$N_{\text{exp}} = \int_{D_2}^{D_1} \frac{dn}{dD} \Omega_e(D) dD$$

dn/dD: differential surface number density of KBOs (what we want)

$\Omega_e(D)$: survey sensitivity

The solid angle increases with size, whereas the number of TNOs decreases with size.

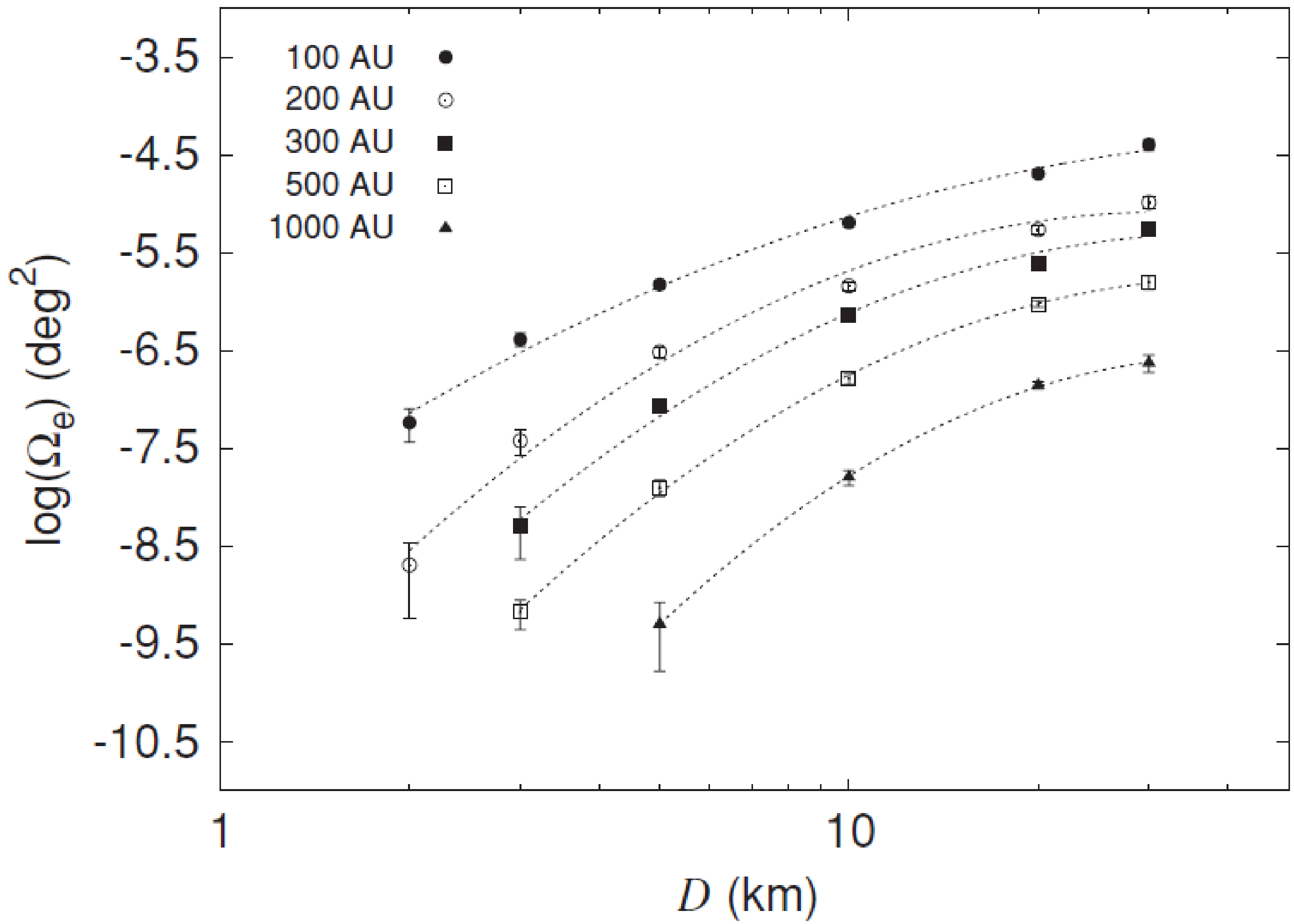


Figure 9. Effective solid angle vs. size for different distances from the TAOS efficiency calculation.

