Solar System Archaeology: What we Learn from Small Bodies in our Solar System

Susan D. Benecchi

18 April 2013

Collaborators: Scott Sheppard, Keith Noll, Will Grundy, Jim Elliot & Marc Buie

Some of the work presented has been supported by a Carnegie Fellowship at DTM
and NASA grants at The Planetary Science Institute

Outline

- Motivation & Background
- Survey Techniques
- Binaries
- Colors
- Variability/Lightcurves
- Summary & Implications

Take home messages:

- Objects in the Kuiper Belt can be used as tracers for planetary migration.
- The characteristics of Kuiper Belt objects can help us learn about the distribution of material in the original solar nebula.

Outline

- Motivation & Background
- Survey Techniques
- Binaries
- Colors
- Variability/Lightcurves
- Summary & Implications

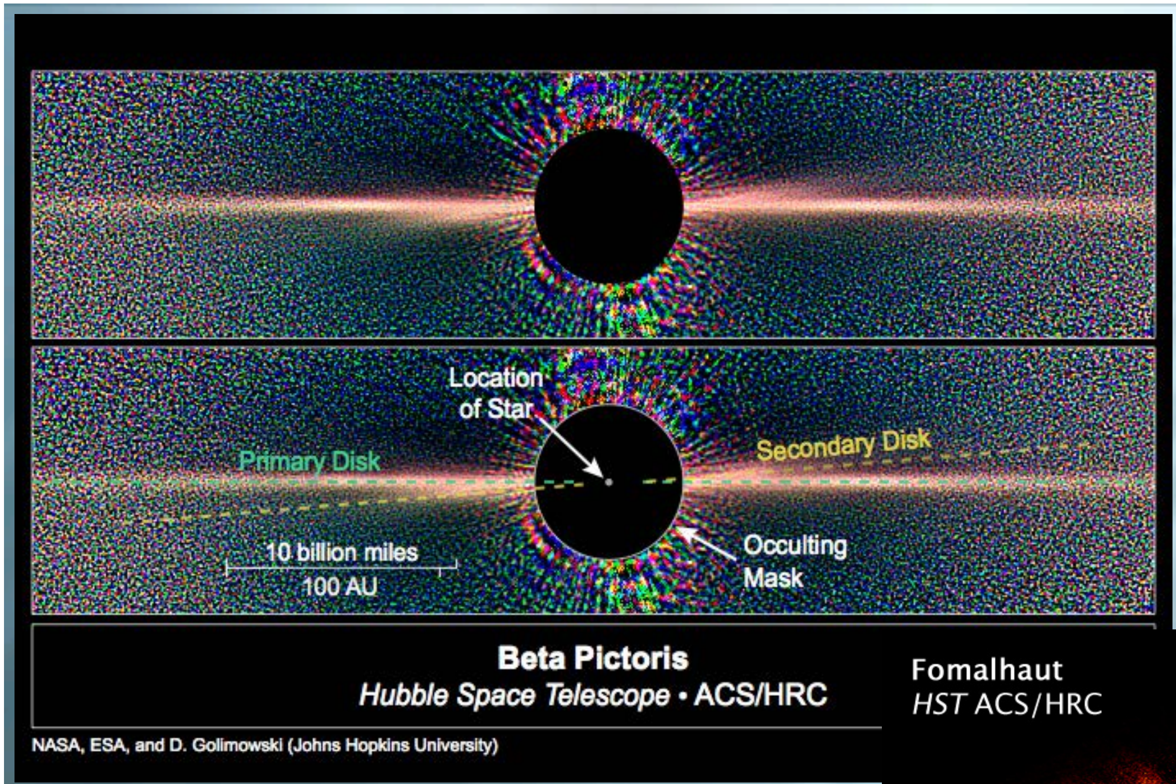
Take home messages:

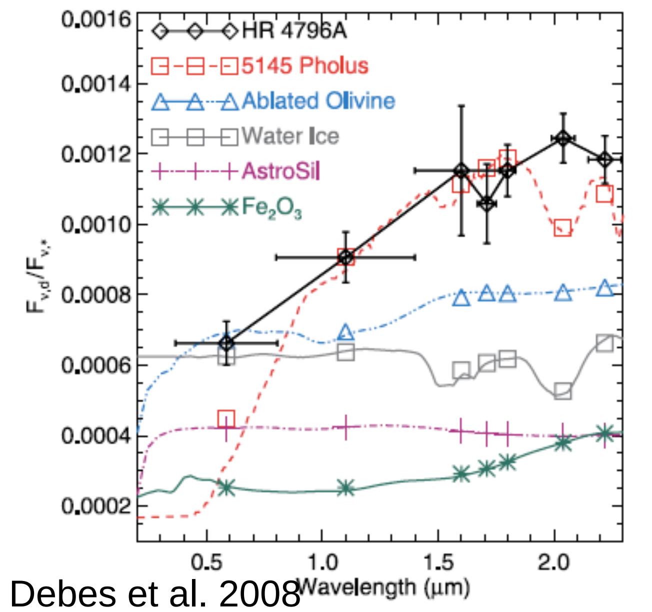
- Objects in the Kuiper Belt can be used as tracers for planetary migration.
- The characteristics of Kuiper Belt objects can help us learn about the distribution of material in the original solar nebula.

Motivation

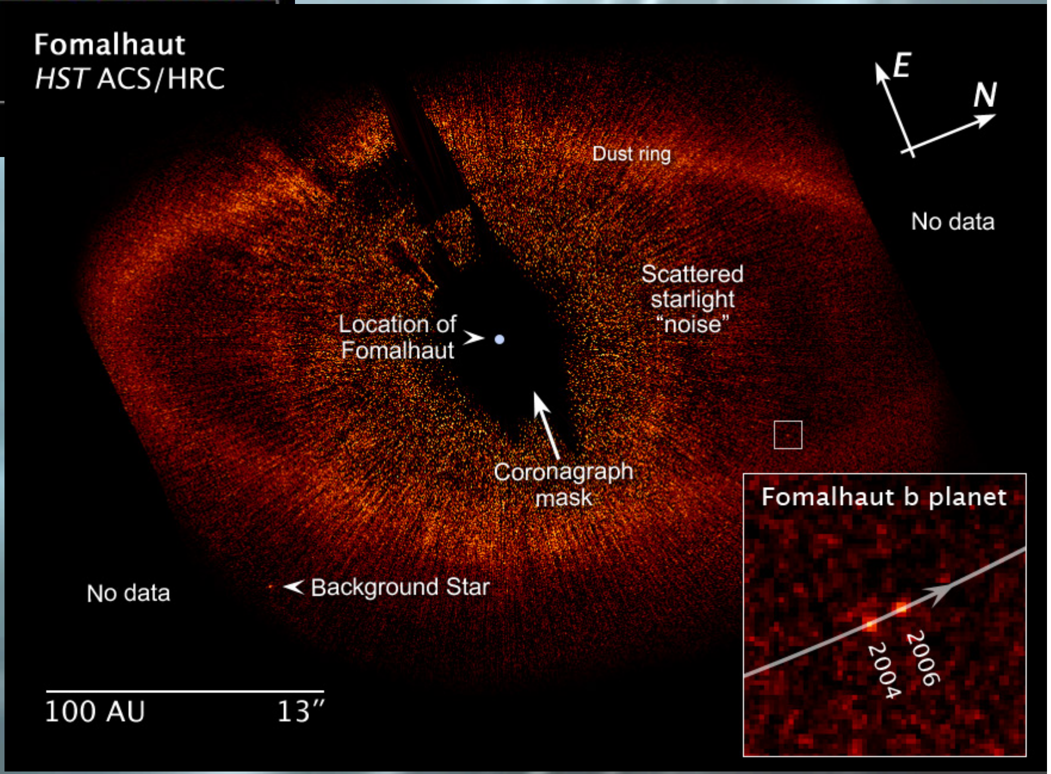
- Study of the planets and small bodies in our solar system (and others) can help us to better understand its formation.
  - Giant planet migration.
  - Giant planet small moons.
  - Dust disks (the results of small body collisions).
- Binaries allow us to determine the physical properties of objects.

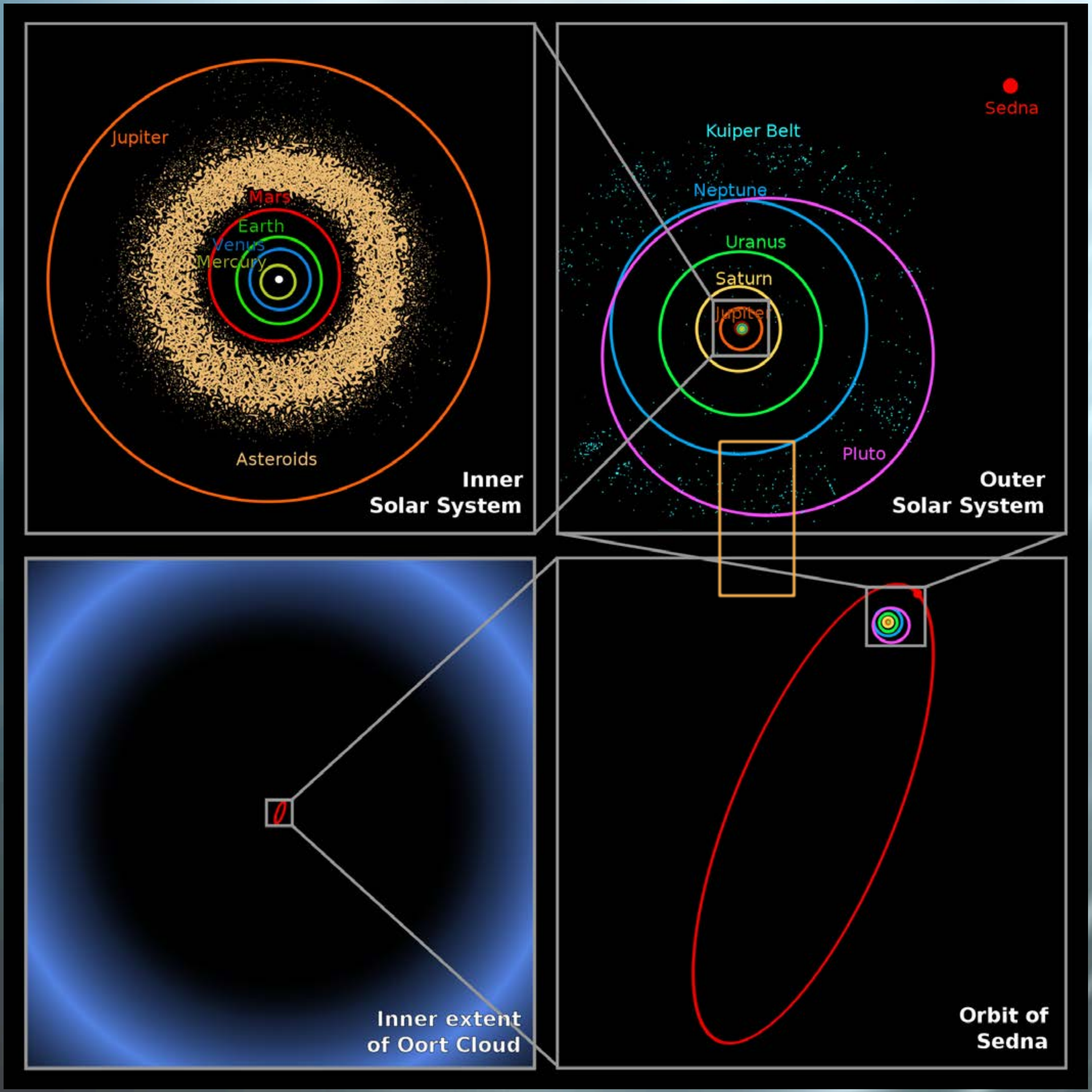
Dust Disks & Exo-planet Systems





Debes et al. 2008





Perspective

1700s — Halley's Comet (short period comets)

1801 — 1st Asteroid, Ceres

1930 — Pluto discovered

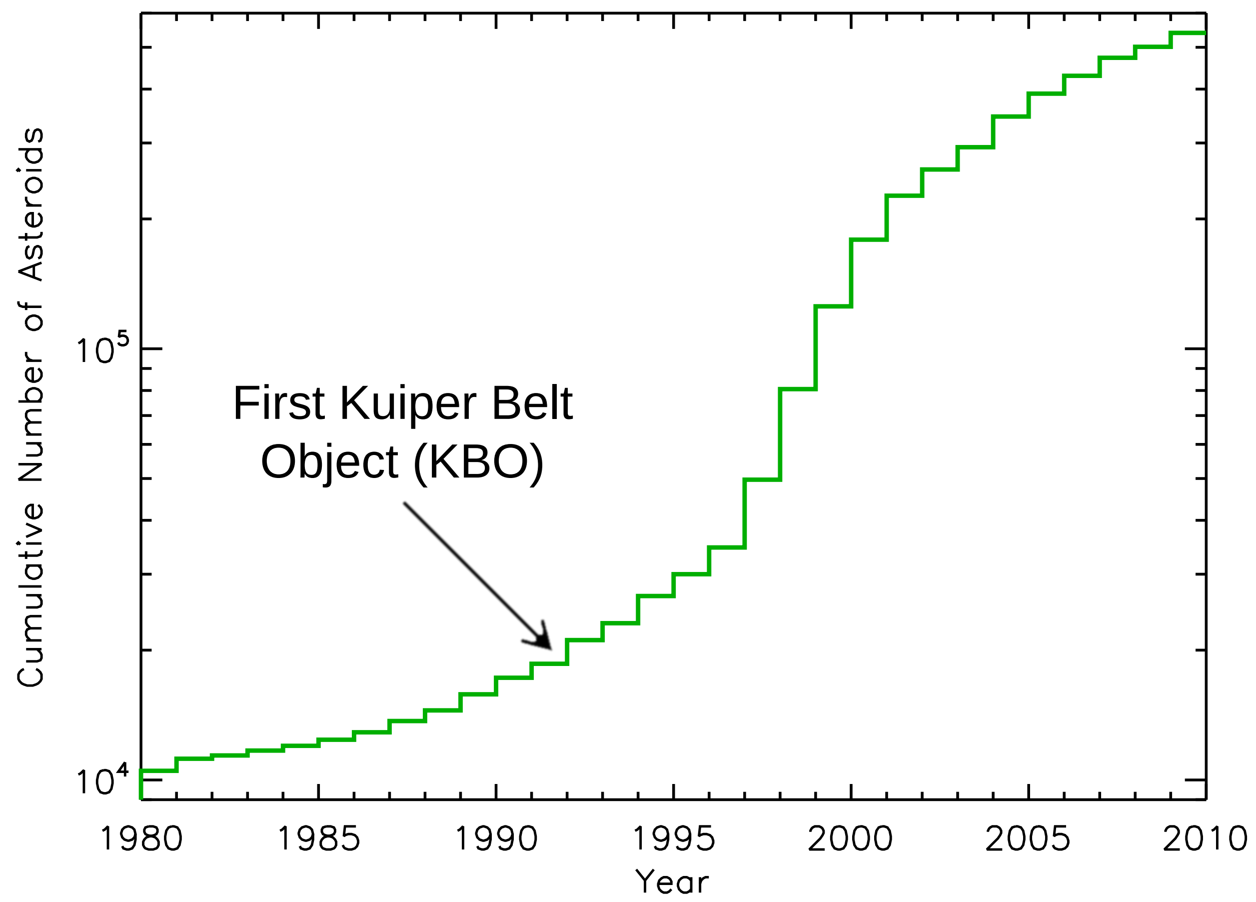
1932/1950 — Opik & Oort theorize about Oort cloud (long period comet reservoir)

1949/1951 — Edgeworth & Kuiper theorize about the Kuiper Belt

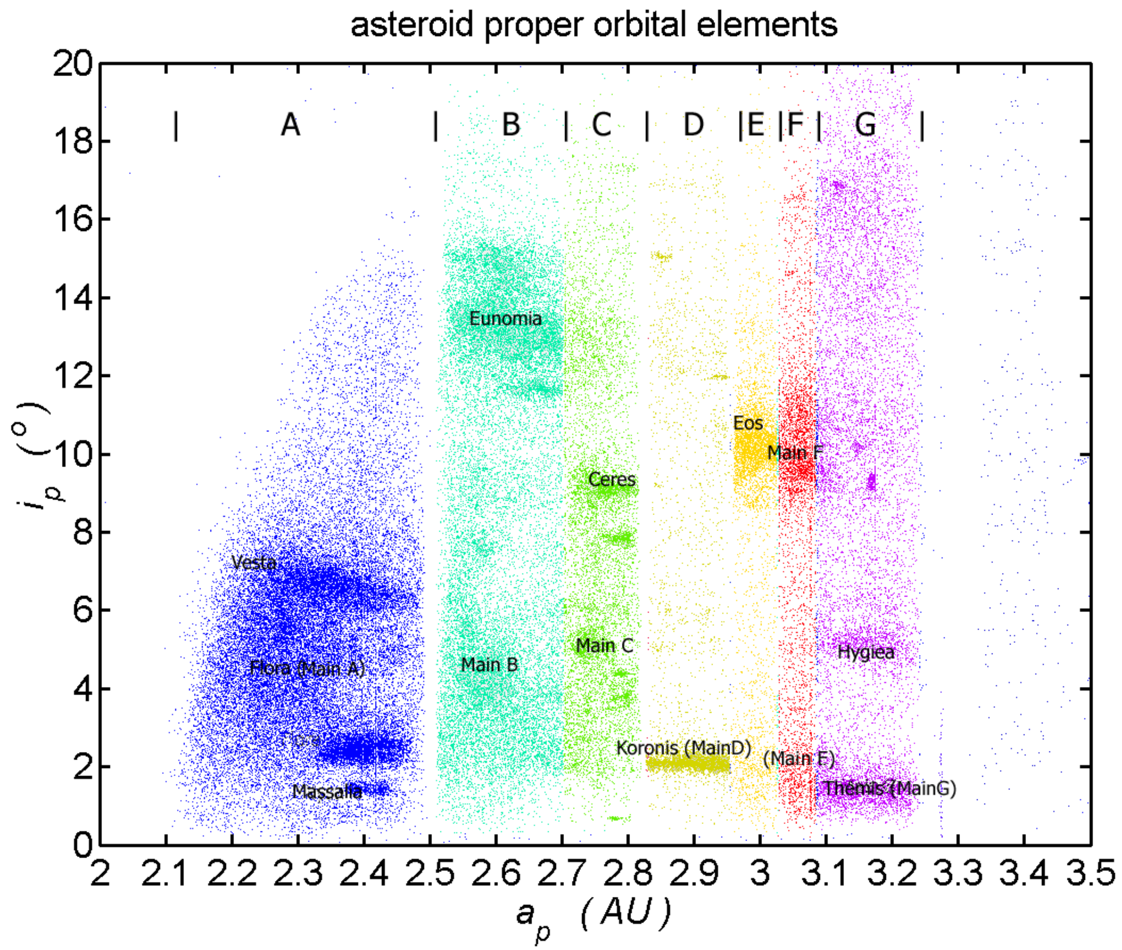
1992 — First Kuiper Belt Object discovered

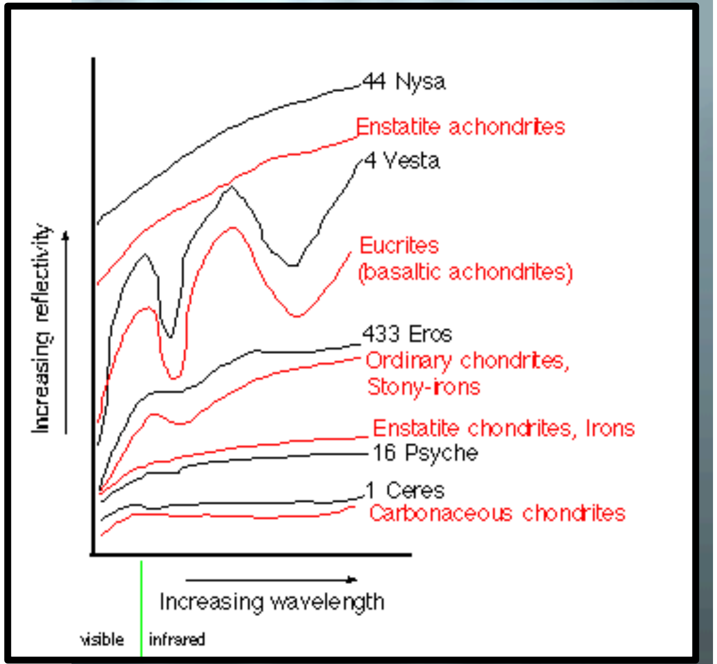
2002 — First binary Kuiper Belt Object, 1998 WW_{31}

