

# An HST/ACS Survey of the Kuiper Belt



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*with co-I's*


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*and for Astrometry:*

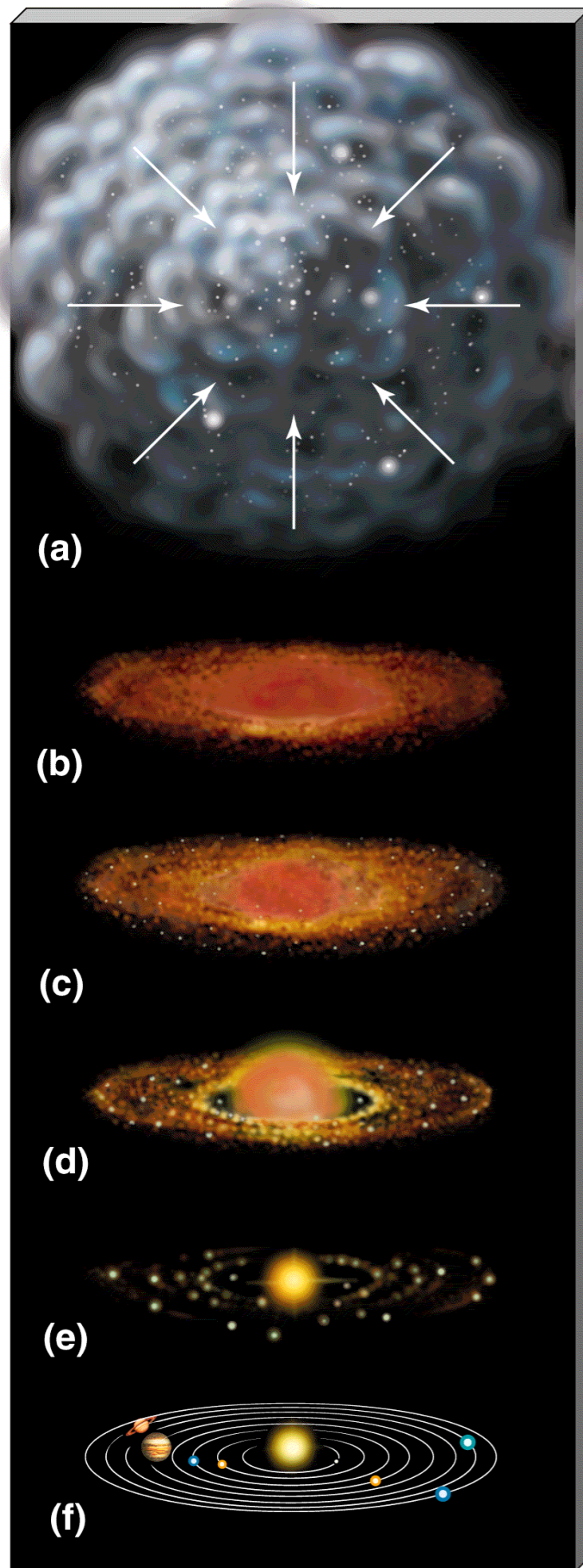
*N. Zacharias (USNO) & J. A. Smith (LANL)*

☀Funded by GO-9433 grants

Background Image: section of summed  
ACS TNO search-field data.

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- The Kuiper Belt as an accretion and dynamics laboratory
  - Design and Execution of the ACS Survey
  - TNO Discoveries & Followup
  - Implications for Solar System Evolution
  - Light Curves and Astrometry

# Planet Formation Scenario:



## Theoretical Expectation:

Collapse of gas / dust cloud to form protostar and nebular disk.

Coagulation of grains, runaway gravitational growth of planetesimals

Oligarchic growth of planetesimals.

Gas accretion onto largest bodies, dissipation of gas, ejection of small bodies

Mature planetary system

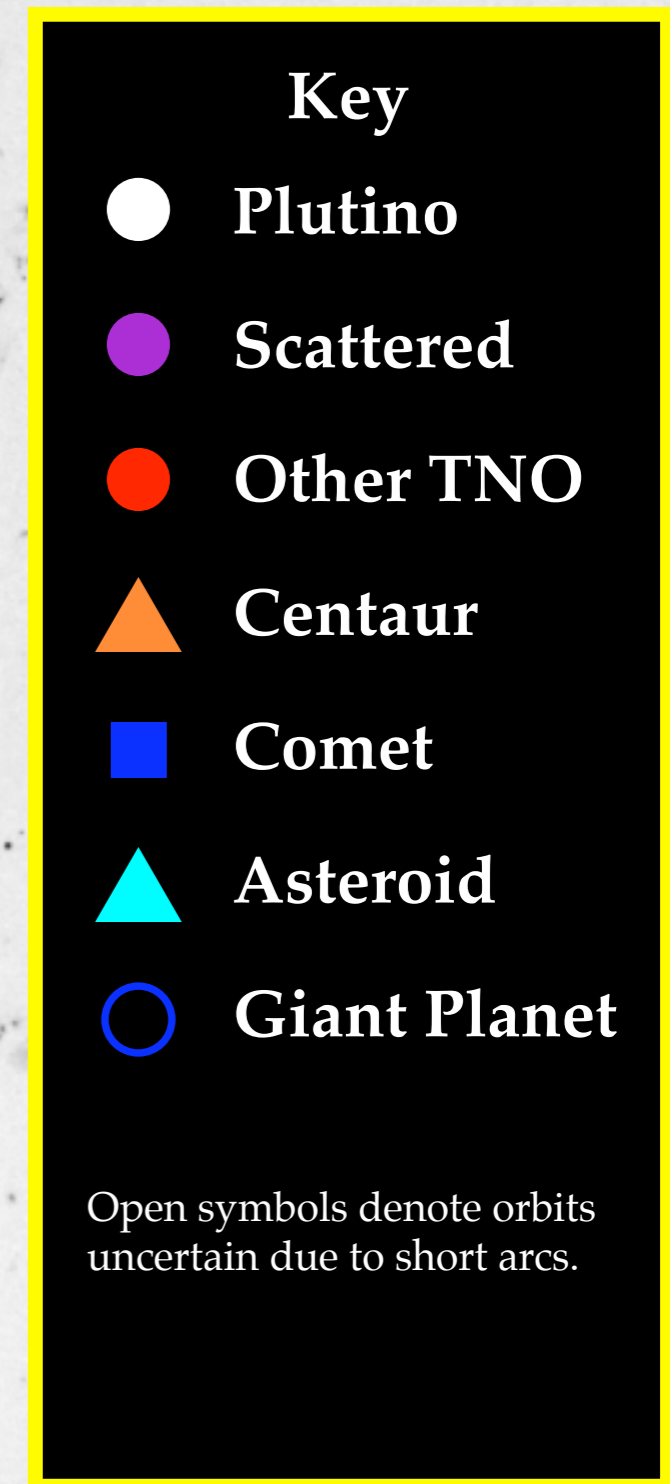
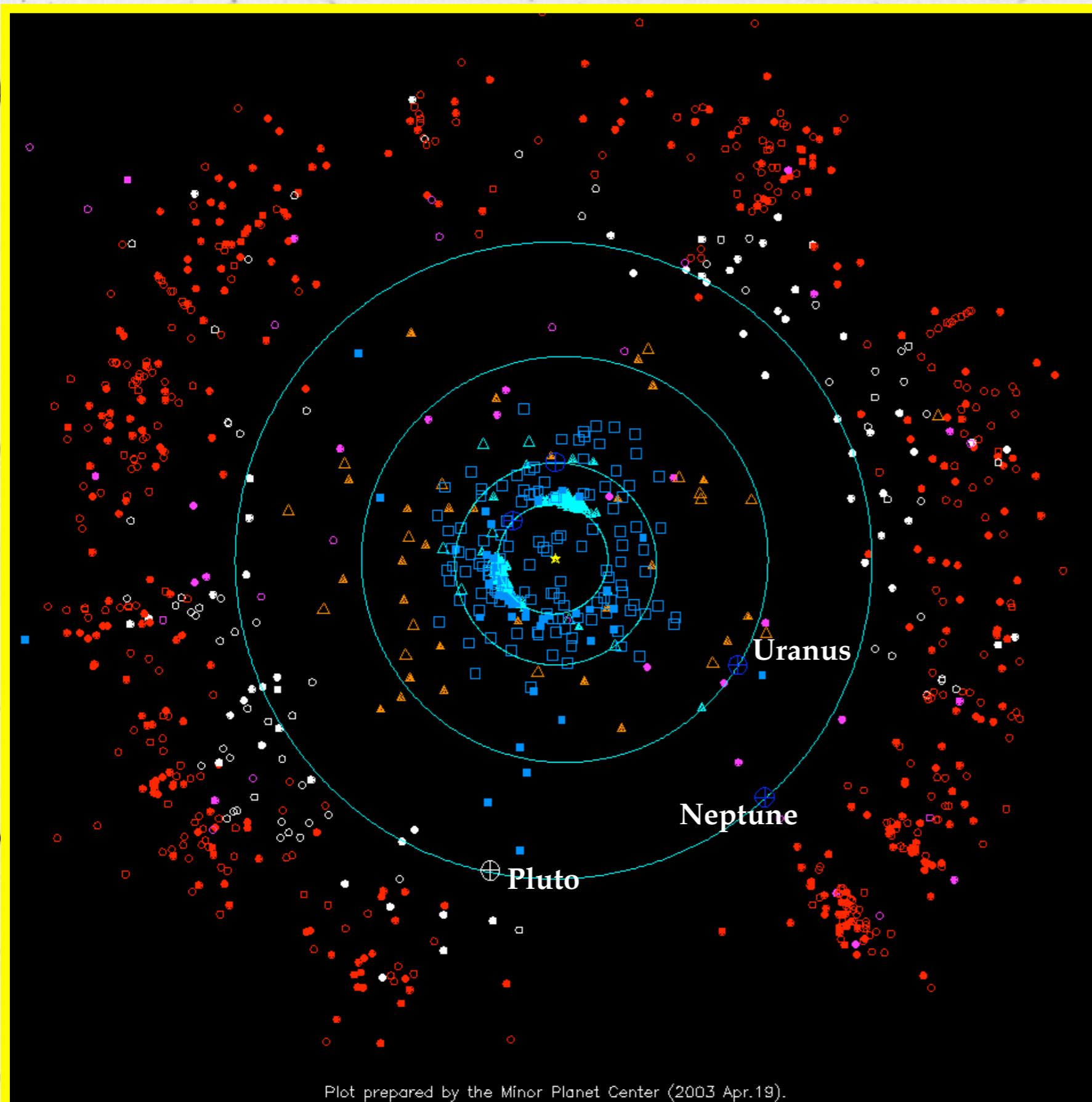
## Observational Evidence:

Nebular / dust phases are observed around other stars

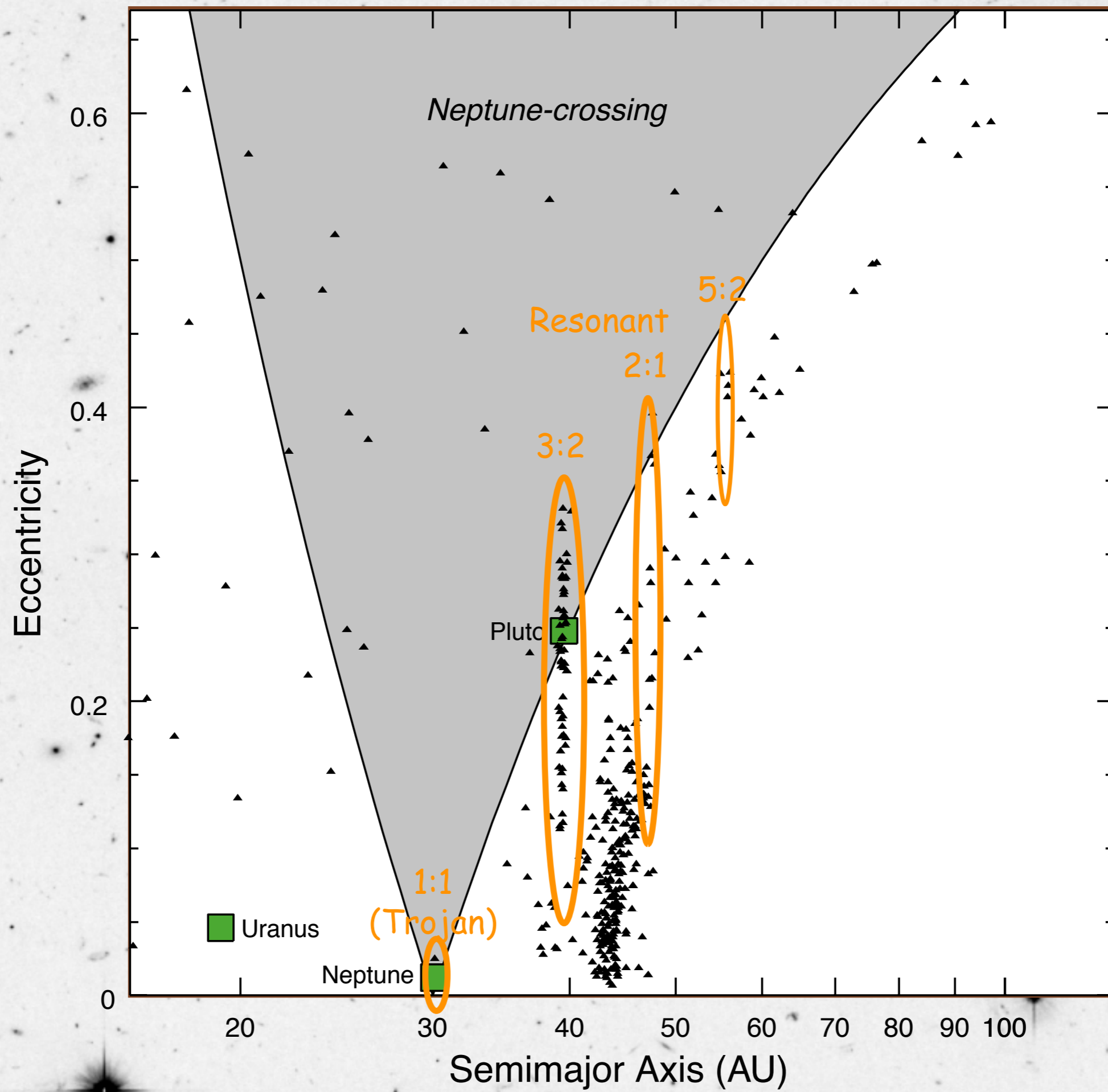
Planetesimal phase is observable only in our outer "fossilized" Solar System - the Kuiper Belt.

