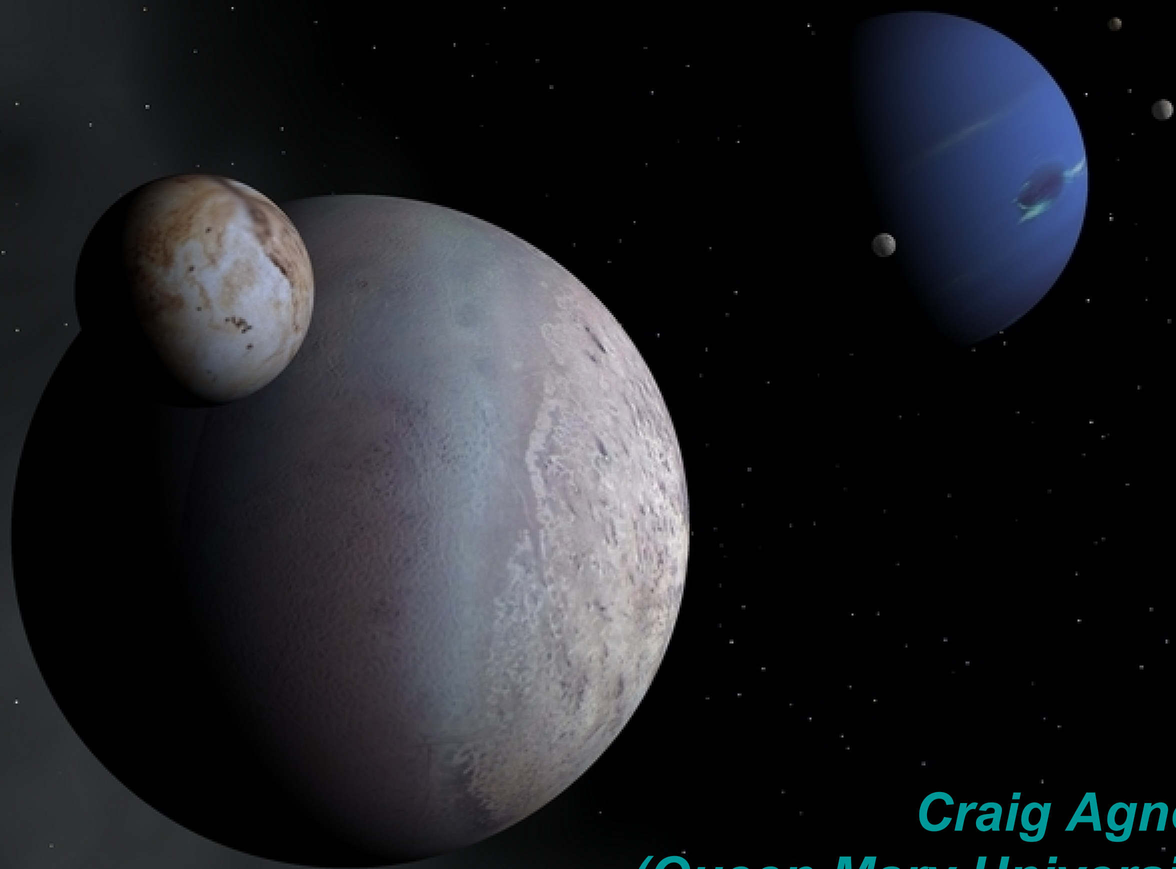
Satellite Origin and Evolution via Three-body Encounters



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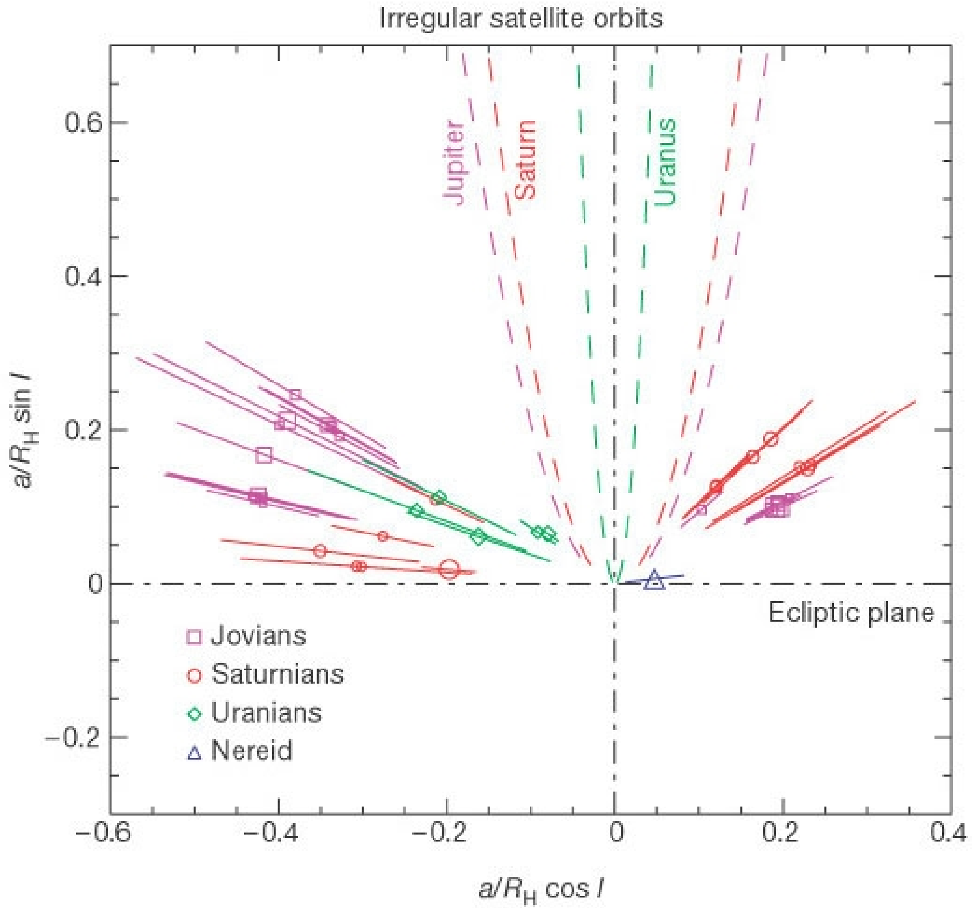
Irregular Satellites

