LA CEINTURE DE KUIPER

&

ET L_EVOLUTION TARDIVE DU SYSTEME SOLAIRE

A. Morbidelli

O.C.A.

10 years after the discovery of the first object_..

770 Trans-Neptunian Objects discovered

362 of which have multi-opposition orbits

(as of march 3, 2003)

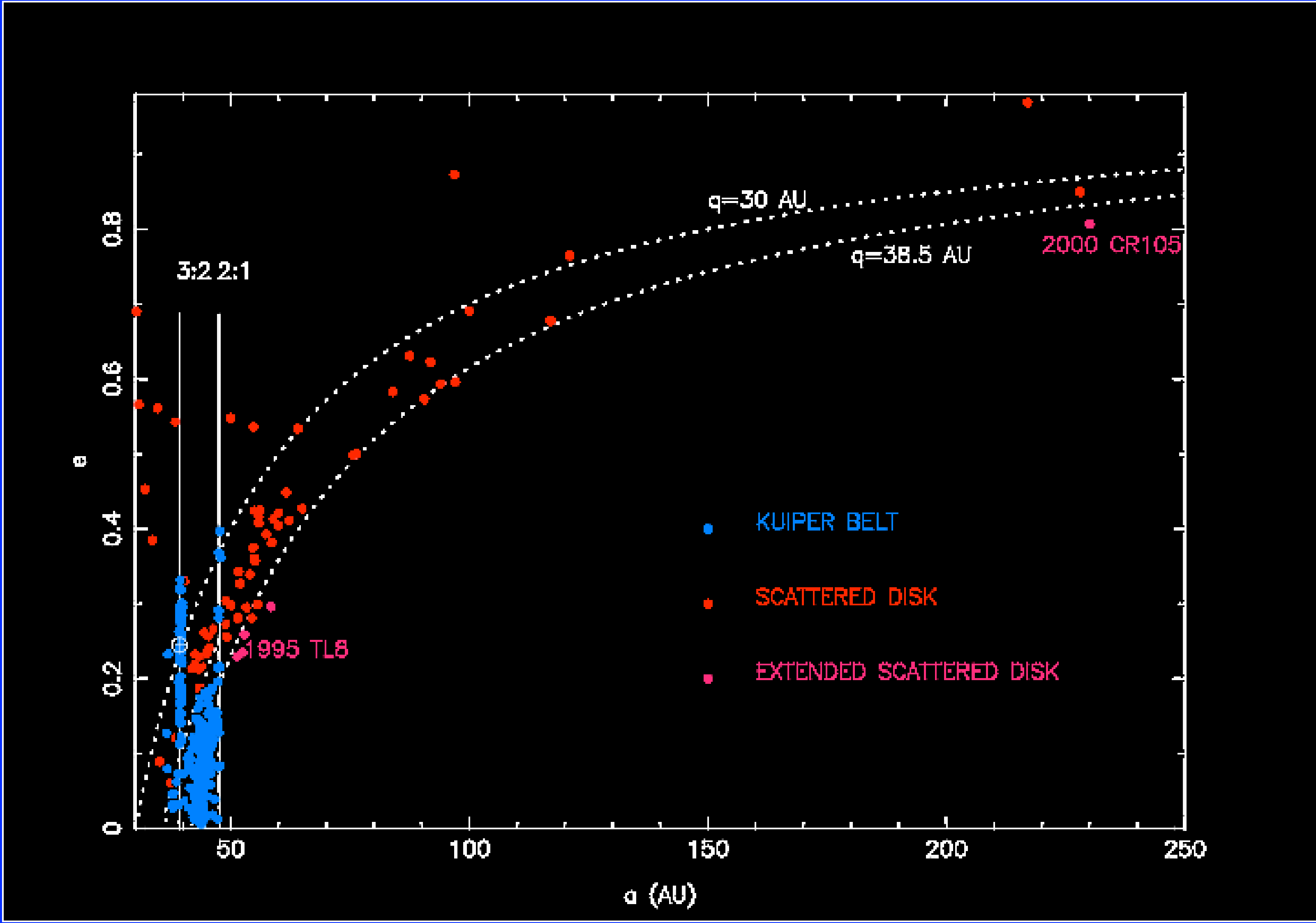
OUTLINE:

PART I: Intriguing observational properties of the TNO orbital distribution

PART II: Models of primordial evolution of the outer Solar System proposed to explain what we see

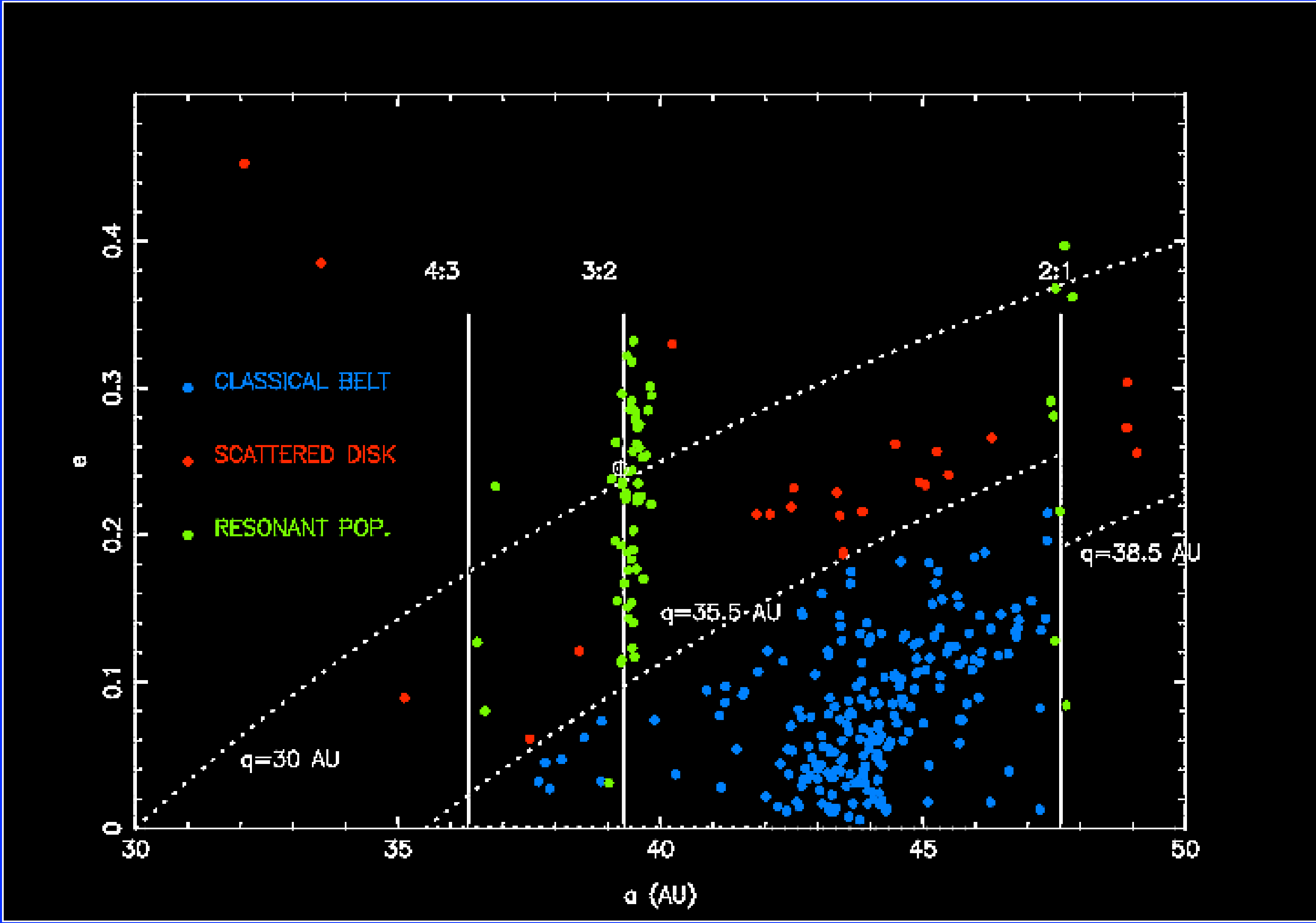
PART III: Open problems _ Uranus & the LHB

ORBITAL DISTRIBUTION OF MULTI-OPPOSITION BODIES



Trujillo et al. (2001): The Scattered Disk and the Kuiper belt constitute roughly equal populations

