FROM THE SCATTERED DISK TO THE OORT CLOUD

The Extended Scattered Disk

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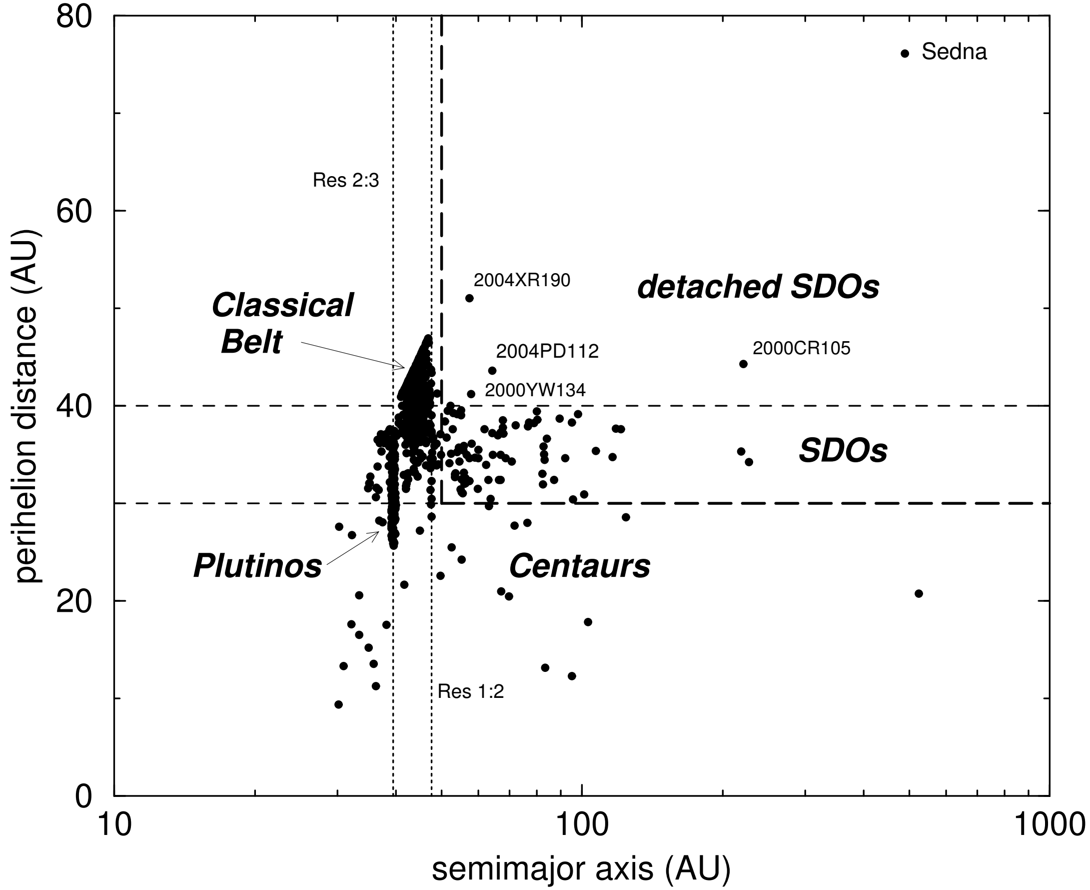
* The observed population
* Resonances among Scattered Disk Objects (SDOs)
* Dynamical evolution of SDOs - Some examples
* High-perihelion Scattered Disk Objects (HPSDOs) - Origin
* The diffusion to the Oort cloud - The Neptune barrier
* Conclusions

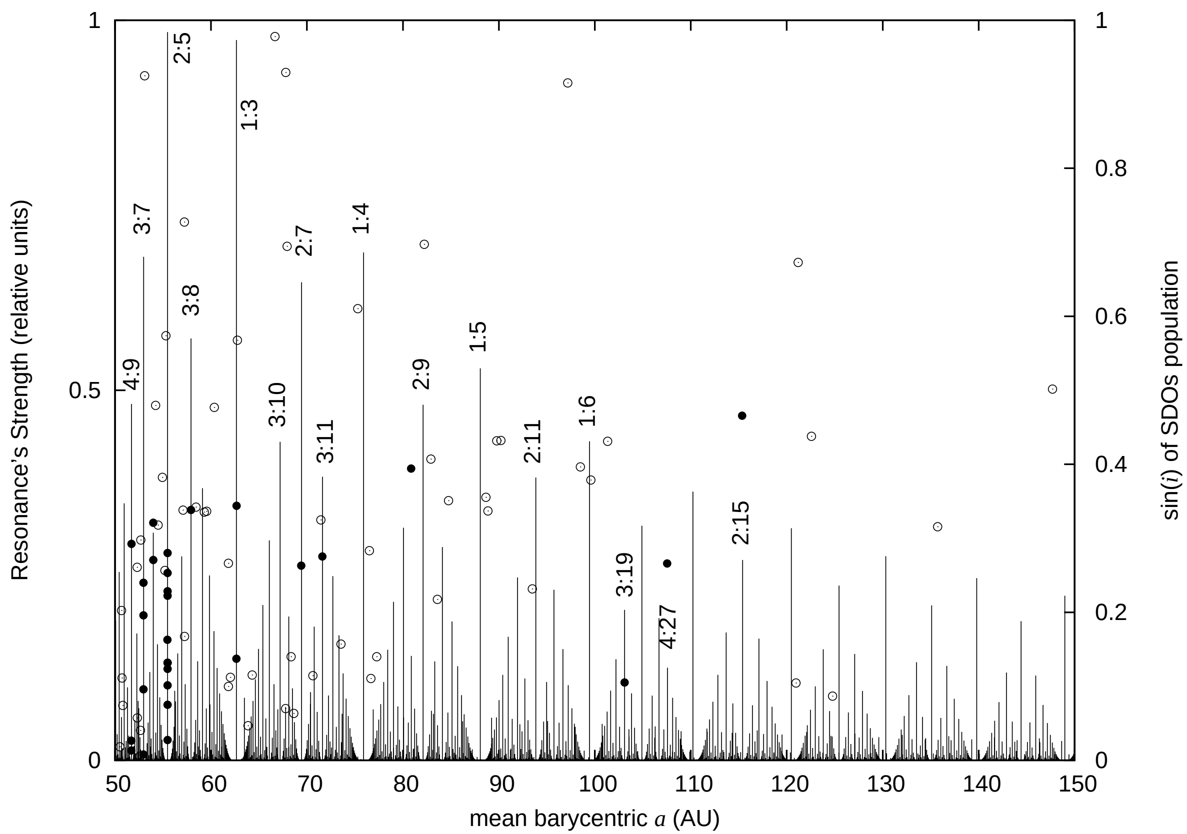
The Observed Population

82 SDOs discovered through June 2006



∗ Mass of the Scattered Disk $\approx 0.01 - 0.1$ $M_\odot$ (Trujillo et al. 2001; Delsanti & Jewitt 2006)

Resonances among SDOs



(Gallardo 2006)

∗ About 40% of the SDOs are found in MMR

∗ Inclinations higher than classical belt objects (highest $i = 46.7°$)

How the Scattered Disk formed?