Wang et al. (2009)

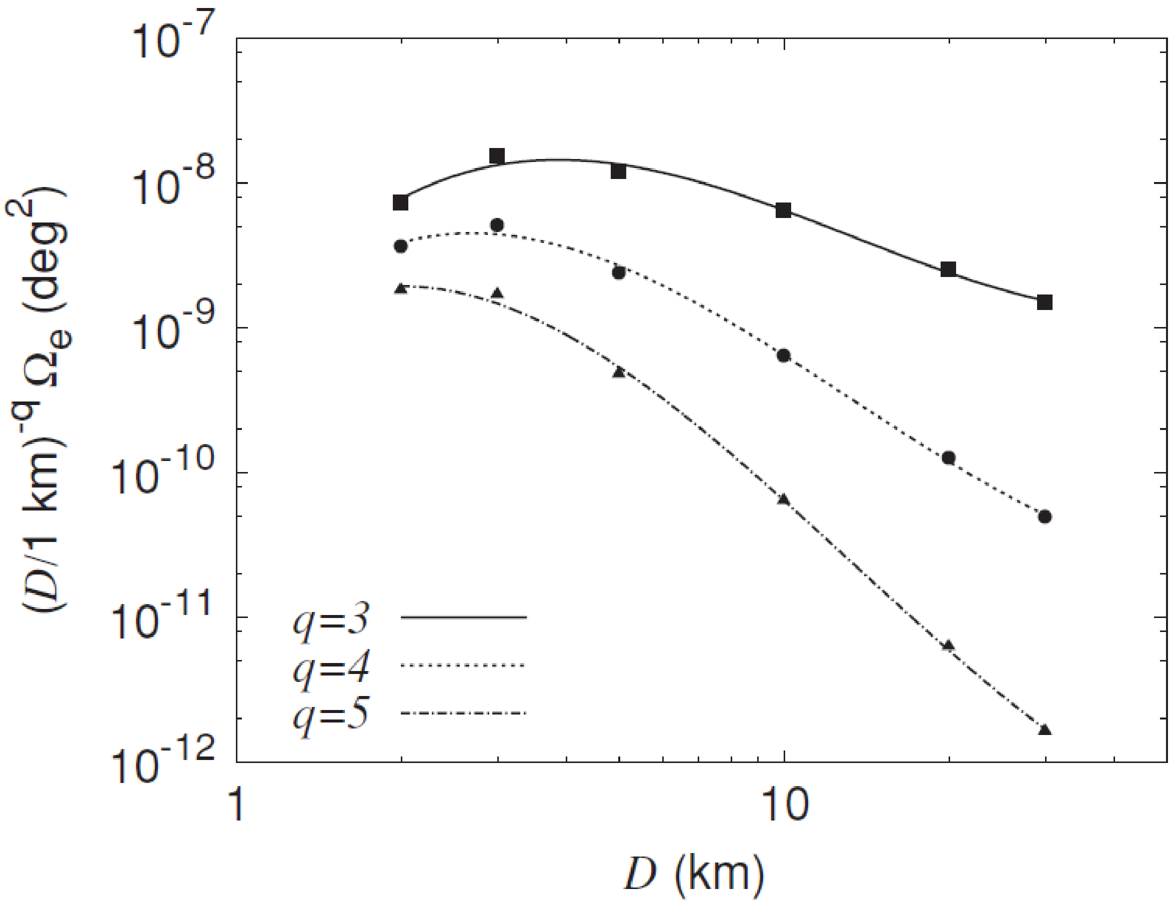


Figure 10. Plot of the product of the power-law size distribution $(D/1\ \mathrm{km})^{-q}$ and $\Omega_e(D, \Delta)$ vs. diameter D at 100 AU, for several values of q. Note that D^{-q} decreases with D, and Ω_e increases with D. The product of these two terms is an indicator of the sensitivity of the TAOS system.