Giant planets have been detected around other stars

# Known Outer Solar-System Bodies (as of 2003 April 19)



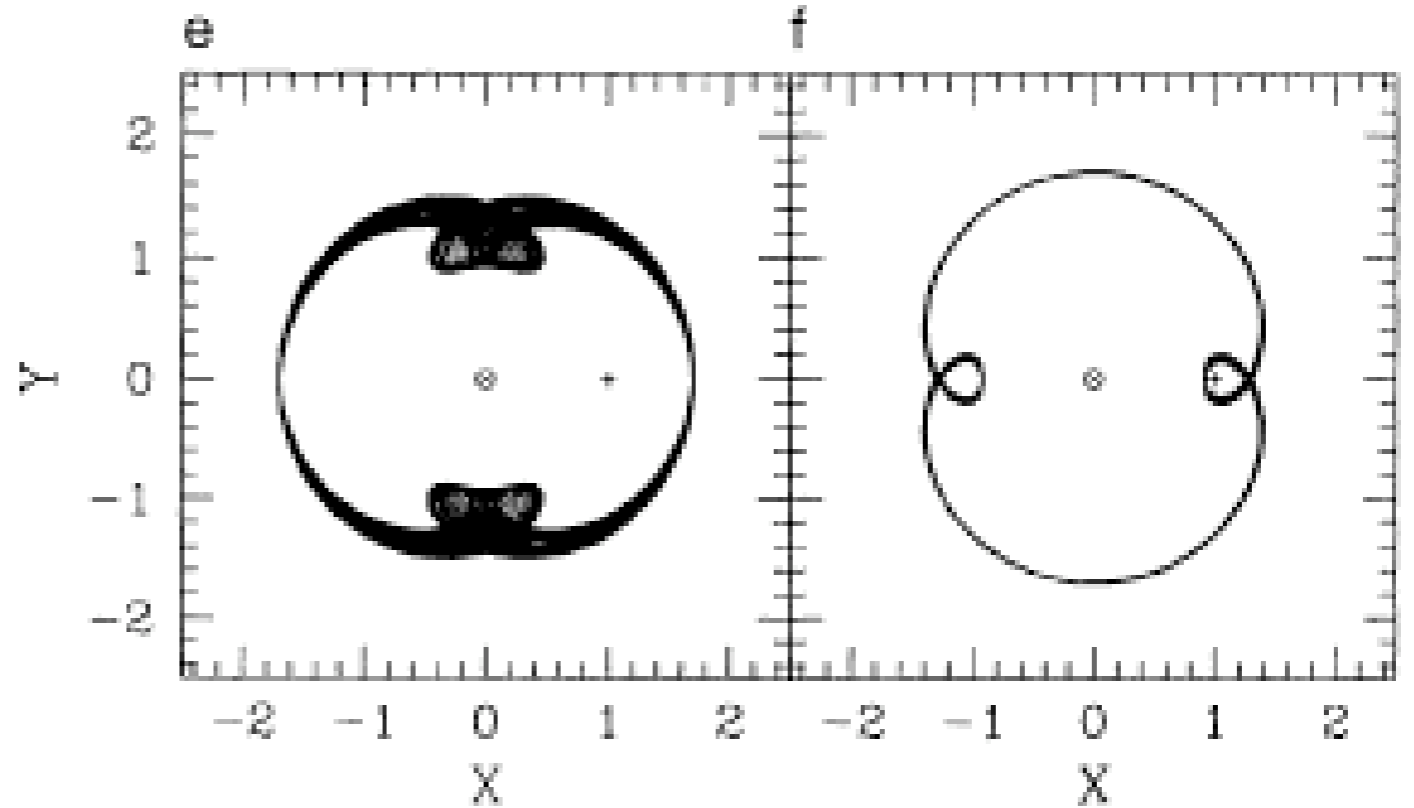
# Outer Solar System Objects (as of 4/03)



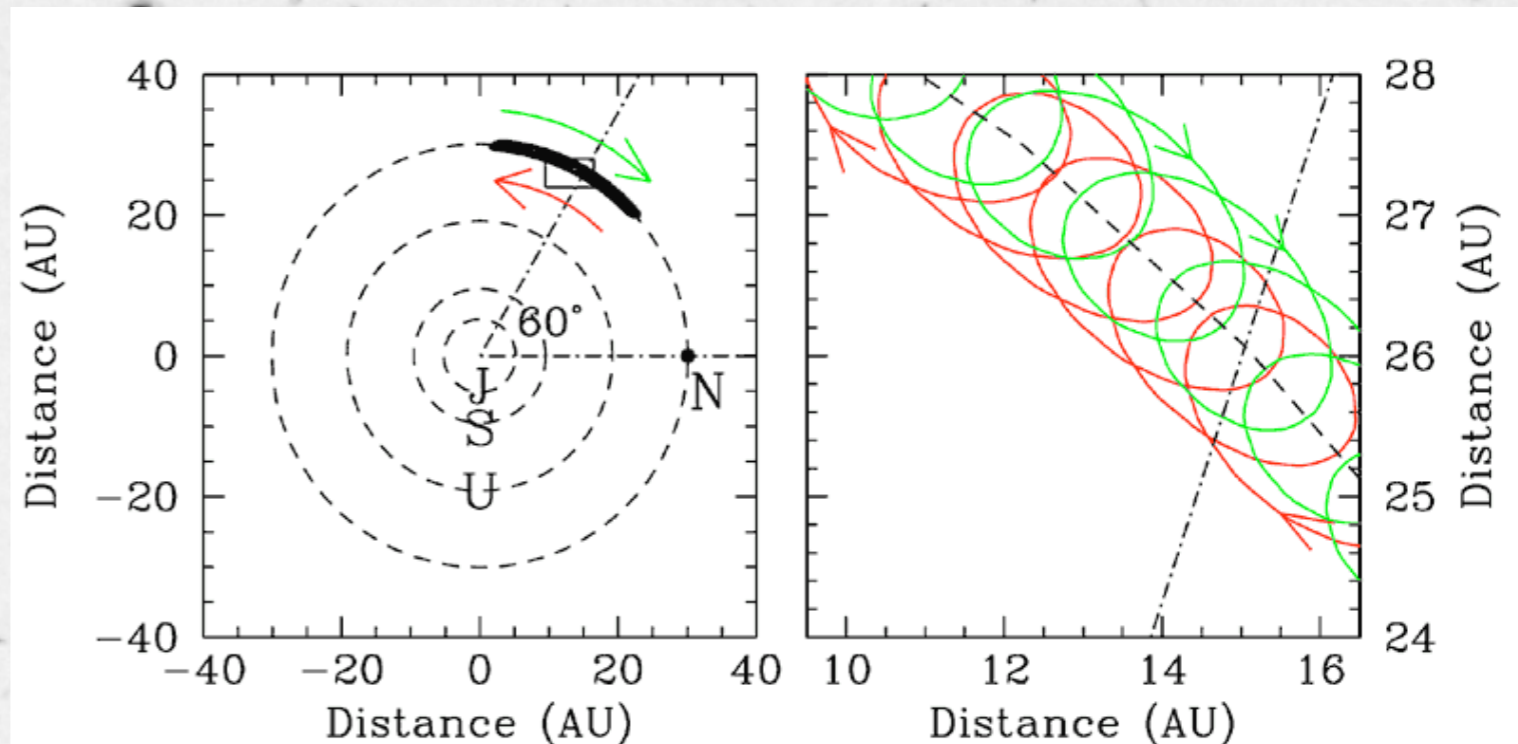
# KBO Resonances and Planetary Migration

3:2 Resonances in Neptune frame (Malhotra 1995)

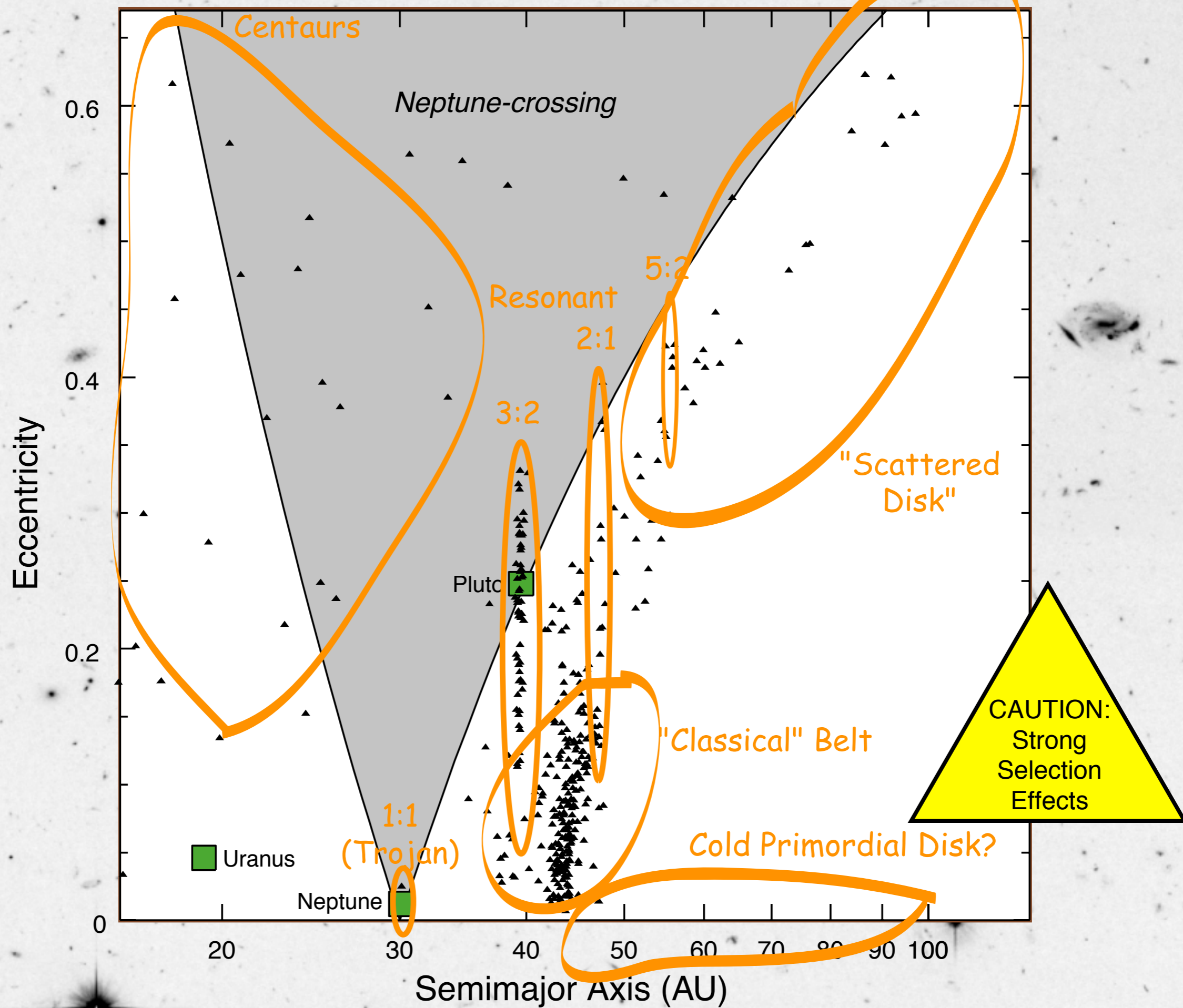
- Pluto and many KBOs ("Plutinos") are locked in 3:2 resonance with Neptune, crossing Neptune's orbit yet avoiding ejection.
- Malhotra (1993) explains "accident" of Pluto's resonance by positing an outward migration by ~8 AU of Neptune during the clearing of the planetesimal disk. Resonances "sweep" through the population, acting like phase-space traps. Prediction is that many KBOs should be found in 3:2 and 2:1 resonances
- KBOs have been found in following resonances (Chiang et al '03): 1:1 ("Trojan"), 5:4, 4:3, 3:2 ("Plutino"), 5:3, 7:4, 2:1, 7:3, 5:2. Resonance sweeping can only explain some of these, obviously not 1:1.



Orbit of 2001 QR<sub>322</sub> in Neptune frame (Chiang et al 2003)



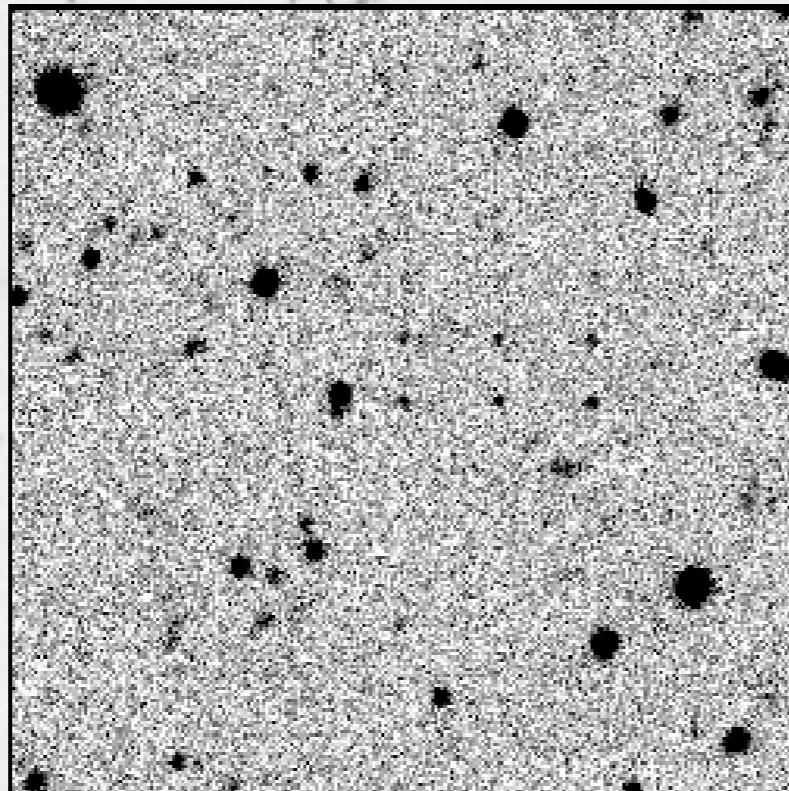
# Outer Solar System Objects (as of 4/03)