- In the last decade over100 irregulars have been discovered.
- Distant eccentric & Inclined orbits about planet
- R~10^2 km and smaller
- Commonly considered captured objects



Burns et al. (2001)

Satellite Capture – the Basics

- Orbital Energy

$$E = \frac{1}{2}v^2 - \frac{GM_p}{r}$$

- Hyperbolic Encounter Orbit

$$E = \frac{1}{2}v_\infty^2$$

- Bound Satellite Orbit

$$E = -\frac{GM_p}{2a}$$

- Capture Mechanisms
  - Pull down (Heppenheimer & Porco)
  - Collisions (Columbo)
  - Gas drag (e.g. Pollack et al.1978)

Enabling Discoveries

- The Kuiper Belt (esp, large KBOs)
- Irregular satellites at each giant planet (e.g. Gladman, Holman, Sheppard)
- Improved understanding of giant planet formation and migration (e.g., core-accretion, Nice Model)
- Binary asteroids and KBOs

Three-body encounters are common

Close Encounters of the 3-body Kind

Basic types of encounters:

- Binary-Planet
- Planet-Planet with interlopers

Main Outcomes:

- Disruption of bound pairs
- Exchange of partners
- Creation of bound pairs

Neptune's Satellite System

Satellite	a_s/R_N	e	$I(°)$	R_s (km)
Naiad	1.9119	0.000	4.74	29
Thalassa	1.9851	0.000	0.21	40
Despina	2.0823	0.000	0.07	74
Galatea	2.4560	0.000	0.05	79
Larissa	2.9157	0.000	0.20	94
Proteus	4.6639	0.000	0.55	209
Triton	14.064	0.0004	156.834	1353
Nereid	218.56	0.7512	7.23	170
S/2002 N1	638.	0.43	114.9	27
S/2002 N2	884.	0.27	50.4	16
S/2002 N3	931.	0.36	35.9	18
c02 N4	995.			16
S/2003 N1	1890	0.49	125.1	18
S/2002 N4	1930	0.39	137.4	22