For q=3, the TAOS sensitivity peaks at D=3 km at Δ=100 AU

Wang et al. (2009)

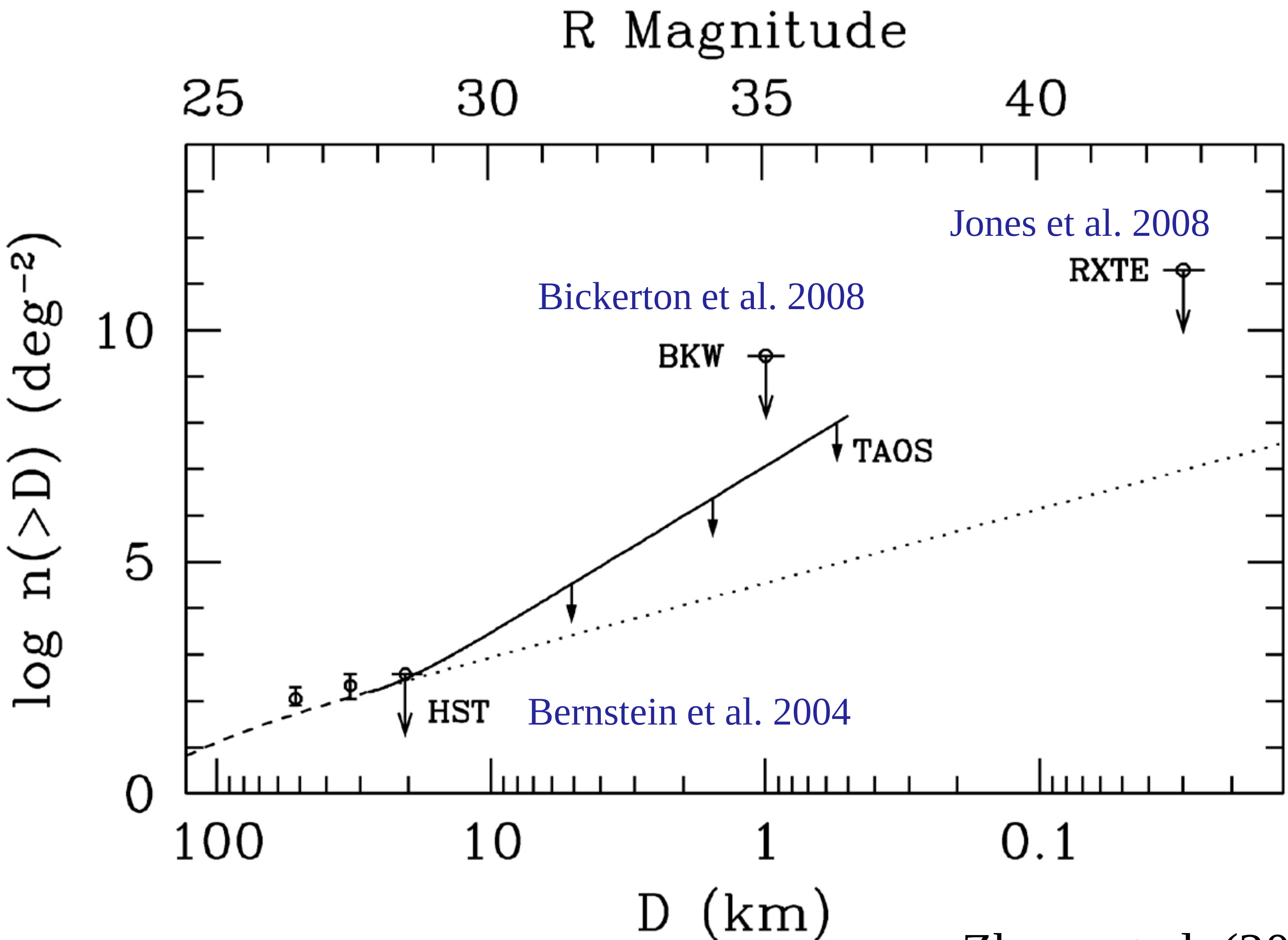
Setting $N_{exp} < 3$; i.e., any model with a size distribution such that N > 3 is inconsistent with our data at 95% confidence level.

Assuming a power-law distribution

$$dn/dD = n_B(D/28 \text{ km})^{-q},$$

such that the cumulative size distribution is continuous at 28 km with the results of Bernstein et al. (2004).