∗ Diffusion from the classical belt:

(i) Instability region between $\sim 40 - 43$ AU due to overlapping of MMR and secular resonances (Duncan et al. 1995; Jones et al. 2006);
(ii) Diffusion from the chaotic borders of the 2:3 and 1:2 MMR (Nesvorný & Roig (2001);
(iii) Injection of fragments (1-10 km) from collisions (Davis & Farinella 1997; Stern and Colwell 1997)

∗ A fossil scattered disk after Neptune's migration (Gomes 2003)

Numerical simulations

Two models:

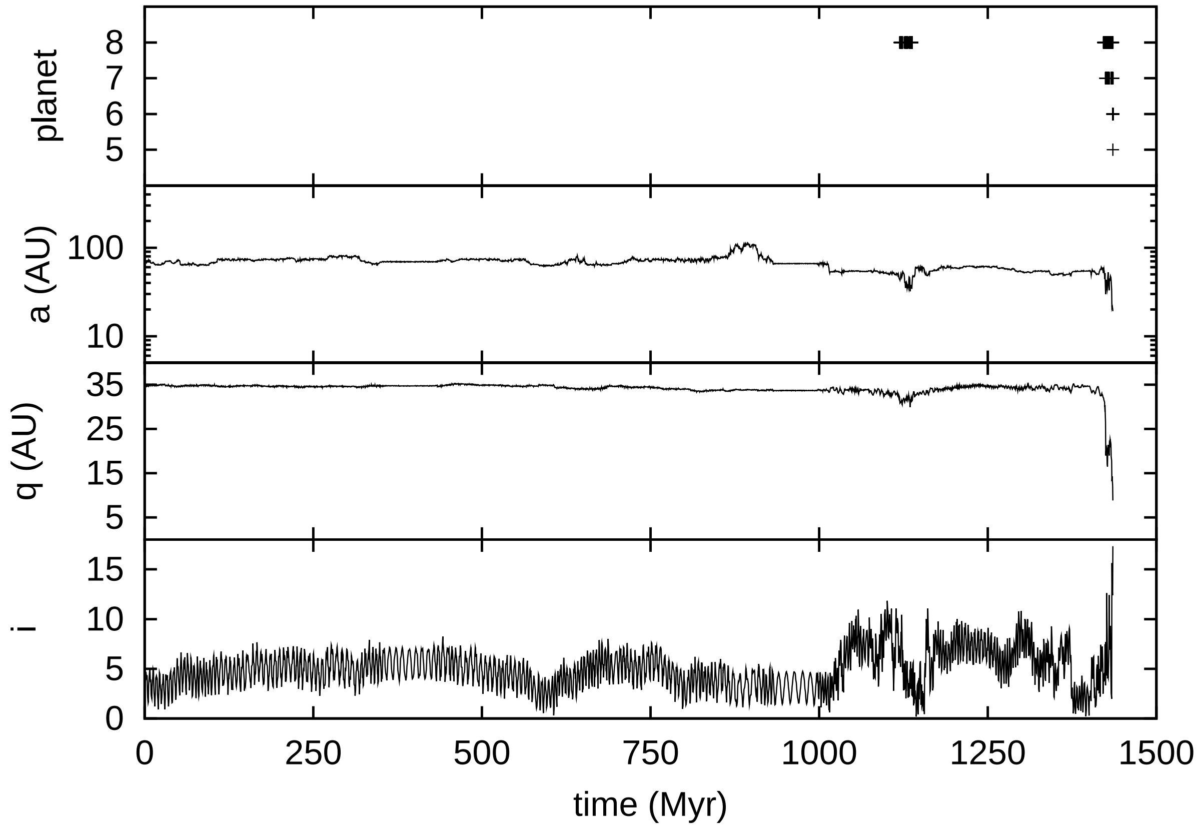
∗ *MODEL 1*

The observed population and their clones (399 objects) (Fernández et al. 2004)

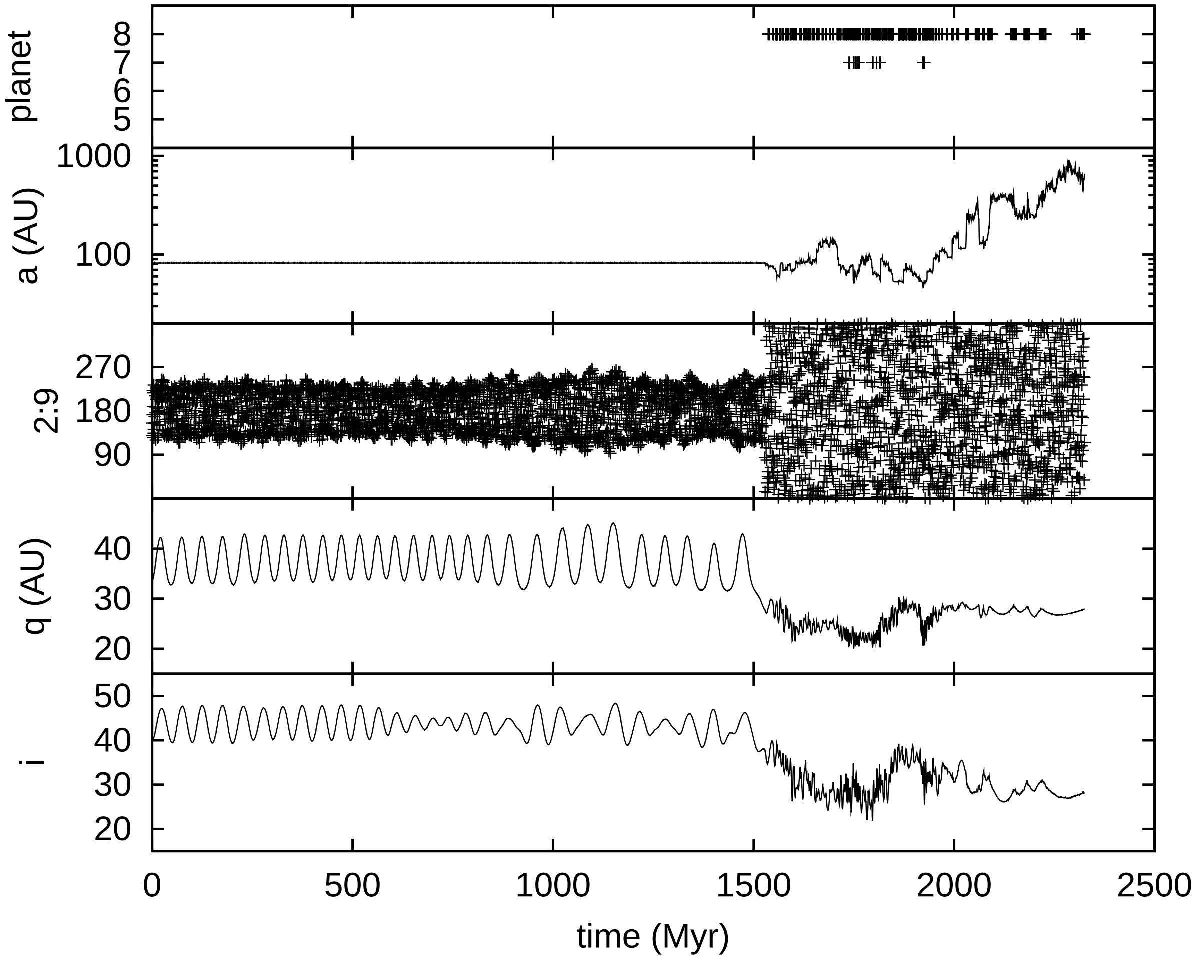
∗ *MODEL 2*

The migration model (an initial population of 10^4 planetesimals between 14 and 26 AU, and Jovian planets at distances 5.65, 8.2, 11.5 and 13.8 AU) (Gomes 2003; Gomes et al. 2005)