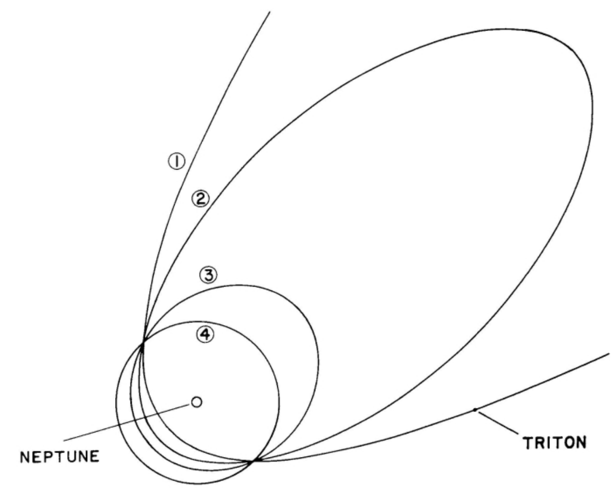
Post-Capture Tidal Evolution of Triton

- Tidal dissipation in Triton causes orbital decay

  $a_T < 2000R_N \rightarrow 14R_N$

  e_T: $1 \rightarrow 0$

  qT: $7R_N \rightarrow 14R_N$



- Post capture orbit was eccentric

- Large Inclination is preserved through tidal evolution

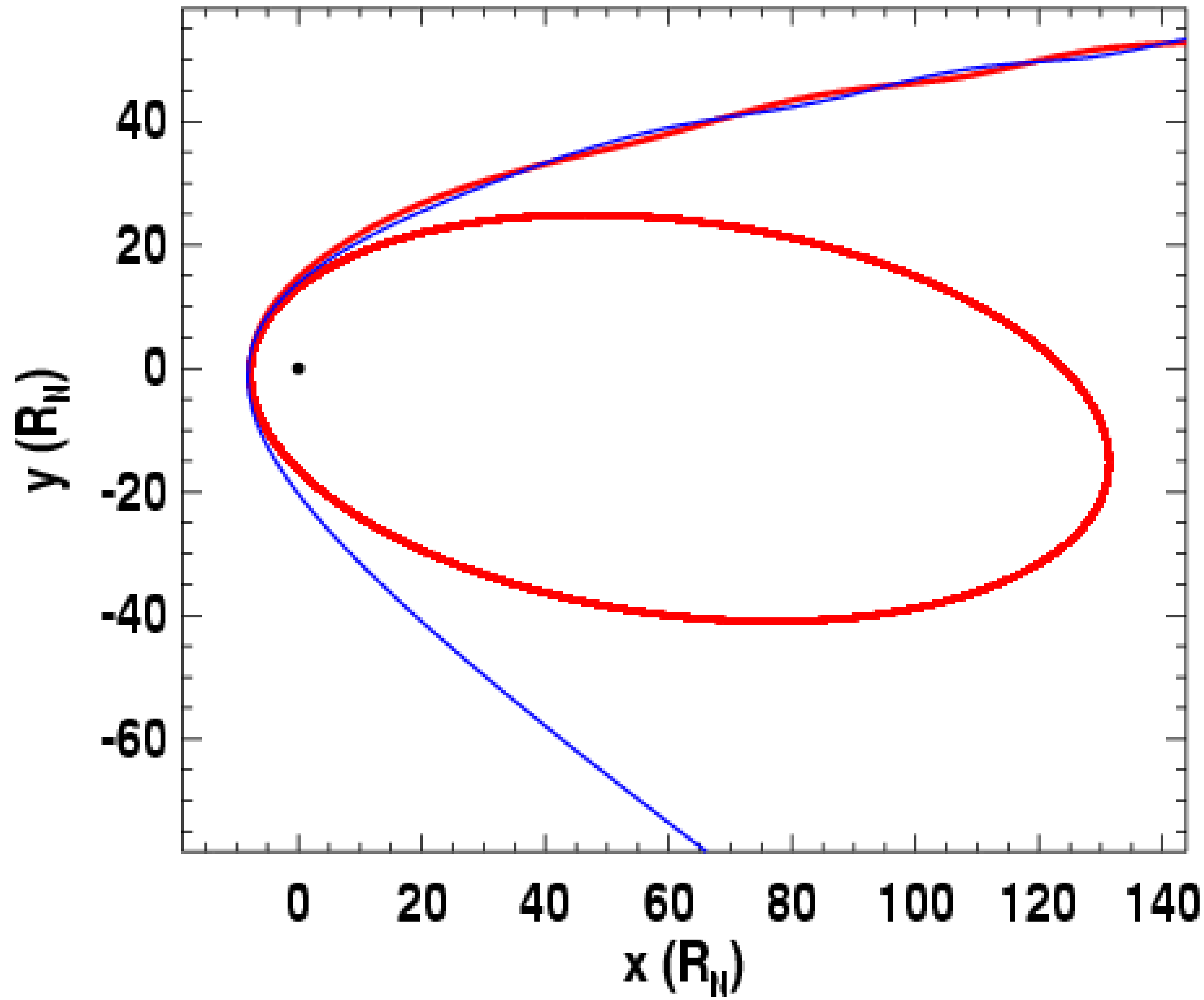
Binary Exchange Capture

Requirements

1. 3-body Binary-Planet Encounter
2. Disruption of the binary
3. An encounter velocity (v_∞) low enough for capture of one binary component.

Agnor & Hamilton 2006, Vokrouhlicky et al. 2008, Philpott, Hamilton & Agnor 2010, Gaspar et al. 2011

Binary Exchange Capture



Tidal Disruption Radius of Binaries

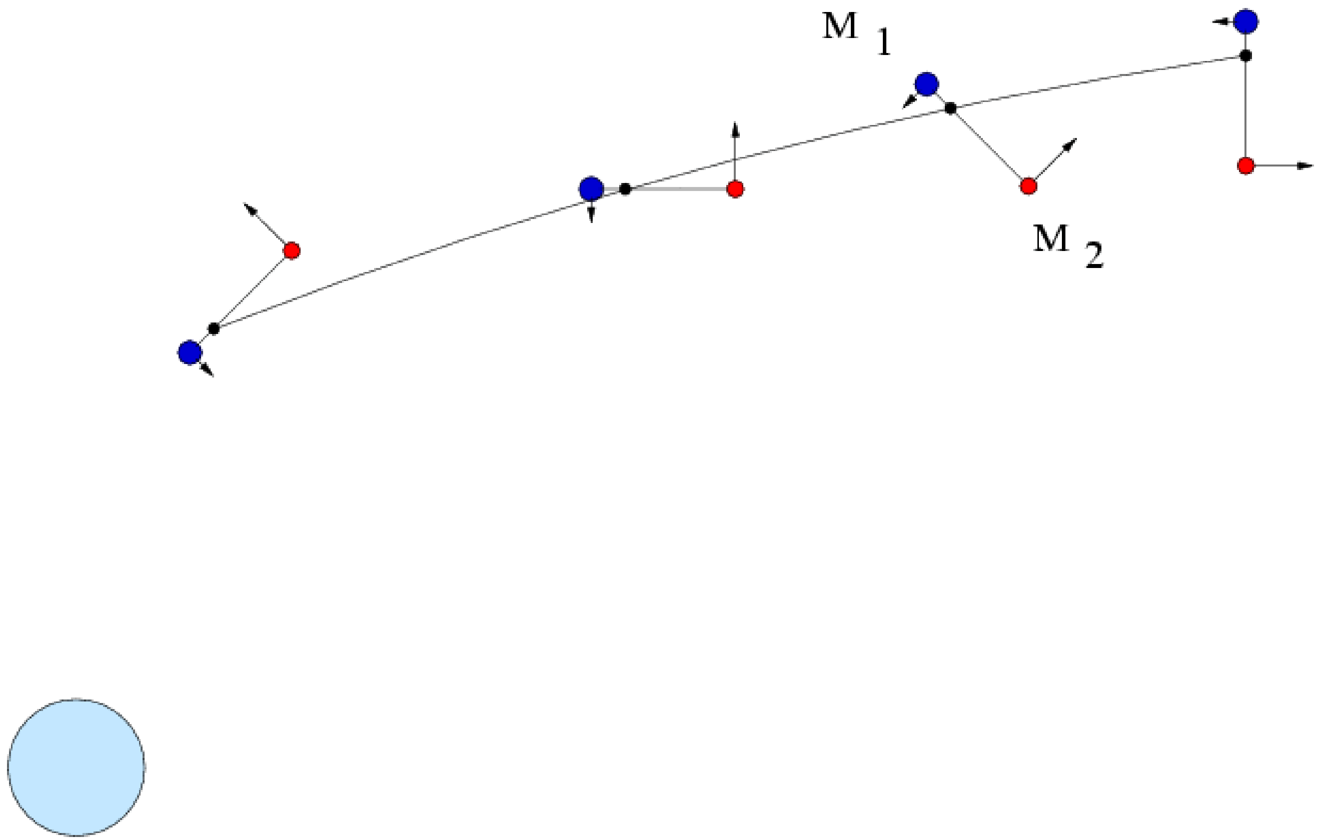
Roche radius of a single body (M_1)

$$R_{Roche} = R_P \left(\frac{3\rho_P}{\rho_1} \right)^{1/3}$$

Tidal disruption radius of a binary

$$r_{td} = R_P \left(\frac{a_B}{R_1} \right) \left[\left(\frac{3\rho_P}{\rho_1} \right)^{1/3} \left(\frac{1}{1 + M_2 / M_1} \right)^{1/3} \right]$$