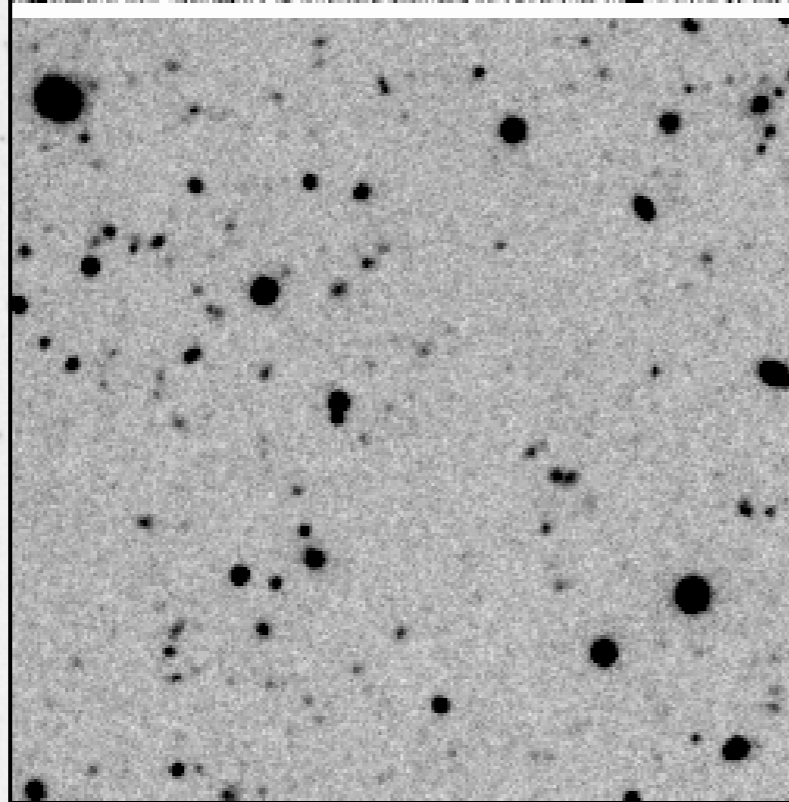
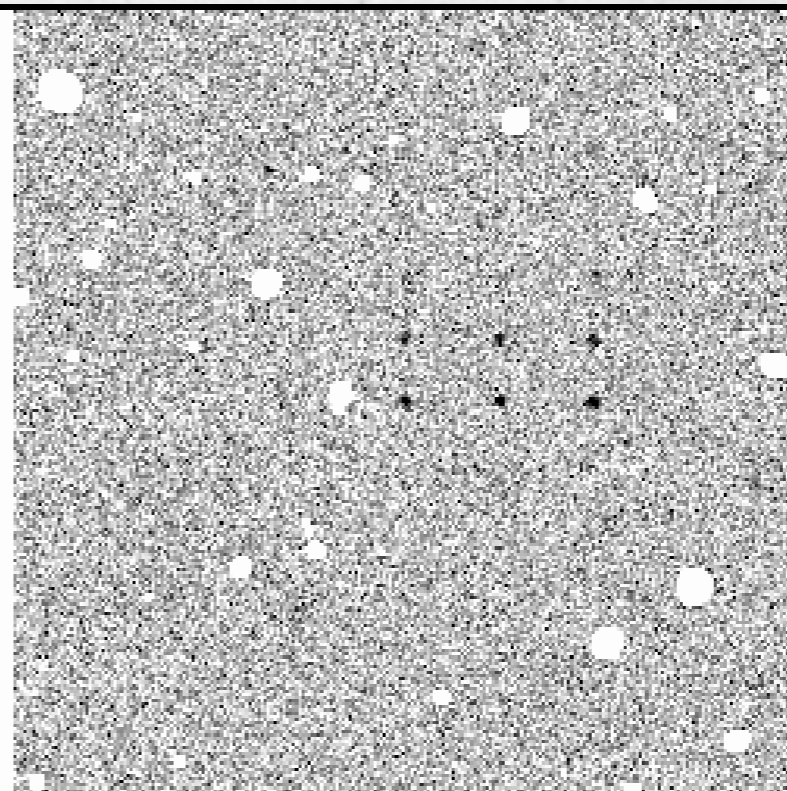
## *Finding Faint TNOs*

- Recall that distant TNOs have  $f \propto r^{-4}$
- Traditional response to fainter target is longer integration, but S/N gain for **moving** objects stops when object trails across sky background. TNOs move few arcsec per hour.
- Non-sidereal tracking of telescope only works for one preselected motion vector, not appropriate for a survey
- Ground-based exposures limited to ~10 minutes before trailing, or  $m_R \lesssim 24$
- **Digital Tracking:** Take short exposures, shift and add digitally to follow any candidate orbit, then run detection algorithm.
- Used successfully from ground in 1992 by GMB, with Cochran et al WFPC2 data, many other times since.

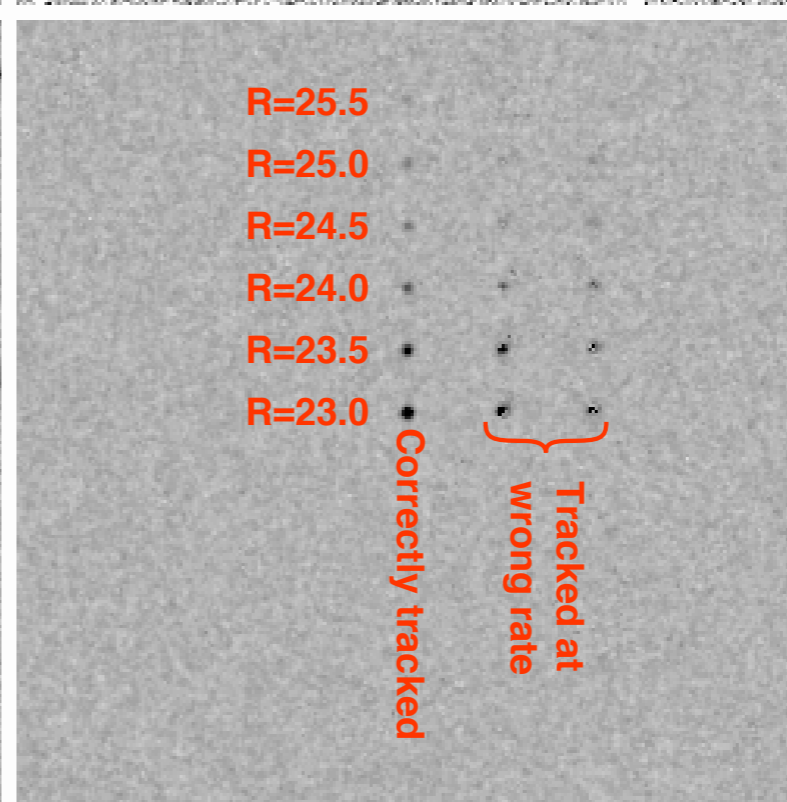
a) Original Single Exposure



(c) Single Exposure,  
Fixed Objects Subtracted/Masked

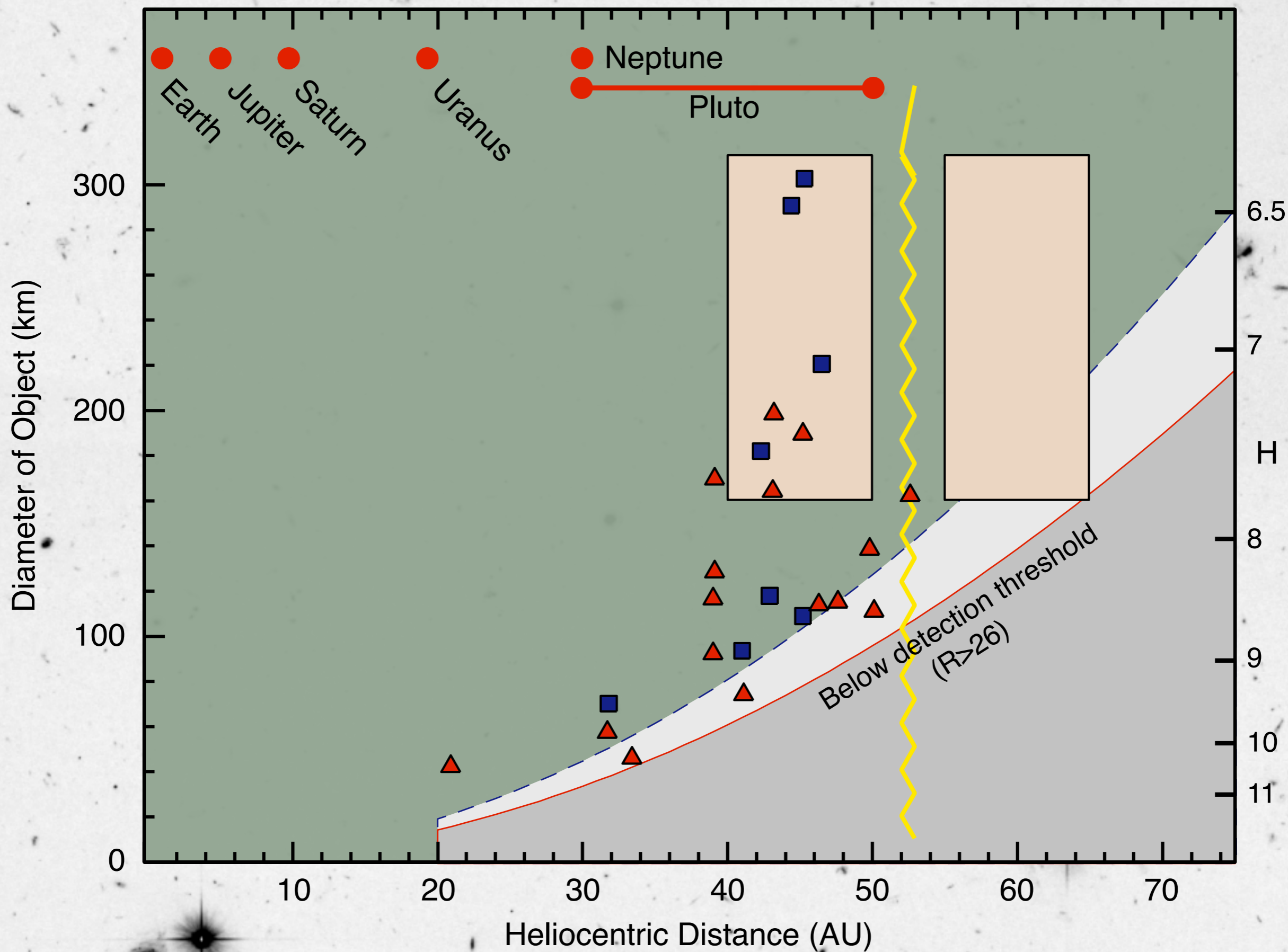


(b) Combined Image  
Track at Sidereal Rate



(d) Combined Image  
Track at KBO rate

*Ground-Based Survey of 1.5 Square Degrees*  
*Allen, Bernstein, & Malhotra (2001)*

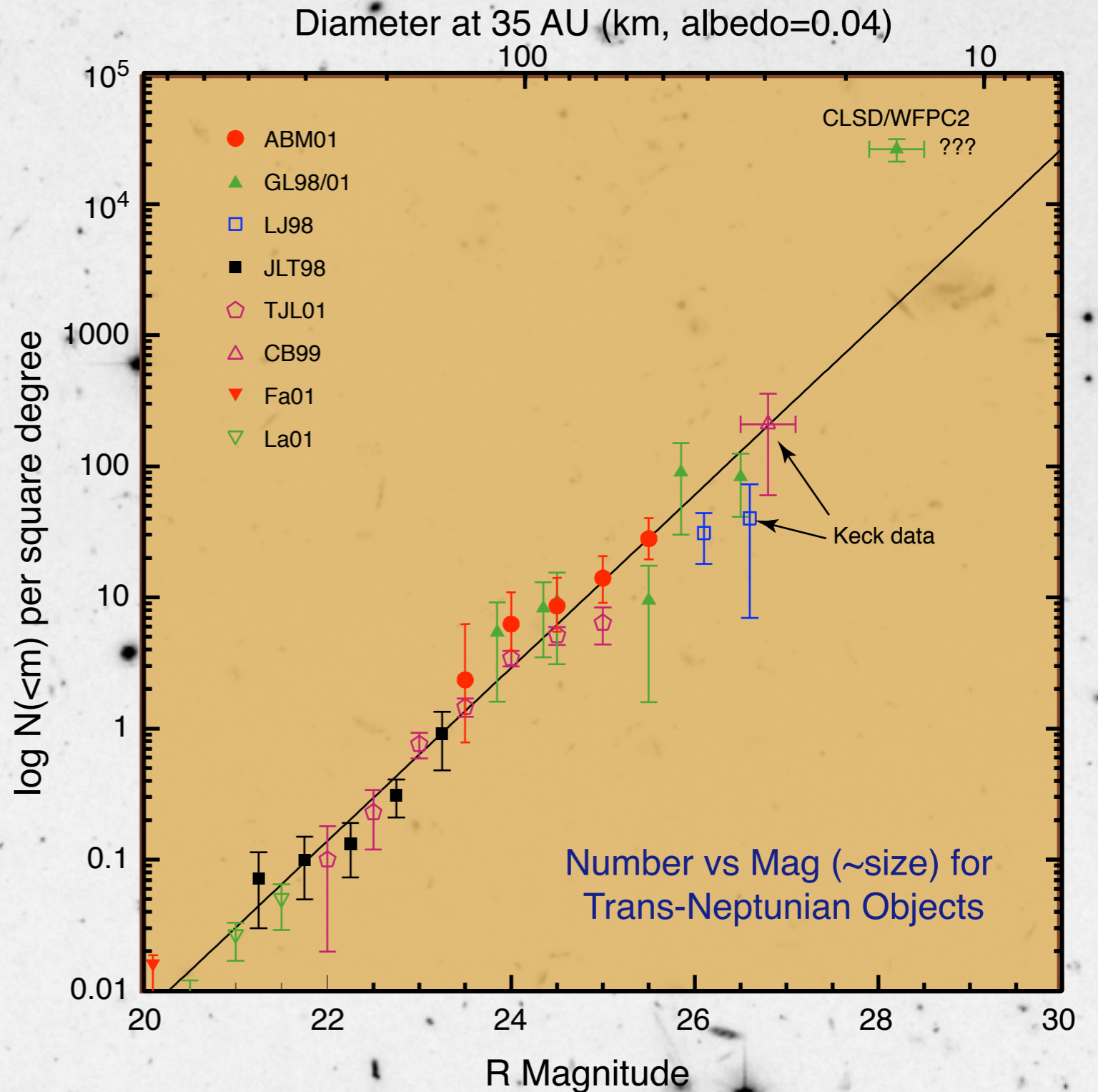


# Size Distribution of KBOs

- For fixed distance, mag distribution is the size distribution.
- Faintest two points on this plot known to be contaminated by false positives!
- Data seem consistent with a single power law,