Small Body Discoveries



Asteroid Families





- Orbits related
- Physical characteristics related

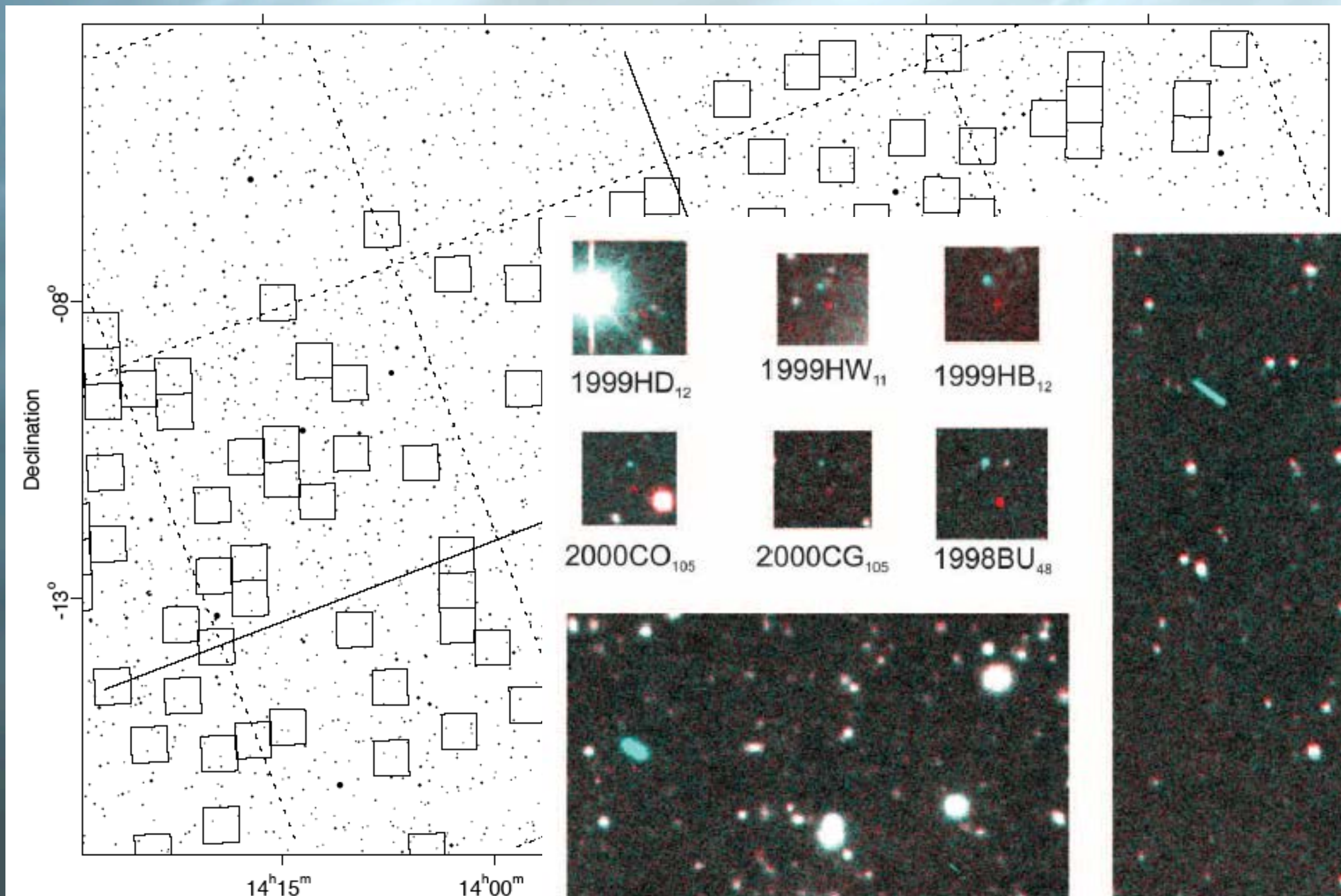
Outline

- Motivation & Background
- Survey Techniques
- Binaries
- Colors
- Variability/Lightcurves
- Summary & Implications

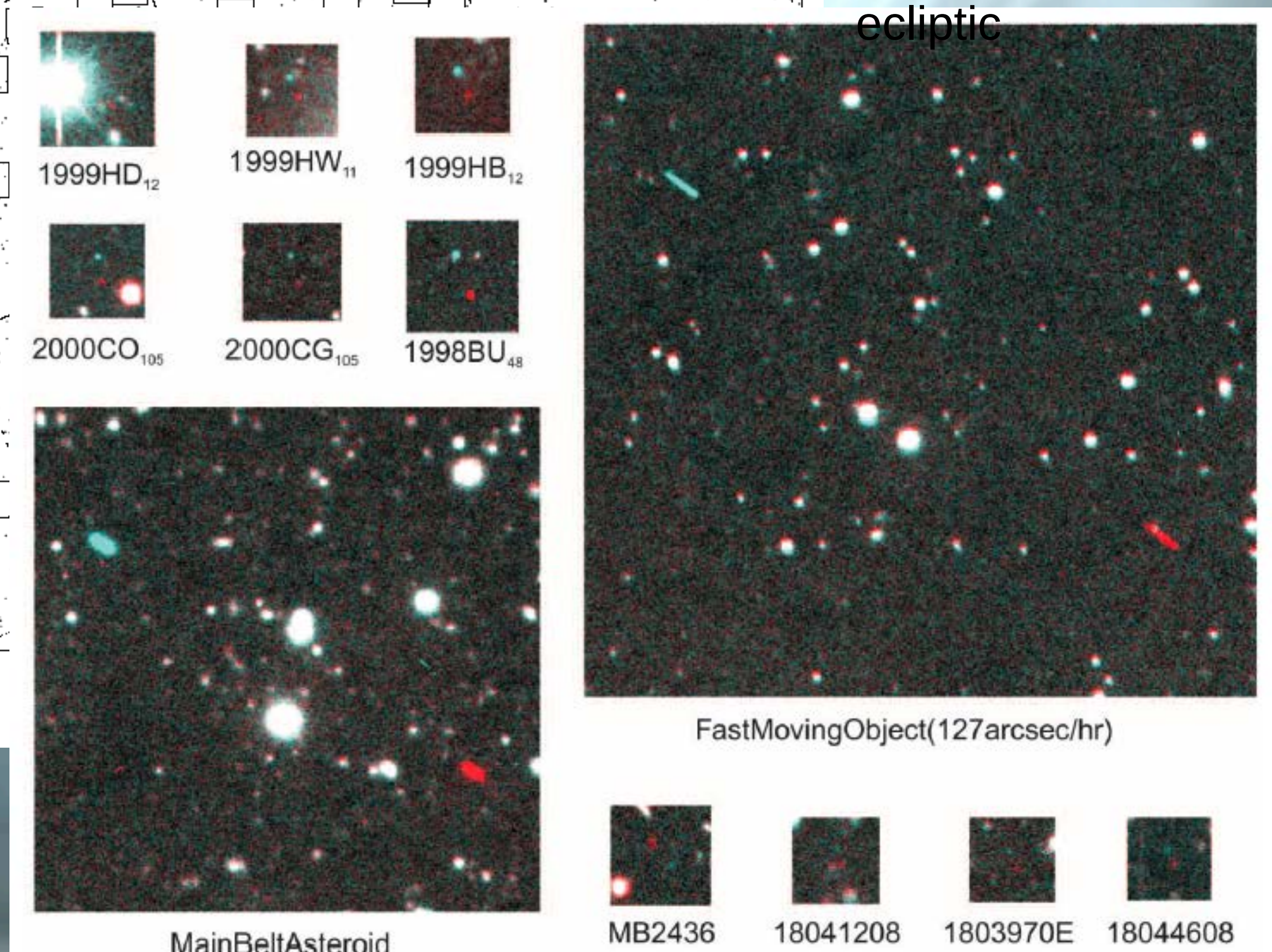
Take home messages:

- Objects in the Kuiper Belt can be used as tracers for planetary migration.
- The characteristics of Kuiper Belt objects can help us learn about the distribution of material in the original solar nebula.

Example: The Deep Ecliptic Survey



Millis et al. 2002

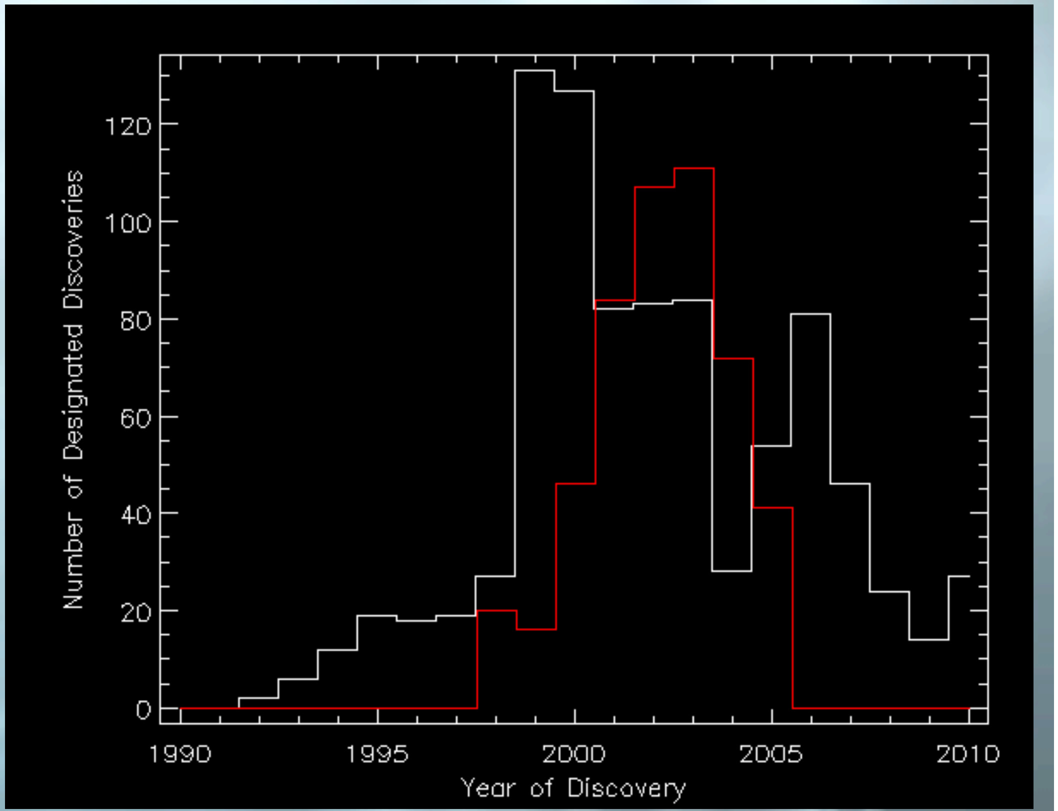


- Box=0.6°x0.6° on the sky
- ±6.5° of the ecliptic

Near Earth: ≥75 "/hr
Main Belt: 30-40 "/hr
Centaurs: 5-15 "/hr
Kuiper Belt: ≤5 "/hr

DES Discoveries

- Searched 800 square degrees
- 321,146 astrometric measurements, many main belt objects
- 498 objects designated through the Minor Planet Center (MPC) and another 371 undesignated objects



Discoveries by year: DES in red

References: Millis et al. 2002, Elliot et al. 2005

Notable objects

- The First Neptune Trojan: 2001 QR_{322} (Chiang et al. 2003)
- Dynamically Extreme Objects: 2000 CR_{105}, 2000 OM_{67}, 2001 FP_{185} & 2000 OJ_{67} (Buie et al. 2003)
- The first high inclination Centaur: 2002 PL_{149}
- Binaries: 2003 UN_{284}, (88611) Teharon, 2003 QY_{90} & 2005 EO_{304} (Kern 2006+ref therein)

THE OUTER SOLAR SYSTEM

This animation shows the motion of the outer part of the solar system over a 100-year time period. The sun is at the center and the orbits of the planets Jupiter, Saturn Uranus and Neptune are shown in light blue (the locations of each planet are shown as large crossed circles).

Comets: blue squares (filled for numbered periodic comets, outline for other comets)
High-e objects: cyan triangles
Centaurs: orange triangles
Plutinos: white circles (Pluto itself is the large white crossed circle)
"Classical" TNOs: red circles
Scattered Disk Objects: magenta circles

The individual frames were generated
the PGPLOT graphics library. The an
RISC OS 4.03 system using !InterGif.

Current KBO Population

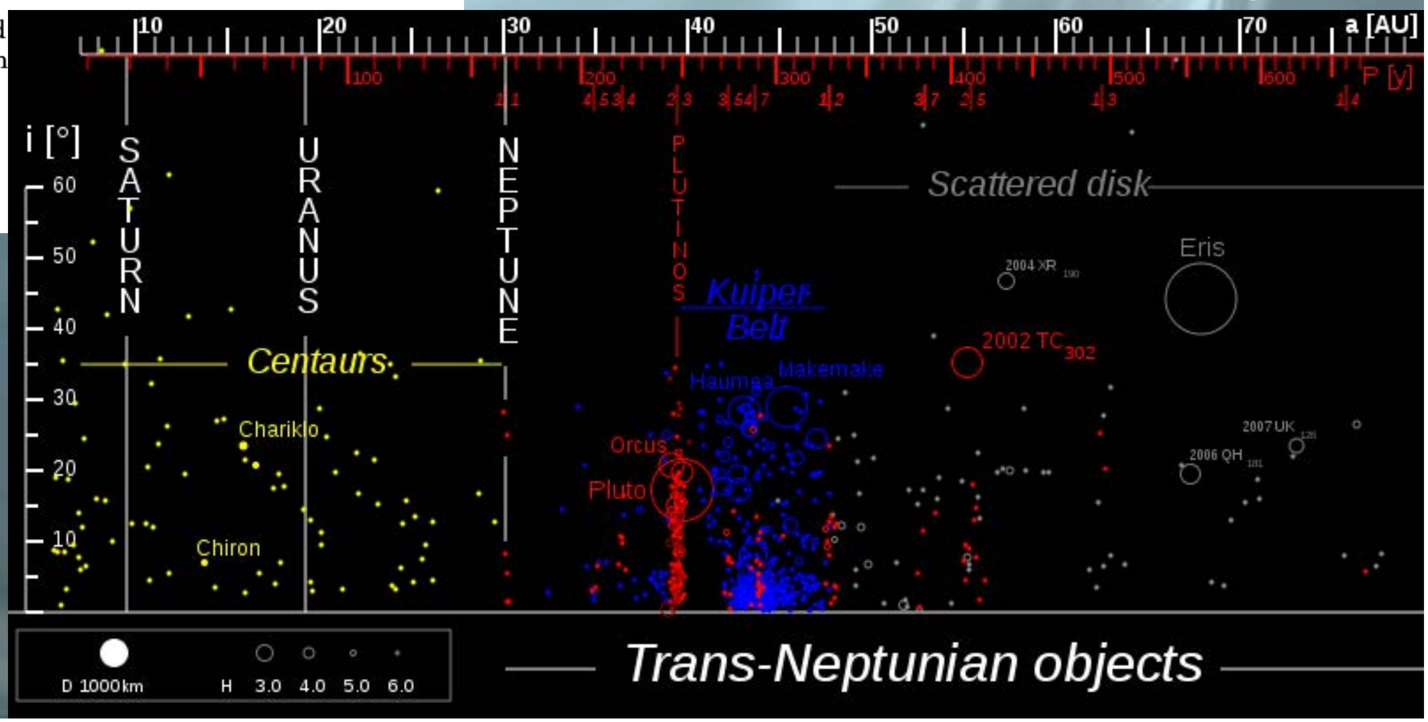
Focus on End-Members

- Objects in dynamically interesting locations
  - Cold Classical Kuiper Belt
  - Resonance populations
  - Centaurs (transition objects)
- Large Objects
- Binaries

Edge-on

Face-on

~1600 Objects

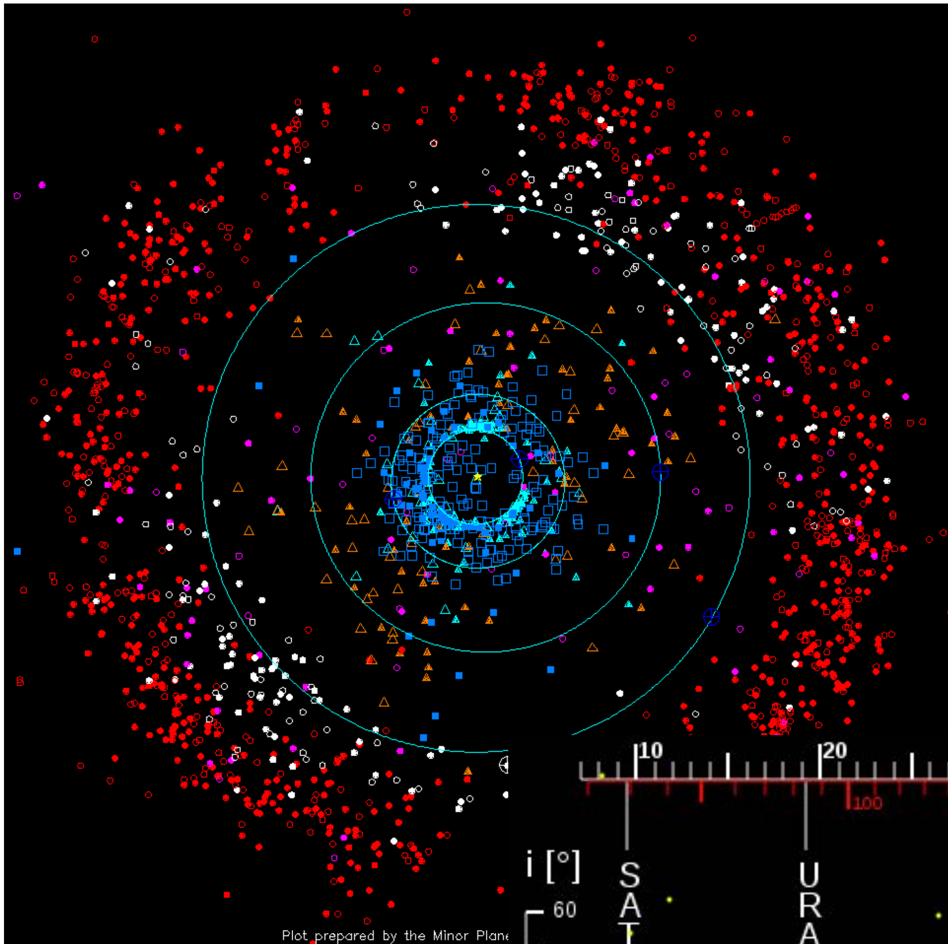


S. D. Benecchi
18 April 2013

Current KBO Population

Focus on End-Members

- Objects in dynamically interesting locations
  - Cold Classical Kuiper Belt
  - Resonance populations
  - Centaurs (transition objects)
- Large Objects
- Binaries