Impulse Approximation



Impulse Capture Model

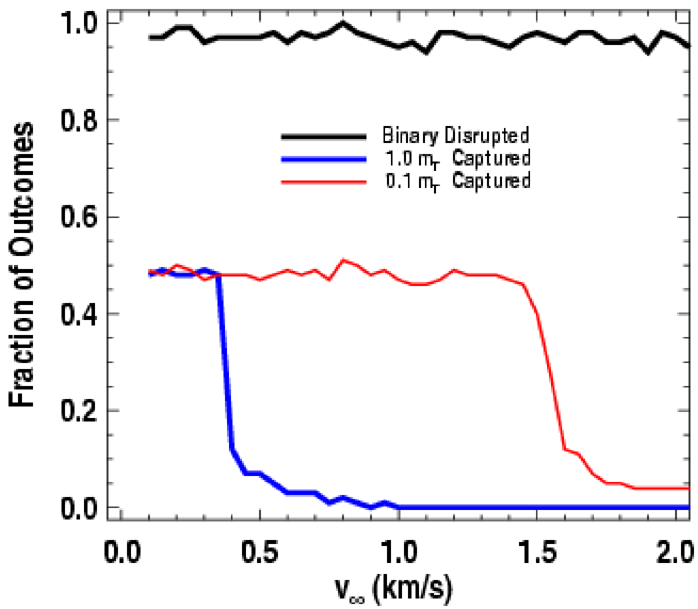
Speed decrease required for capture

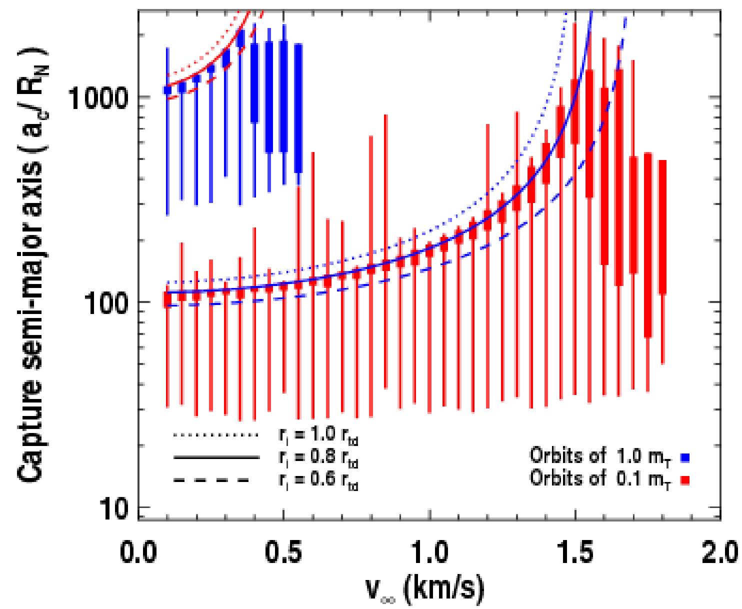
$$\Delta v_c = \sqrt{v_\infty^2 + \frac{2GM_p}{r}} - \sqrt{GM_p\left(\frac{2}{r} - \frac{1}{a_c}\right)}$$

Speed change from binary disruption

$$\Delta v_i \approx \frac{M_j}{M_i + M_j}\left(\frac{G\left(M_1 + M_2\right)}{a_B}\right)^{1/2}$$

Example Triton Capture: M_T - $M_T/10$





$M_1 = M_T$ $M_2 = M_T/10$ $a_B = 20R_1$ $e_B = 0$ $I_B = 0$ $q_{enc} = 8R_N$

Agnor & Hamilton (2006)

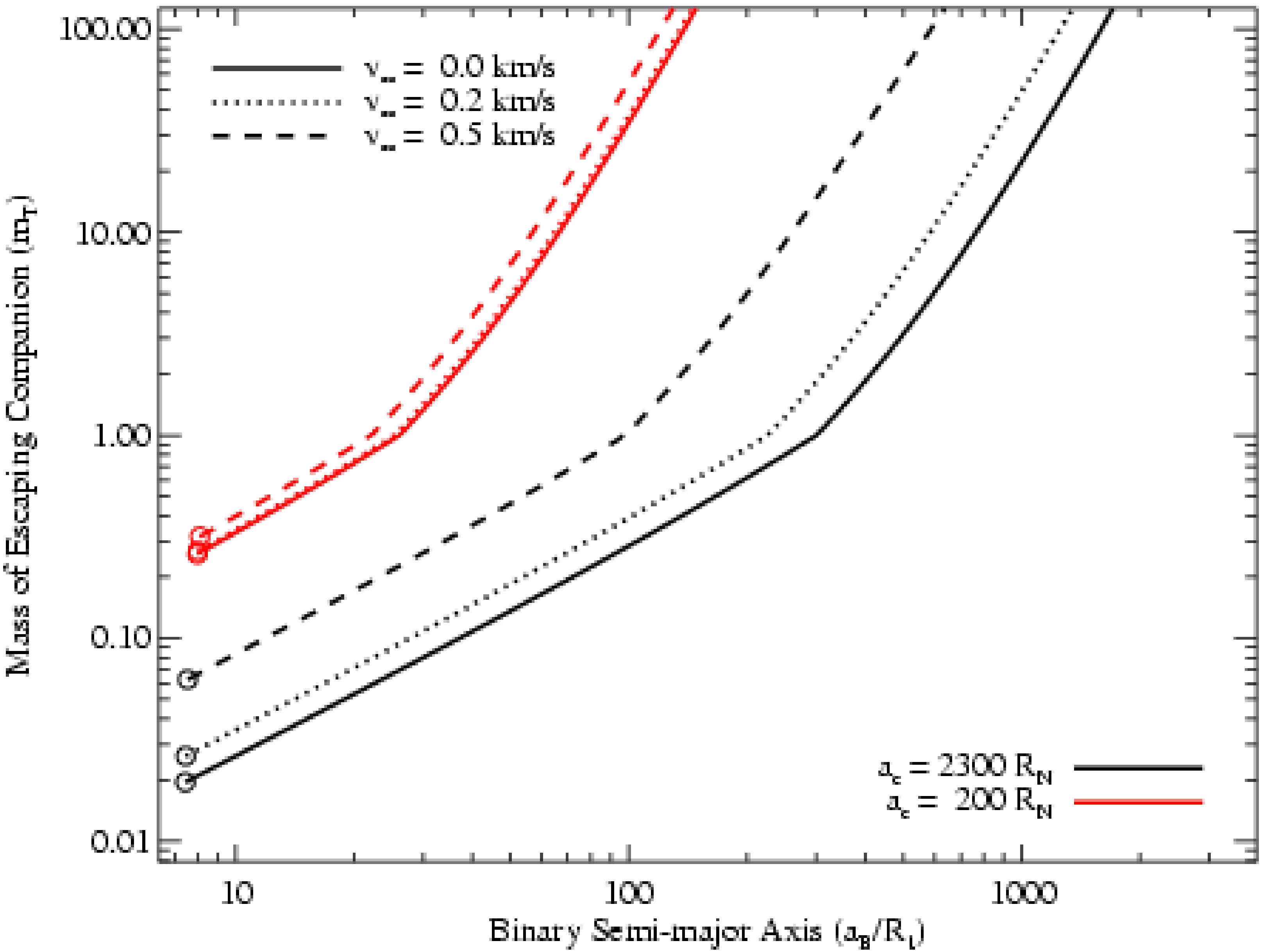
Estimating Binary Characteristics for Capture