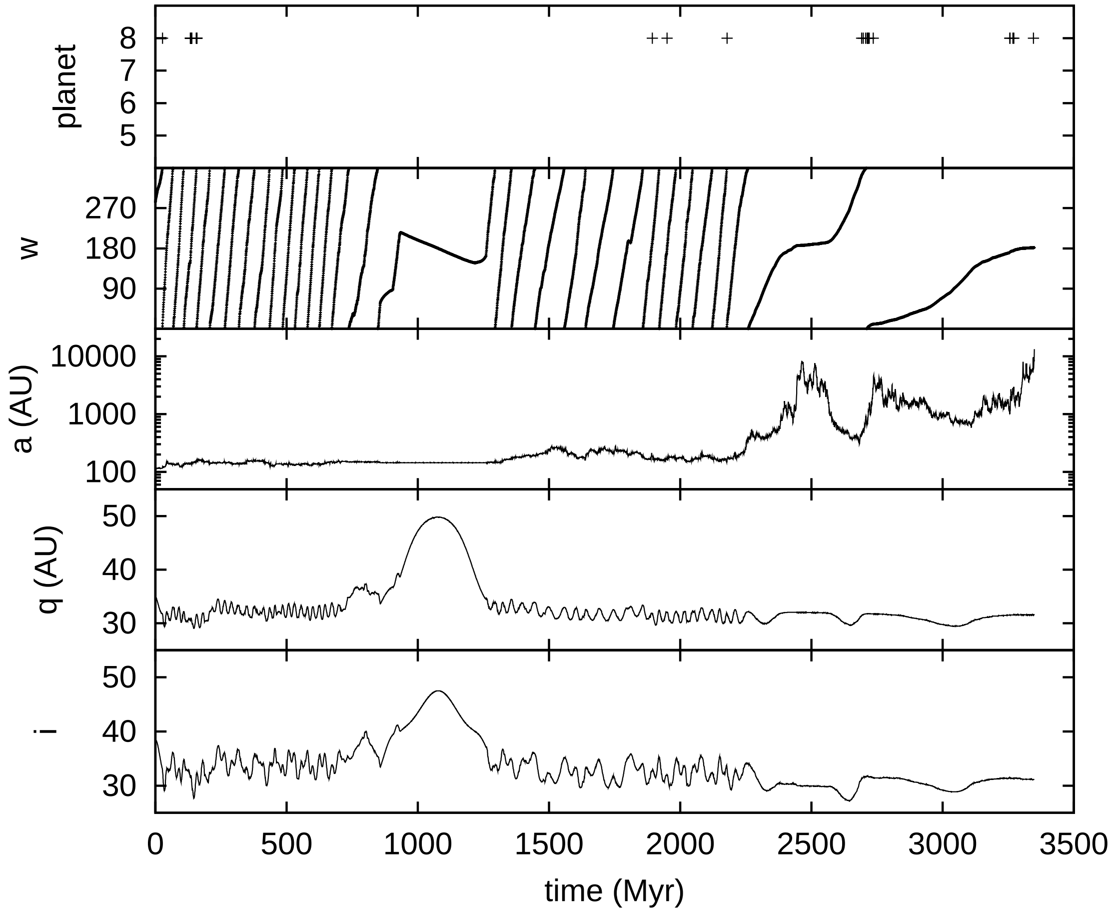
Dynamical evolution and different end states of SDOs



SDO 2002 GY_{32} that ends up in Jupiter's zone



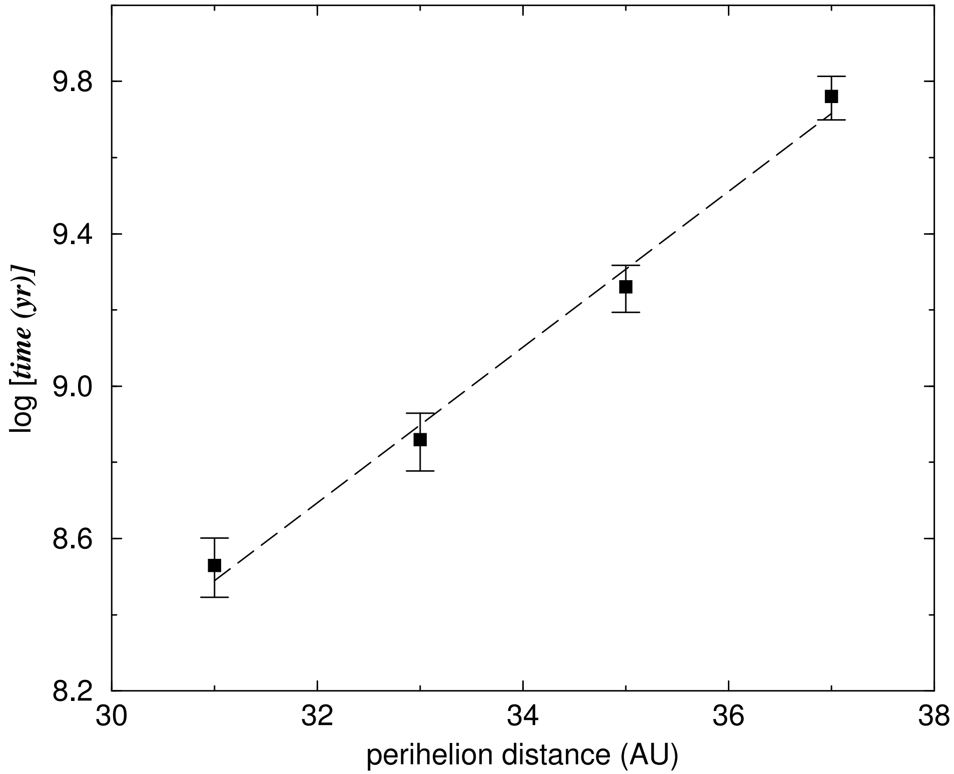
SDO 1999 DG_8 that ends up ejected in a hyperbolic orbit



SDO 1999 DP_8 that ends up in the Oort cloud

* $*$ q raises for a while by MMR+KR (Duncan & Levison 1997)