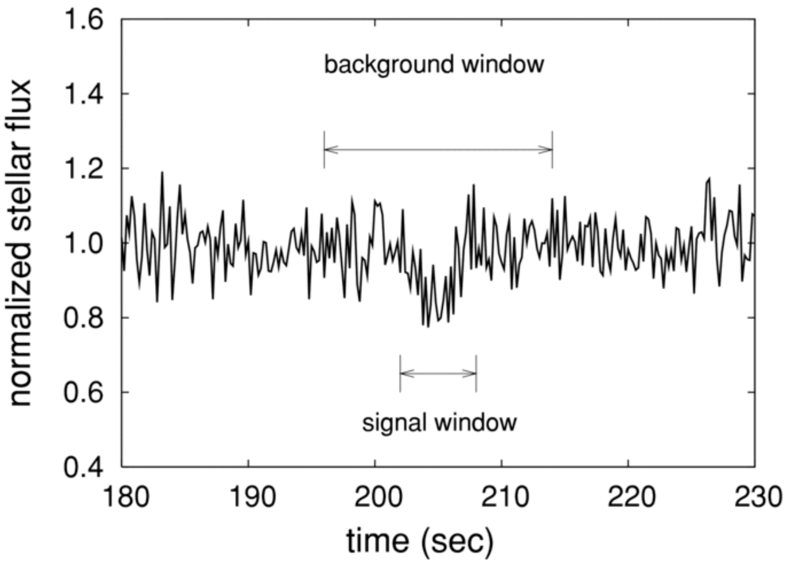
Integration from D_2=28 km to our detection limit of D_1=0.5 km with N_{exp}=3, gives q=4.60.

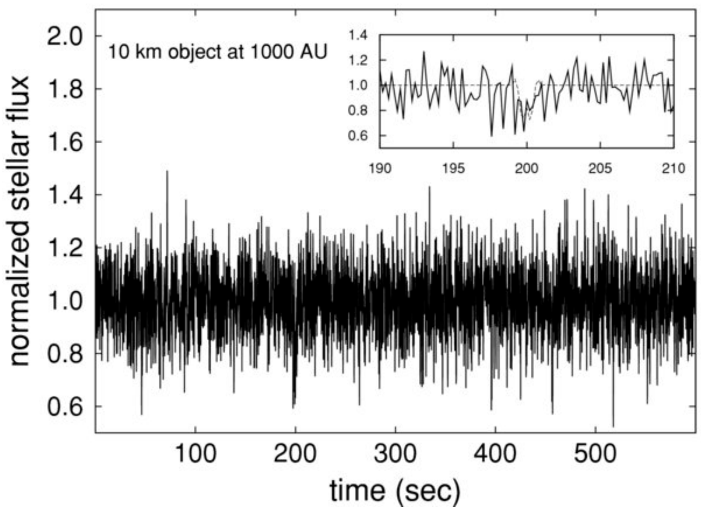


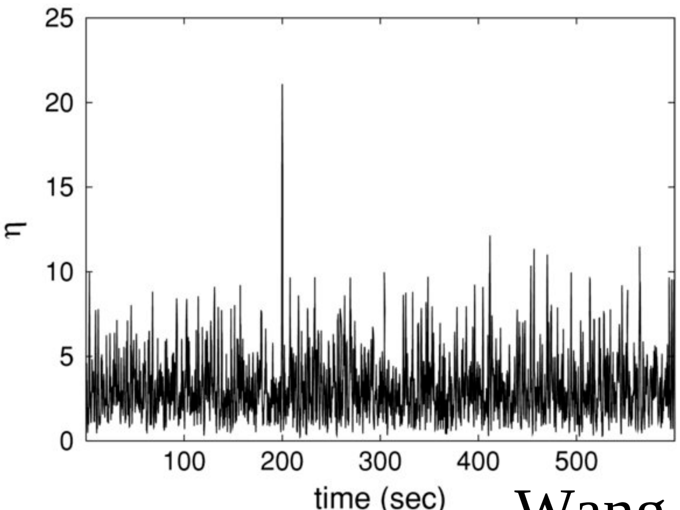
Zhang et al. (2008)