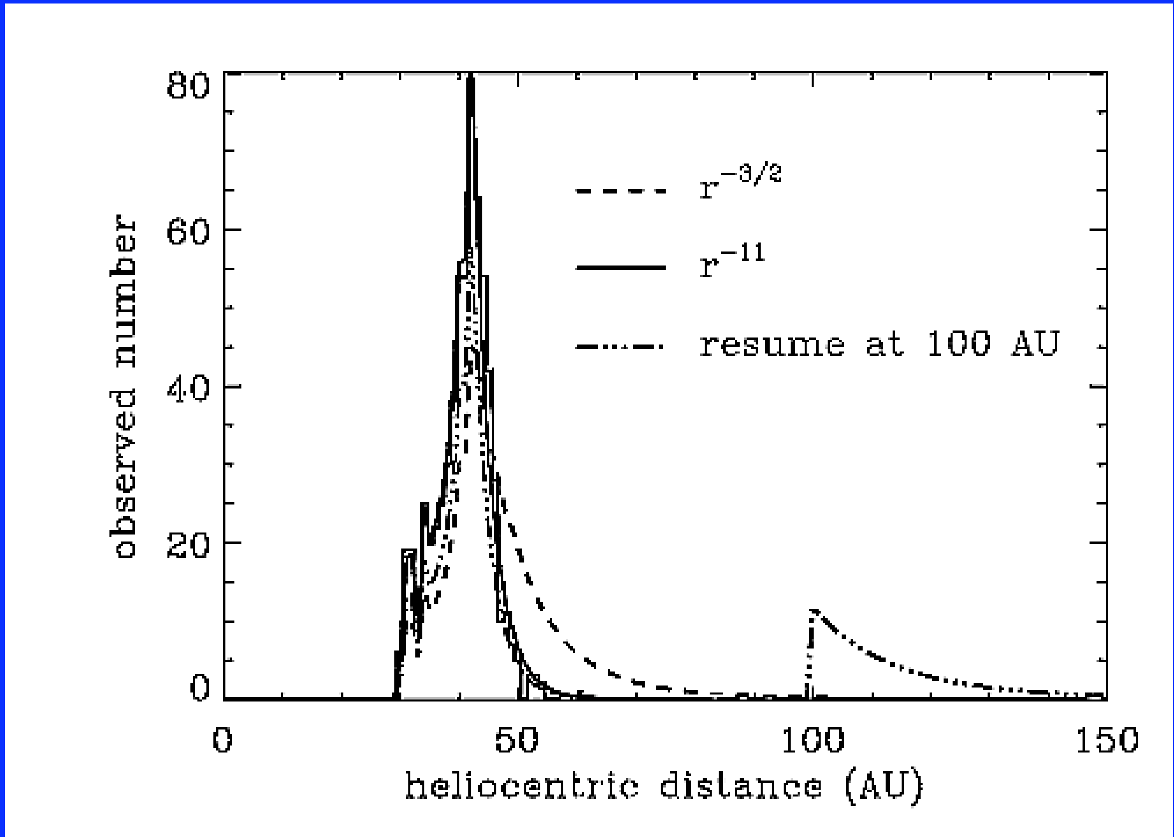
ORBITAL DISTRIBUTION OF MULTI-OPPOSITION BODIES



Trujillo et al. (2001): The resonant population constitutes ~10% of the classical population