- Simulations show that the pericenter of capture orbit is comparable to that of the encounter
  - $q_c \sim q_e$
- Disruption along capture orbit $r_{td} > q_c$ constrains binary semi-major axis.

$$\left(\frac{a_B}{R_1}\right) > \left(\frac{q_c}{R_p}\right)$$

- Describe the capture orbit with pericenter & eccentricity (q_c & e_c)
- We set $\Delta v_i = \Delta v_c$ and determine the mass of the escaping companion required.
- Disruption and capture at pericenter (q_c) allows
  - smallest Δv needed for capture
  - smallest a_B
  - smallest escaping companion mass (m_e)

Triton Capture Binaries



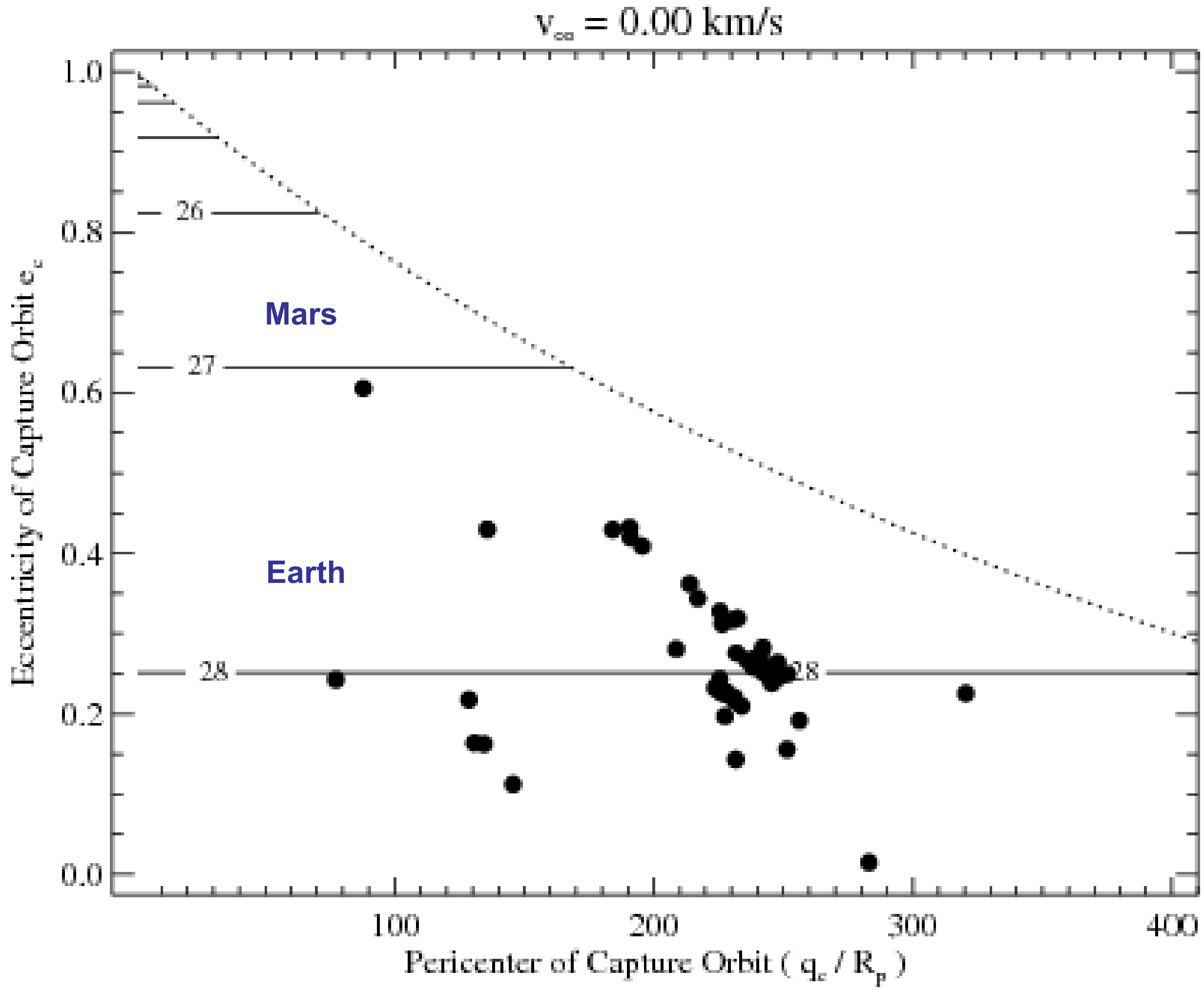
Jovian Irregulars

- For disruption

$$\left(\frac{a_B}{R_1}\right) > \left(\frac{q_c}{R_p}\right)$$

- Contour values indicate the logarithm of companion mass in grams

- Points show orbits of know irregulars

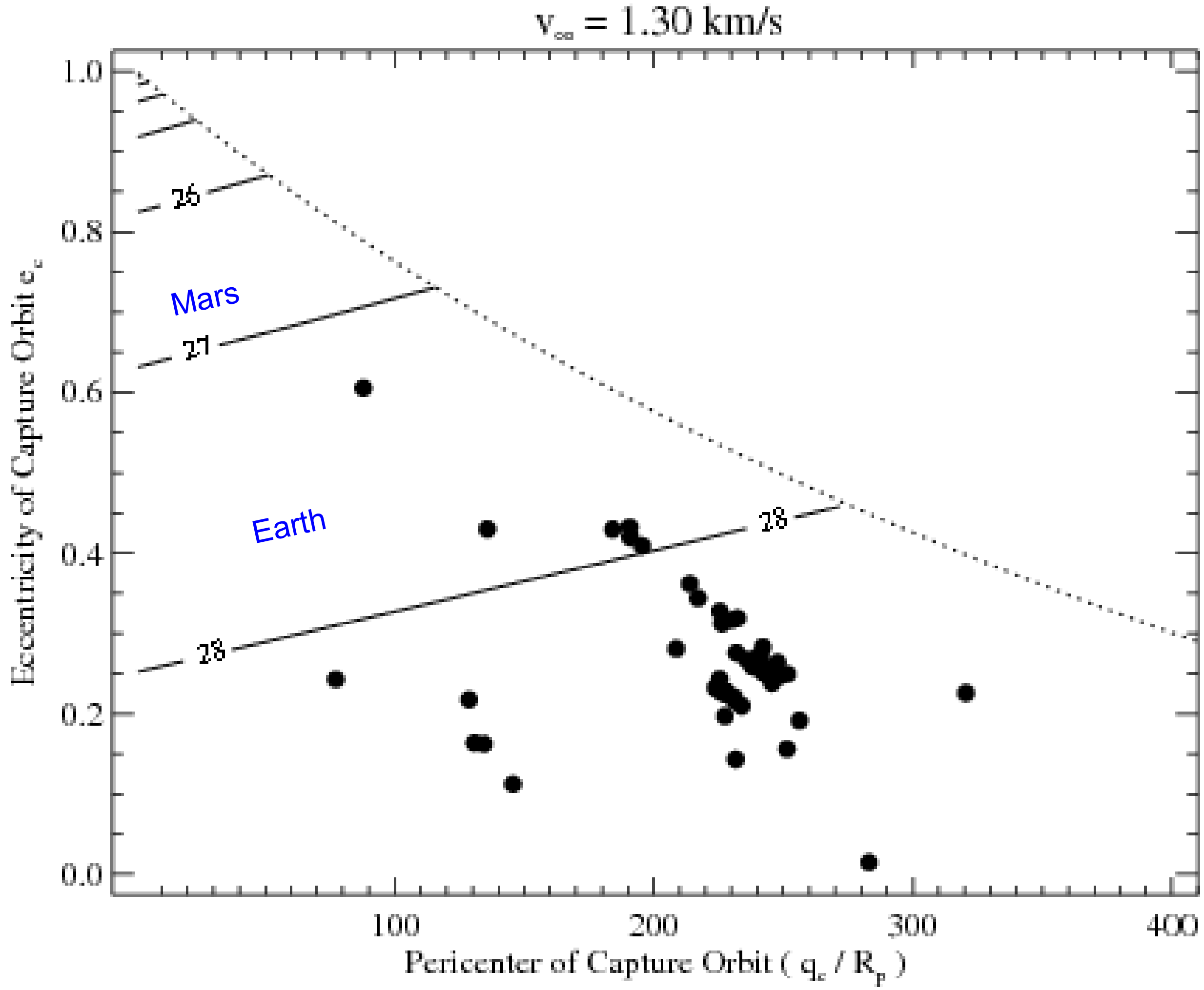


Jovian Irregulars

- For disruption

$$\left(\frac{a_B}{R_1}\right) > \left(\frac{q_c}{R_p}\right)$$