Dynamical lifetimes of SDOs

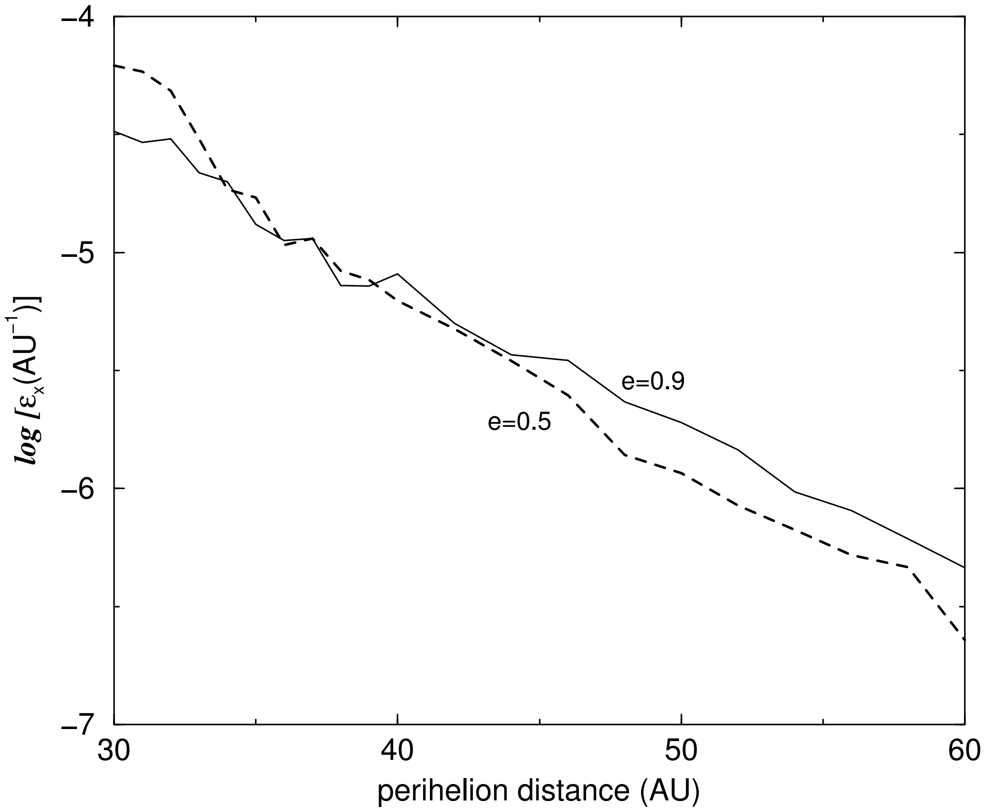


Dynamical half-life

$$t_{dyn} \simeq 10^{\frac{(q-33.5)}{4.7}} \text{ Gyr}$$

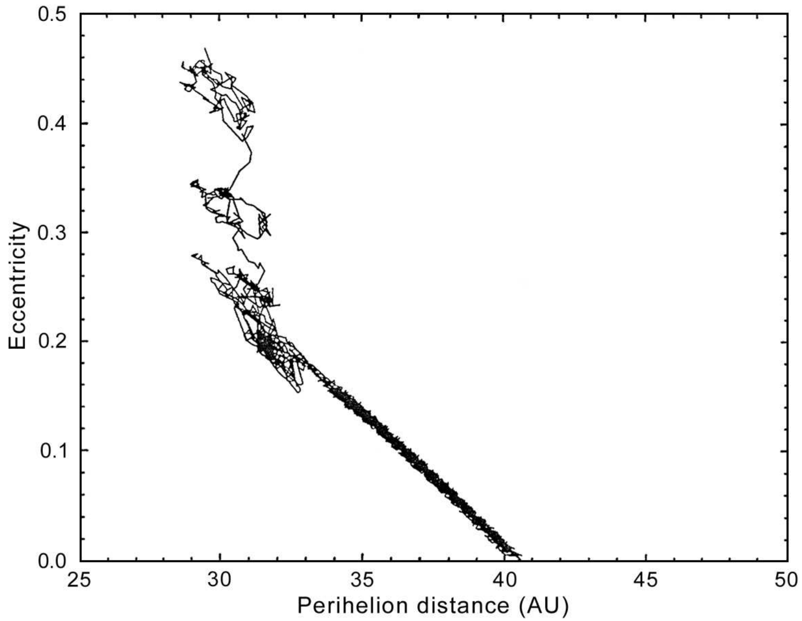
Average half-life for different q: $\bar{t}_{dyn} \sim 1.8 \times 10^9$ yr

Typical energy changes per orbital revolution



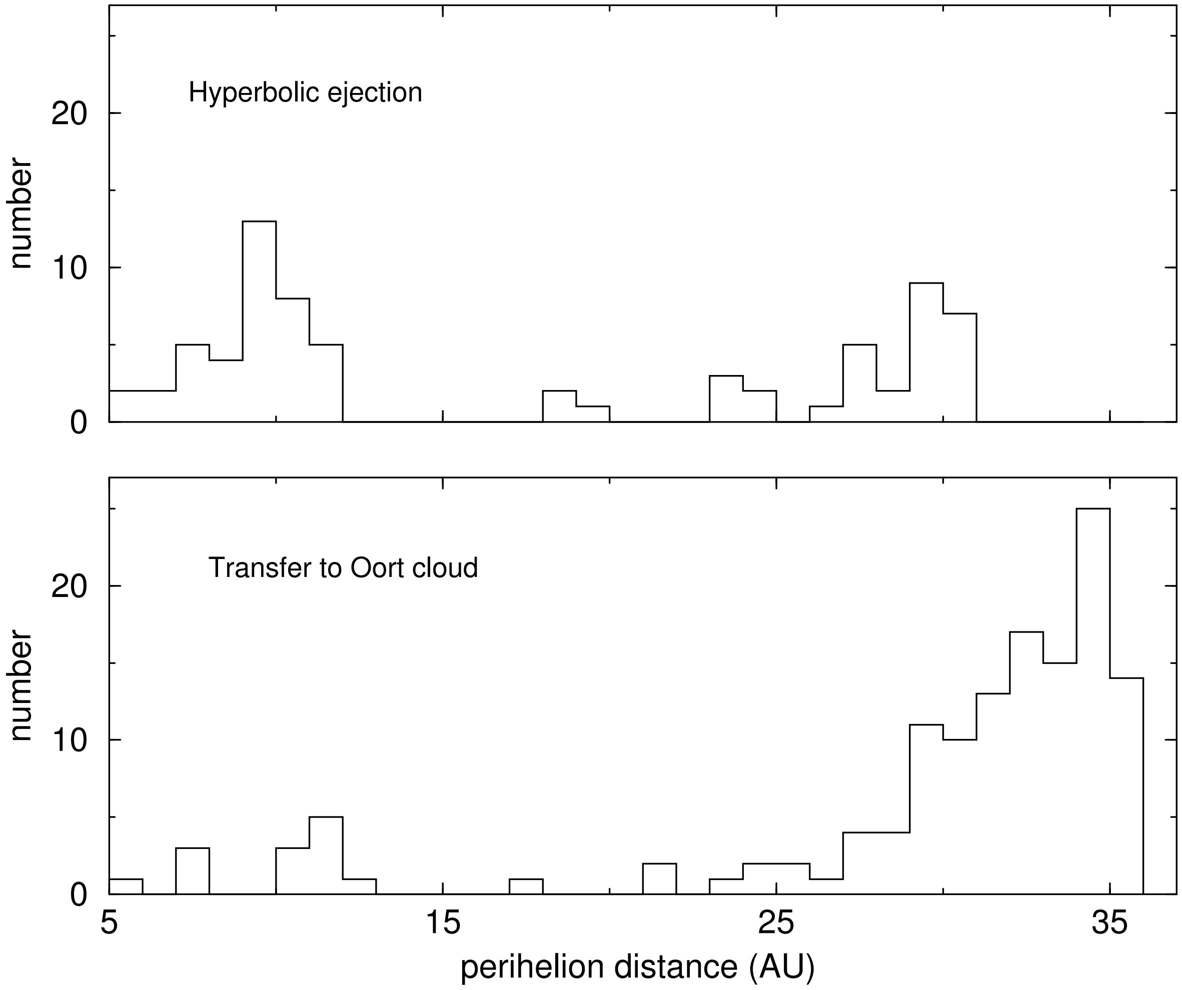
The Neptune barrier

∗ Two competing process: decrease of q vs. diffusion of a.
∗ At first, as q decreases, e increases keeping a more or less constant (Holman & Wisdom 1993).
∗ But when the body approaches Neptune, it will be most likely scattered outward
∗ About 60% of the bodies scattered outward have perihelia beyond Neptune's orbit ($31 < q < 36$ AU) at the moment of reaching the Oort cloud

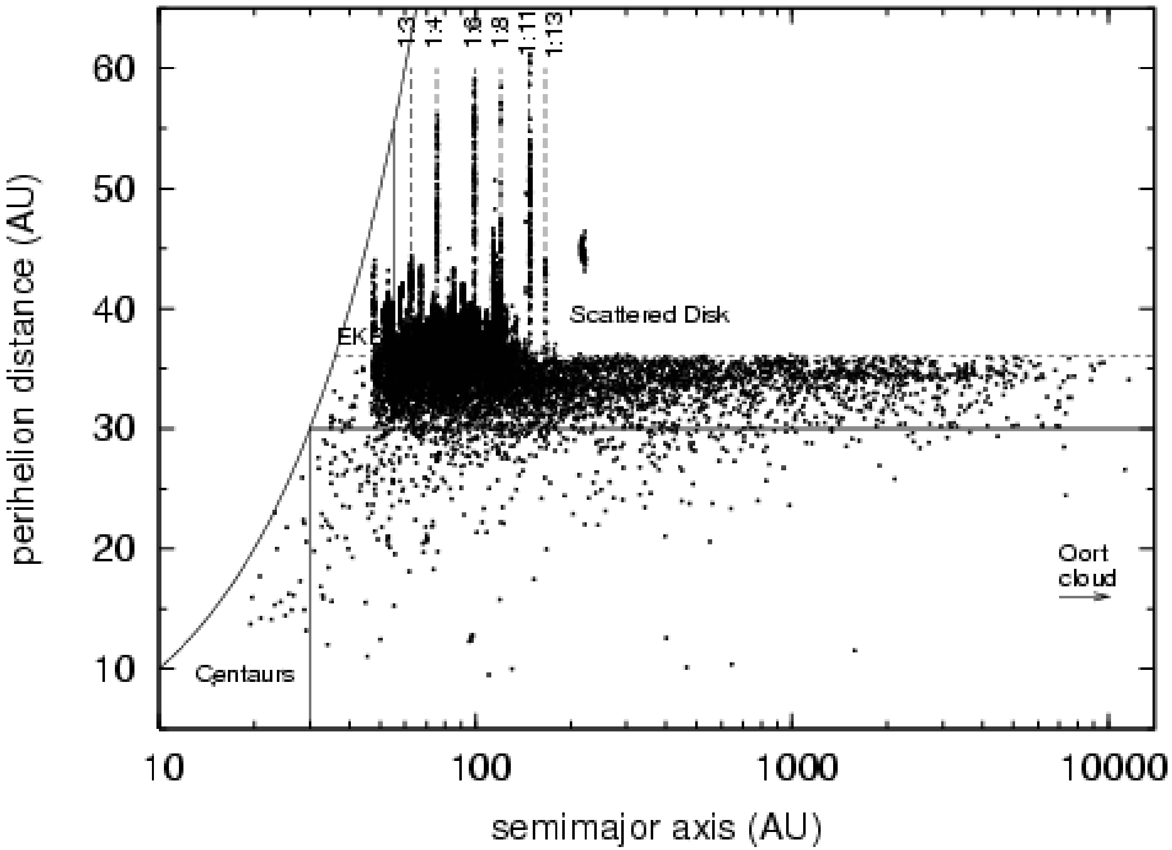


(Holman & Wisdom 1993)