Evidence for an outer edge of the Kuiper belt at ~ 50 AU

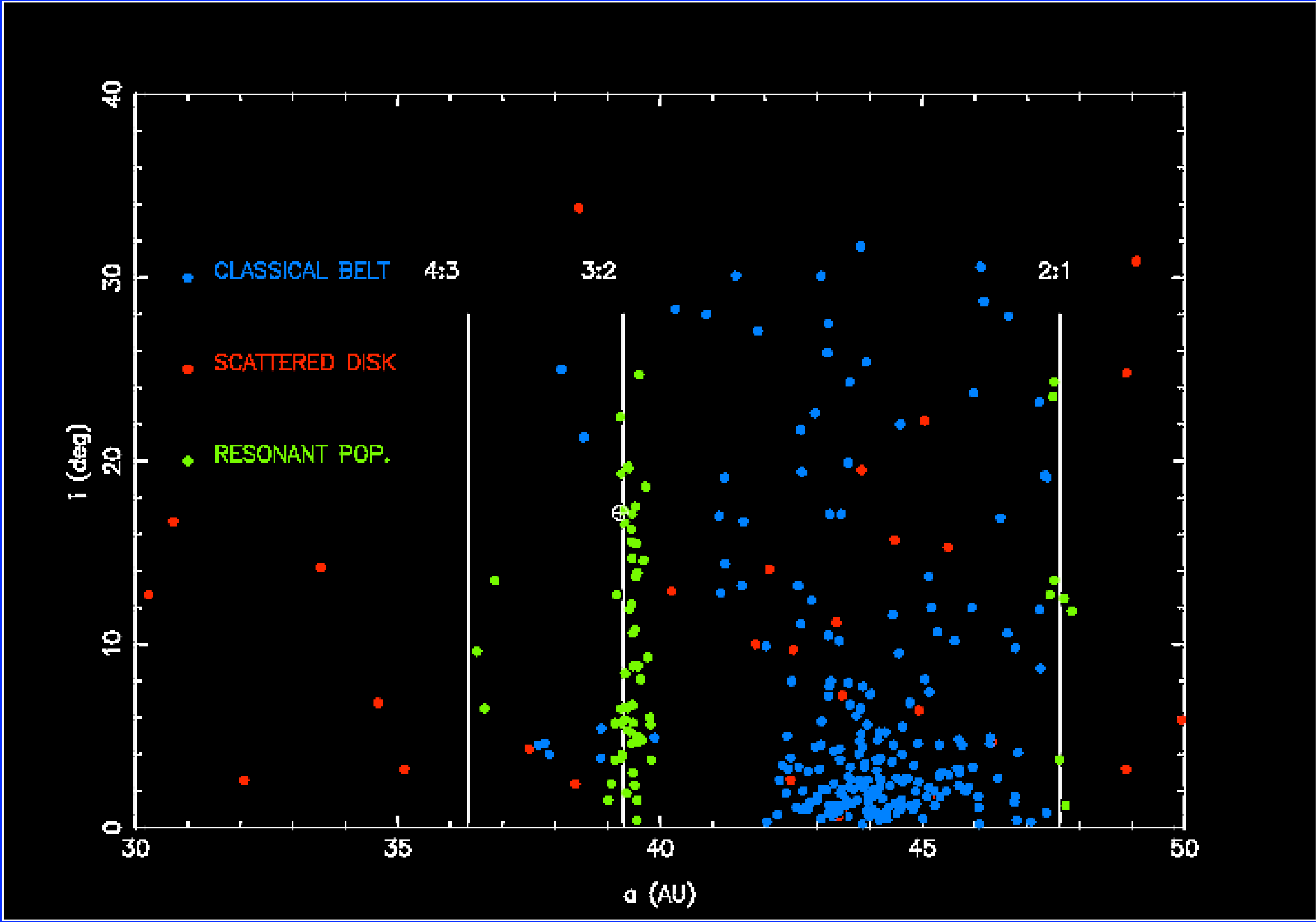
I:



Modeling by Trujillo and Brown (2001)

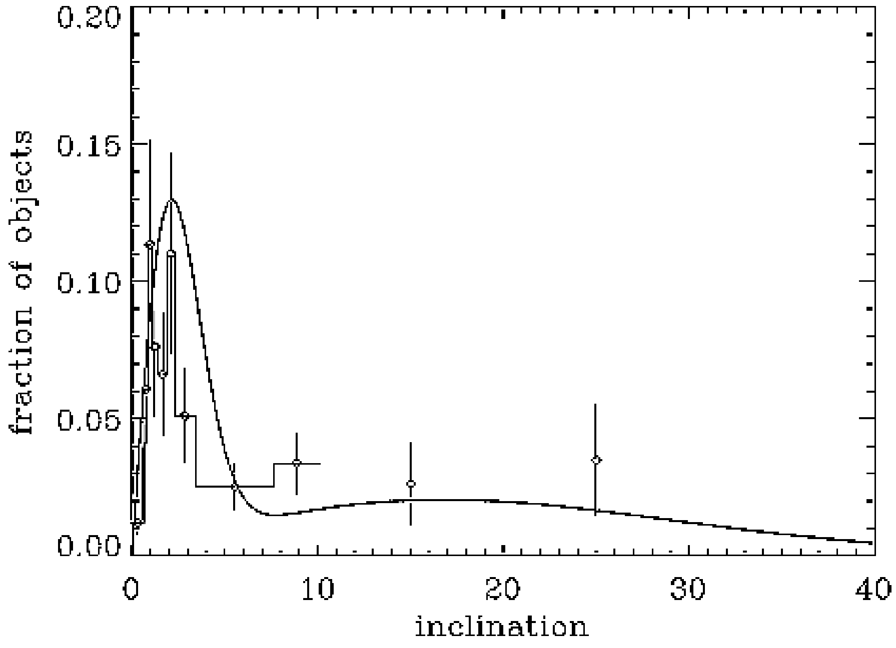
II: **Targeted observations by Allen *et al.* (2001) rule out with 95% CL the existence in the 50-60 AU range of a belt of D>200km bodies comparable ot that in the 40-50 AU range.**