- $e \sim v_\infty / v_K = 0.10$



Capture via Binary-Planet Encounter

- smallest Δv is needed for capture to orbits with
  - small pericenters
  - Big orbits (large a & e)

Best Candidates are at Neptune!

- Triton $a_B/R_1 > 5$ $m_c > 10^{24}$ g (~$0.02M_T$) Includes binaries similar to Pluto/Charon (Agnor & Hamilton 2006)

- Nereid $a_B/R_1 > 45$ $m_c > 10^{25}$ g (~M_{Pluto}) Includes binaries similar to Pluto/Nix Pluto/Hydra.

- Nereid's eccentric orbit (e=0.75) may be an artifact of capture rather than from perturbations from Triton.

Capture of Irregulars

- Capture of distant irregulars directly to observed orbits requires:
  - $a_B/R_1 > 100\text{-}300$ (for binary disruption)
  - Jupiter $m_c > 10^{27} - 10^{28}$ g
  - Saturn $m_c > 10^{26} - 10^{27}$ g
  - Uranus $m_c > 10^{25} - 10^{26}$ g
  - Neptune $m_c > 10^{25} - 10^{26}$ g
- Capture directly to observed orbits involves exchanges of distant satellites between large planetary embryos and planets (i.e. swapping irregulars) …..