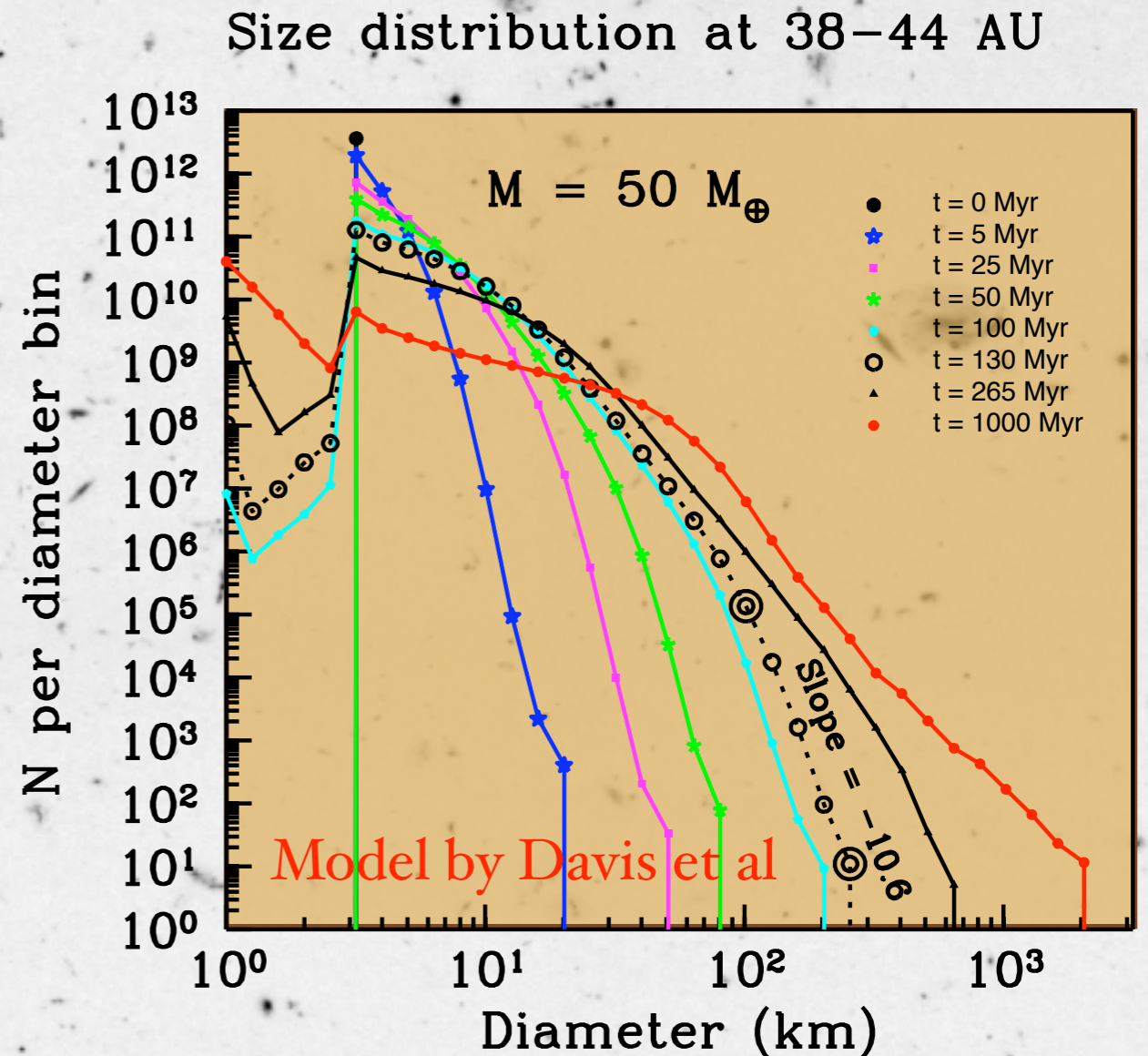
$$N(< m) = 10^{0.63(m-23)}$$

$$\Rightarrow \frac{dN}{dr} \propto r^{-q}, \quad q = 4.0 \pm 0.5$$



# Theoretical Expectations for Size Distribution

- Single power law must break down to avoid divergent mass, surface brightness.
- Modelling of collisional accretion and erosion requires detailed numerical study, assumptions about fracturing, dynamics, etc.
- Dohnanyi shows that  $q=3.5$  is a point of steady-state collisional cascade under scale-free fracturing laws. Expect this below some disruption scale.



*Does this size break exist? Kuiper Belt is perhaps our only opportunity to test an accretion model!*

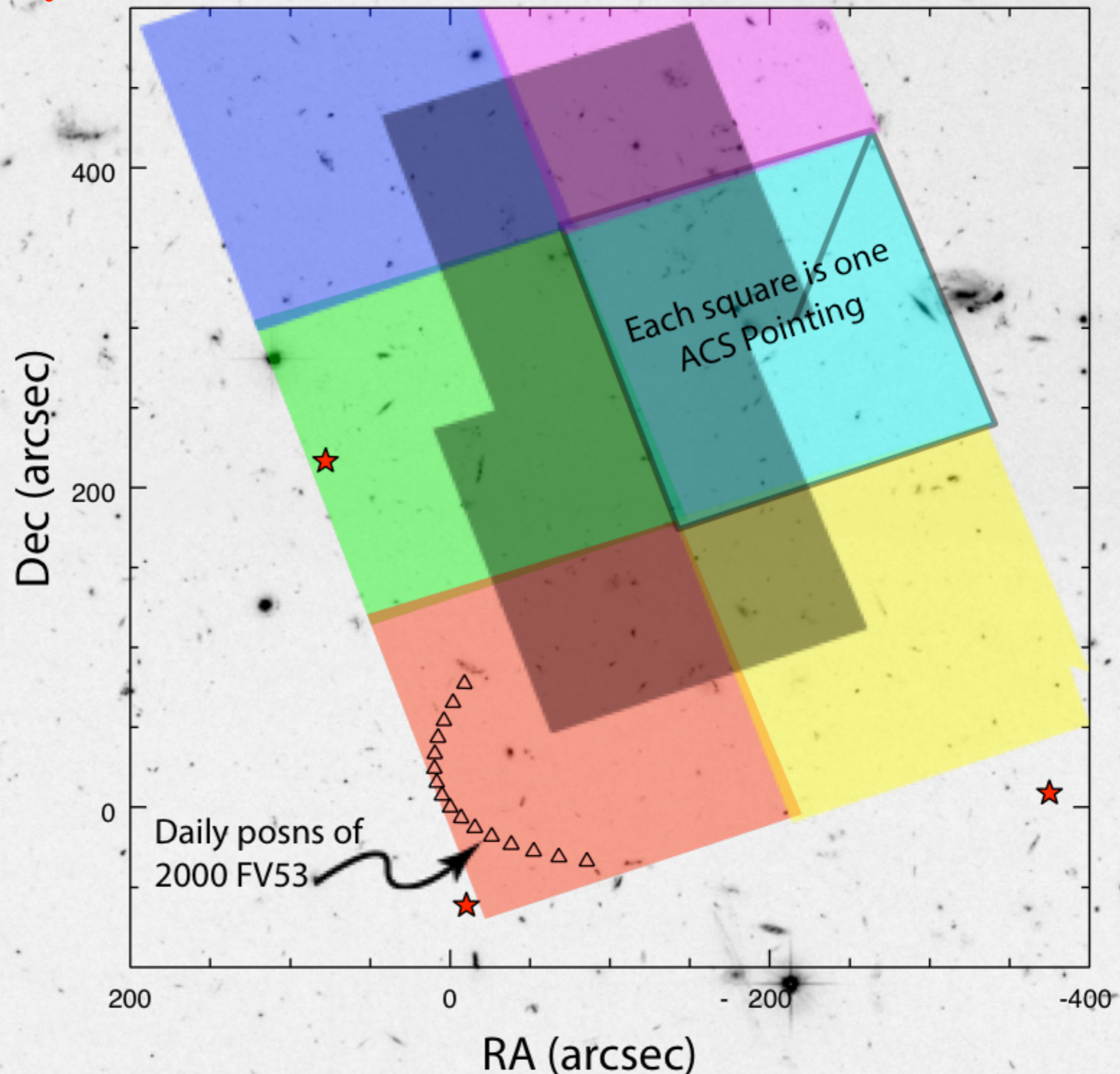
## *Outstanding Kuiper Belt Questions*

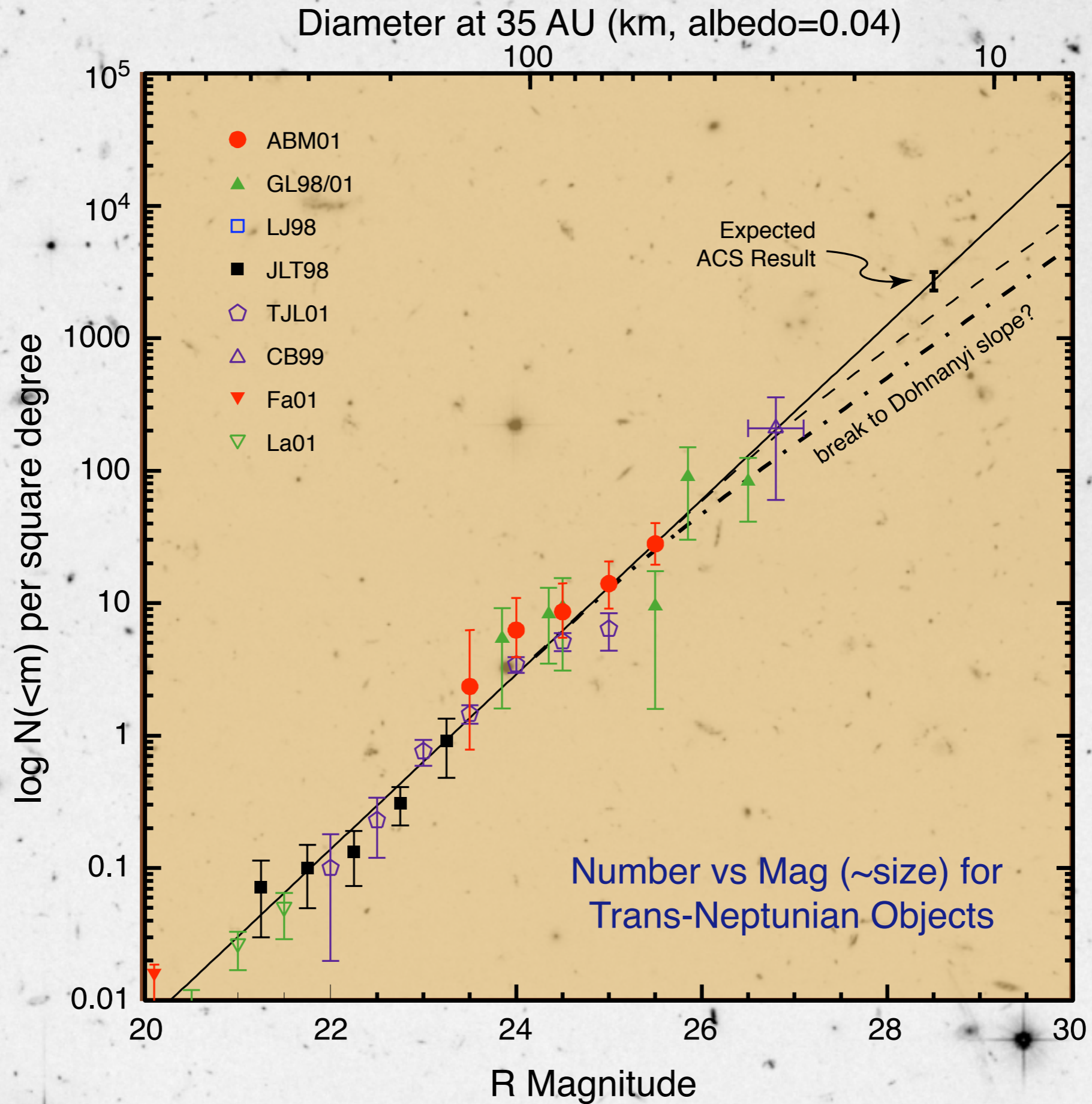
- What is the size (magnitude) distribution of objects?
- Are the dynamical classes physically distinct?
- What event(s) or process(es) heated the planetesimal disk?
- Is there truly a truncation? What caused it?
- Are any of the dynamical classes viable source reservoir for the observed 1-10 km Jupiter family comets?
- What can we learn about the history of the solar system, and planetary systems in general?

## *Plan for the ACS Survey*

- Six ACS fields, 0.02 square degrees (12x HDF)
- Observe each field 22 ksec over 5 days
- Sum flux over 30 exposures in  $\approx 10^{14}$  candidate orbits
- Wait 5 days; most TNOs pass stationary points and reverse
- Observe another 15 ksec to confirm discoveries
- Detection limits:  $m < 29.2$  in F606W
- Expect 85 detections under extrapolation.