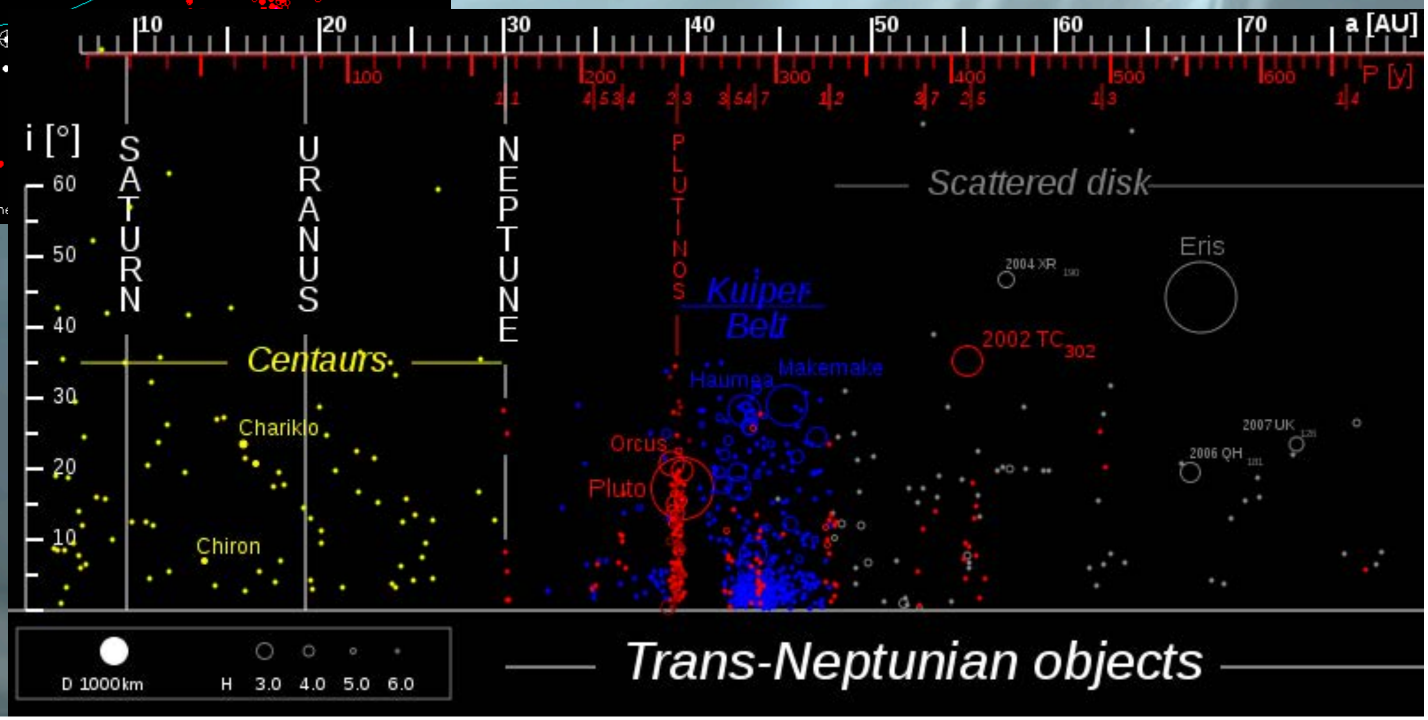
Face-on

~1600 Objects

S. D. Benecchi

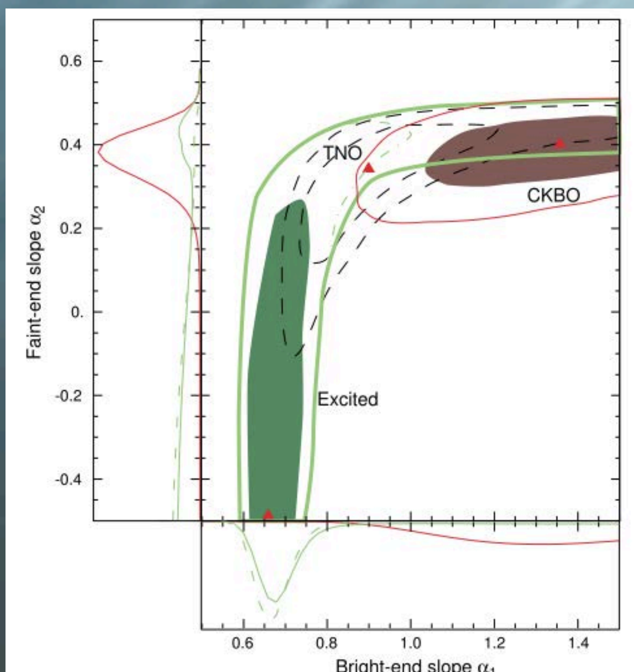
18 April 2013

Edge-on

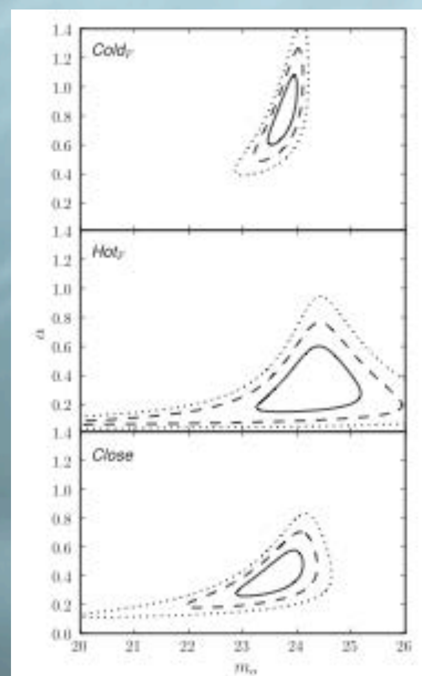


Dynamical Studies: Differences between classes

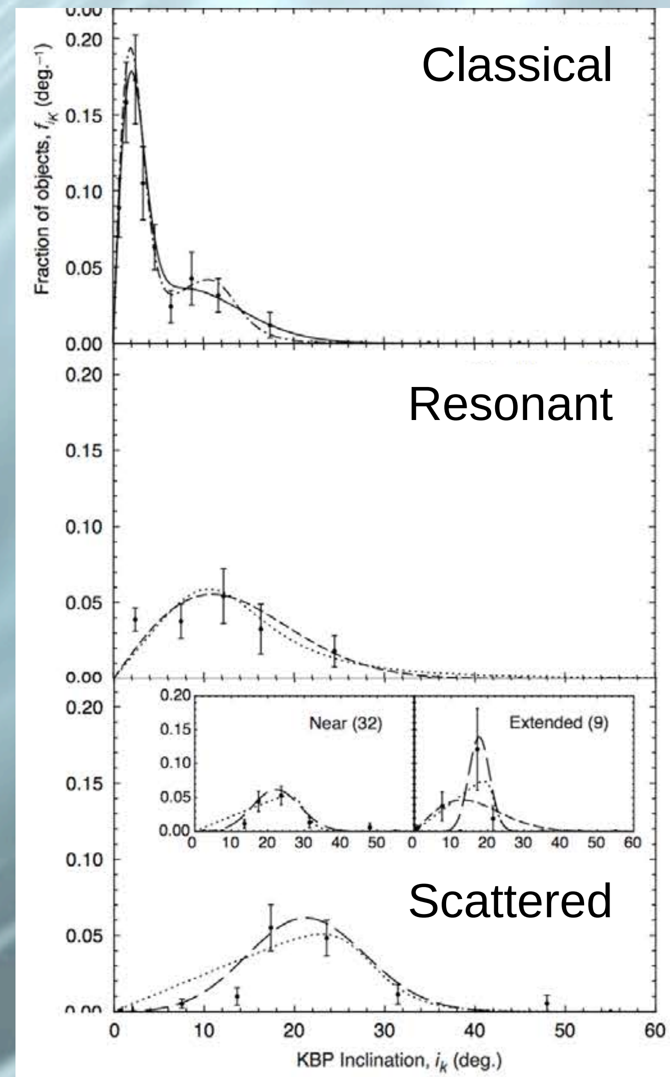
- Inclination distribution
  - Classical population double peaked
- Luminosity function/size distribution
  - Classical & Excited populations different
  - Classical divides farther still: cold/hot



(Bernstein et al. 2004)

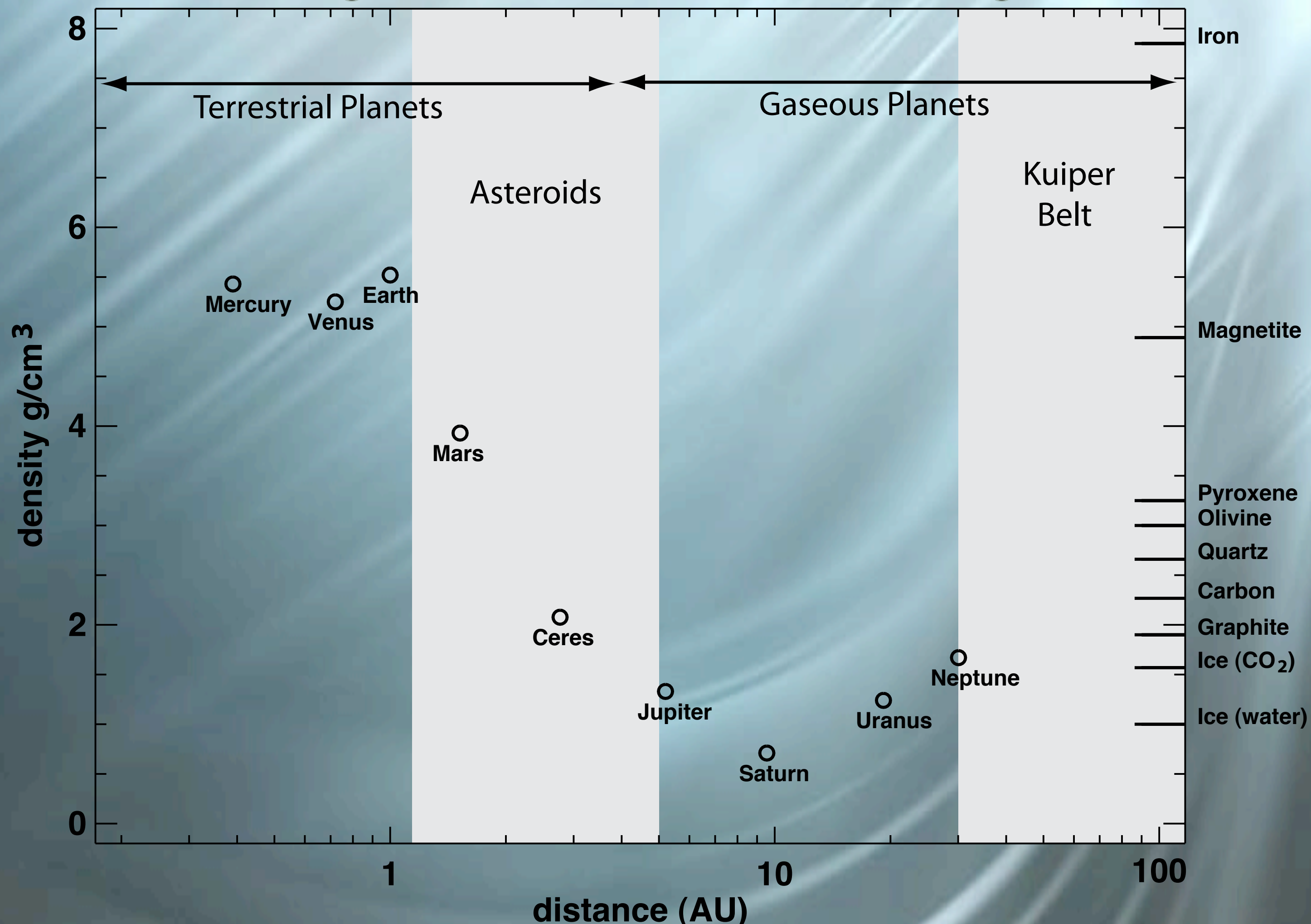


(Fraser et al. 2010)



(Gublis et al. 2010)

Density in the Solar System



Outline

- Motivation & Background
- Survey Techniques
- Binaries
- Colors
- Variability/Lightcurves
- Summary & Implications

Take home messages:

- Objects in the Kuiper Belt can be used as tracers for planetary migration.
- The characteristics of Kuiper Belt objects can help us learn about the distribution of material in the original solar nebula.

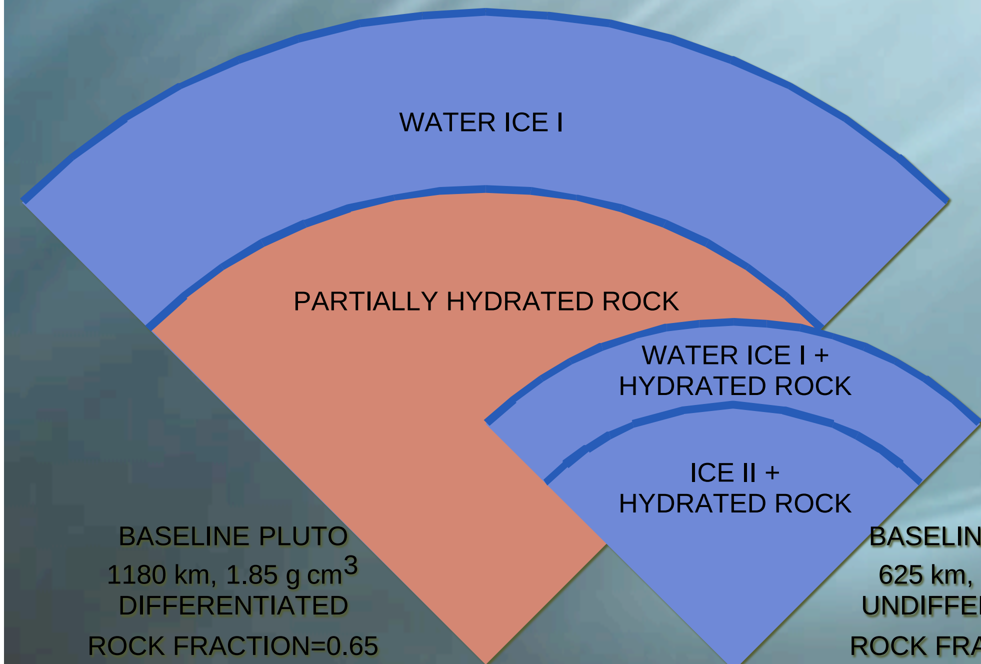
Binaries

- binary orbit -> system mass. Kepler's 3rd law

$$\left(m_p + m_s\right) = 4\pi^2 a^3 / GP^2$$

- diameters assuming (or measuring) an albedo, *p*.

$$d = \frac{2r\Delta}{R\sqrt{p}} 10^{-0.2\left(m_{kbo} + \alpha\beta - m_{sun}\right)}$$



McKinnon et al 1997

- Density -> Suggest composition.

$$\rho = \frac{m_p + m_s}{\frac{4}{3}\left[\left(\frac{d_p}{2}\right)^3 + \left(\frac{d_s}{2}\right)^3\right]\pi}$$

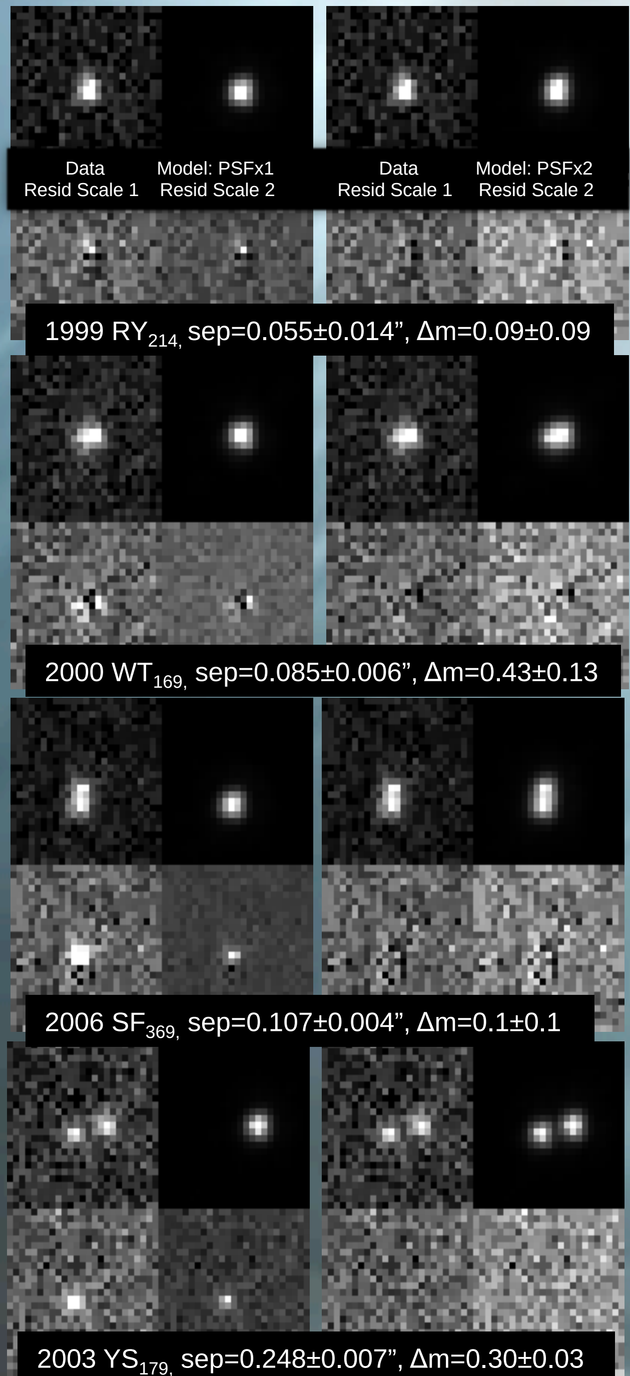
HST Binary Search

Dataset Details

- WFPC2 and ACS/HRC, 3 programs
- 329 objects, 3-4 images each
- Analyzed data with standard HST pipeline and iterative PSF fitting of images using models generated with Tiny Tim considering both single and binary results.

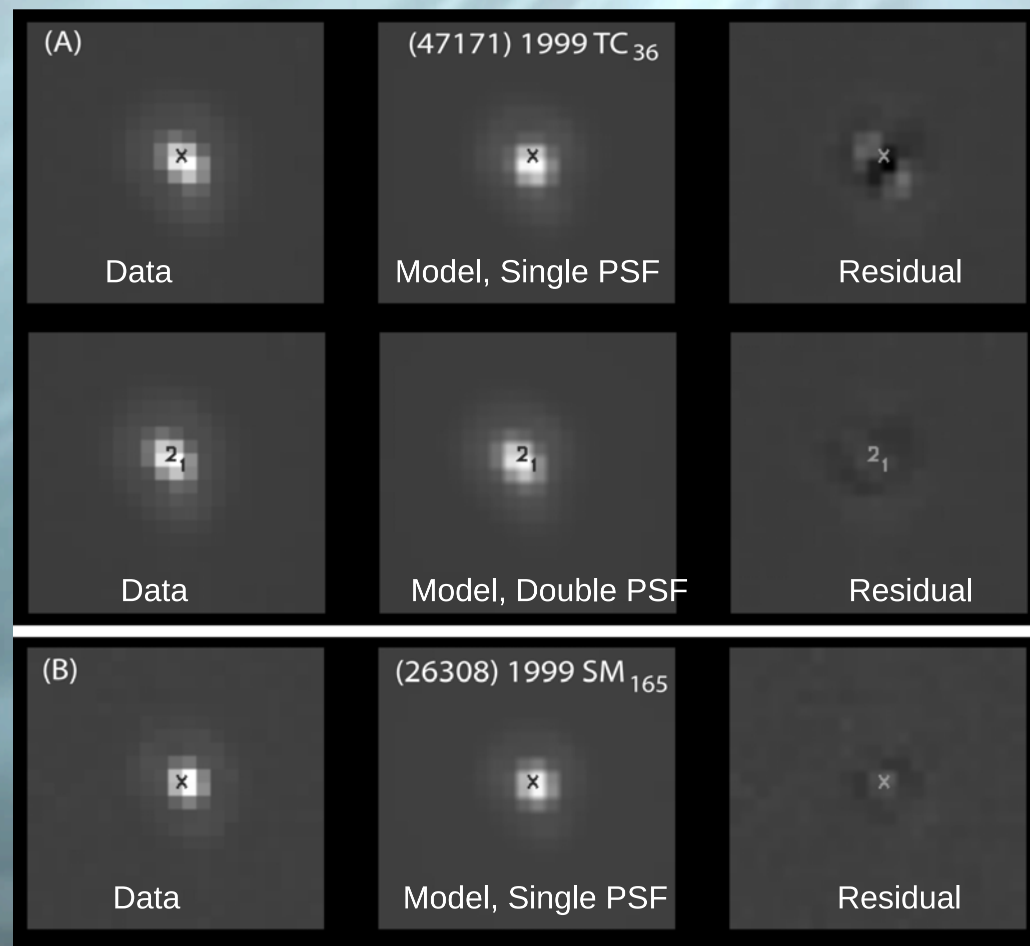
Science Motivation: Binaries allow us to extract physical information (density/composition) about these objects from a distance. Also because these systems can be broken up they tell us about the dynamical excitation in the Kuiper Belt.