Histogram-distributions of the perihelion distances of SDOs when they reach the end states indicated in the figures

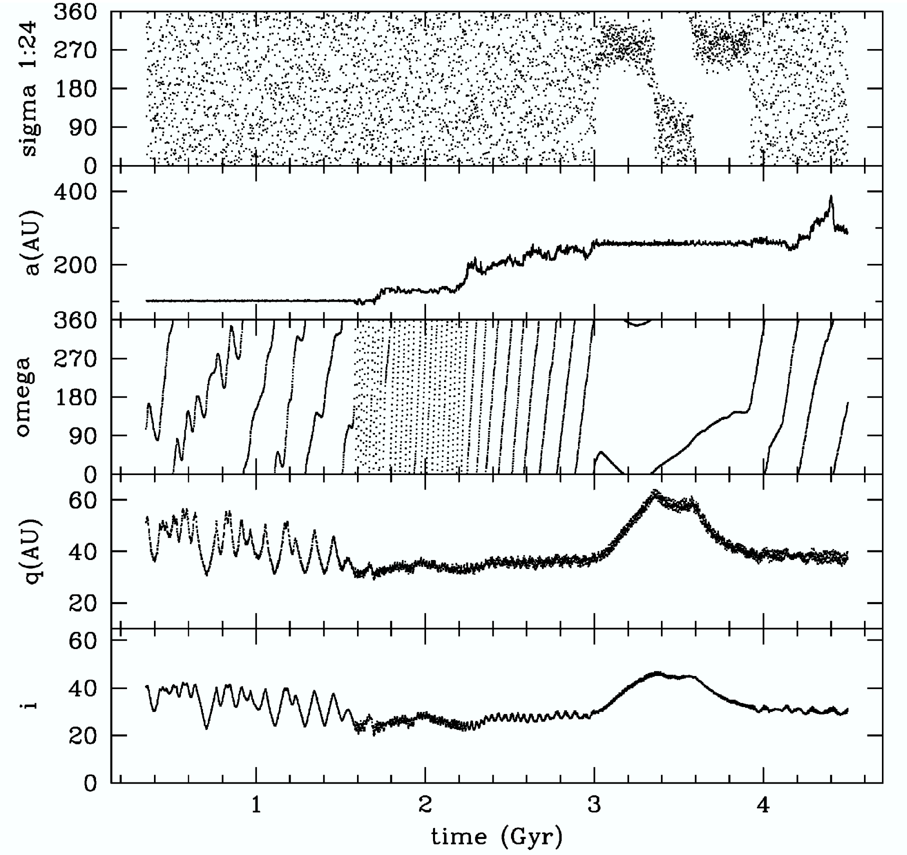


Scattering to the Oort cloud



* No objects with $q > 36$ AU are found to diffuse to the Oort cloud
* Current injection rate of SDOs to the Oort cloud: 5 yr^{-1}

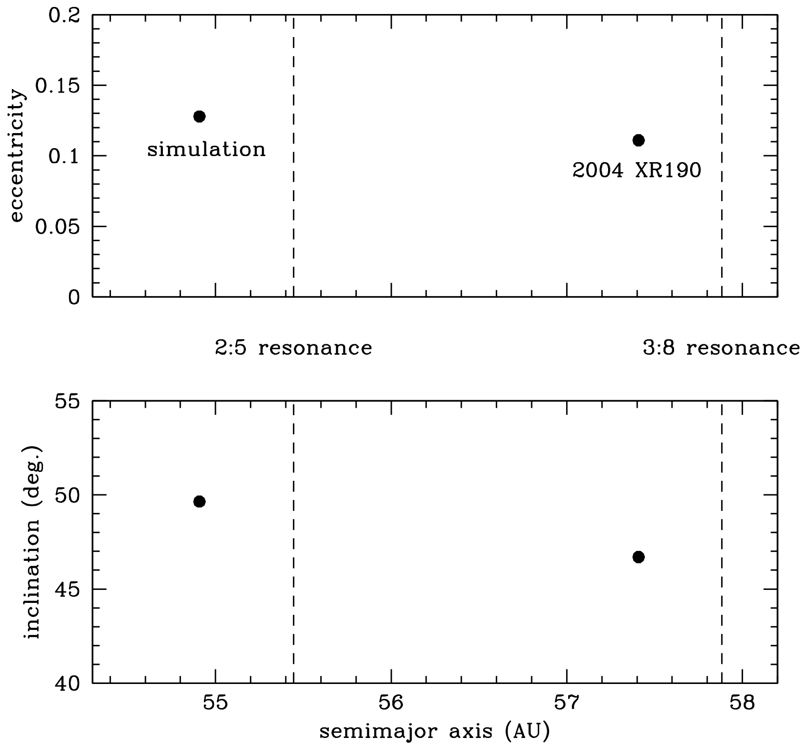
The formation of a high-perihelion scattered disk



Orbital evolution of a fictitious body temporarily trapped in the 1:24 MMR with Neptune. The Kozai resonance also works to raise the perihelion to ~ 64 AU (Gomes et al. 2005)

The case of 2005 XR_{190}

Anomalous SDO in a low-eccentricity orbit : $q = 51.03$ AU, $a = 57.4$ AU, $i = 46.7°$