Capture First, Orbit Evolution Second

- Alternatively small mass binaries can facilitate capture to:
  - Small pericenter
  - Large orbits / eccentricity. (Philpott et al. 2010, Gaspar et al 2011)
- Post-capture eccentricity evolution is then required to deliver objects to observed orbits, by e.g.
  - gas drag
  - collisions
  - planet migration (Cuk & Gladman 2006)

3-body Capture & Planet Evolution

Giant Planet Formation:

- Low encounter velocity

  $V_\infty \sim 0$ km/s

Migration (e.g. Nice Model):

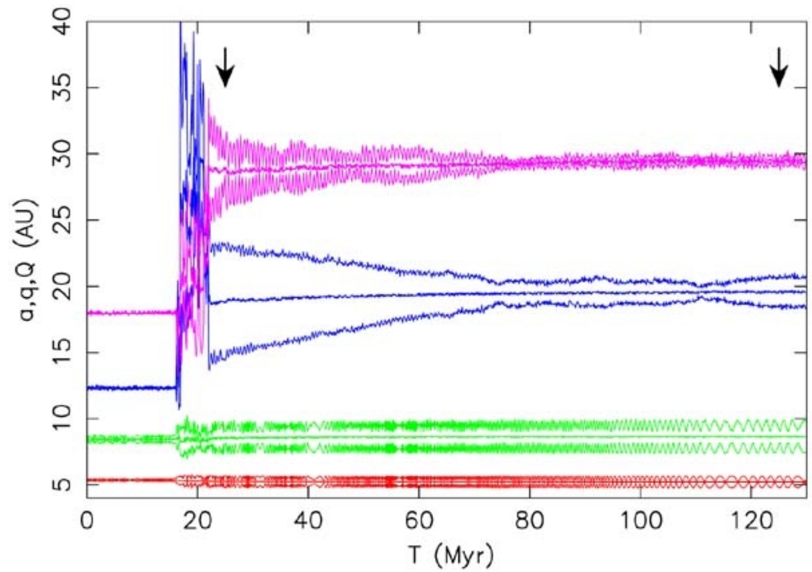
- Planet-Planet scattering (Nesvorny et al. 2007)

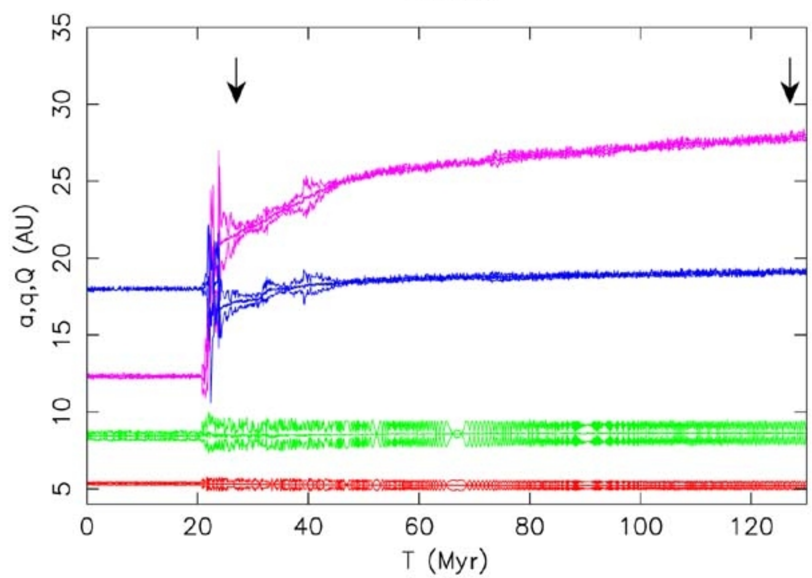
- Planetesimal-driven migration (Vokrouhlicky et al. 2008)

  binary-planet encounters

- Higher encounter velocity

  $V_\infty \sim 5$ km/s





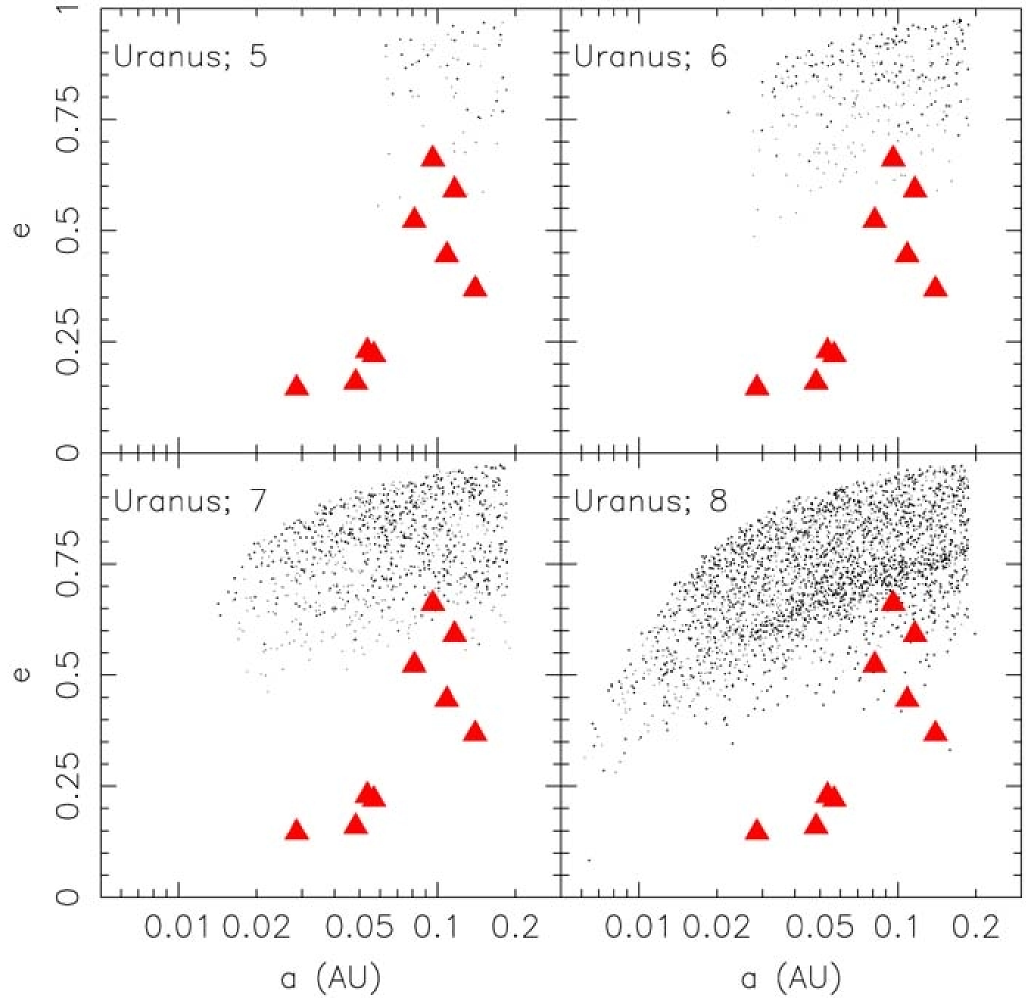
Capture During Planetesimal-Driven Migration