Sample Data

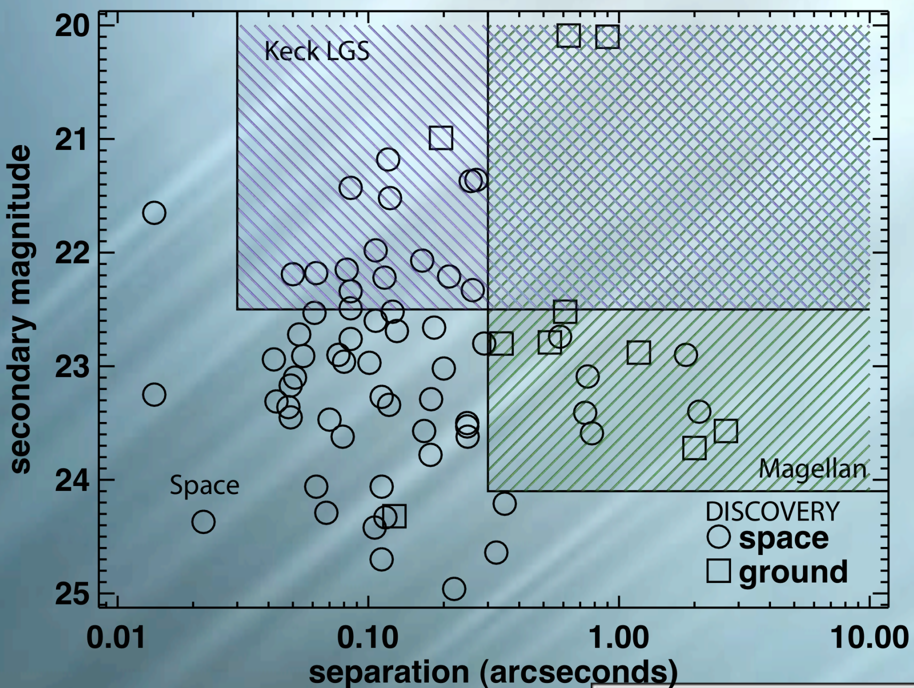


← WFPC2

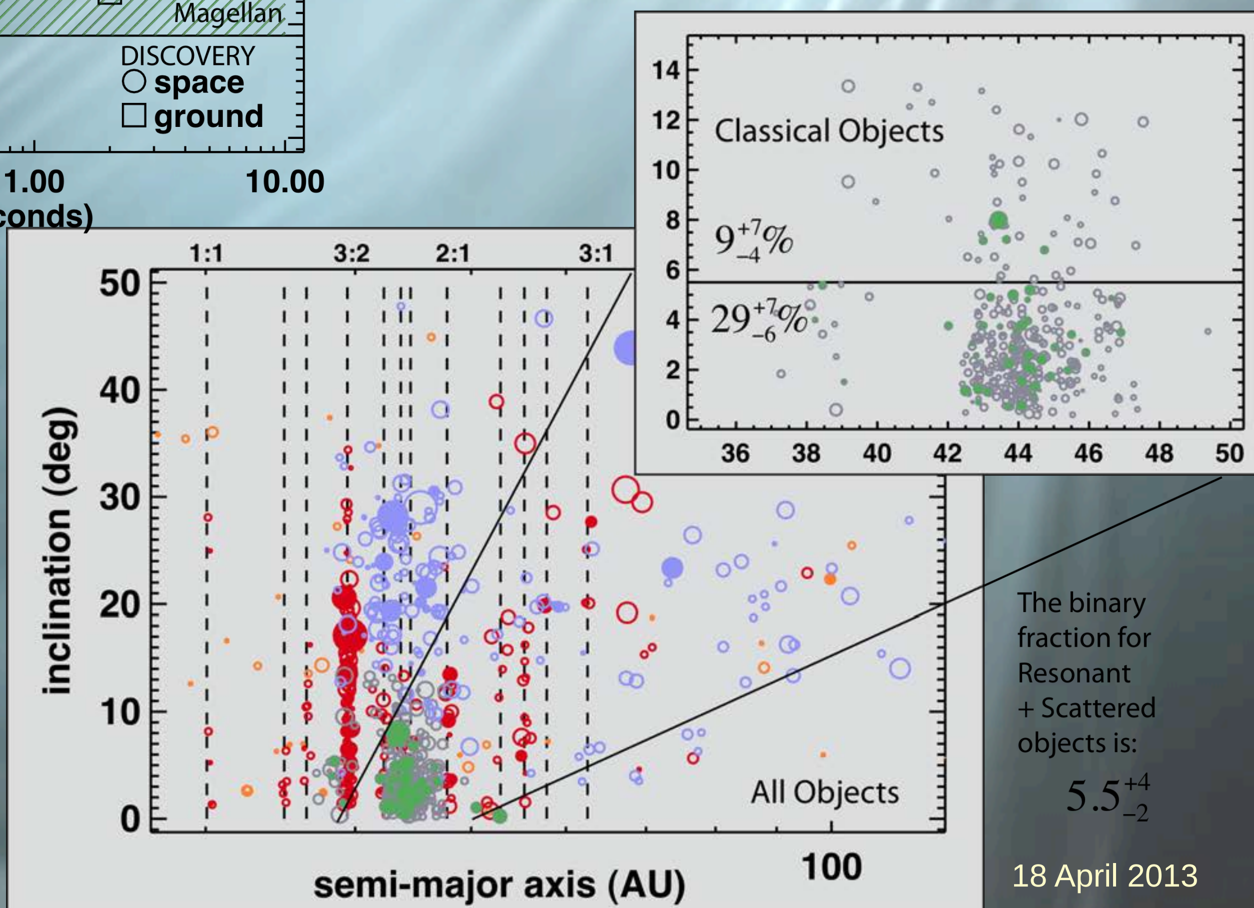
ACS/HRC ↓



Binaries in the Kuiper Belt



Adapted from Kern & Elliot, 2006



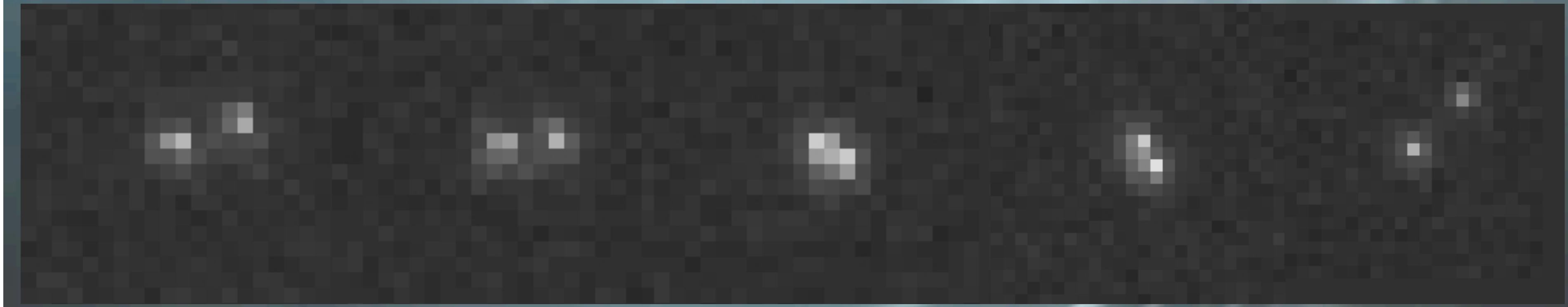
Filled circles are binaries.

Updated from Noll et al. 2008

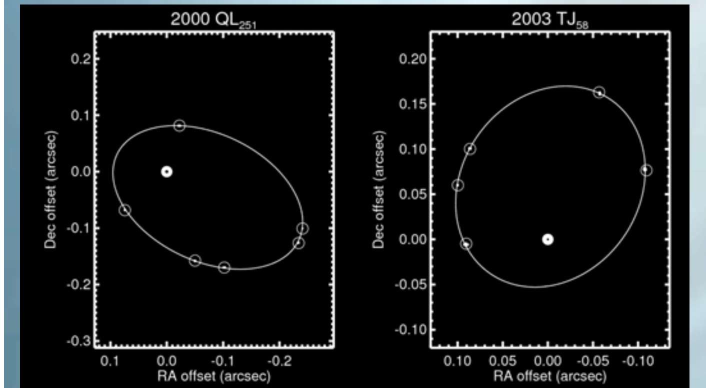
Binary Orbits

- HST/WFPC2 and HST/ACS programs (also some Keck LGS AO)
- 4 observations per HST orbit, 5 or more orbits per object
- Filter: F606W ~ V, F814W ~ I
- 18+ objects
- Analyzed data with standard HST pipeline and iterative PSF fitting of binary images with Tiny Tim models.

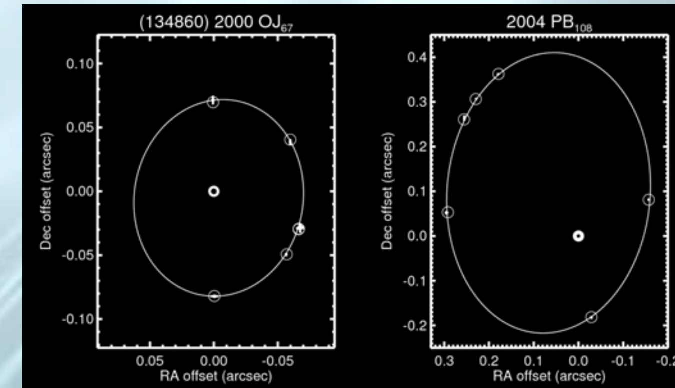
Science Motivation: Measure system mass for objects in the Kuiper Belt to learn about density/composition. Also to learn about scattering in the Kuiper Belt.

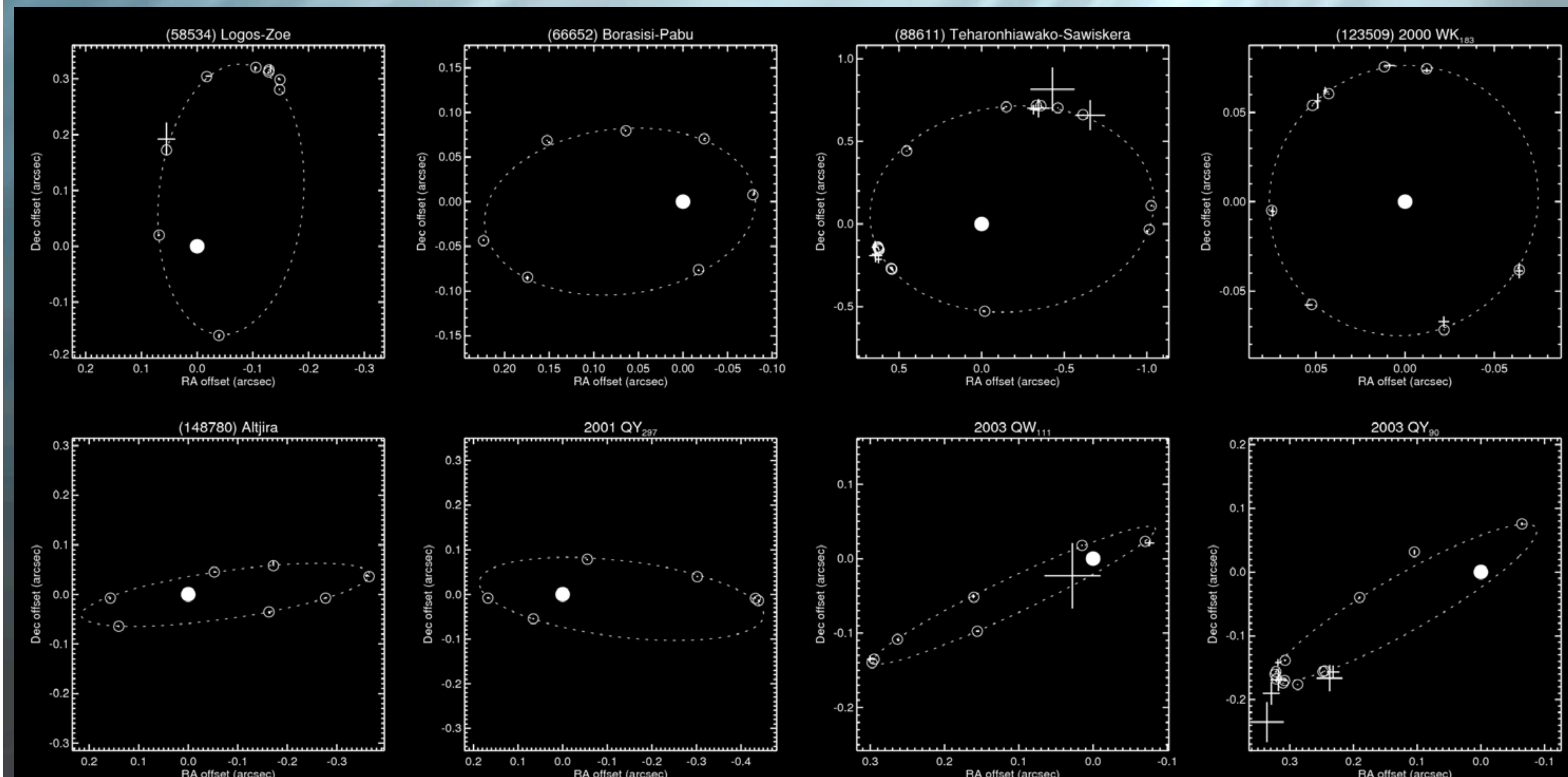


2001 QL_{251}, 5 HST visits with WFPC2, Grundy et al. 2009 Icarus

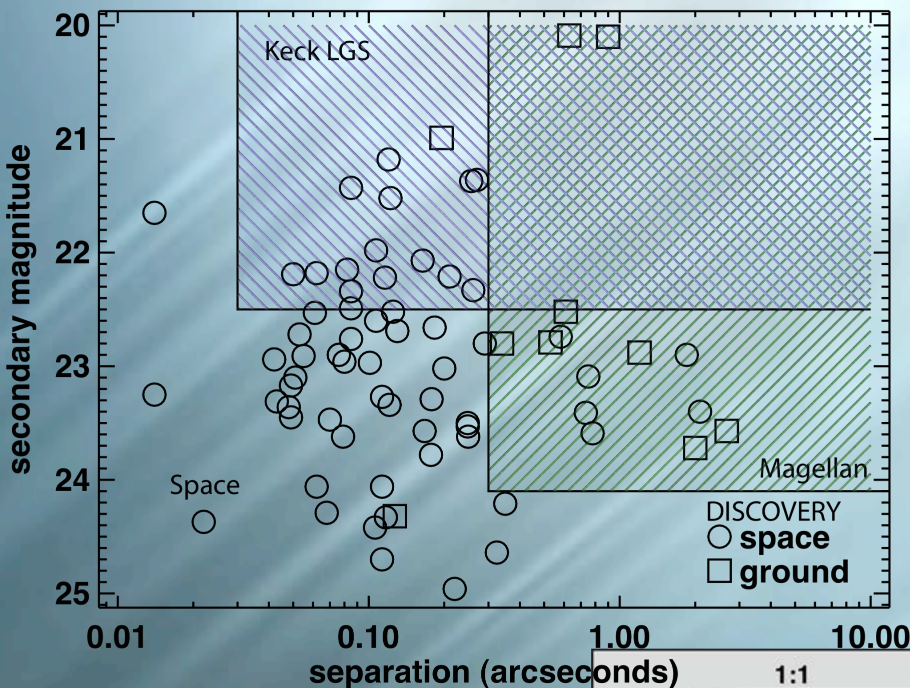


Orbits



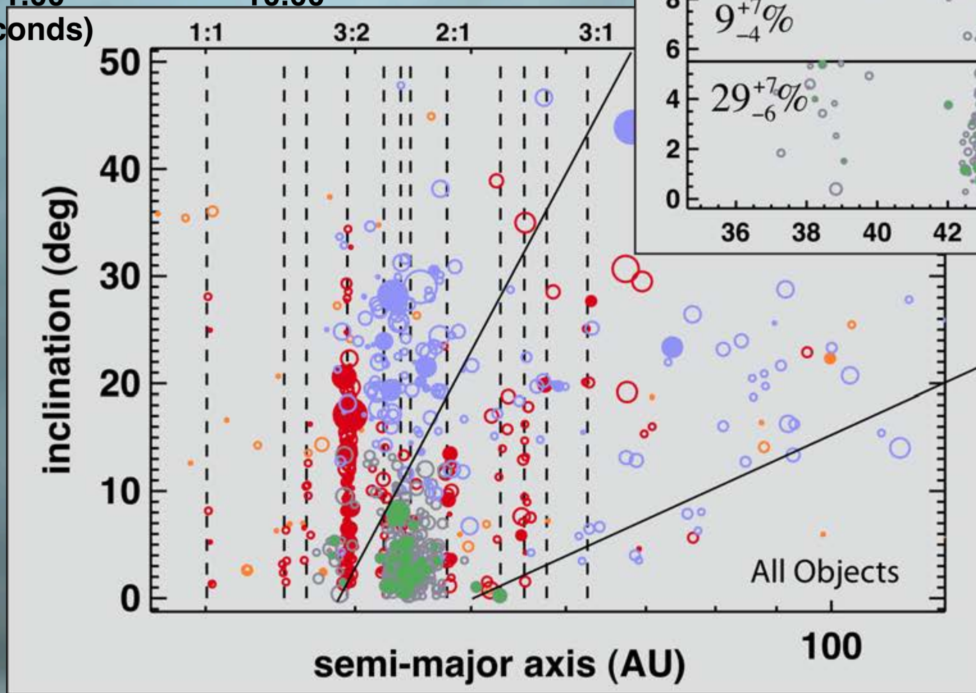


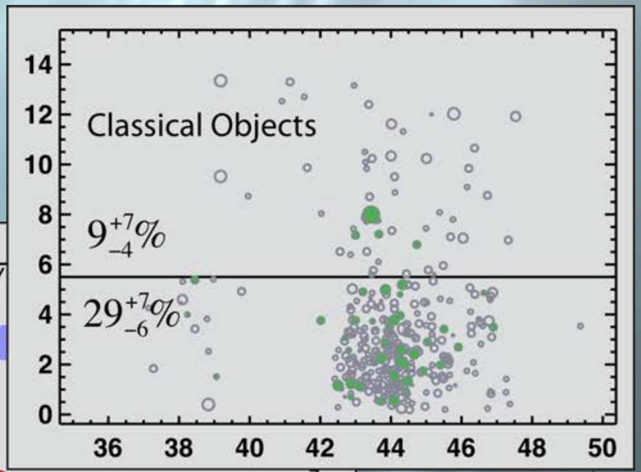
 Grundy et al. 2009, 2011



Current Inventory of Binaries

Adapted from Kern & Elliot, 2006





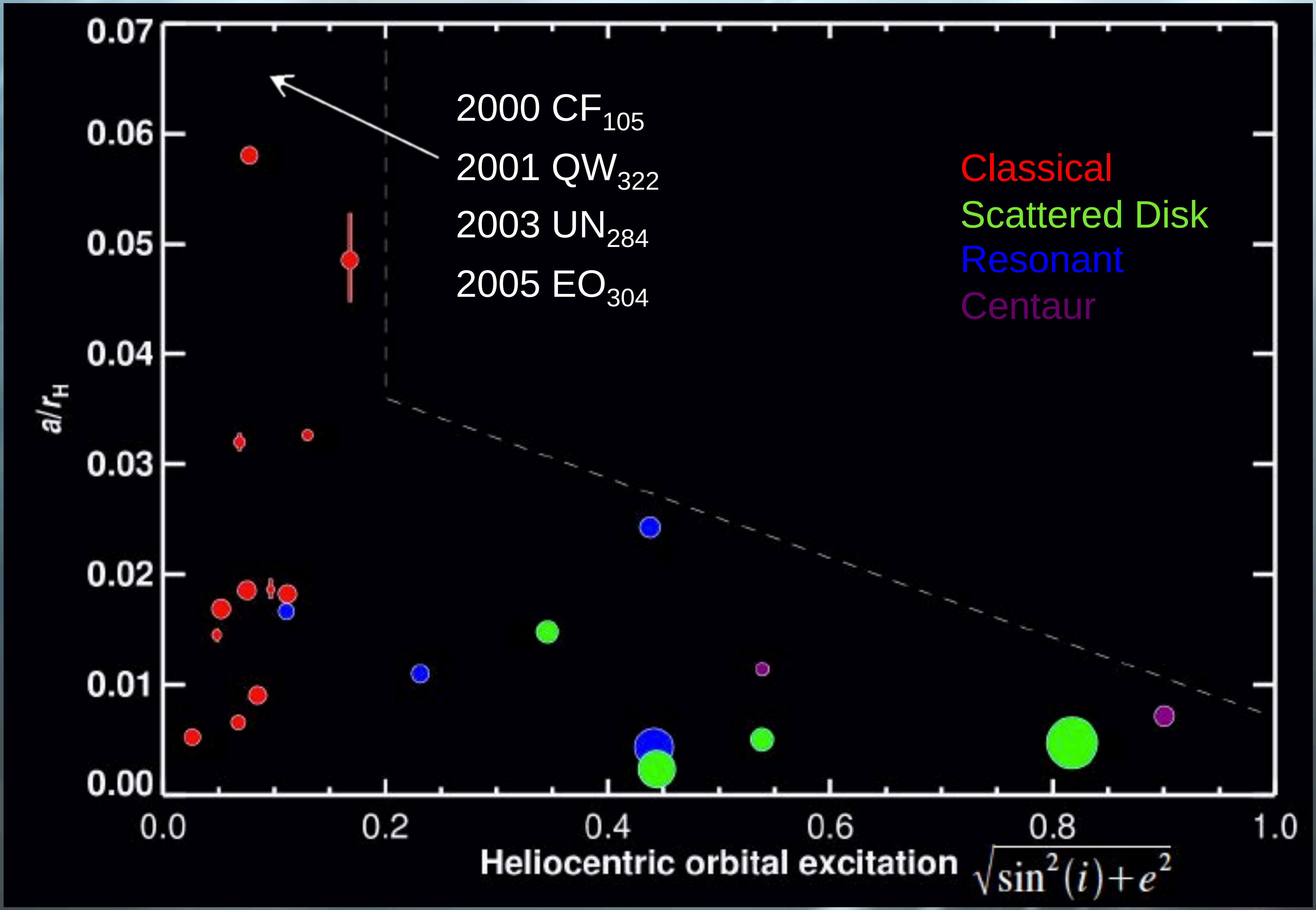
The binary fraction for Resonant + Scattered objects is:

5.5^{+4}_{-2}

Filled circles are binaries.