TAOS looking for Sedna-like Objects

Instead of 1-2 data point drops, look for shallow, but long, flux reduction → large, Sedna-like TNOs, or even inner Oort cloud objects







Wang et al. (2009)

Running similar efficiency tests, with injected events by large TNOs

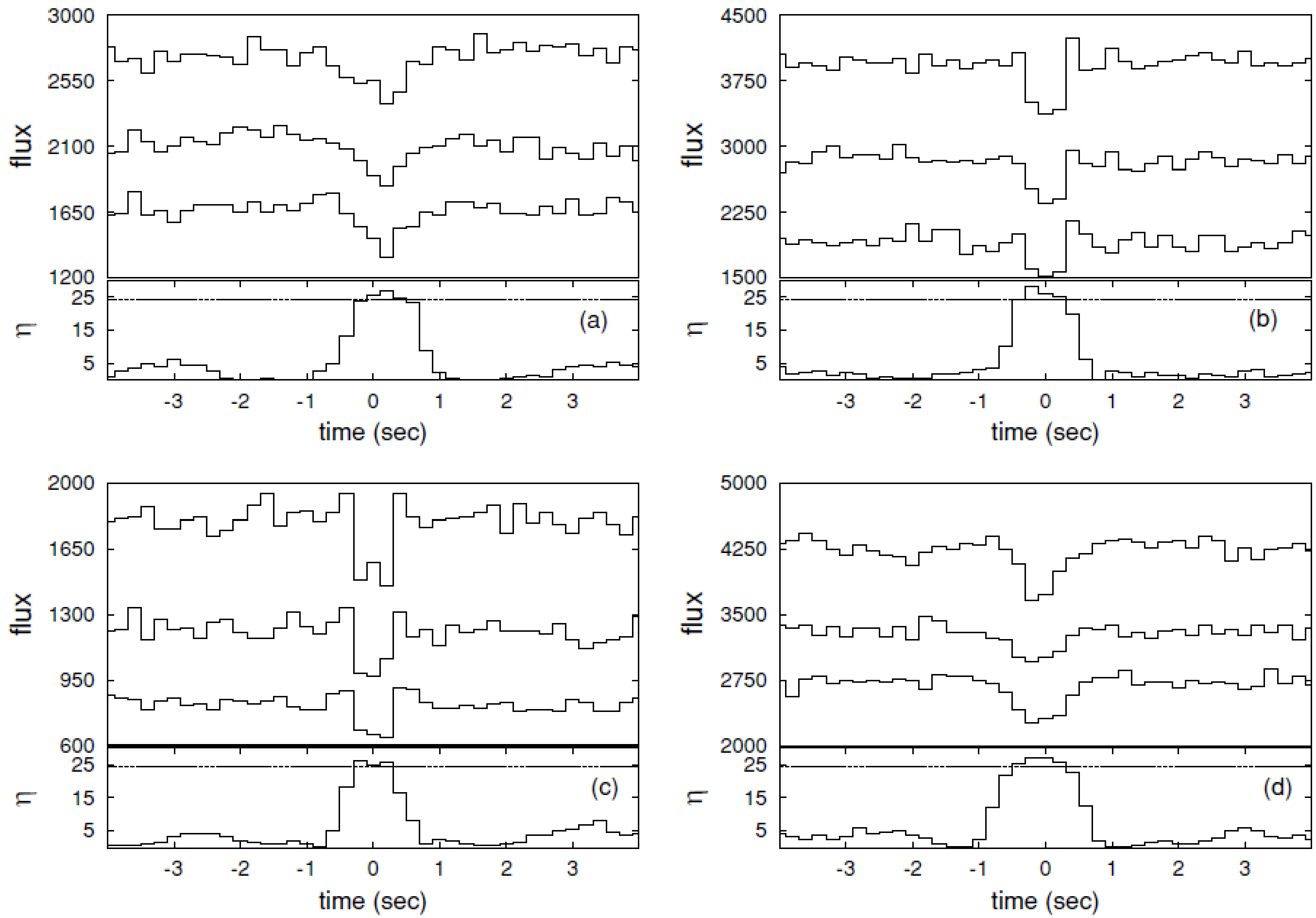


Figure 8. During the efficiency test, synthetic events were added into TAOS light curves. Examples of light curves with the synthetic events in three TAOS light curves are shown in the upper part of each panel and the corresponding η values in the lower part of each panel. Some constants were added to second and third light curves to separate them for clarity. The dotted lines are the η value for $F \leqslant 10^{-8}$. (a) 2 km, 200 AU, $\phi = 68.^\circ 8$; (b) 3 km, 500 AU, $\phi = 45.^\circ 9$; (c) 5 km, 1000 AU, $\phi = 34.^\circ 4$; and (d) 10 km, 1000 AU, $\phi = 34.^\circ 4$.