Vokrouhlicky et al. 2008

- Binary-planet exchange capture
- Assumed binary distribution
- Nice model encounters

Results:

- Capture efficiency is low
- Capture orbits are too eccentric



captured bodies observed irregulars

Capture During Planet-Planet Scattering

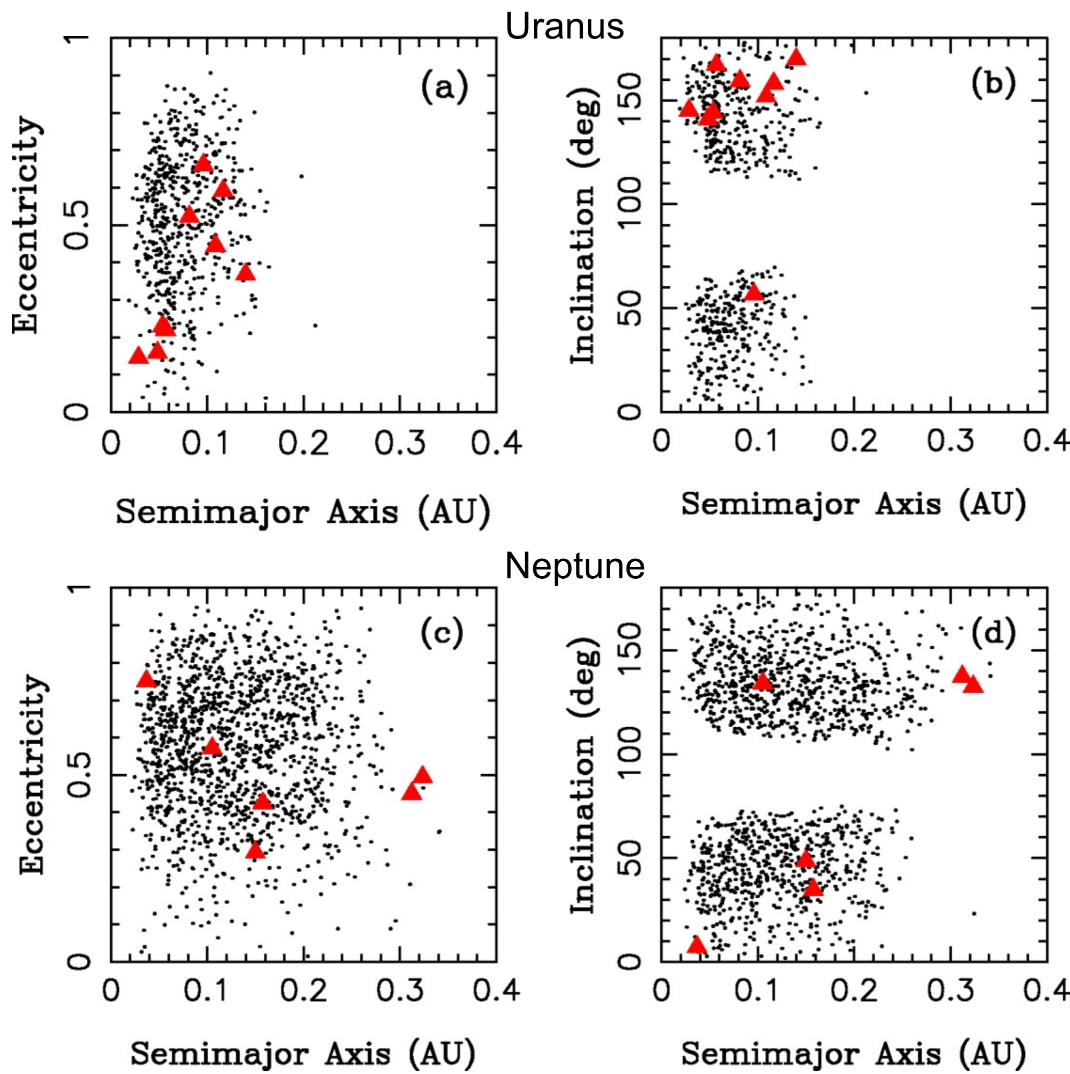
Nesvorny et al. 2007

- Planet scattering in a sea of planetesimals
- Use Nice model scattering dynamics

Results:

- Capture efficiency reasonable
- Capture orbits agree with observed irregs

All planets must be involved in scattering.



captured bodies observed irregulars

Summary

- In principal 3-body encounters can account for the capture of any satellite.

- Impulse model allows simple estimates of required encounter parameters needed for capture.

- Capture and survival of irregular satellites are very sensitive to late planetary evolution
    - ***the context for capture is the key***

- Three-body encounters offer a viable mechanism to explain the origin of irregular satellites, & Triton.

3-body Capture of Phobos & Deimos

- Three-body capture works in principal for the terrestrial planets.
- Capture orbit would be eccentric and inclined.
- The general challenges for a capture origin (high e, I) remain.
- It is difficult to conceive of Martian satellites as pristine captured asteroids.