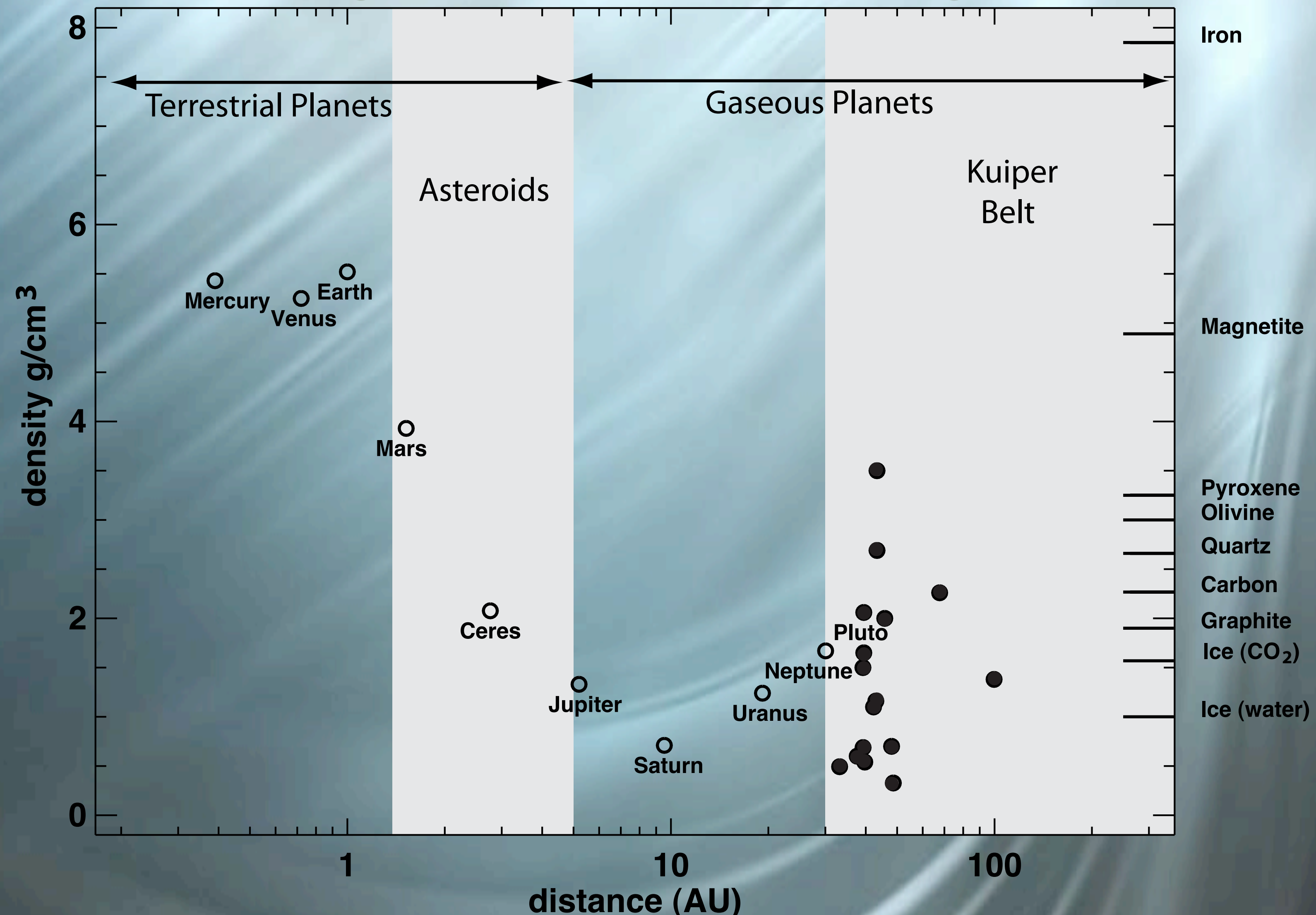
Updated from Noll et al. 2008

Tightness -vs- Excitation



Grundy et al. 2011

Density in the Solar System



S. D. Benecchi 18 April 2013

Summary

- 22 orbits (more in progress), 8 with orbital ambiguity resolved: 6 prograde and 2 retrograde
- Periods range from 5 to over 800 days
- Semi-major axis ranges from 1,600 to 37,000 km
- Eccentricities range from 0 to 0.82
- System masses range from $2x10^{17}$ to $2x10^{22}$ kg
- Most of the systems are near equal mass but the most massive systems are lopsided
- The distribution of orbital properties suggests that the most loosely-bound TNO binary systems are only found on dynamically cold heliocentric orbits, and that small TNOs may be highly dissipative

Outline

- Motivation & Background
- Survey Techniques
- Binaries
- Colors
- Variability/Lightcurves
- Summary & Implications

Take home messages:

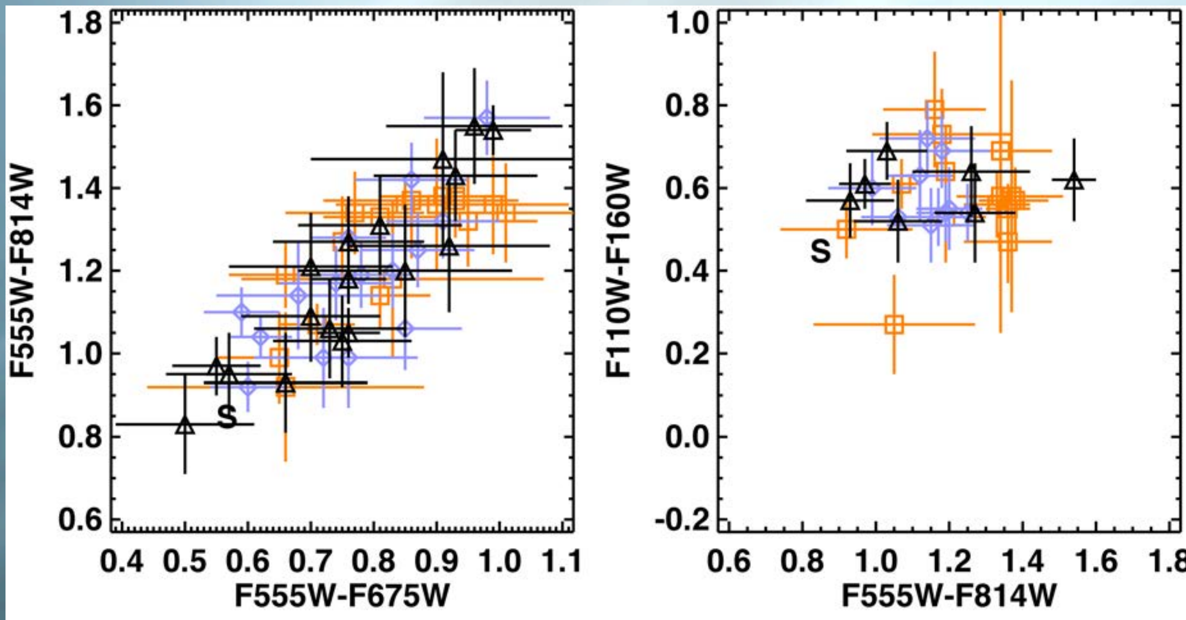
- Objects in the Kuiper Belt can be used as tracers for planetary migration.
- The characteristics of Kuiper Belt objects can help us learn about the distribution of material in the original solar nebula.

KBO Colors (Singles and Binaries)

- Compilation of all color data from the literature
  - Objects that have multiple measurements are combined with weighted averages
  - BVRI, JHK (optical and IR)
- Resolved colors of 22 binaries in F606W,F814W (VI)
- Archive HST dataset (WFPC2, NIC2)
  - 70 objects with F555W,F675W,F814W (VRI)
  - 69 objects in F110W,F160W (JH)
  - 24 overlap optical/IR
  - 299 objects in the final database

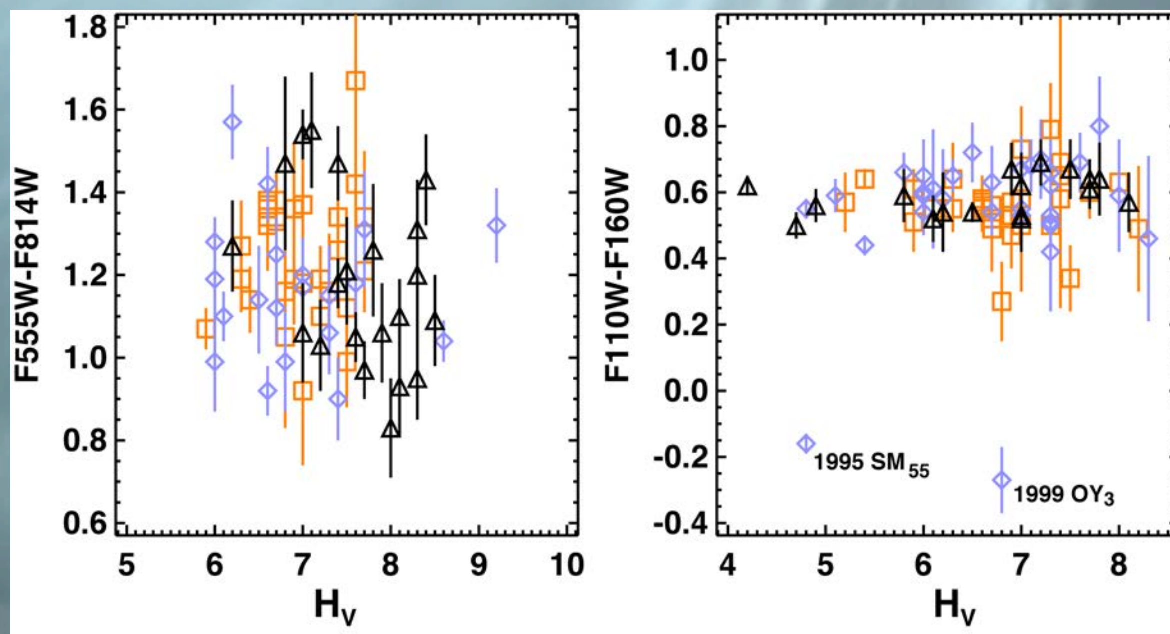
Science Motivation: Look for dynamical or physical signatures left over from giant planet migration. Ask the questions, are binaries representative of the larger population?

KBO Colors



Archive HST dataset (WFPC2, NIC2)+ Compilation of all color data from the literature = 299 objects in the final database

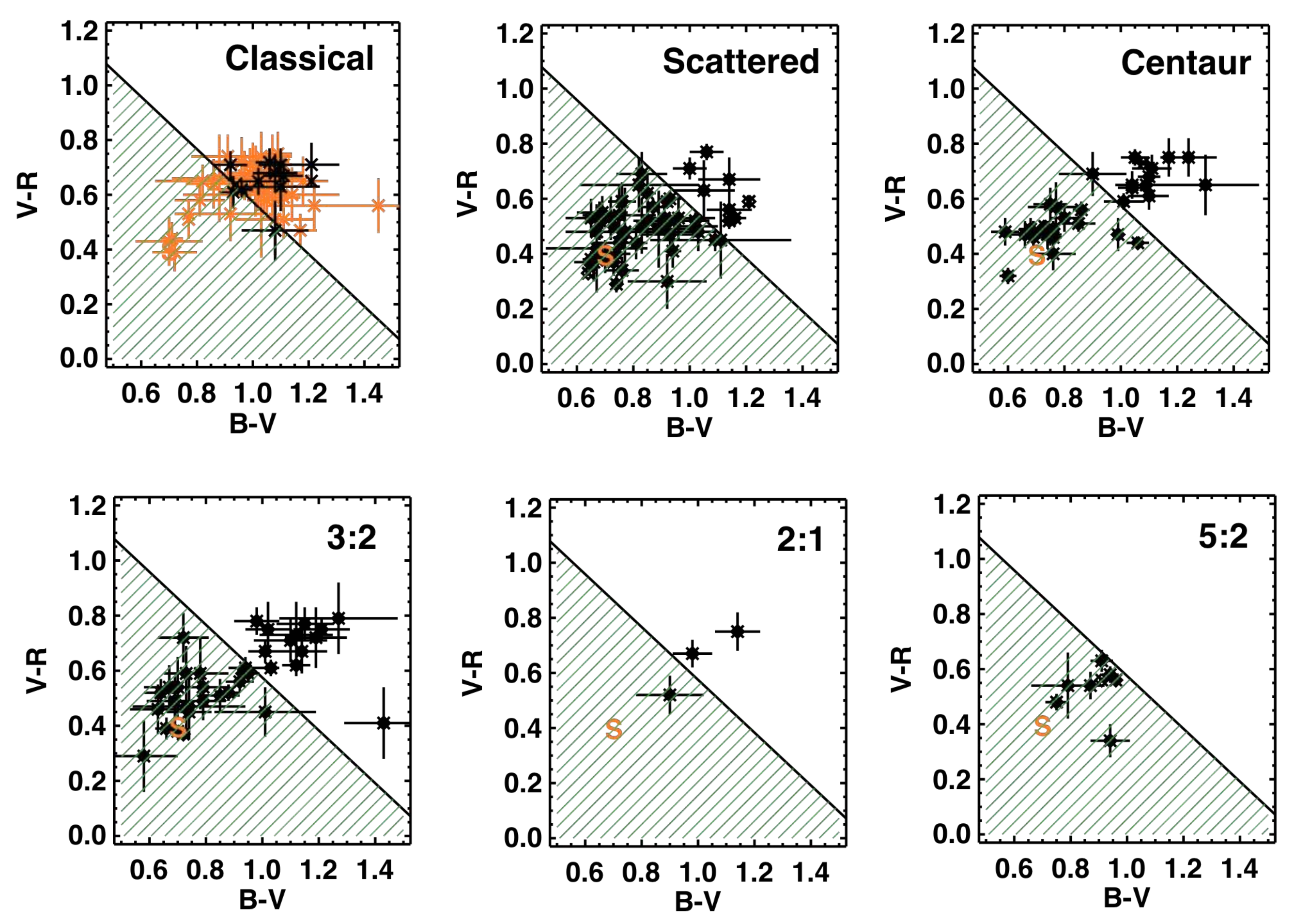
□ Cold Cassical
Δ Resonant
◆ Excited



Science Motivation: Look for dynamical or physical signatures left over from giant planet migration.

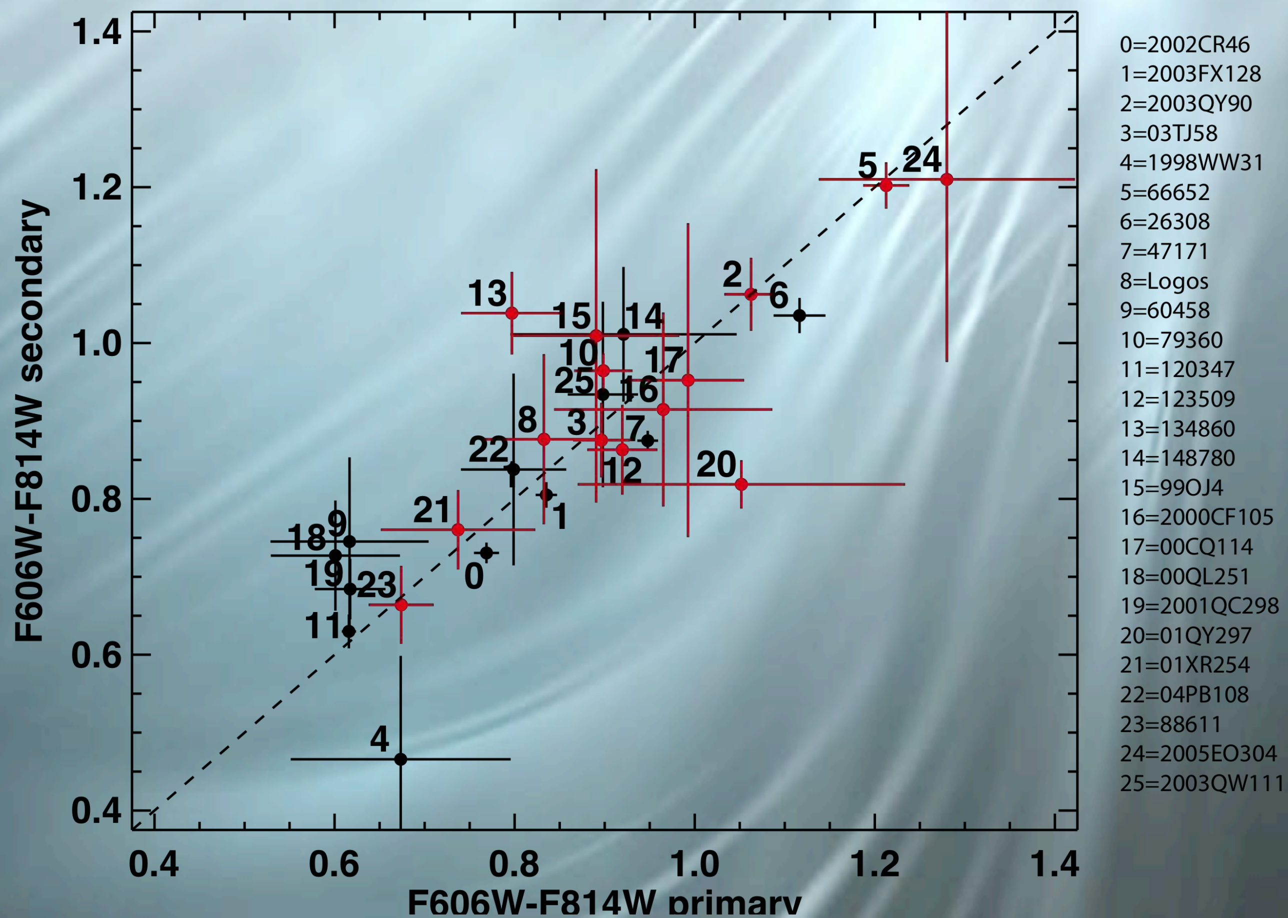
Benecchi et al. 2011

Dynamically separated colors of KBOs



Resolved Colors of Binary Components

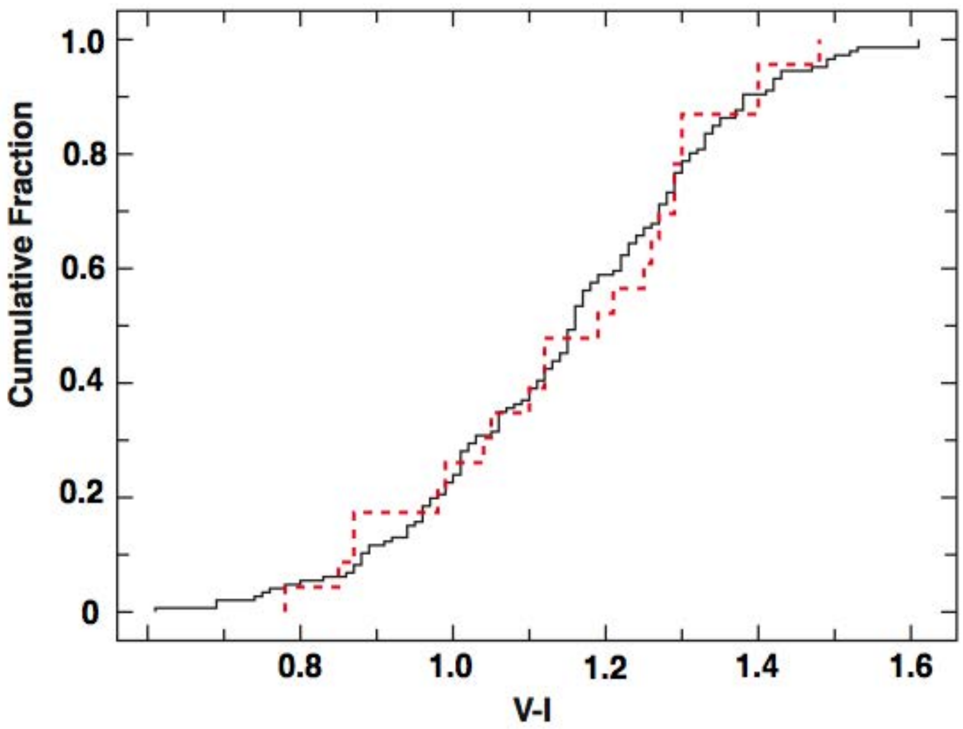
- Primary and secondary components are identical in color.
- Correlated with Spearman Rank probability of 99.976%.