The HST/ACS Kuiper Belt Search Fields





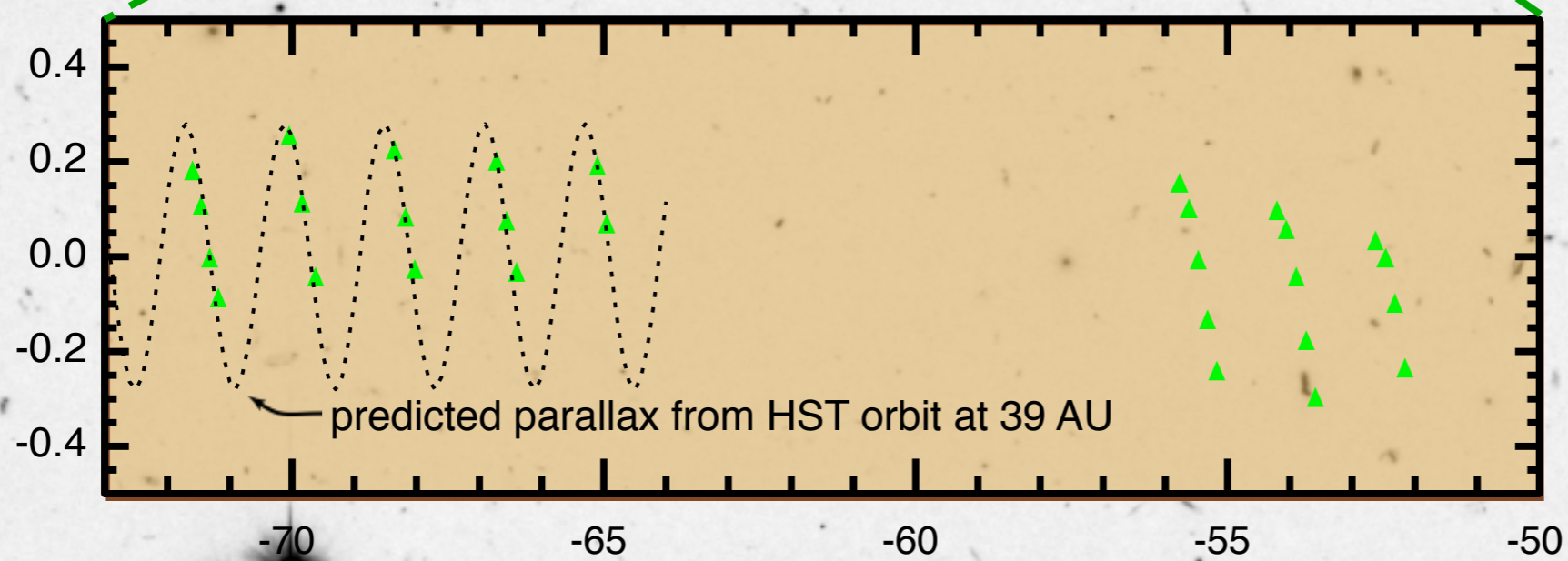
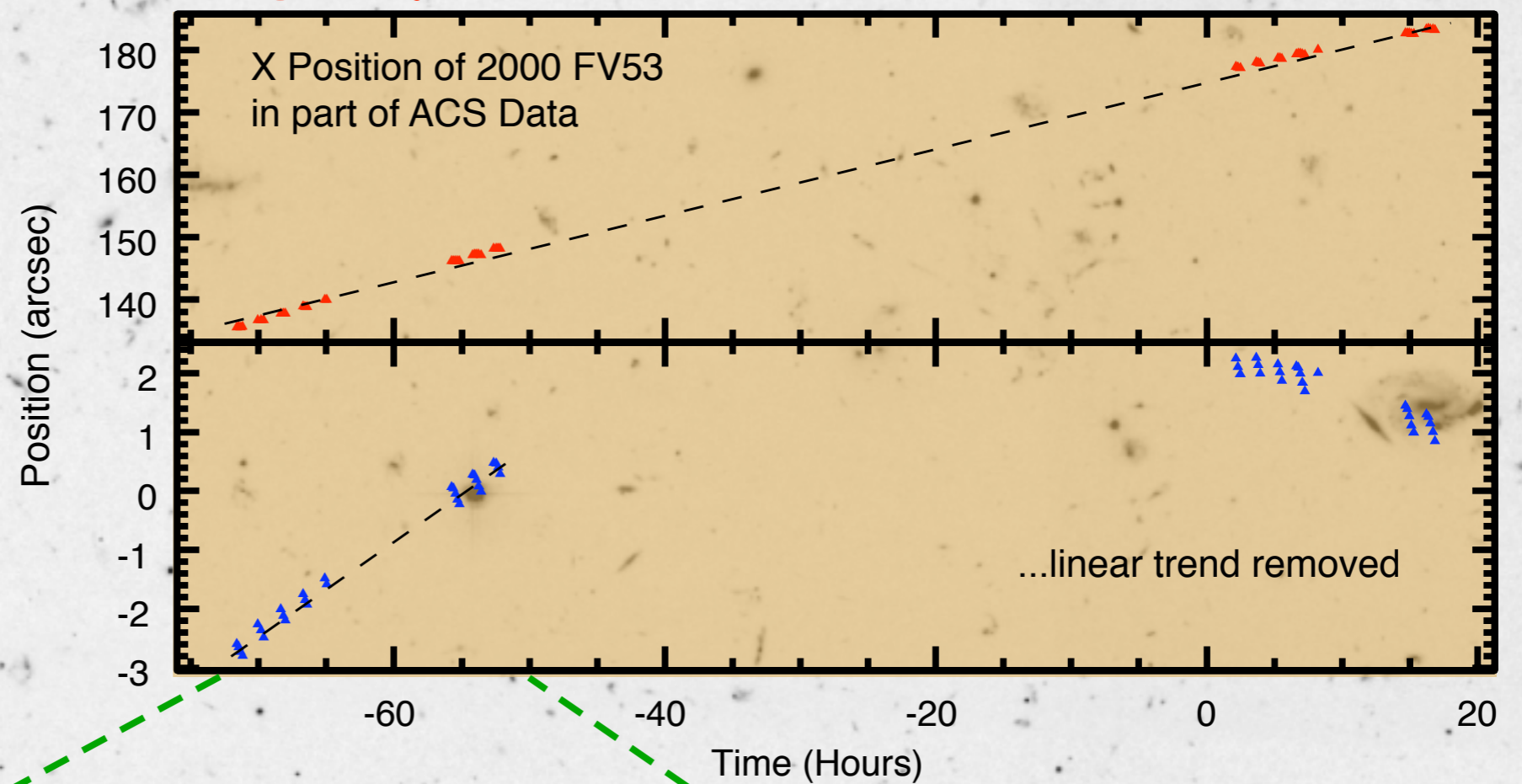
## *All it takes is*

- 116 orbit Cycle 11 allocation (executed in 125 orbits, thanks Tony Roman!)
- 30,000 lines of C++ code
  - ◆ New Fourier-domain PSF characterization method
  - ◆ PSF interpolation across ACS
  - ◆ Image registration & distortion (Anderson)
  - ◆ Image combining with reduced PSF distortion
  - ◆ Image subtraction
  - ◆ Digital tracking addition & detection
  - ◆ Orbit calculation and trailed-PSF fitting directly to images.
  - ◆ Several CPU-years on P4 processors

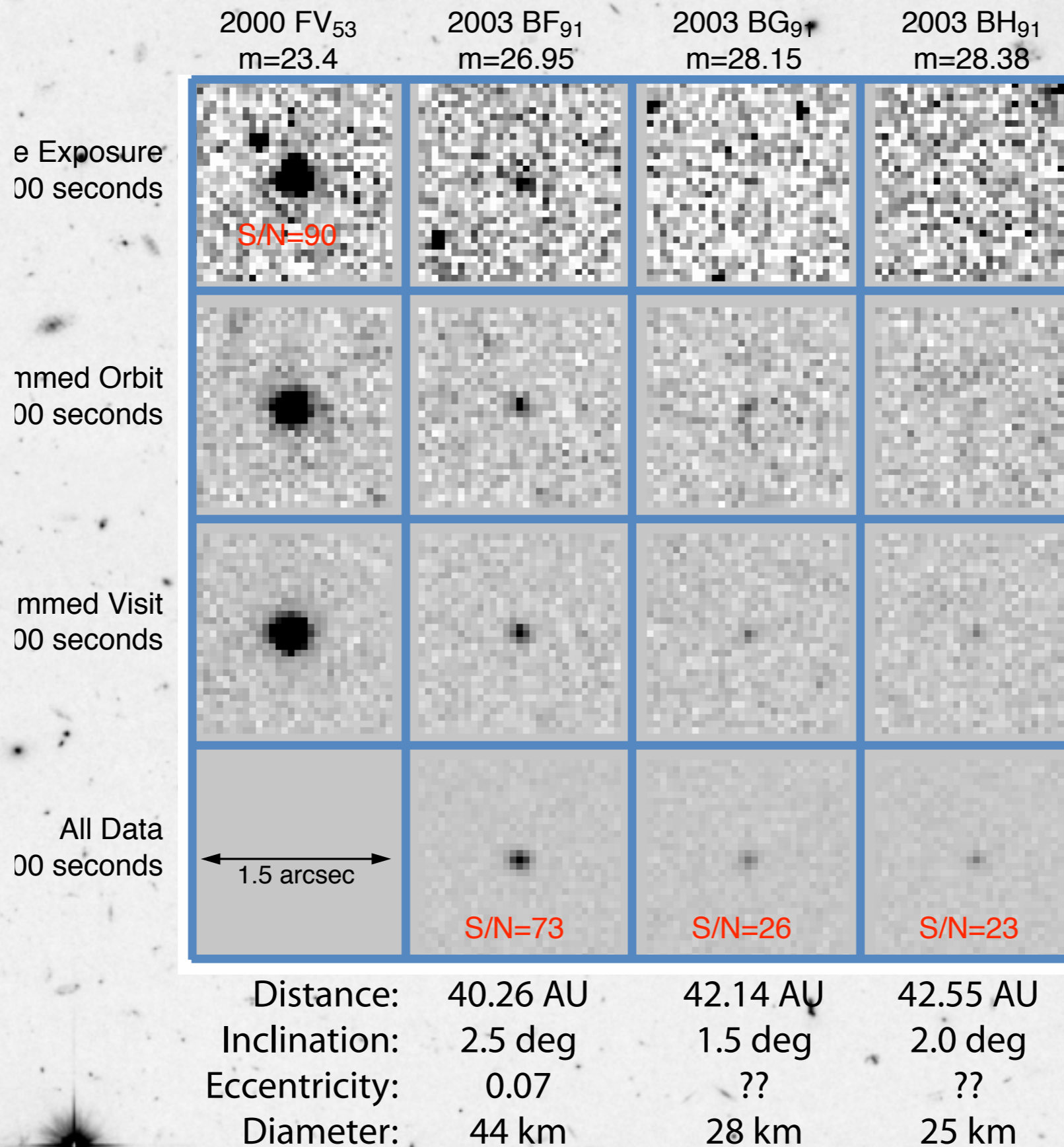
## *Schedule*

- Feb 2002: Phase II request
- Aug 2002: Preparations begin in earnest
- Jan 26 2003: First TNO observation
- Feb 09 2003: Last observation
- April 14 2003: All candidates identified
- April 29 2003: Keck retrieval run (Magellan clouded out)
- August 2003: Deep search complete

# *Illustration of ACS Data Quality*



# TNO Discoveries in the ACS Survey



Faintest solar system  
objects ever detected!  
1 photon per 5  
seconds at HST

# *Analysis of all survey data*

Combine data from all large, well-characterized surveys within 3 degrees of the invariable plane.

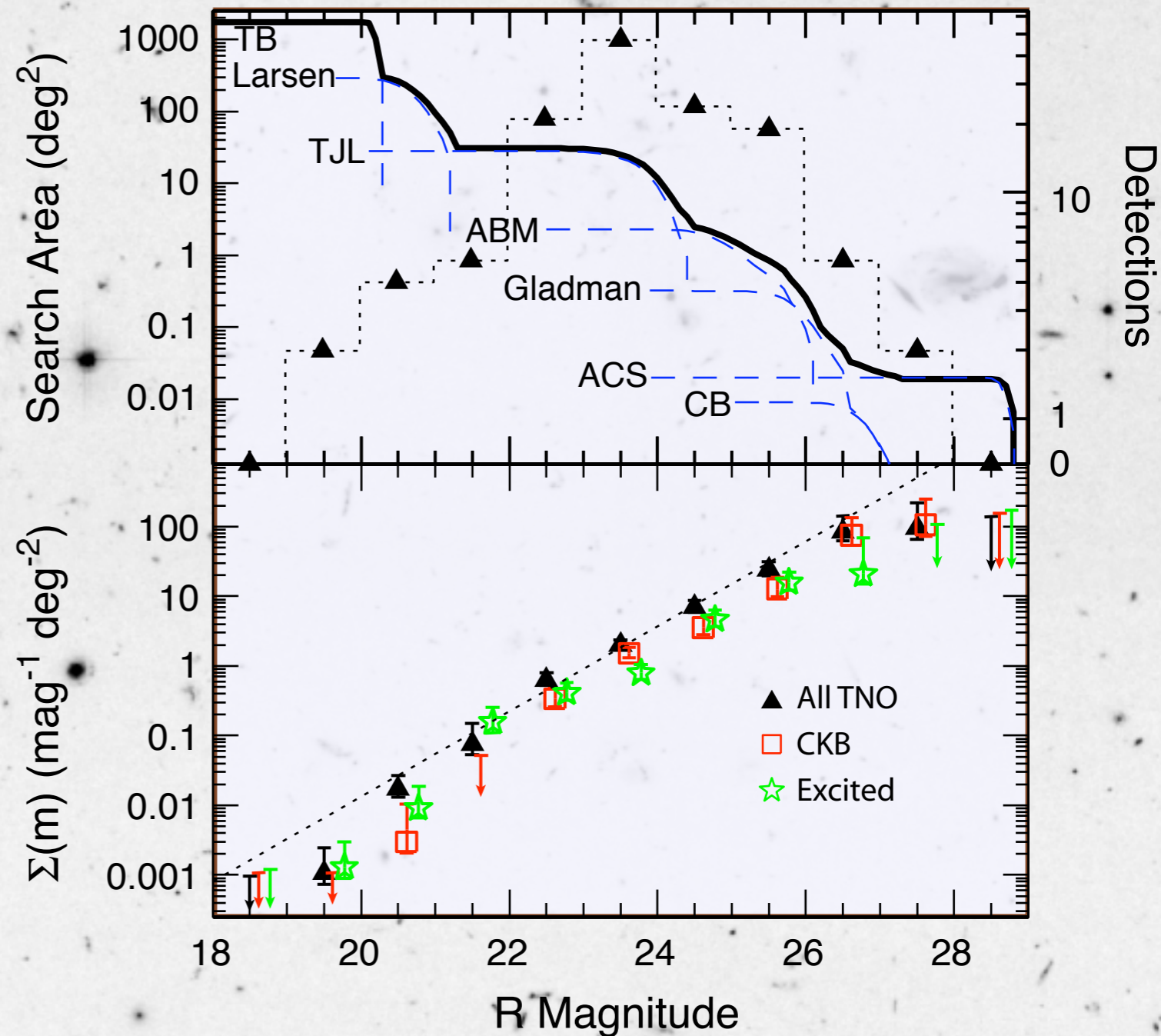
Deviation from single power law at high confidence.