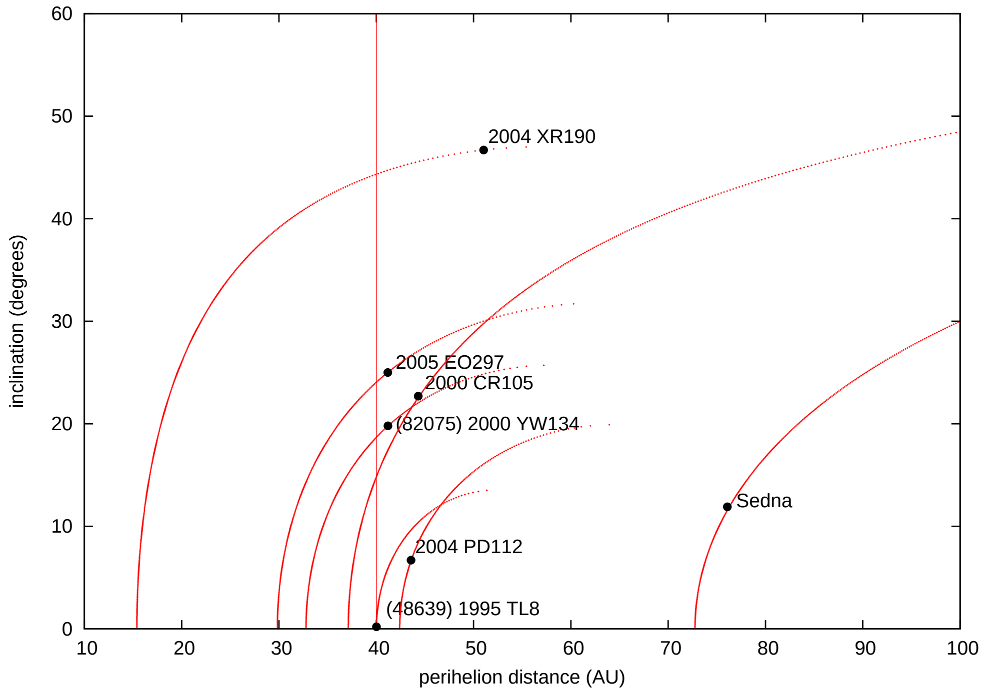


The Kozai resonance

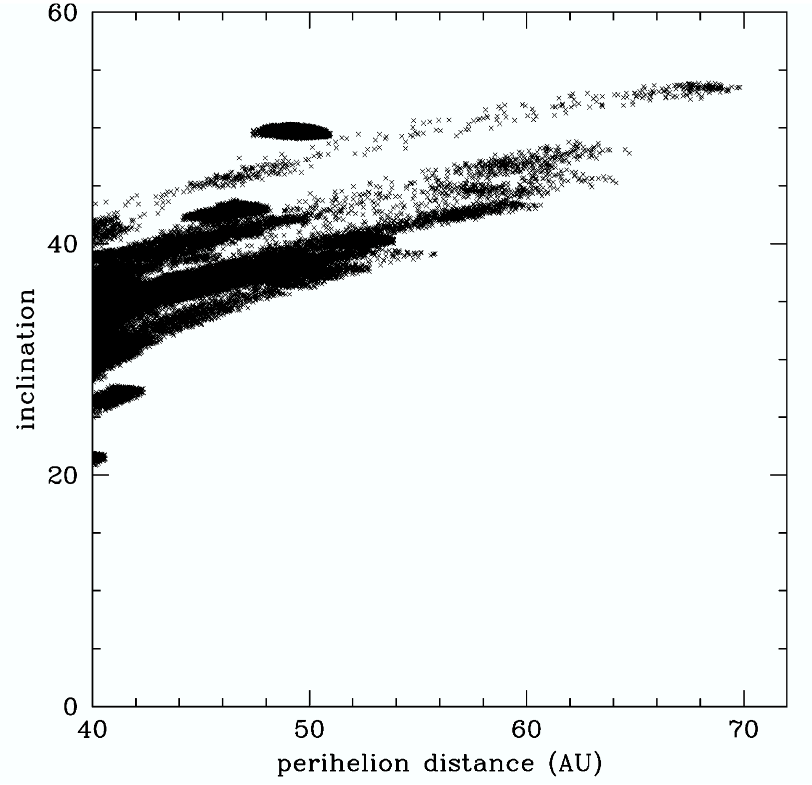
Conditions:

$*$ $H = \sqrt{1-e^2}\cos i$, $H =$ constant

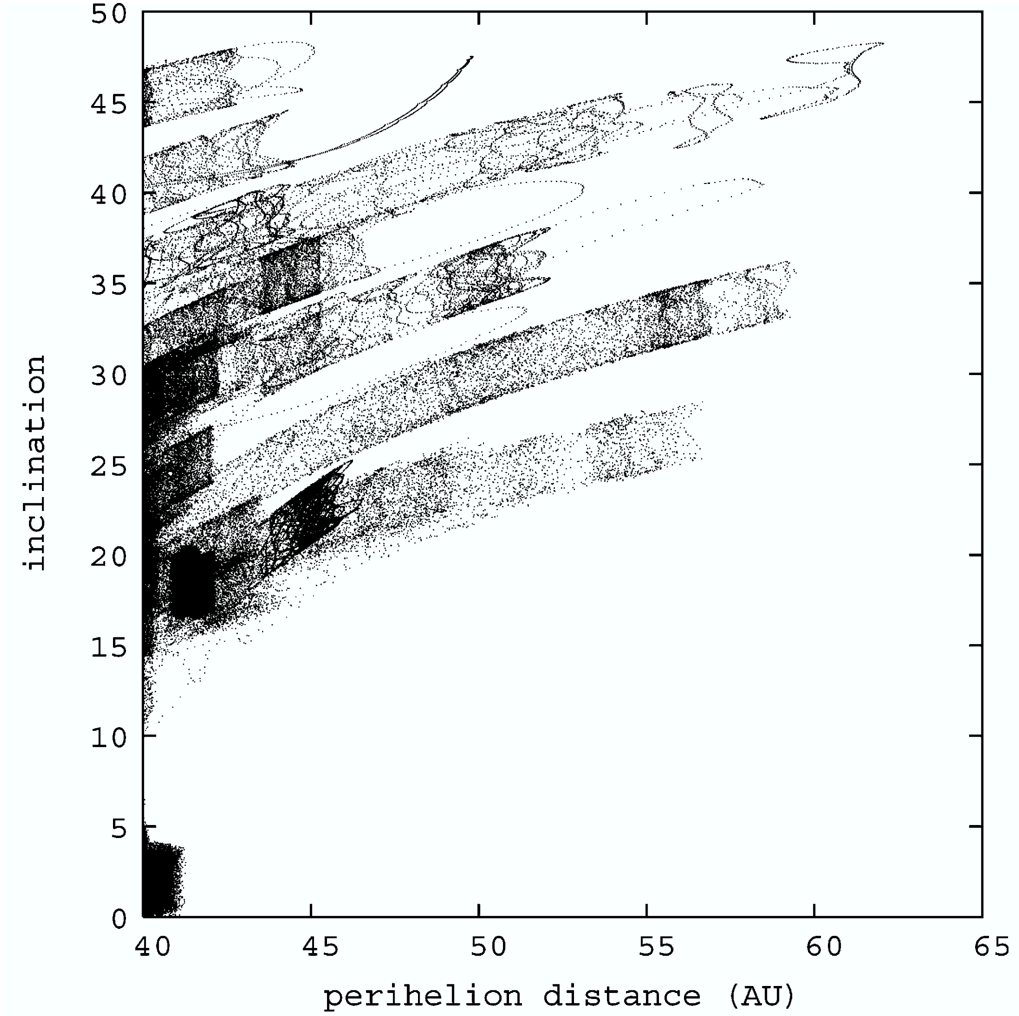
$*$ Mean a constant



Distribution of perihelion distances and inclinations

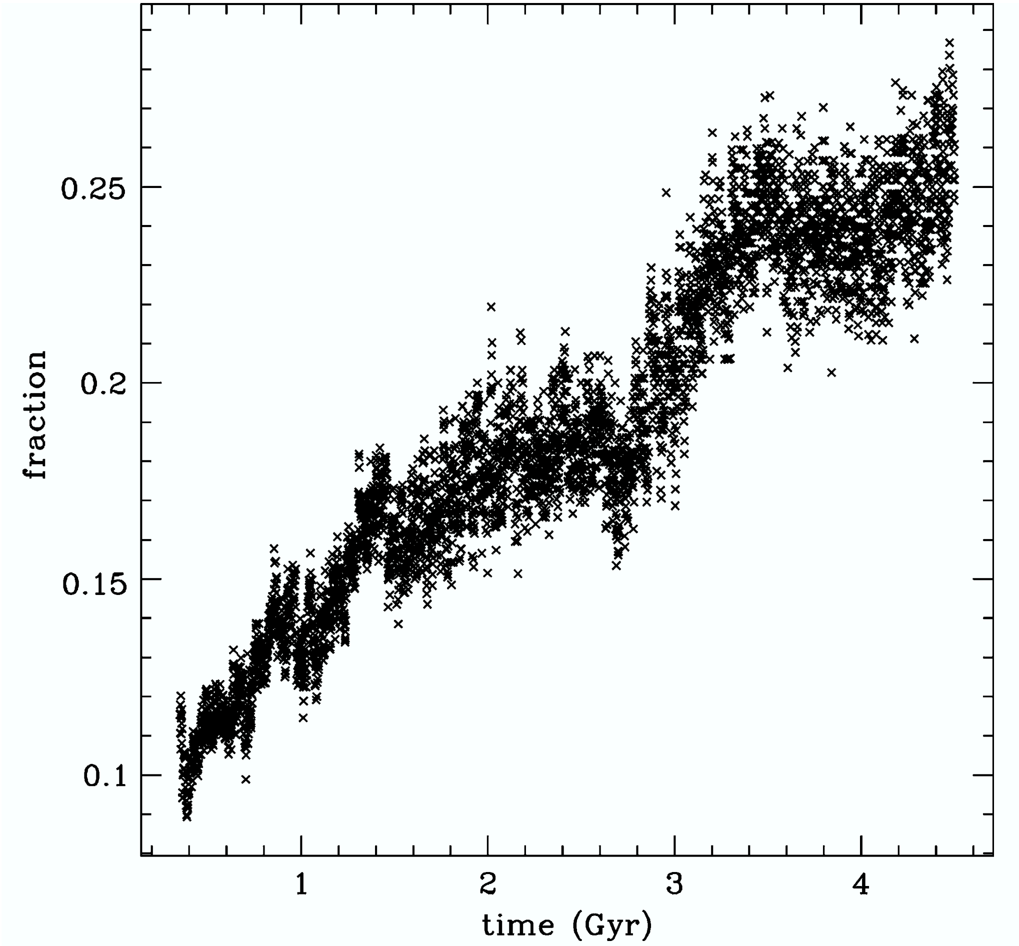


Model 1

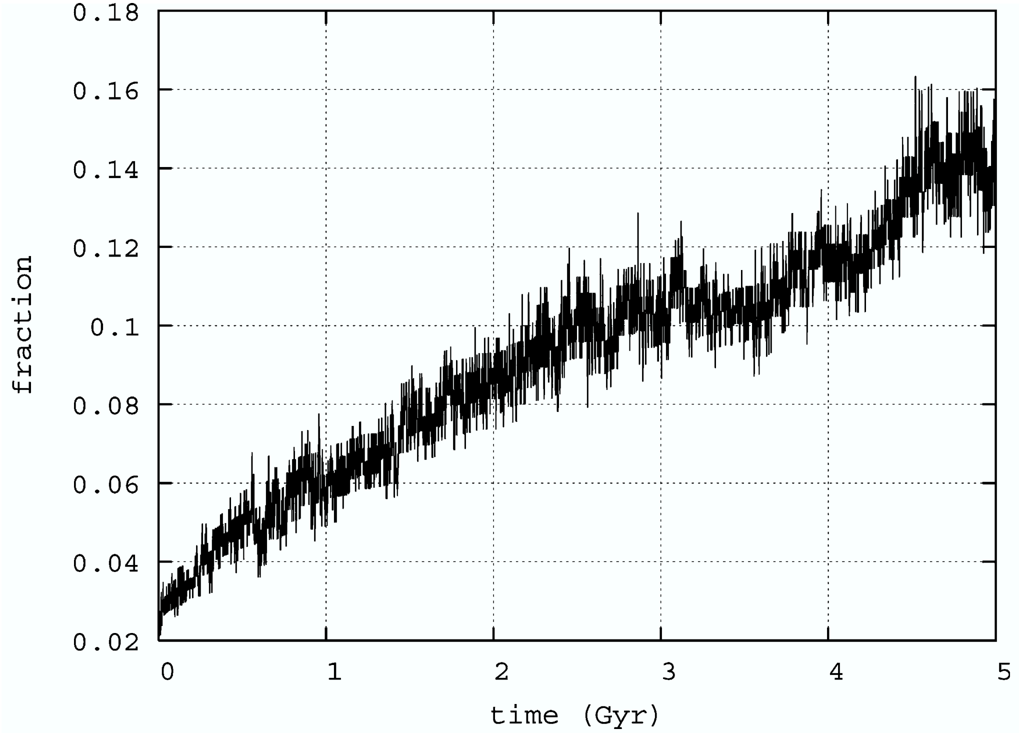

inclination
perihelion distance (AU)
0
5
10
15
20
25
30
35
40
45
50
40
45
50
55
60
65

Model 2

Fraction of HPSDO with respect to the total surviving population



Model 1



Model 2

Do MM + Kozai resonances explain all the HPSDO?

Almost all .... but not Sedna and, perhaps, 2000 CR_{105}

High-Perihelion Scattered Disk Objects

Object	q (AU)	a (AU)	i
2000 CR_{105}	44.3	221	22.7
2000 YW_{134}	41.2	57.9	19.8
2003 VB_{12} (Sedna)	76.1	489	11.9
2004 PD_{112}	43.6	64.3	6.7
2004 XR_{190}	51.0	57.4	46.7
2005 EO_{297}	41.2	63.0	25.0

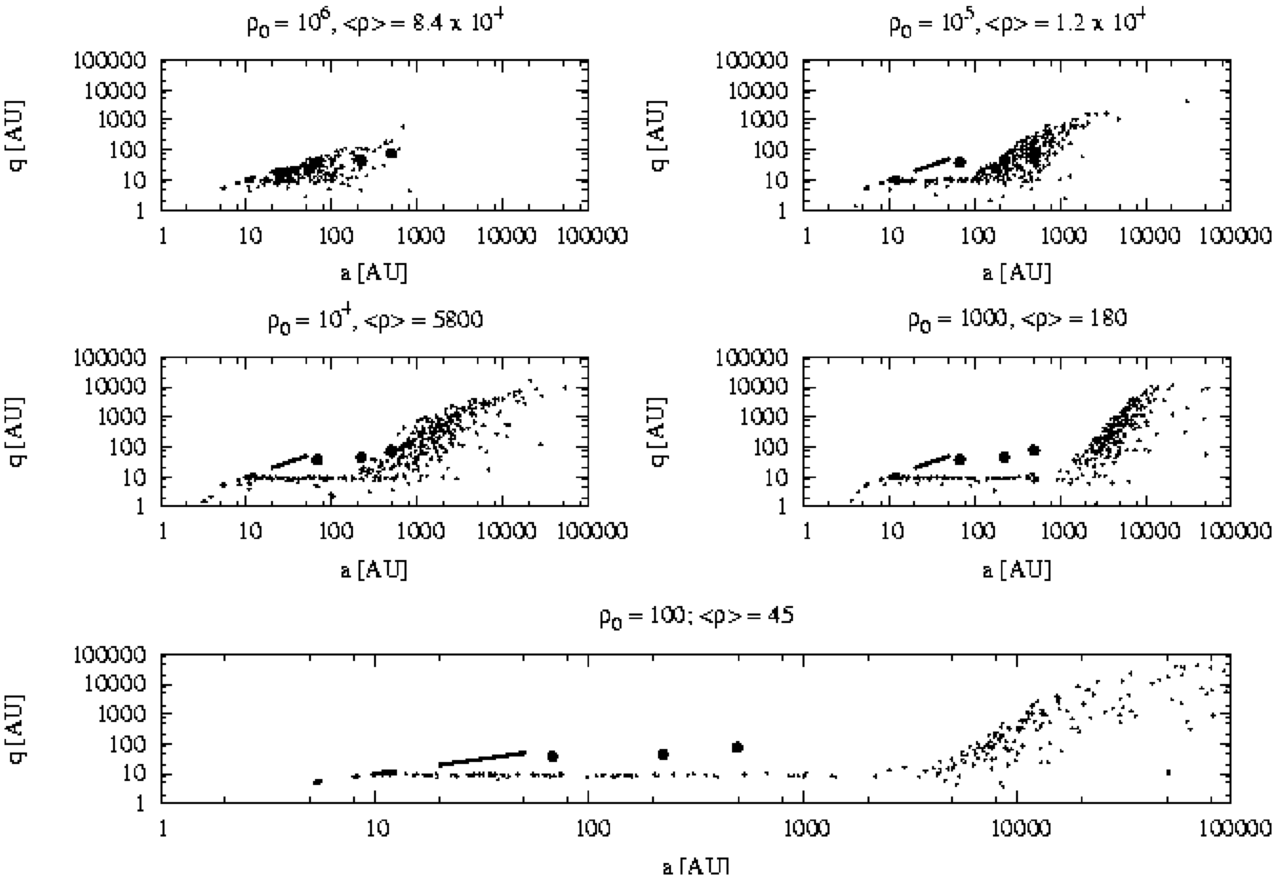
Alternative explanations:

∗ Sun birth in a star cluster

∗ Solar companion

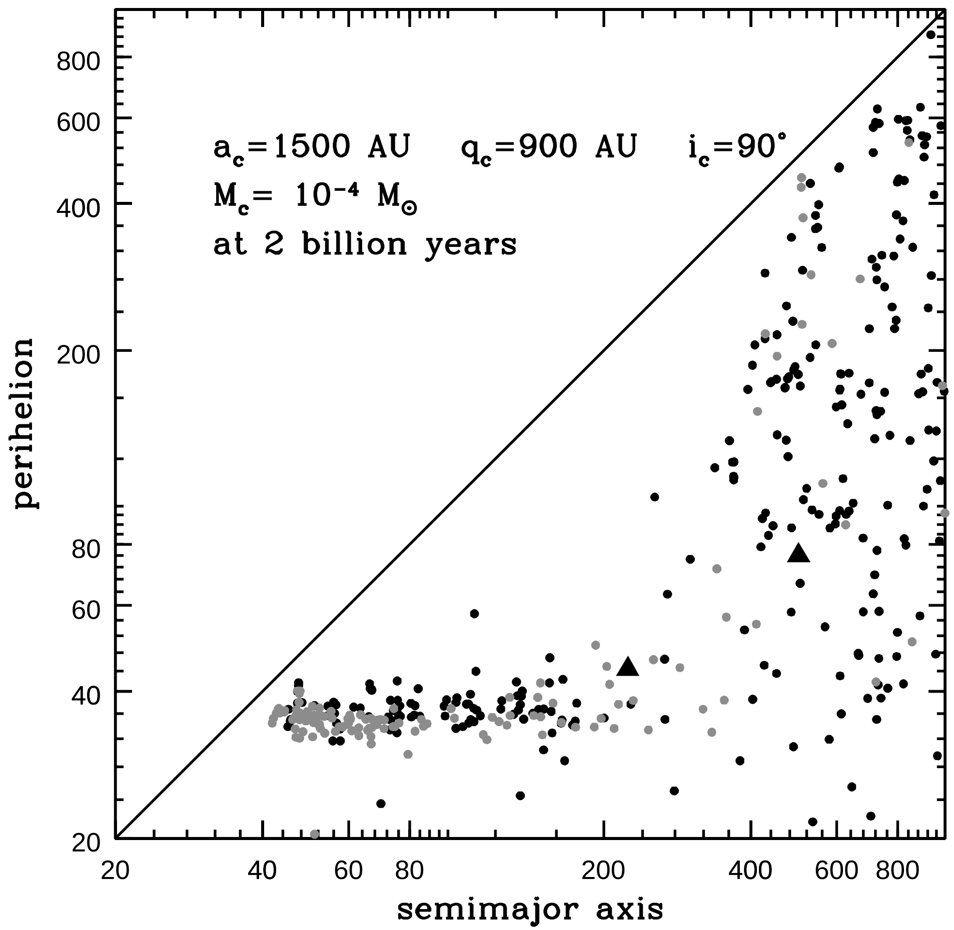
∗ Rogue planet (Brunini & Melita 2002; Morbidelli and Levison 2004)

Sun birth in a star cluster



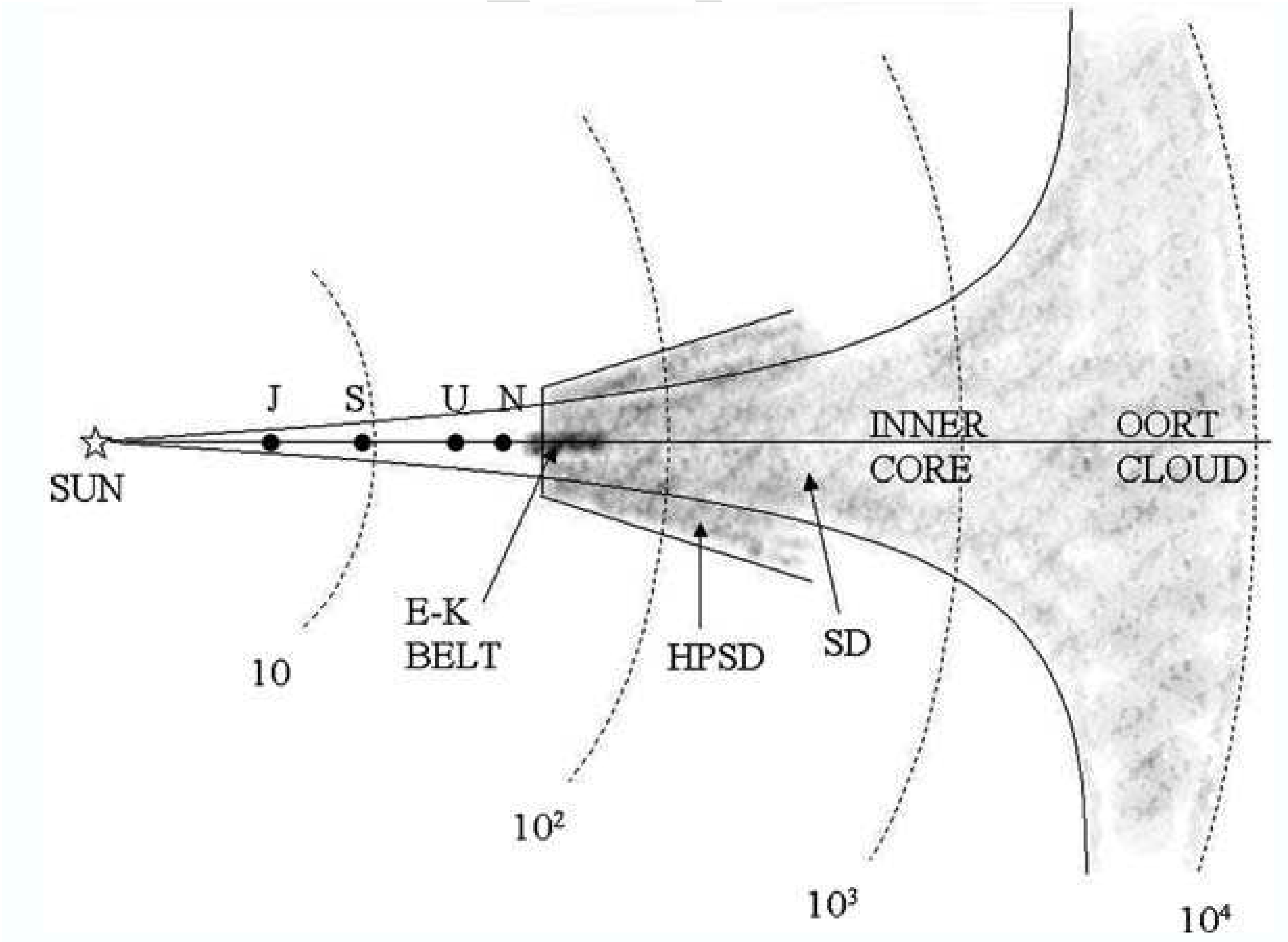
ρ_o: central cluster density ($M_\odot$ pc^{-3})
Big dots : Sedna, 2000 CR_{105}, 2003 UB_{313}
(Brasser, Duncan & Levison 2006)

Solar companion



(Matese, Whitmire & Lissauer 2006; Gomes, Matese & Lissauer 2006)

SDOs + HPSDOs + Inner core bodies



Conclusions

$\Rightarrow$ FOSSIL SD vs. LIVE SD (i.e., continuous replenishment from the classical belt.

$\Rightarrow$ Almost all extended or HPSDOs ($q > 40$ AU and $a > 50$ AU) can be explained by the combined action of MMR with Neptune + Kozai resonances.

$\Rightarrow$ Roughly 12-15% of all SDOs may be HPSDOs.

$\Rightarrow$ Sedna, and perhaps 2000 CR$_{105}$, may require an external perturber (members of the inner core of the Oort cloud).

$\Rightarrow$ Most of the SDOs diffusing to the Oort cloud have perihelia beyond Neptune's orbit. Neptune acts as a dynamical barrier.

$\Rightarrow$ On the other hand, no objects diffusing to the Oort cloud have $q > 36$ AU. Resonance sticking might be the main cause.

$\Rightarrow$ The contribution of SDOs to the Oort cloud may be quite substantial even at present (~ 5 yr^{-1}).