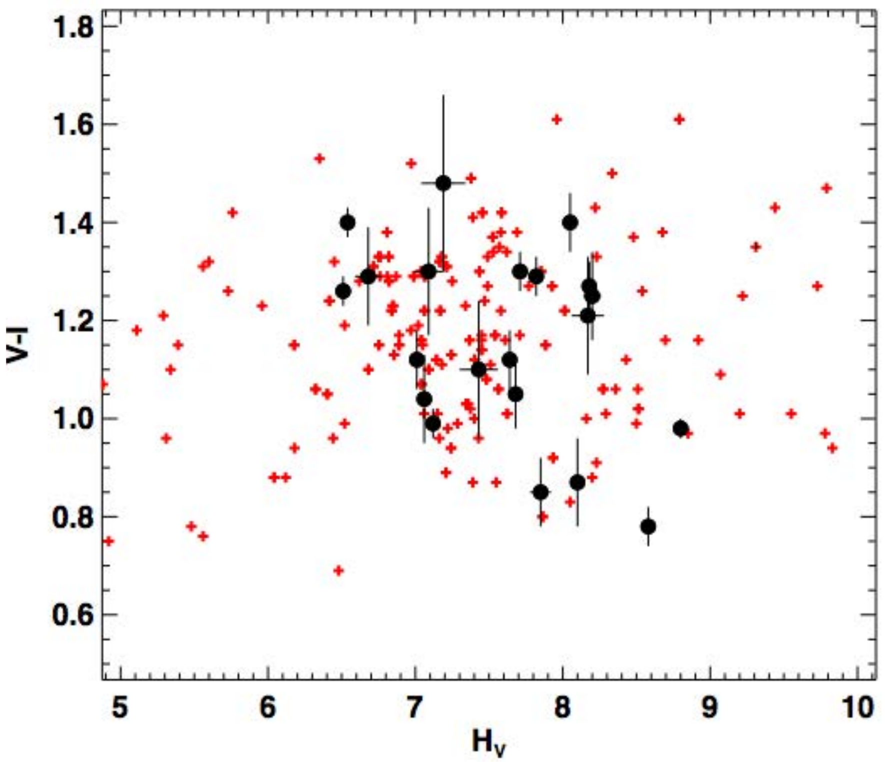


Benecchi et al. 2009

Comparison: Binaries & “Singles”

K-S Test –> Probability the distribution is the same for (assumed) singles and binaries
–> 98.8% (for all objects)
–> 73-98.8% (Use same classification)





MBOSS (Hainaut & Delsanti 2002) and
HST (Stephens et al. 2007) Color surveys

Benecchi et al. 2009

Discussion

- Cold Classical objects, *i*<6°, come from a different distribution than the Resonant or excited objects, both optical and infrared colors support this conclusion
- No significant correlations between color and dynamical properties (*semi-major axis, eccentricity, inclination and perihelion*)
- Centaur colors are bimodal
- Suggestions among resonance objects, but not really enough statistics
  - The colors of the approximately equal sized binaries in our sample are representative of the larger KBO population → the coloring mechanism is not unique to binary systems.
  - KBO color is related to the region of formation or to the region in which these objects currently reside.

Outline

- Motivation & Background
- Survey Techniques
- Binaries
- Colors
- Variability/Lightcurves
- Summary & Implications

Take home messages:

- Objects in the Kuiper Belt can be used as tracers for planetary migration.
- The characteristics of Kuiper Belt objects can help us learn about the distribution of material in the original solar nebula.

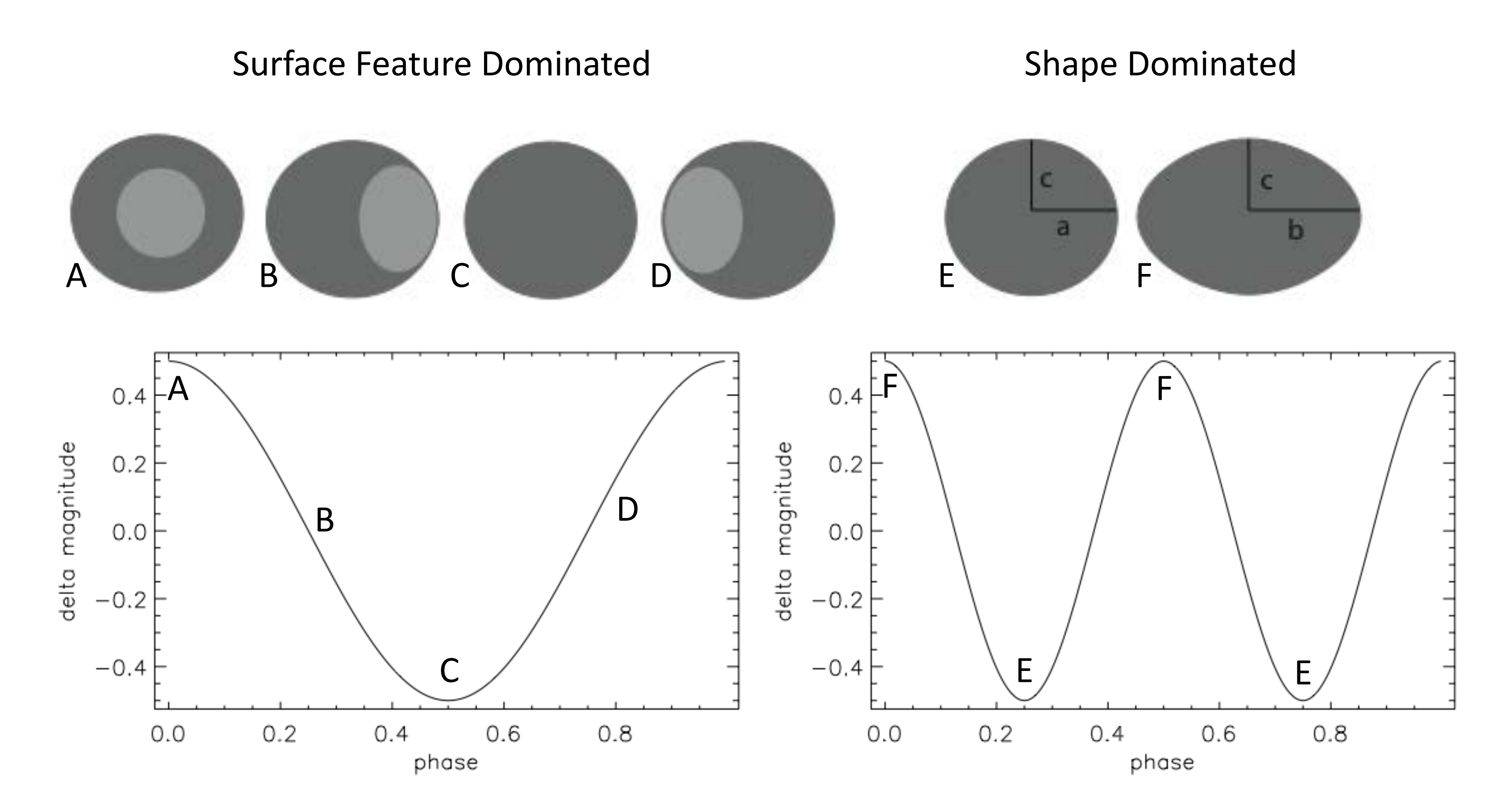
Lightcurves

Dataset Details

- du Pont, Magellan
  - Observed objects on at least 3 nights, preferably 2 observing runs.
  - ~33 objects (to report on) + 7 resolved binaries (data under analysis)
  - Large Southern Hemisphere TNOs, Binary TNOs, Bright Haumea Family TNOs
- Synthesis with datasets in the literature
  - Biases:
    (1) Smaller objects are harder to get observing time to observe.
    (2) Long duration periods (>20 hours) are harder to obtain.

Science Motivation: Investigate how rotation is influenced by size, shape and dynamical interactions. Again, are binaries representative of the larger population.

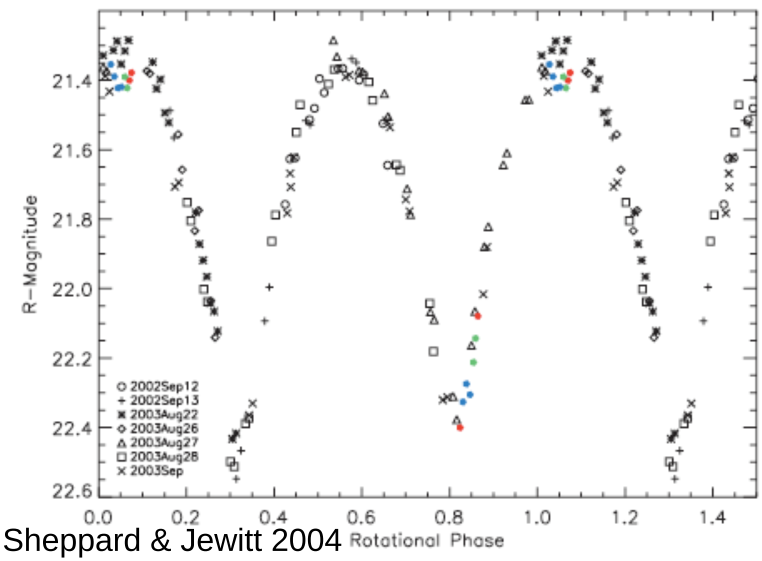
Single Object Lightcurve Interpretations



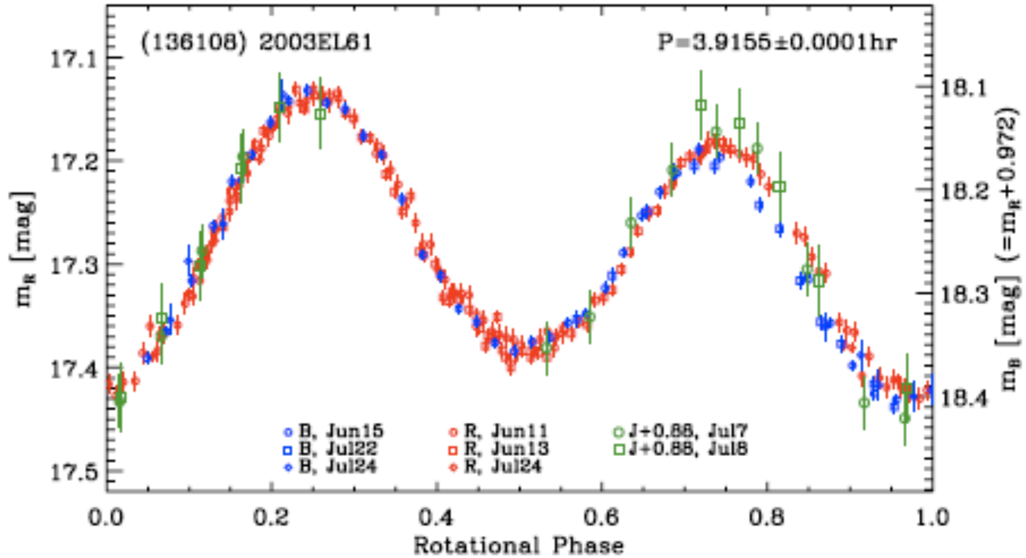
The amplitude of the lightcurve can tell us about the spherical/elongated nature of the object.