Split the TNO sample into “Classical” KB and “Excited” populations. CKBs defined as:

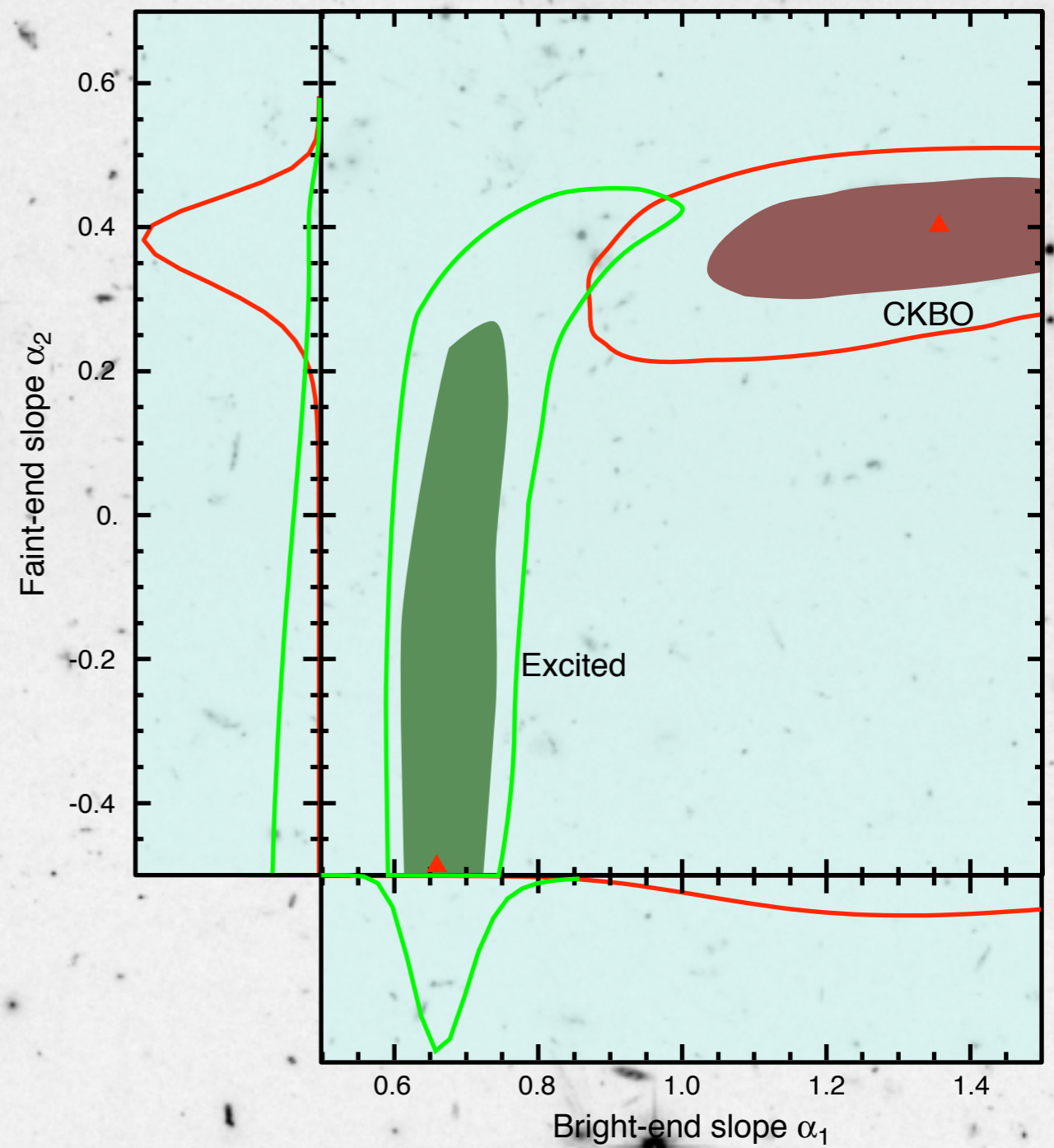
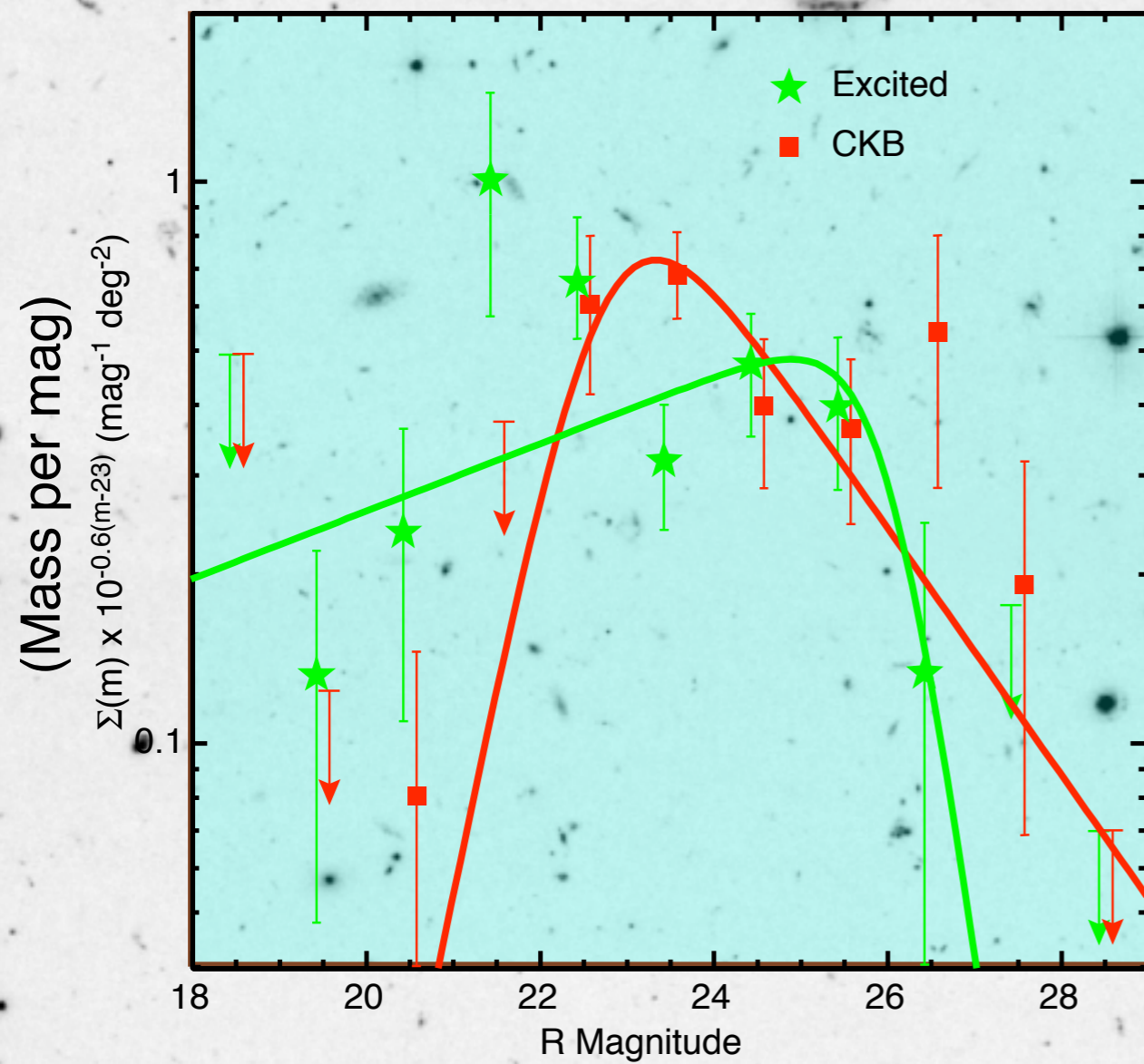
$$38\text{AU} \leq d \leq 55\text{AU}$$

$$i < 5^\circ$$

LFs of dynamical classes distinct at 96% confidence.



# *Double-power-law fits to the Magnitude Distribution*



## What does it mean?

Stern (1995) gives sizes below ~200 km as subject to disruption in current collisional environment:

TABLE 2. Critical eccentricities ( $e^*$ ) for erosion.

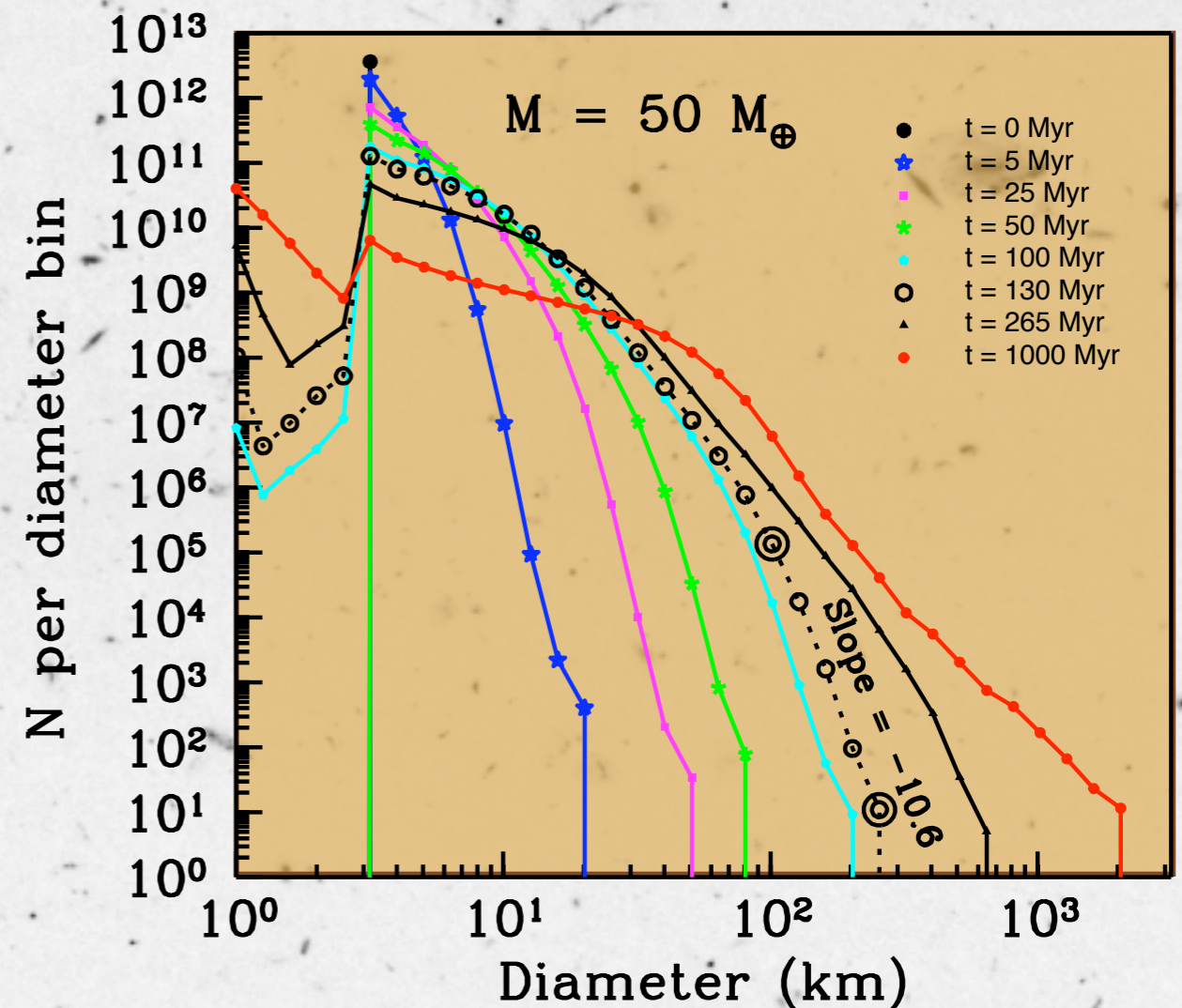
Target Radius	35 AU (Strong)	60 AU (Strong)	35 AU (Weak)	60 AU (Weak)
001 km	$7 \times 10^{-3}$	$9 \times 10^{-3}$	$1 \times 10^{-3}$	$1 \times 10^{-3}$
010 km	$6 \times 10^{-3}$	$7 \times 10^{-3}$	$2 \times 10^{-3}$	$3 \times 10^{-3}$
100 km	$5 \times 10^{-2}$	$6 \times 10^{-2}$	$2 \times 10^{-2}$	$3 \times 10^{-2}$
170 km	$9 \times 10^{-2}$	$1 \times 10^{-1}$	$4 \times 10^{-2}$	$5 \times 10^{-2}$

Notes to TABLE 2

Strong implies  $\rho=2 \text{ g cm}^{-3}$  and  $s=3 \times 10^6 \text{ erg g}^{-1}$ ; weak implies  $\rho=0.5 \text{ g cm}^{-3}$  and  $s=3 \times 10^4 \text{ erg g}^{-1}$ . In both cases we take  $\kappa=8$  and  $v_{ej}=0.20v_{esc}$  (e.g., Davis *et al.* 1989); see Sec. 6 for additional details.

Crudely, this is size of potential break in size distribution.

Size distribution at 38–44 AU



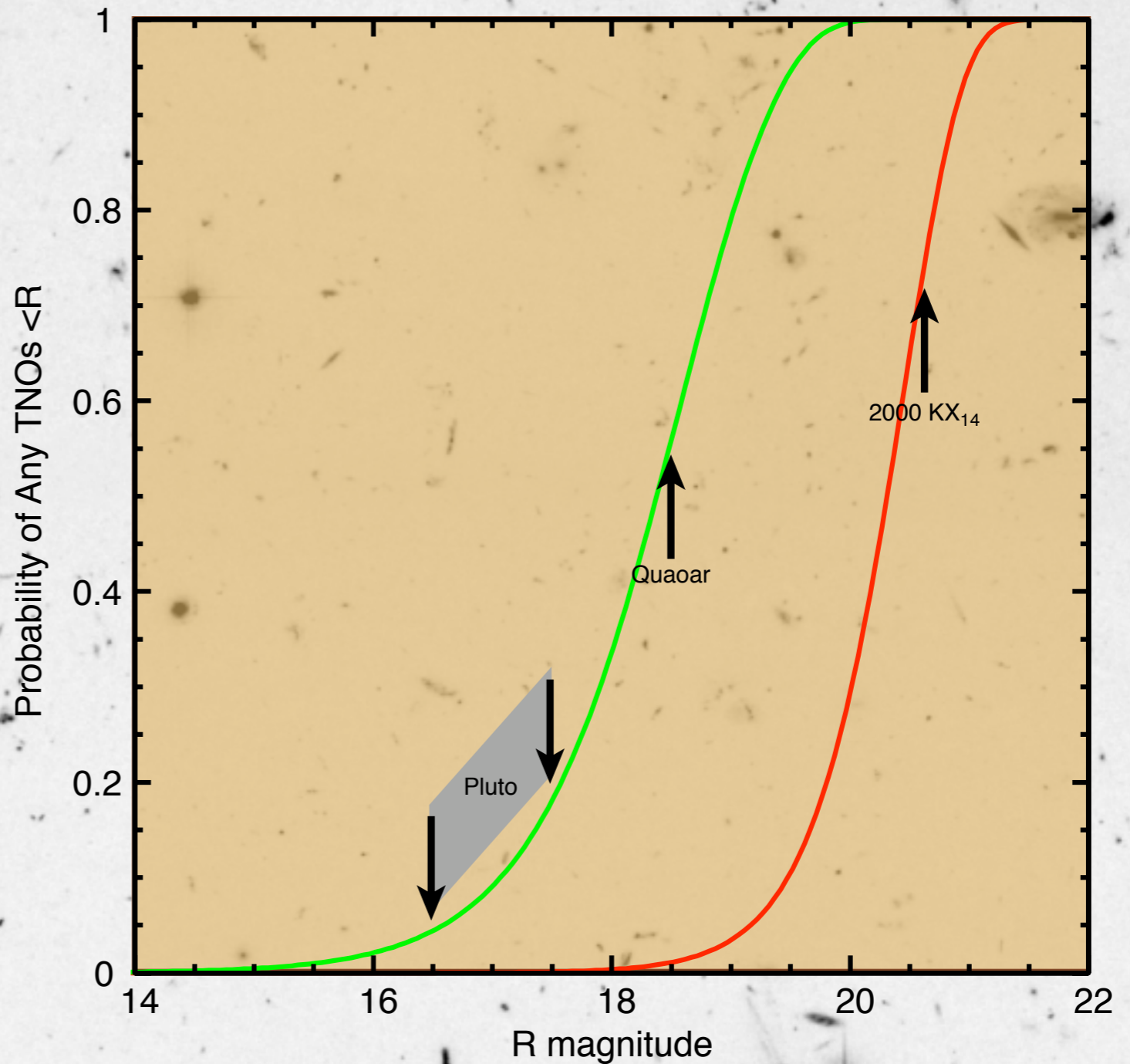
Resembles >1 Gyr phases in Davis simulation - Excited older than CKB