THE INCLINATION DISTRIBUTION



Evidence for a bimodal de-biased inclination distribution

Brown (2001)

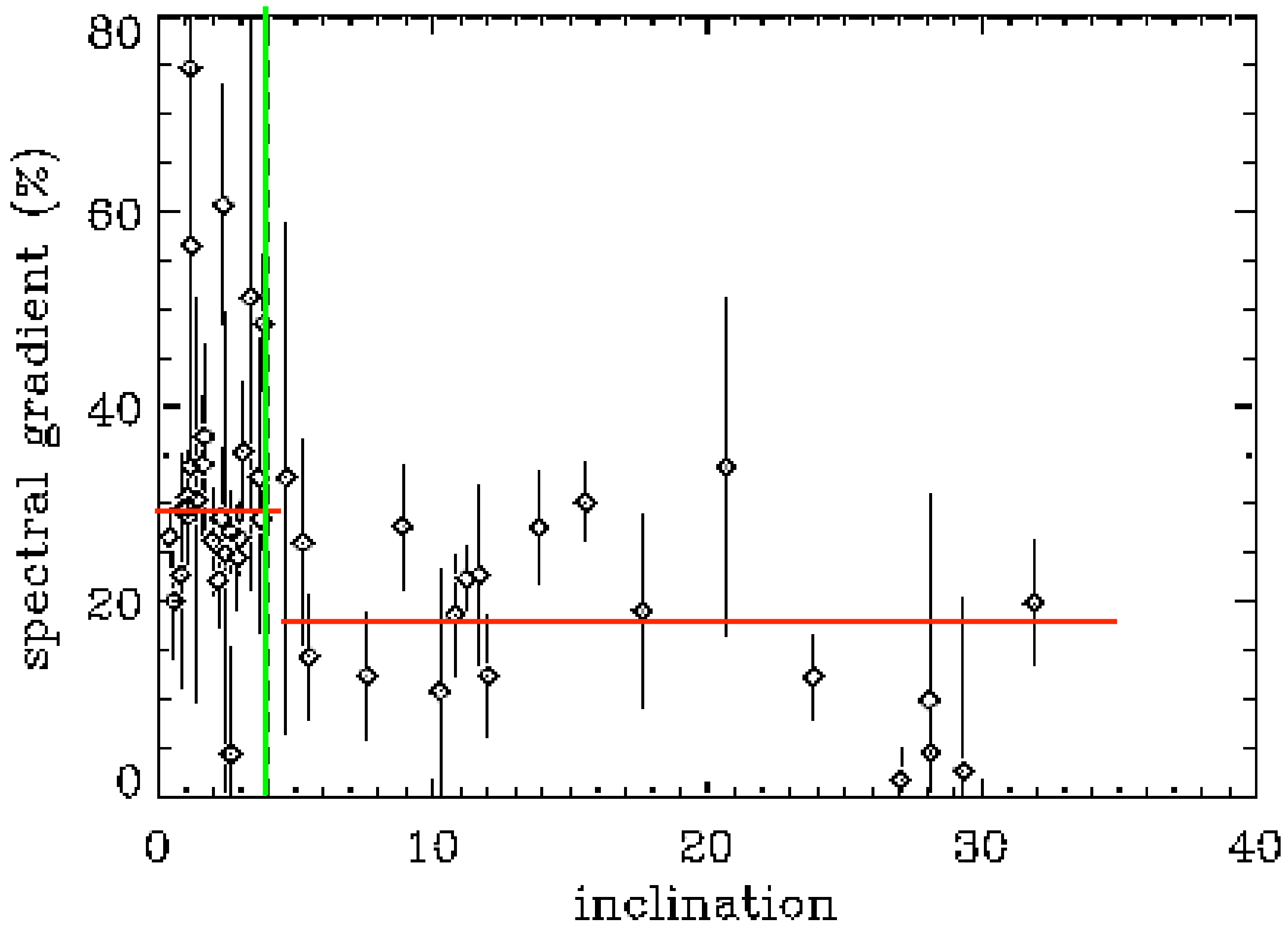


COLD POPULATION: i<4^o

HOT POPULATION: i>4^o

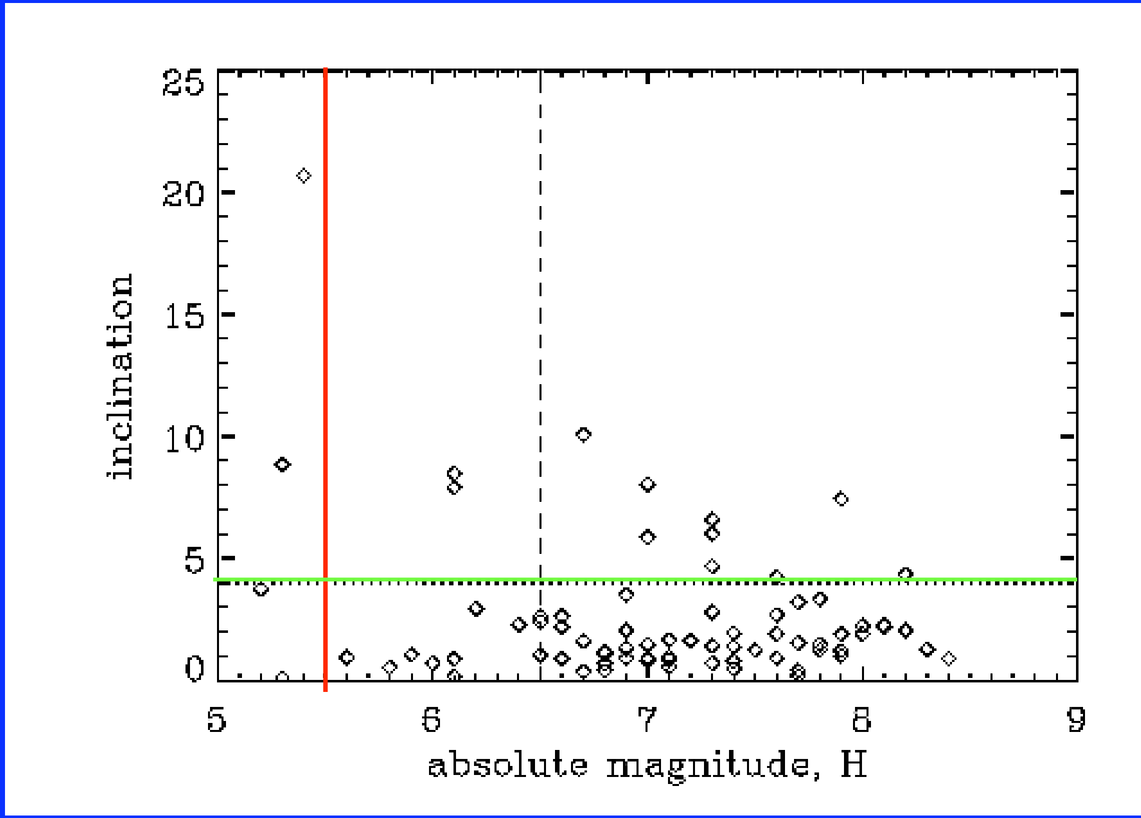
PHYSICAL DIFFERENCES BETWEEN THE HOT AND COLD POPULATIONS OF THE CLASSICAL BELT: I) THE COLOR DISTRIBUTION

Trujillo and Brown (2002), Tegler and Romanishin (2000), Doressoundiram et al. (2001)



PHYSICAL DIFFERENCES BETWEEN THE HOT AND COLD POPULATIONS OF THE CLASSICAL BELT: II) THE SIZE DISTRIBUTION

Levison and Stern (2001)