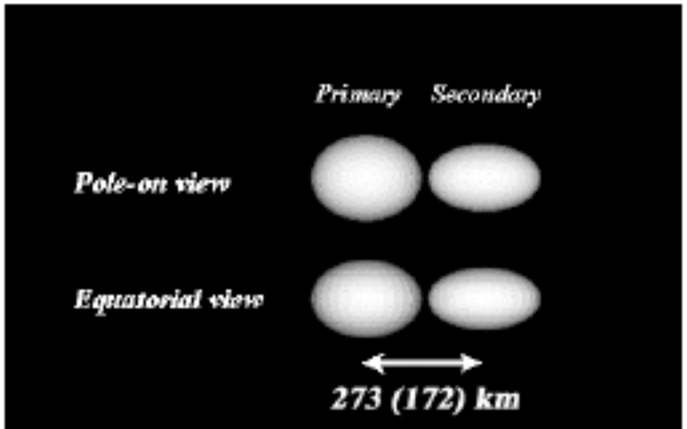
$$a/b = 10^{0.4\Delta m}$$

Lightcurve Interpretations: 2001QG$_{298}$ and (136108) Haumea

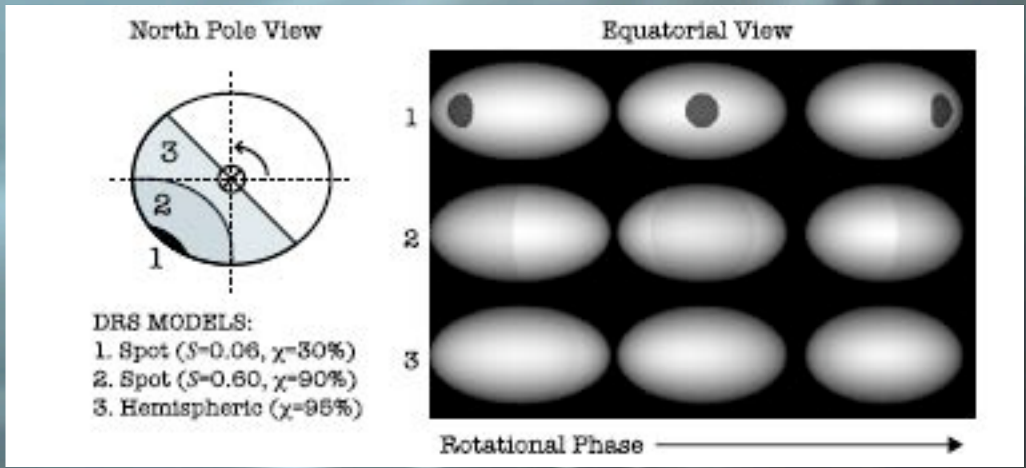


Sheppard & Jewitt 2004



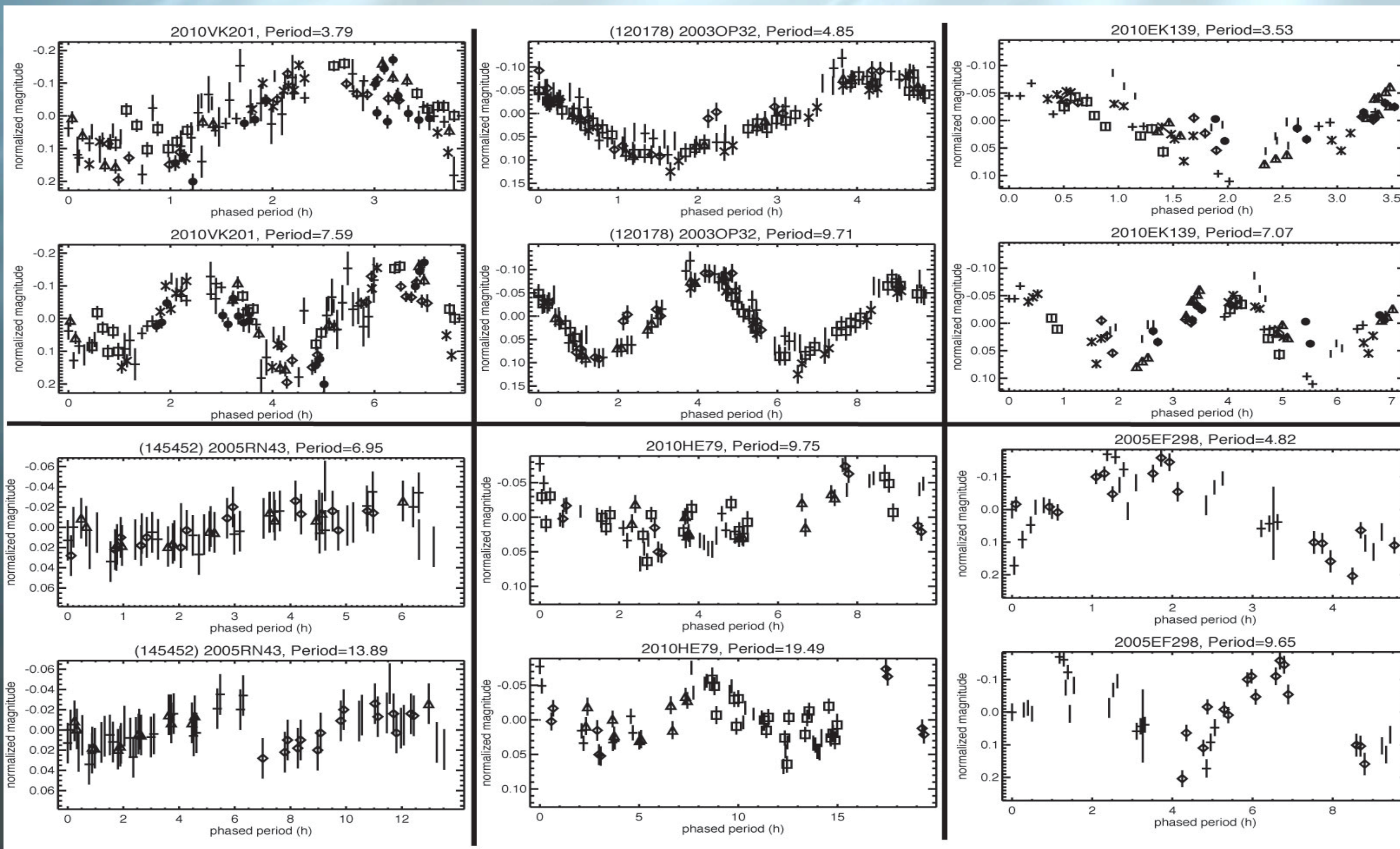


Takahaski & Ip, 2005



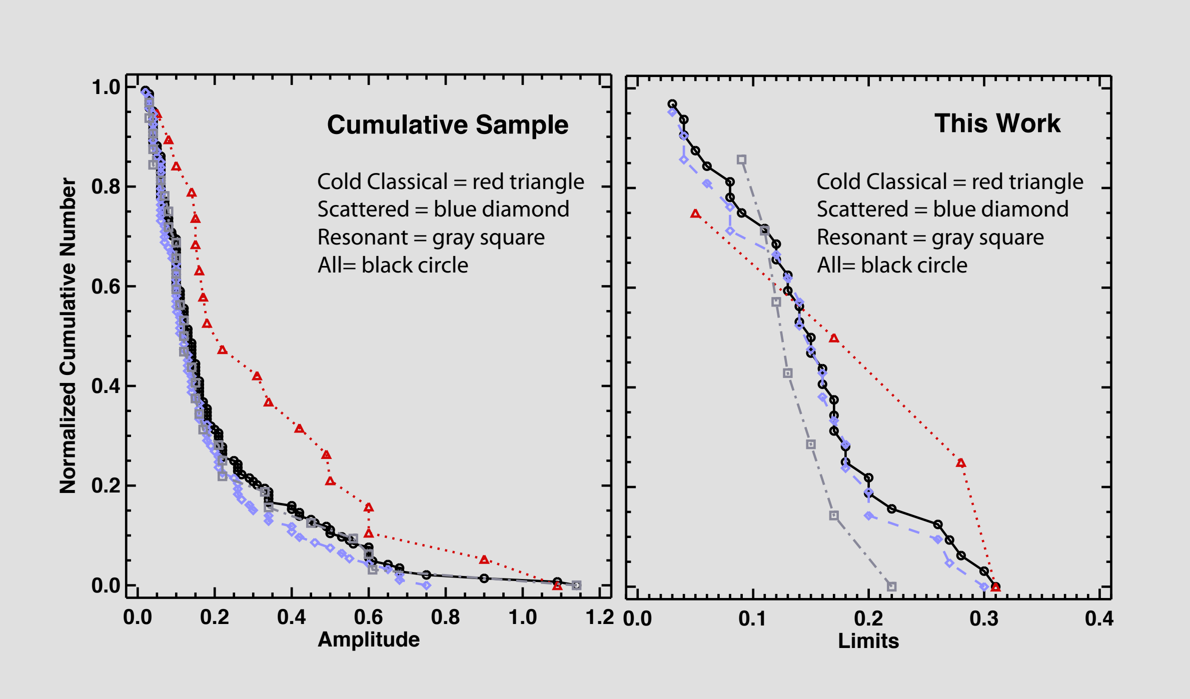
Lacerda et al. 2008

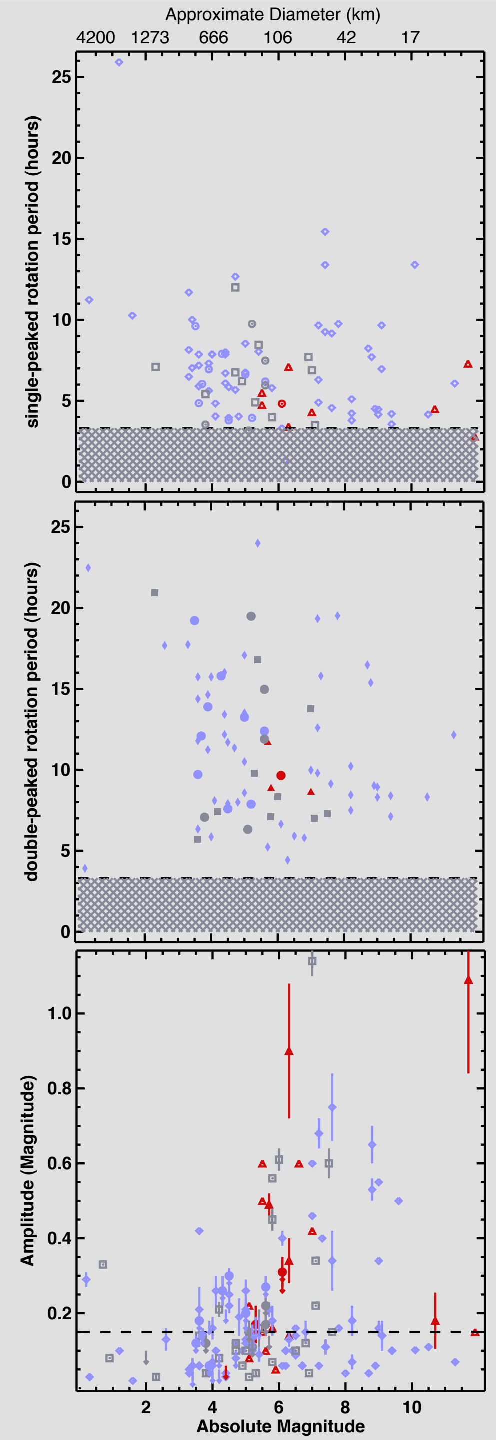
Sample Lightcurves



Benecchi & Sheppard 2013

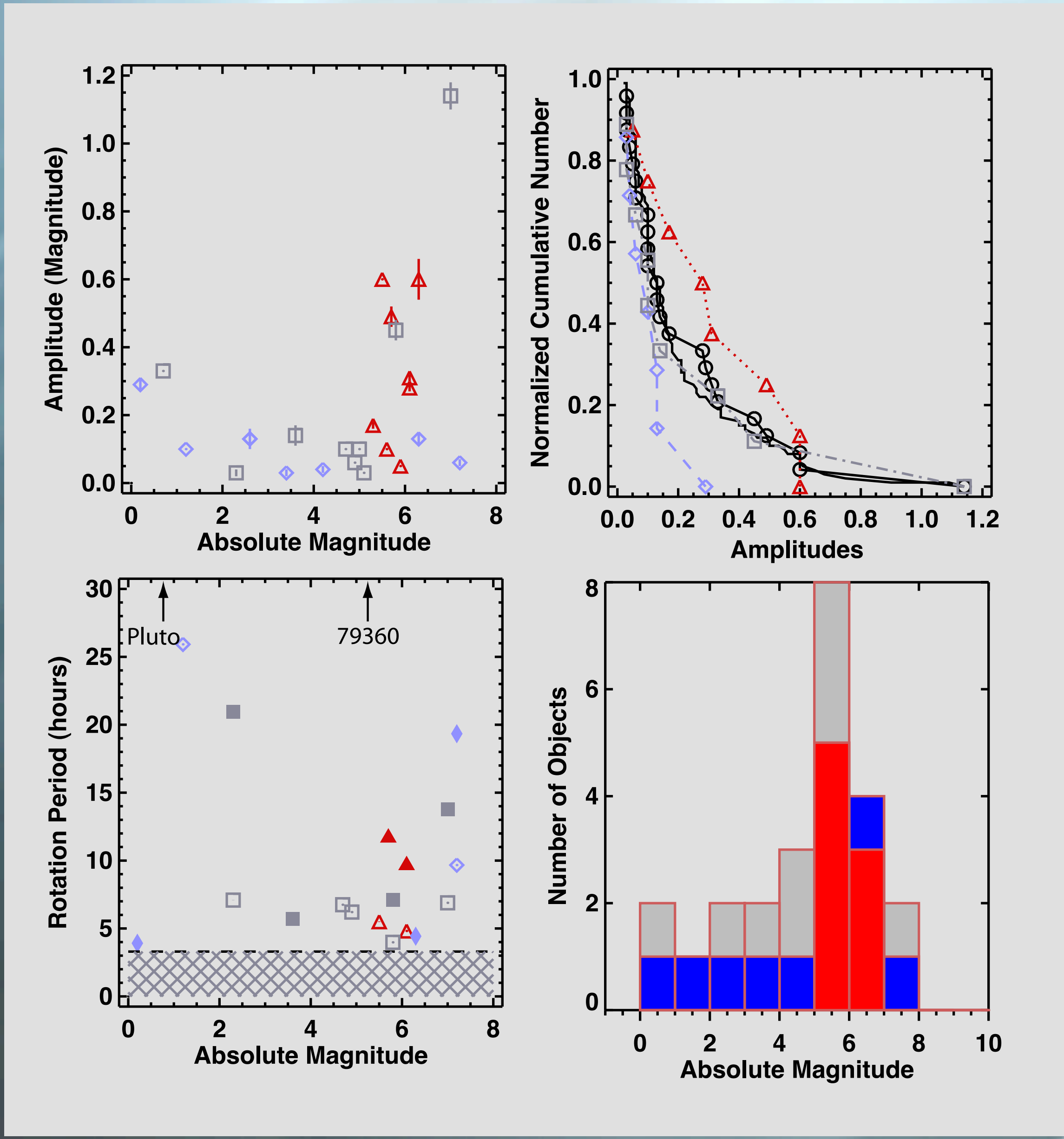
All Lightcurves Combined





The Cold Classical lightcurve properties are different from the Scattered and Resonant Population at the 3-sigma level… however, there may be some observational biases to be sorted out.

Benecchi & Sheppard 2013

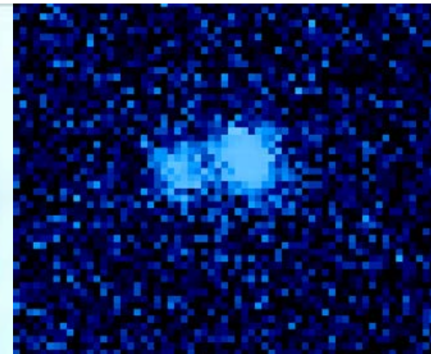


Binary Lightcurve Properties

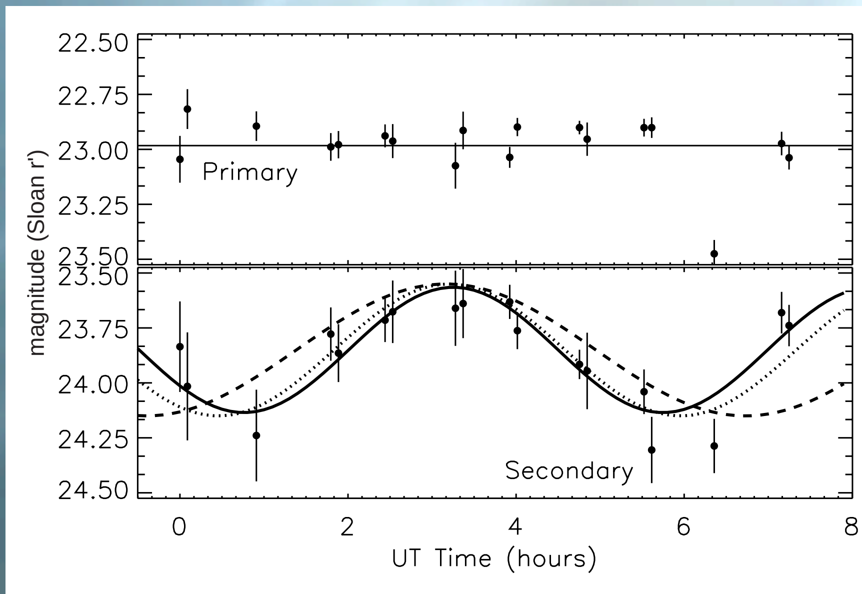
Mostly mirrors the larger TNO population, but special cases: tidally locked objects, contact binaries. Typically these are smaller objects then measured for the larger TNO population. Wide binary lightcurve results to come in a few months.

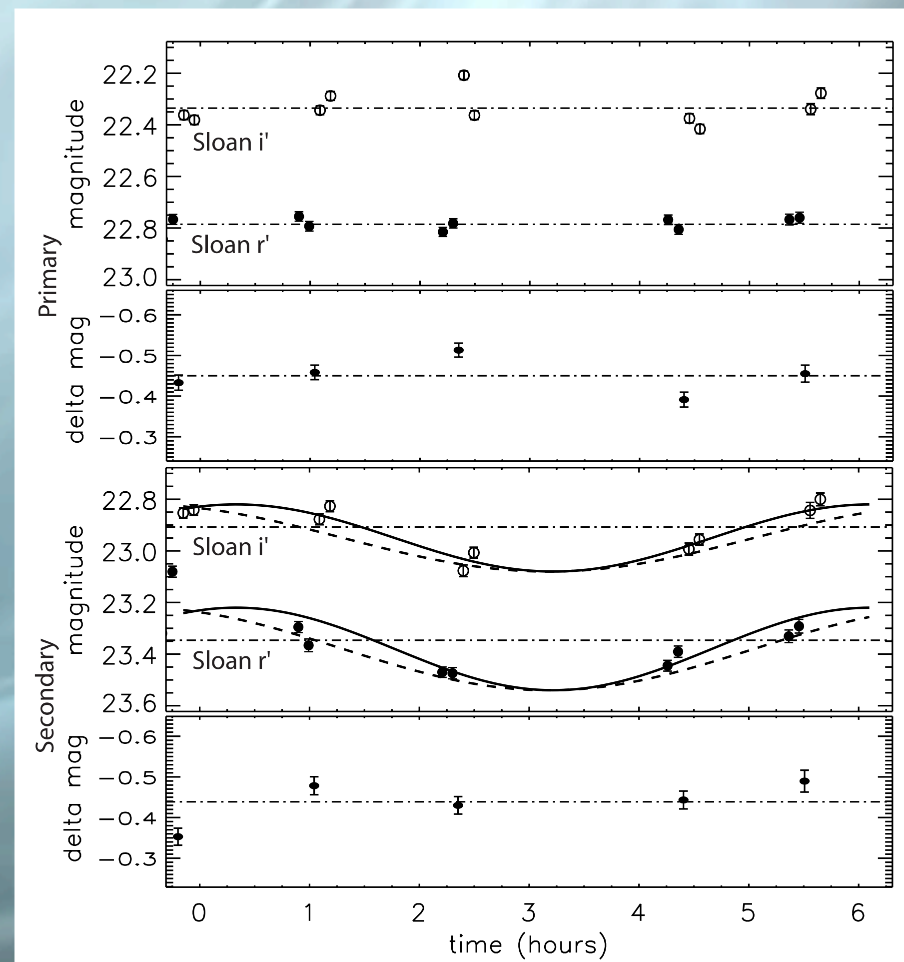
Benecchi & Sheppard 2013

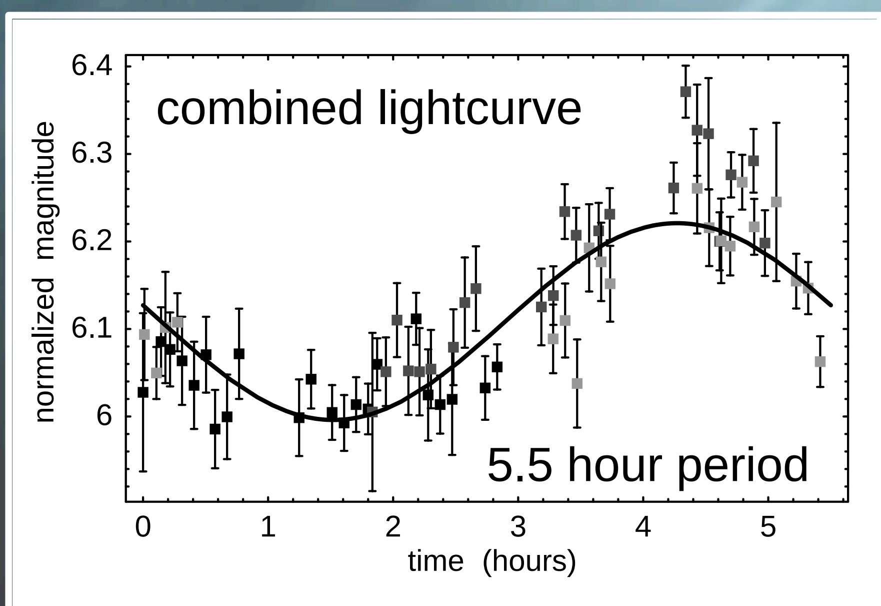
Resolved Binary: (88611) Teharon



The secondary variation dominates the lightcurve.

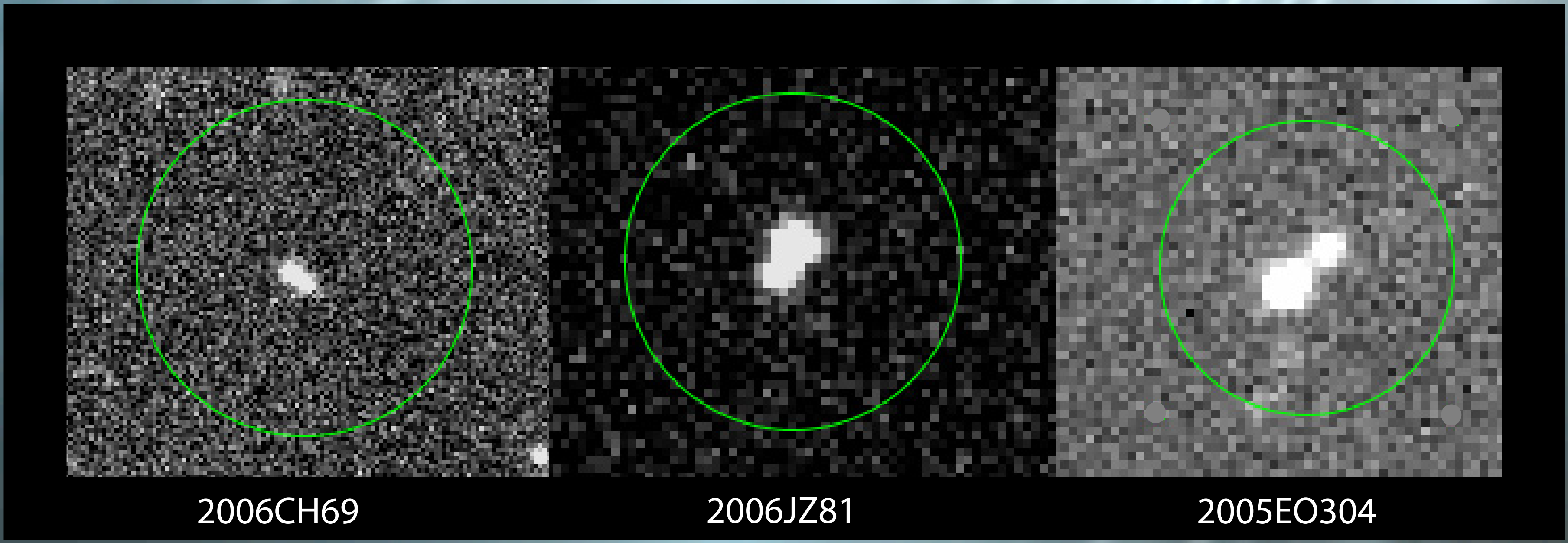






Kern 2006

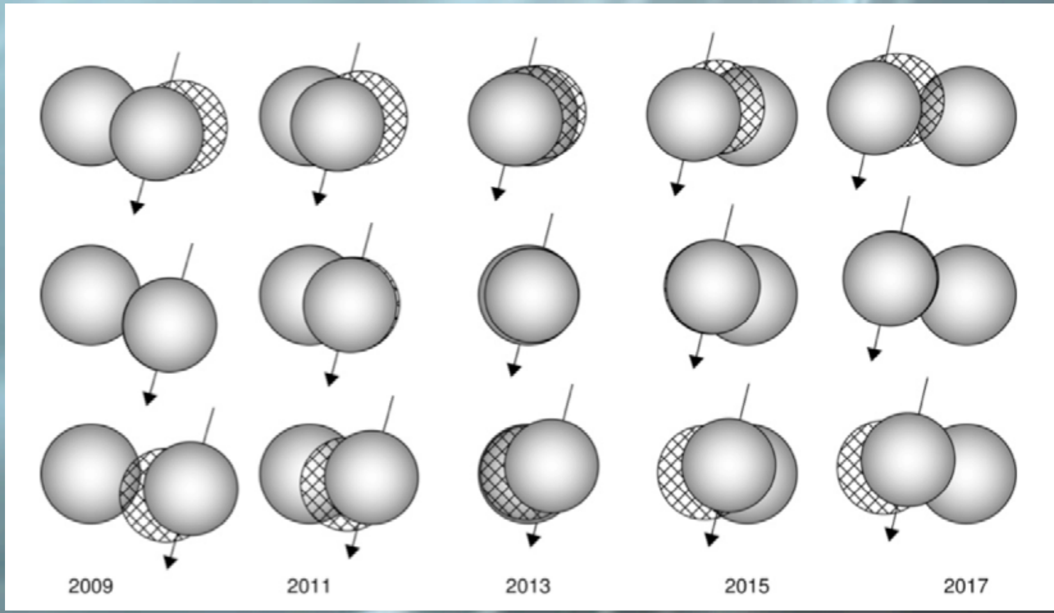
Binary Lightcurves (resolved and unresolved): Investigating Interaction History