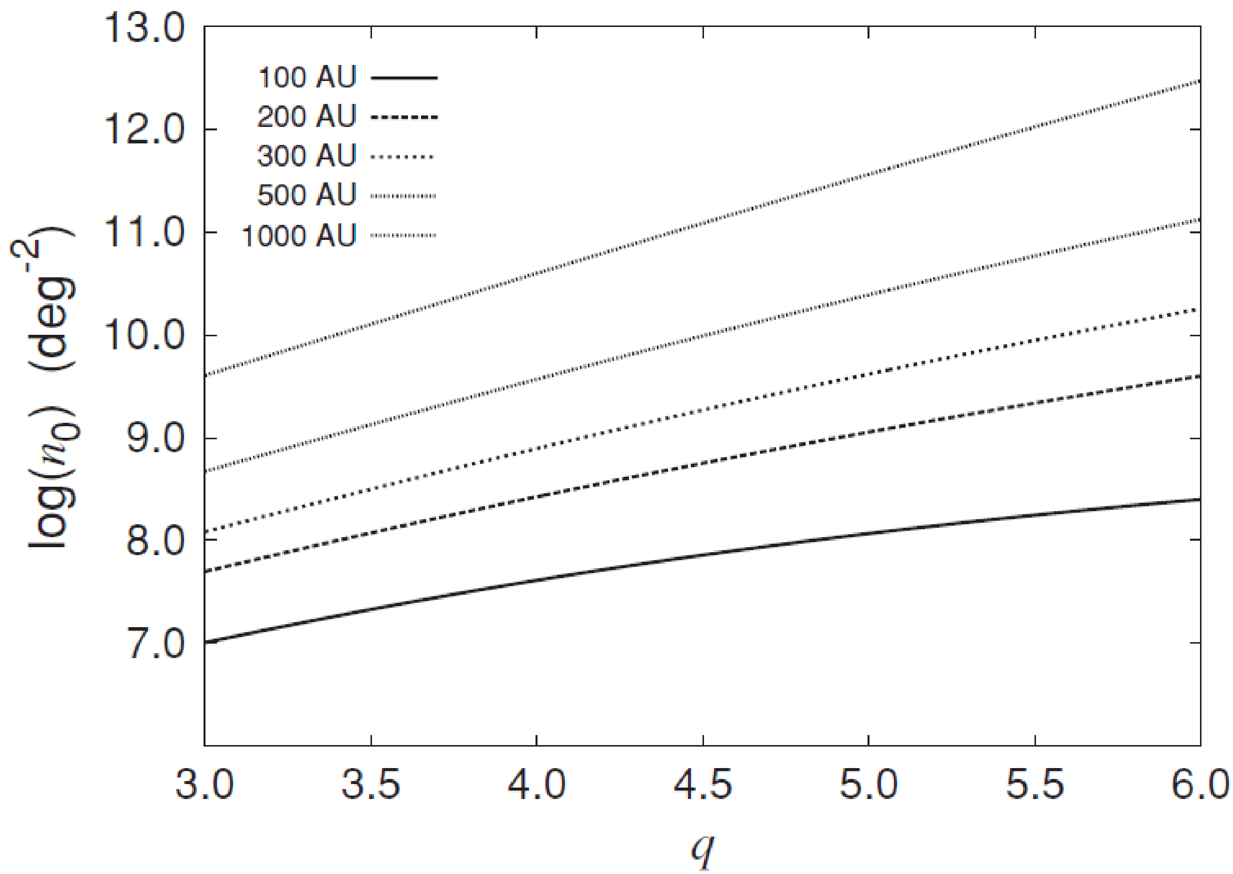


Figure 11. Upper limits of number density with objects larger than 1 km for various q and Δ. Any model with n_0 above the relevant line is ruled out at the 95% c.l.