# Implications

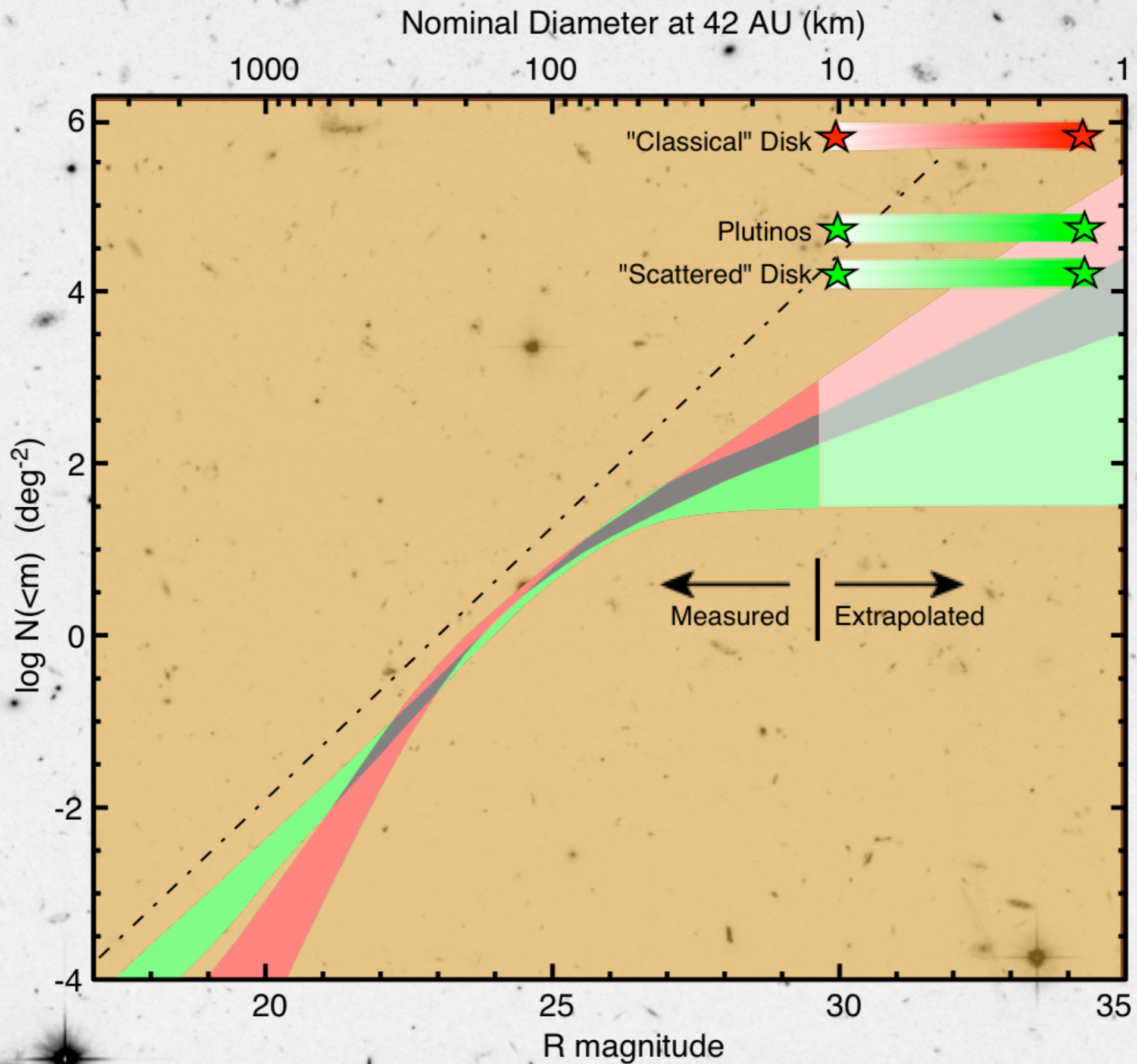
- Total mass of the CKB: (for  $p=0.04$ ,  $\langle d \rangle = 42$  AU,  $\rho = 1000$  kg/m<sup>3</sup>):

$$0.010 M_{\oplus} \pm 15\%$$

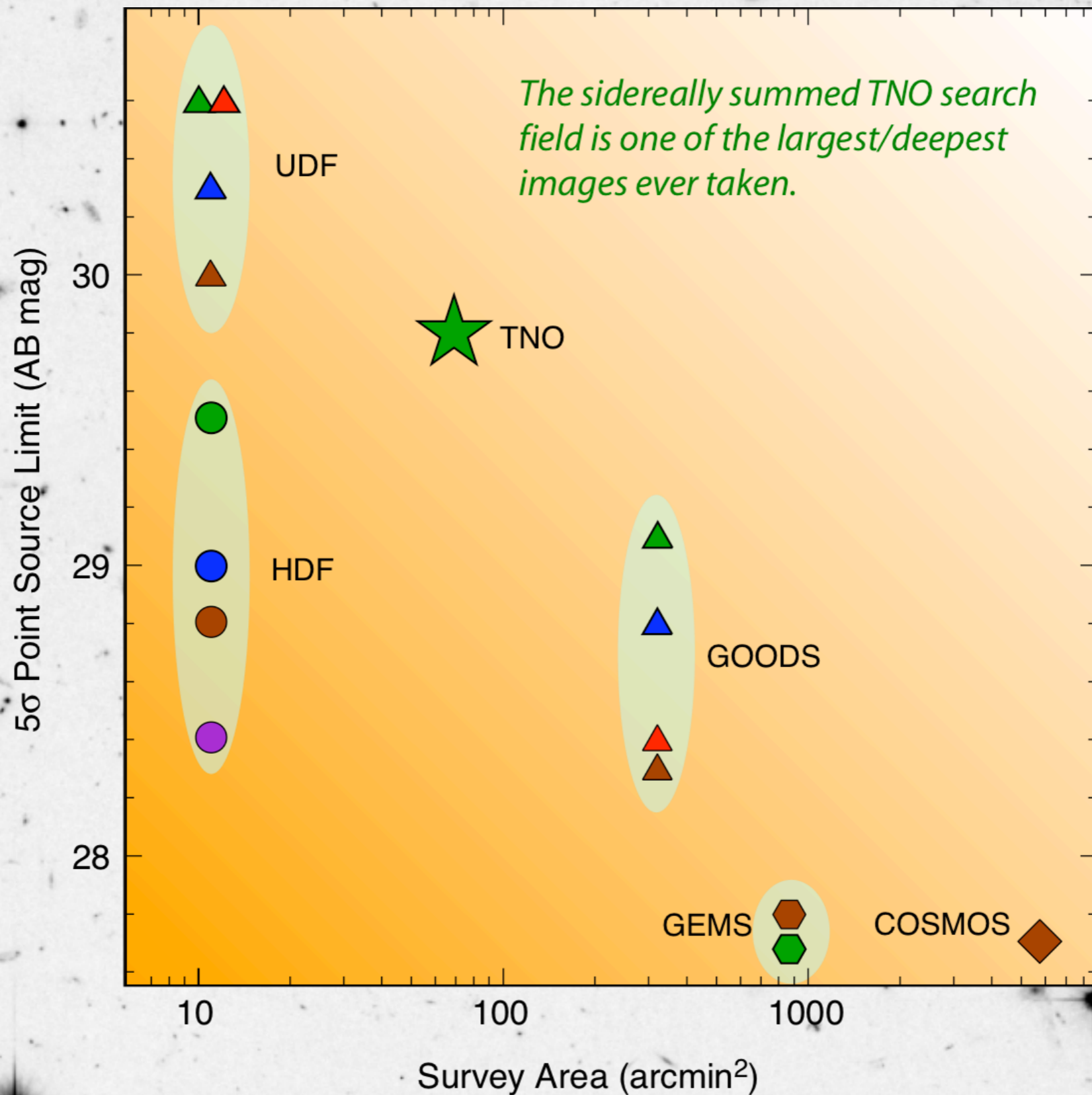
- Extrapolation of Excited bright end predicts largest object in the Pluto-Quaoar range. Pluto is uniquely but not anomalously large.
- Note largest CKBO is predicted (and is, so far) 60x lower mass.



# *Are KBOs a viable source reservoir for Jupiter-family comets?*



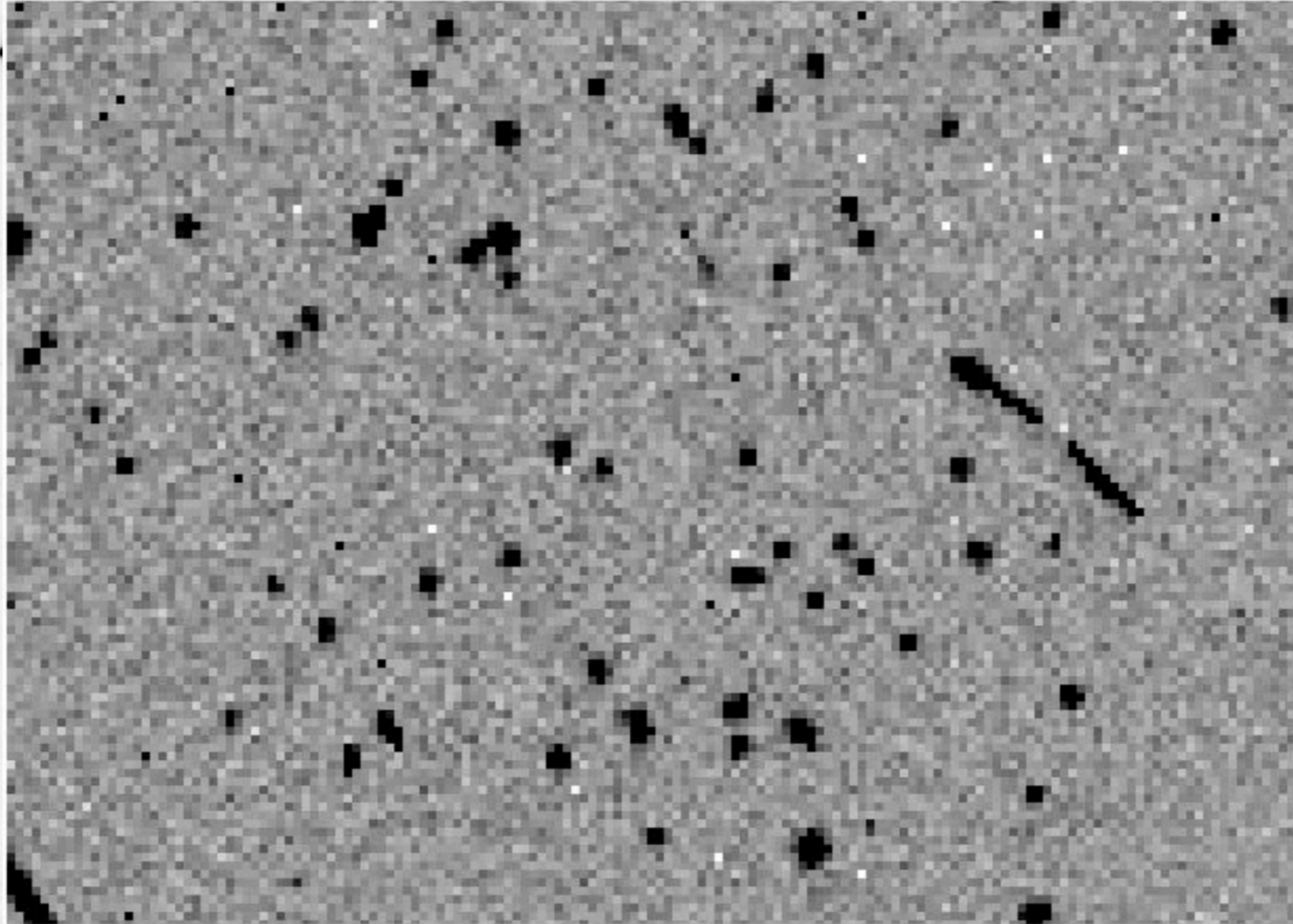
*One astronomer's noise is another's signal*



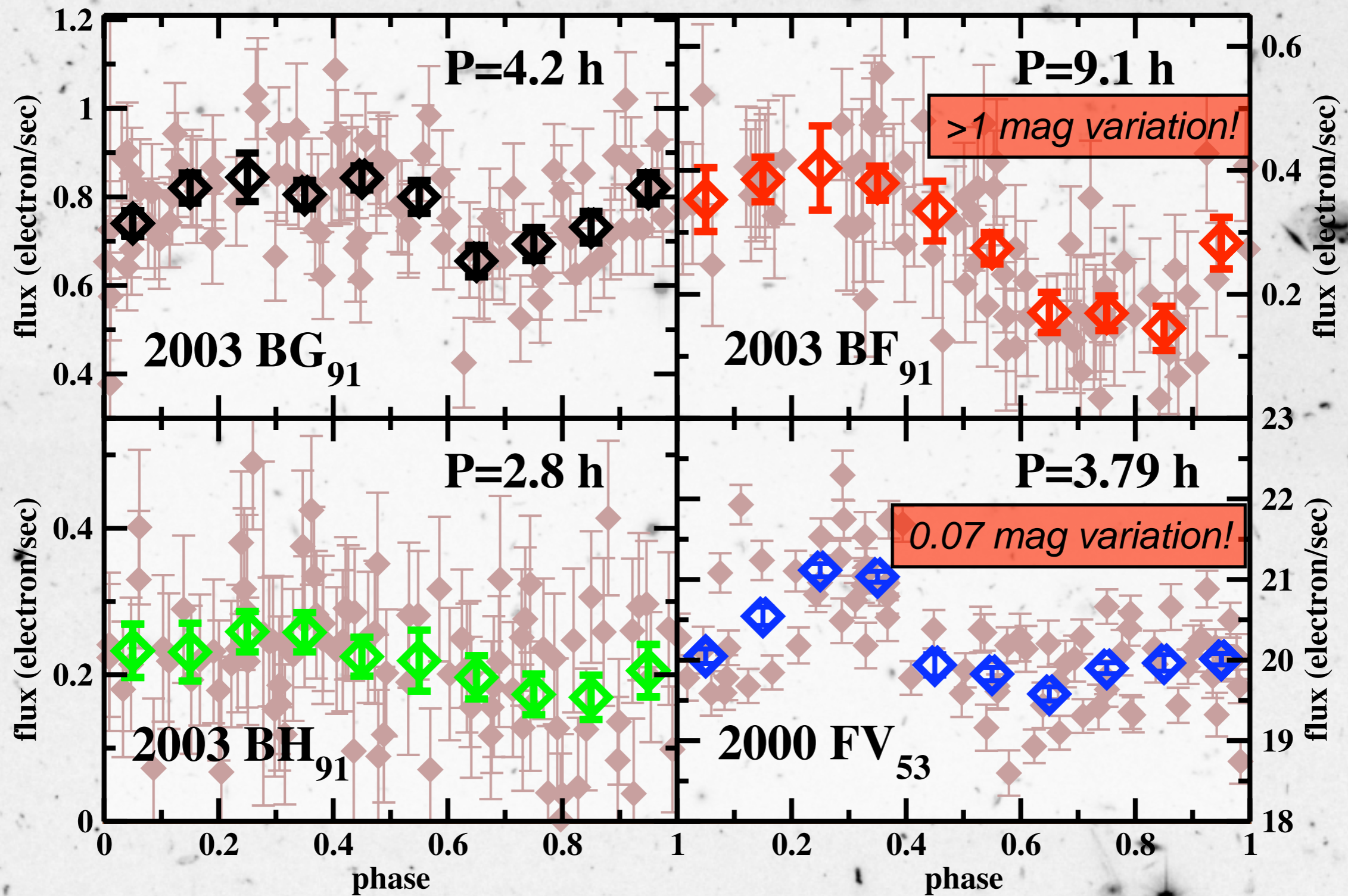
## *Cycle 13 Observations*

- Additional 6 orbits granted and executed in May 2004 (GO-10268, PI Trilling)
- Retrieve the 3 new objects to determine eccentricity - really CKB objects?
- Additional astrometry will give sufficient orbital info to locate these objects with JWST in 2010.