Data collected with MegaCam at Magellan, March 2012 (still under analysis)

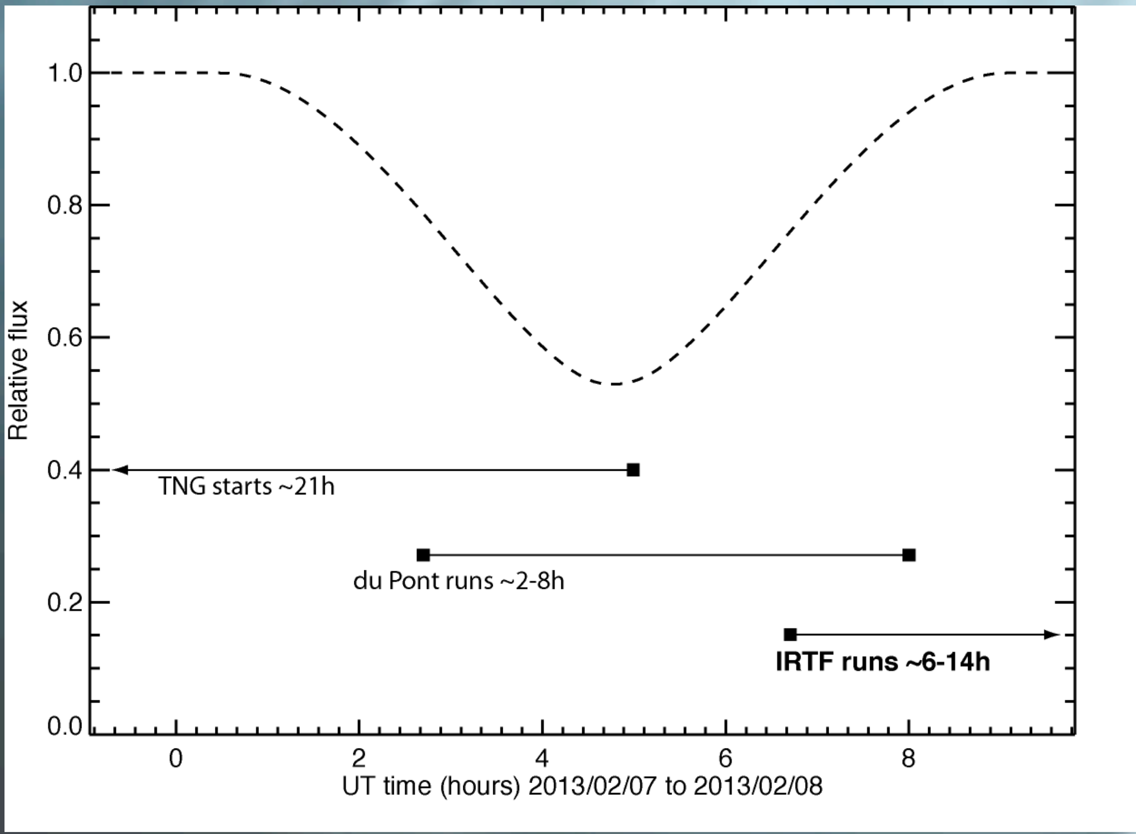
(79360) Sila/Nunam Mutual Events

- *Science Goal:* Mutual events occur when the components of a binary system occult and eclipse each other. Combining the results of multiple mutual events over time allows us to determine accurate sizes, and to map shapes and the distribution of surface ices on remote objects in the outer solar system, a task that cannot be accomplished with other types of observations. It also allows us to refine the mutual binary orbit.
- From 2009 until 2017 the Kuiper Belt binary system (79360) Sila/Nunam is undergoing such mutual events.

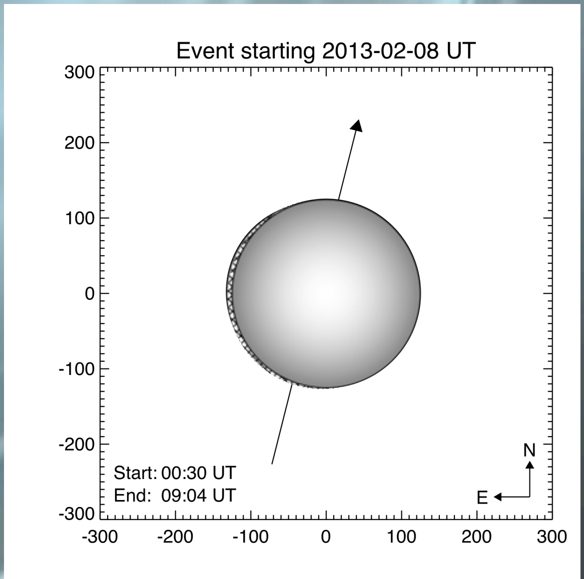


UT 8 February 2013 Event: Prediction
Superior Occultation + Eclipse

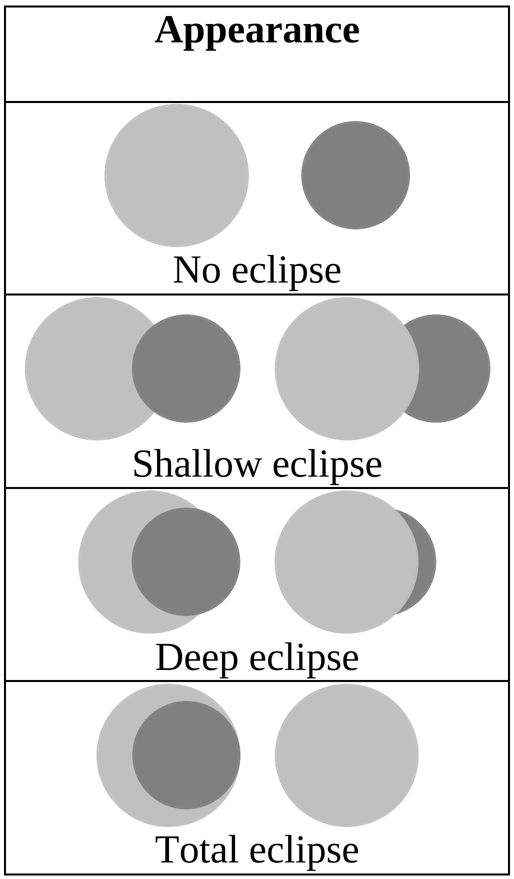
- Combine observations to get full temporal coverage of event.
- IRTF provides part of the event plus the critical out of eclipse baseline.

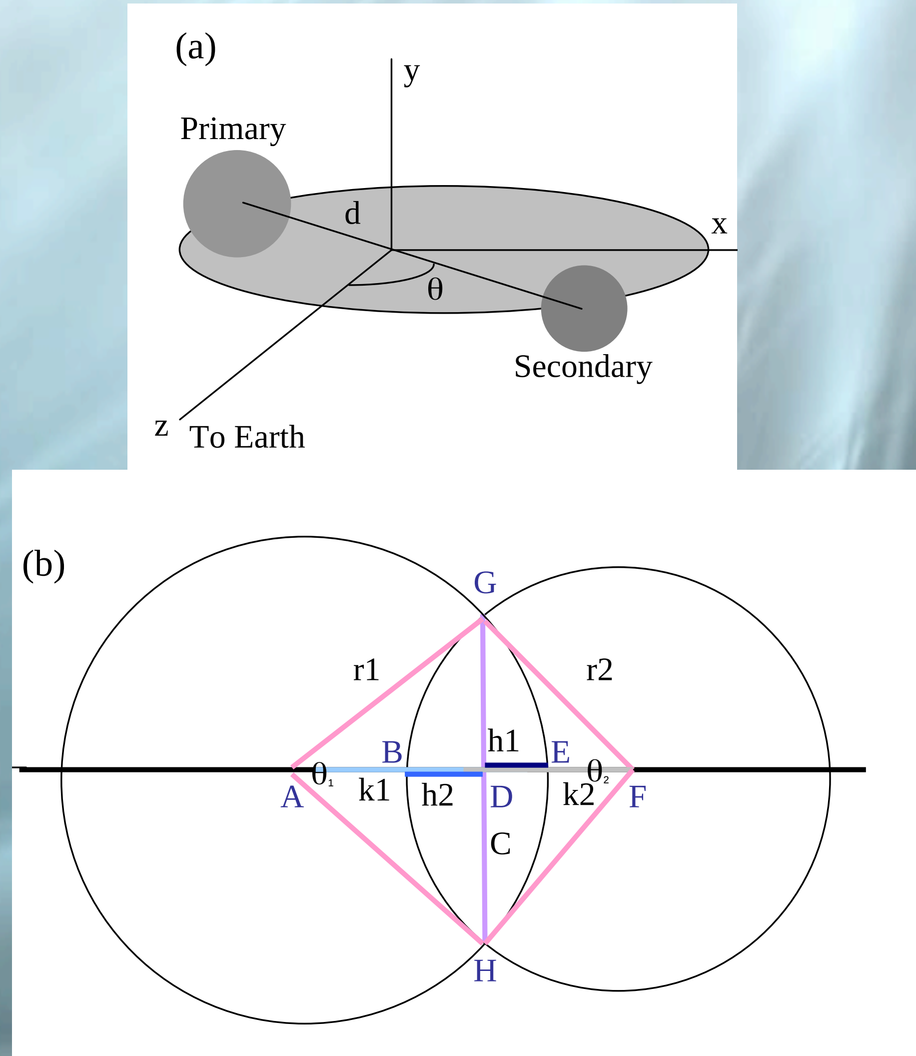


<u>Prediction (UT)</u>
Start: 2013/02/08 00:30
Mid-time: 2013/02/08 04:43
End: 2013/02/08 09:03
Duration: 8.55 hours

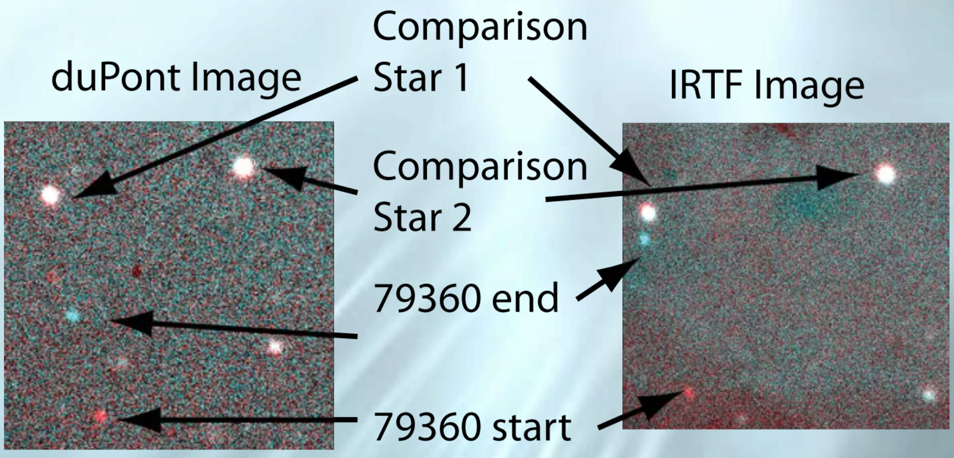


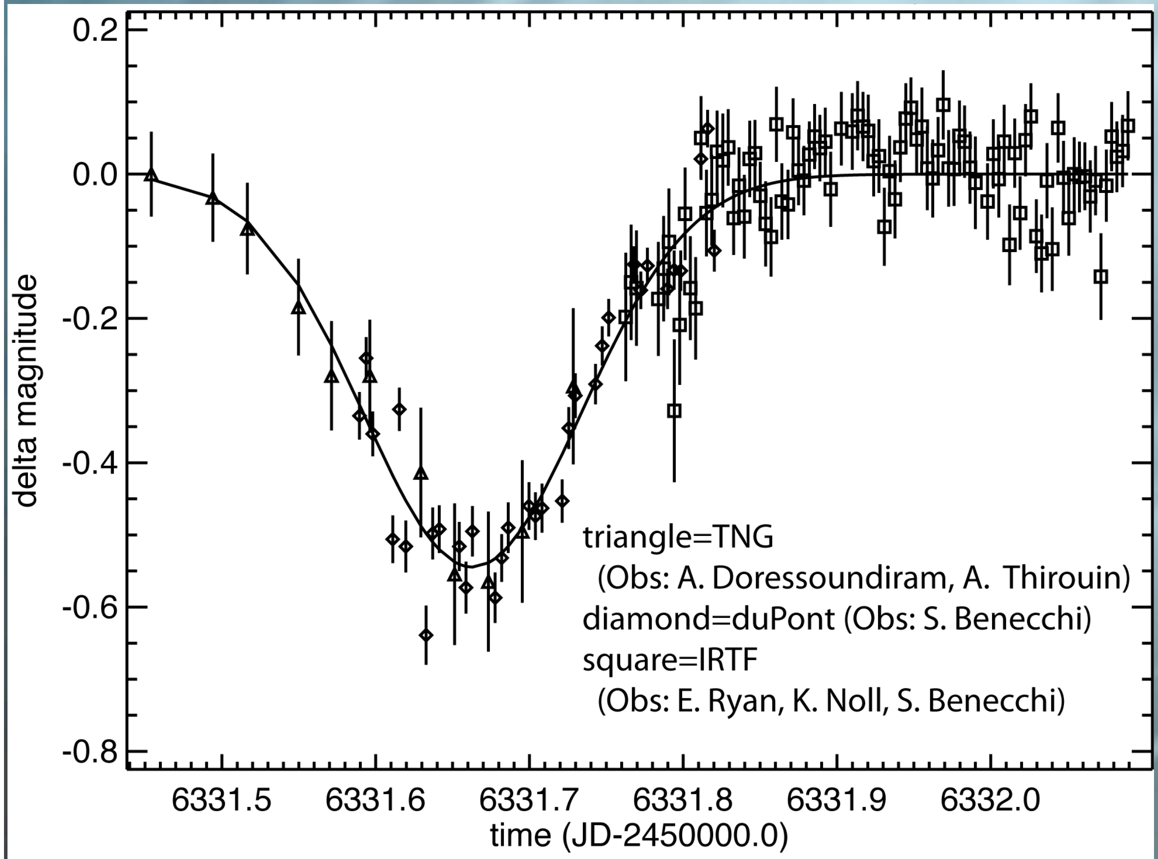
Binary Eclipse Tutorial





UT 8 February 2013 Event: Preliminary Results





<u>Results (UT)</u>

Start: 2013/02/07 22.89844
Mid-time: 2013/02/08 03.90960
End: 2013/02/08 08.91600
Duration = 10.017 hours

<u>Next Steps</u>

- **Combine with Inferior event to refine mutual binary orbit.**
- **Refine timing of future events.**
- **Calculate diameters.**
- **Analyze color data from duPont & TNG.**

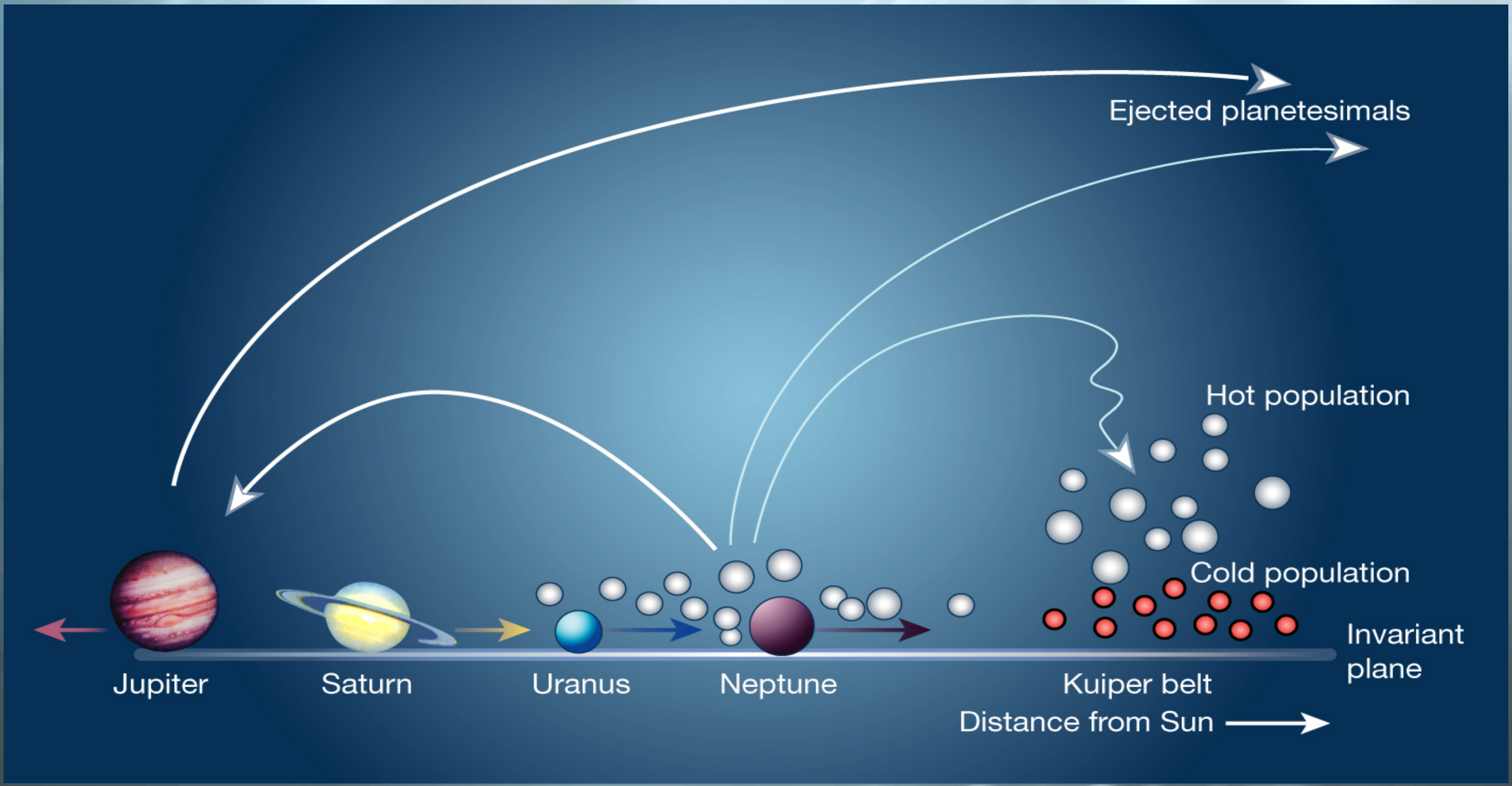
Outline

- Motivation & Background
- Survey Techniques
- Binaries
- Colors
- Variability/Lightcurves
- Summary & Implications

Take home messages:

- Objects in the Kuiper Belt can be used as tracers for planetary migration.
- The characteristics of Kuiper Belt objects can help us learn about the distribution of material in the original solar nebula.

A Schematic of Outer Solar System Formation



The “Nice” model. Figure from Gomes 2003, EMP and West 2003
Model: Series of papers by Morbidelli, Levison, Gomes, Tsiganis, 2005

Reflections on ~20 years of Kuiper Belt Astronomy

- Our planetary system is much larger than we had ever thought.
  - Alan Stern "It's akin to not having maps of the Earth that included the Pacific Ocean as recently as 1992!"
- Planetary locations and orbits can change over time.
  - KBO orbits are artifacts of planetary migration.
- Our solar system, and likely others as well, was very good at making small planets.
  - Many KBOs, Centaurs, Comets and Asteroids

Thanks for listening. Questions?