$$\frac{d\, n_\Delta(D)}{dD} = n_0(q-1)\left(\frac{D}{1\ \mathrm{km}}\right)^{-q}$$

Wang et al. (2009)

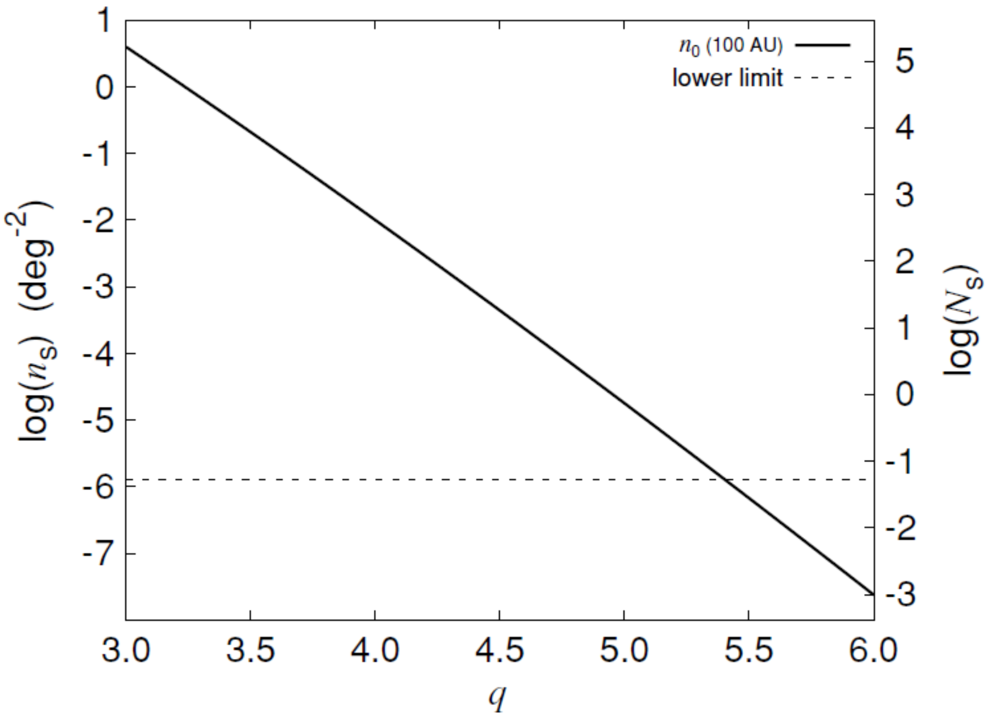


Figure 12. Upper limit on n_s as a function of q at 100 AU. The diagonal line is the 95% upper limit set by the TAOS at 100 AU. The right axis shows the corresponding upper limit on the total expected number of objects larger than Sedna (N_s) in the whole sky, assuming an isotropic distribution. Given that one Sedna actually exists, we can also set a lower limit on the surface density. If our assumption of a power-law model is correct, we can exclude size distributions where $N_s < 0.05$ (dotted line) at the 95% c.l., which corresponds to a value of $n_s < 1.2 \times 10^{-6}$ deg^{-2}.

$$n_s = n_0 \left(\frac{D_s}{1 \text{ km}} \right)^{1-q}$$

D_s=1600 km for Sedna

Wang et al. (2009)

n_s and q are constrained.

Since one Sedna has been found near 100 AU, q > 5.4 is excluded, because it would have given too few large TNOs (at least 1 Sedna) or too many small ones (1 km) to comply with the null TAOS results.

Conclusions

- Stellar occultation offers the only possibility to “detect” small (< 1 km) and distant TNOs.
- The size distribution is presently unknown, but the TAOS experiment shows a clear deficit of small TNOs.
- TAOS II, with 1.3 m telescopes and frame-transfer CCDs (capable of 20 Hz sampling) in preparation
  → fast duty cycle; resolved diffraction patterns
- Space missions too (e.g., *Whipple*, *Ocle Docle*)