*Recovery of 2003 BG<sub>91</sub>*



# *Phased photometry of ACS TNOs*

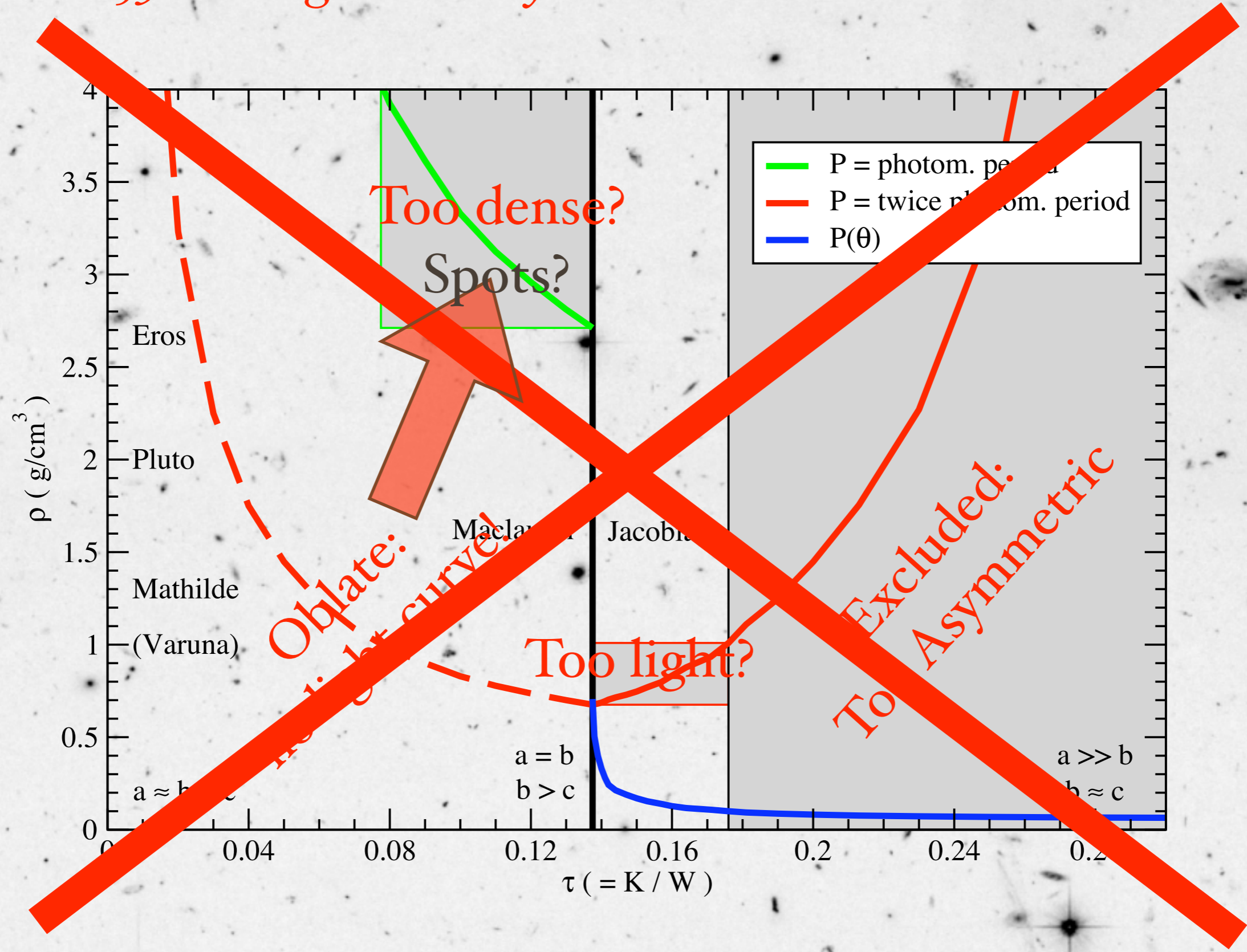


Trilling & Bernstein (submitted to AJ)

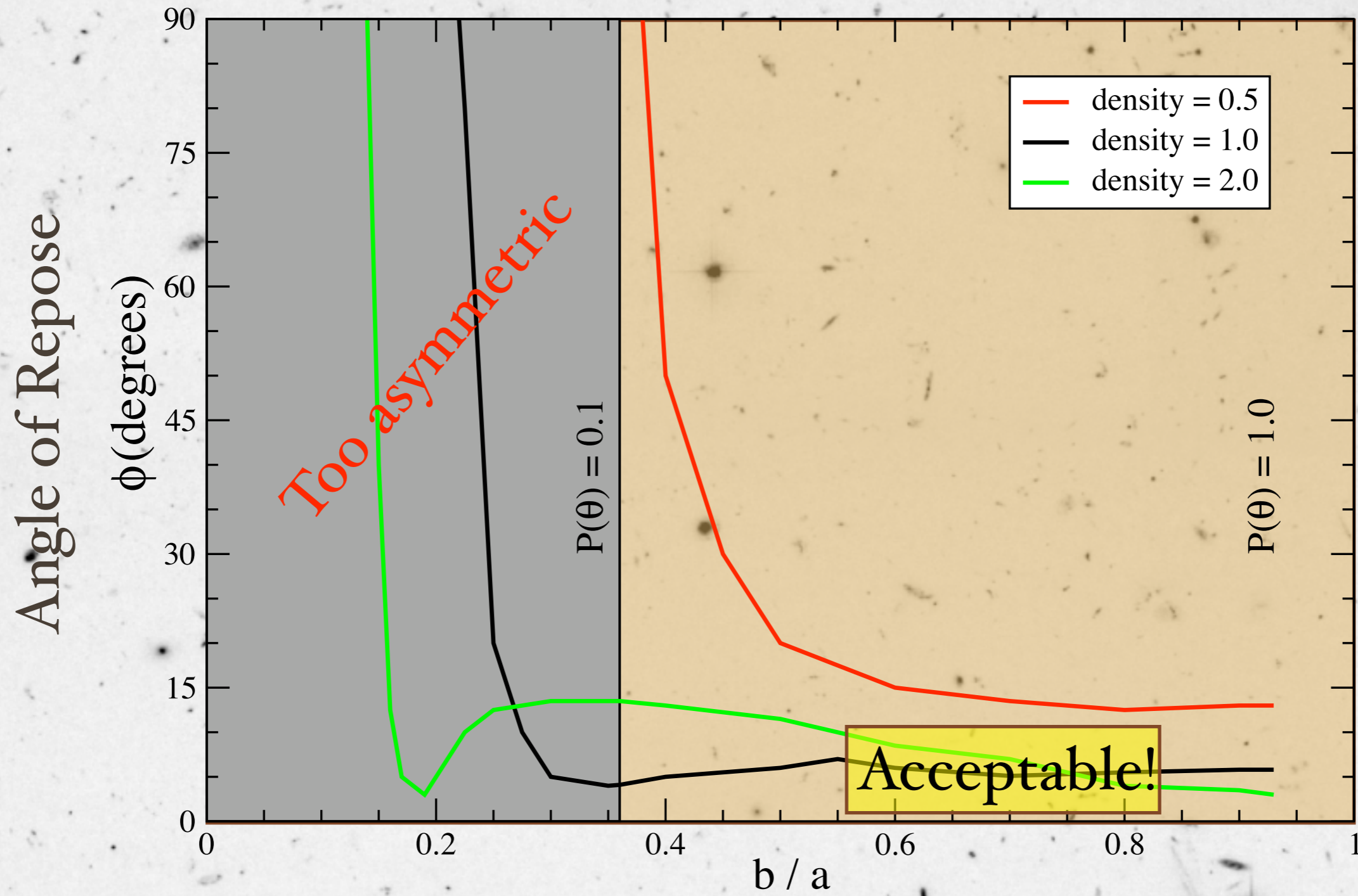
*A Model for 2003 BF<sub>91</sub>*



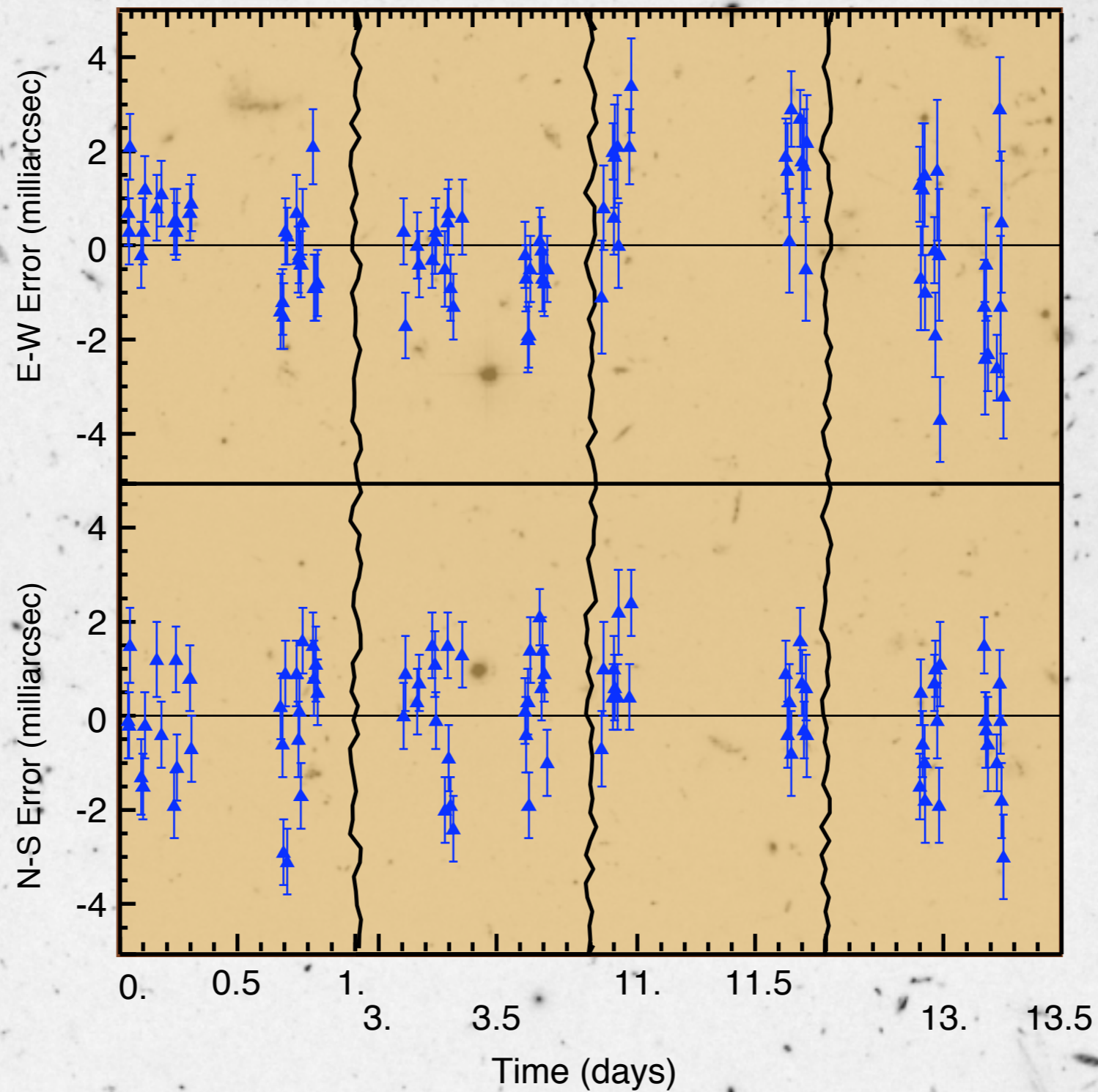
*Is 2000 FV53 a strengthless body?*



# *Rubble-pile solutions*



# *Astrometric Residuals for 2000 FV53*



Bernstein, Zacharias, & Smith (in prep)

## *Is milliarcsecond KBO astrometry just a neat trick?*

- N. Zacharias (USNO): 5 mas tie to ICRS very practical, better over 1-degree patches?
- 1 mas at 40 AU = 30 km = 5 seconds of HST motion
- Detectable photocenter motion on 300-km spotted body
- Displacement from undiscovered solar system masses is

$$\Delta x = 1 \text{ km} \left( \frac{M}{M_{\oplus}} \right) \left( \frac{T}{1 \text{ yr}} \right)^2 \left( \frac{D}{100 \text{ AU}} \right)^{-2}$$

## *Future Developments*

- Sky to  $R=21$  is mostly covered by Palomar/Quest
- NOAO Deep Ecliptic Survey, CFH Legacy survey to expand sky coverage for  $R<24$
- Full sky to  $R=24$  will be done by Pan-STARRS, LSST - 10,000's of objects with full orbital dynamics
- Could reach  $R=26$  over limited regions of sky
- Some further coverage from ACS archive (PI: Tamblyn) or another Large program.
- SNAP could repeat ACS survey to get 10,000's of  $R=28$  objects, detail dynamics/size correlations.
- Occultation surveys (TAOS) explore  $<10\text{km}$  regime
- New Horizons probe flies by 2 (?) KBOs c. 2017

## *Summary*

- ACS works flawlessly for TNO search. Background-limited detection for 29th mag moving objects.
- Clear detection of a feature in the size distribution, with dependence upon dynamical state of subpopulations.
- No sign of cold population beyond 50 AU, for  $D > 40$  km
- Scattered disk a feasible JFC source, but still a stretch?
- Surprising light curves, consistent with rubble pile in 200 km body 2000 FV53
- Additional info forthcoming from followup & astrometry.

# Solar System Discovery Space