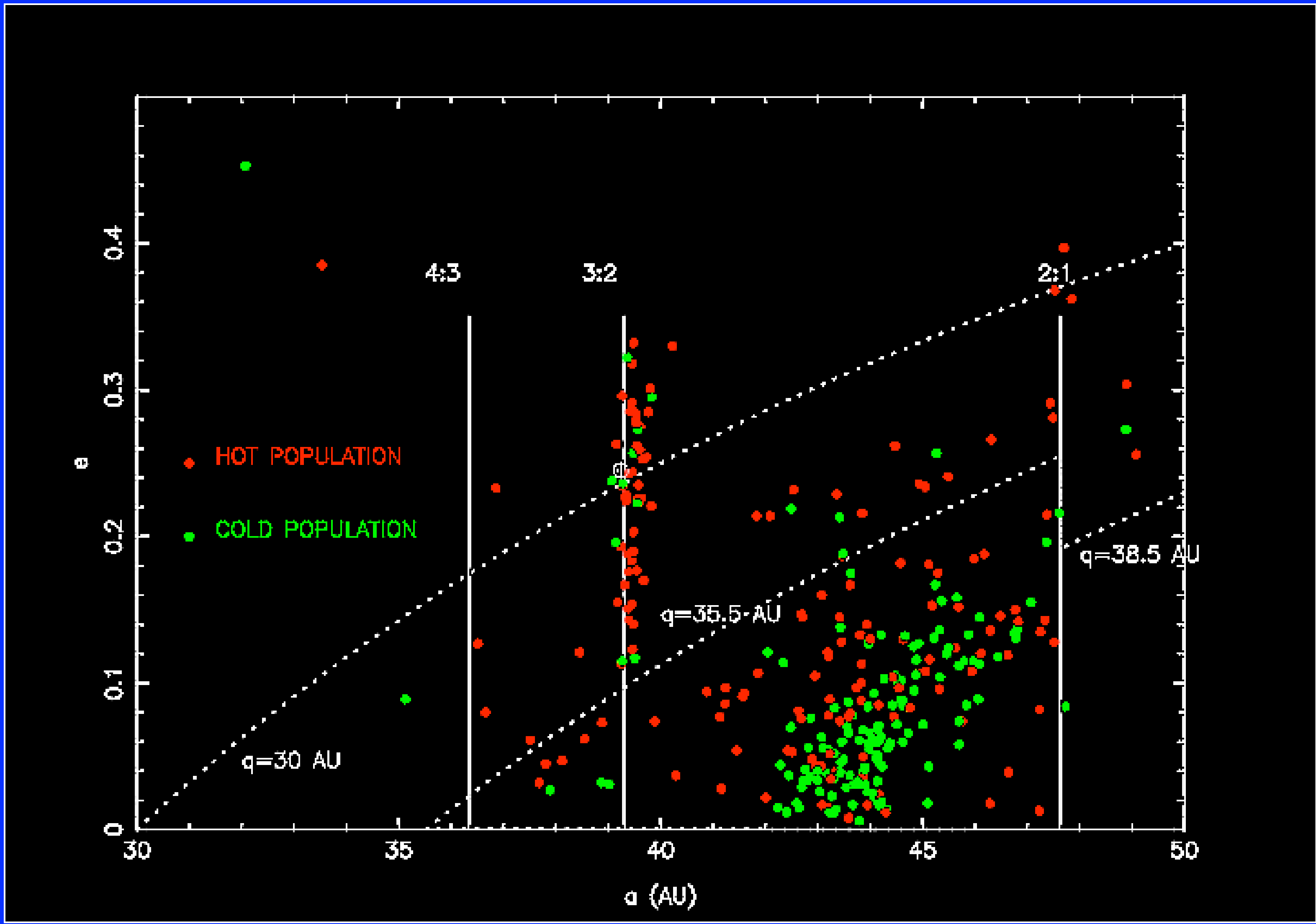


All of the biggest objects (Pluto, Quaoar, Ixion, Varuna, Chaos) are in the HOT population

All bodies with H<5 have i>5° and have i_{med}=19.7°

NOTICE:

THE HOT AND COLD CLASSICAL BELT POPULATIONS HAVE ESSENTIALLY THE SAME (a,e) DISTRIBUTION



THE MISSING MASS PROBLEM

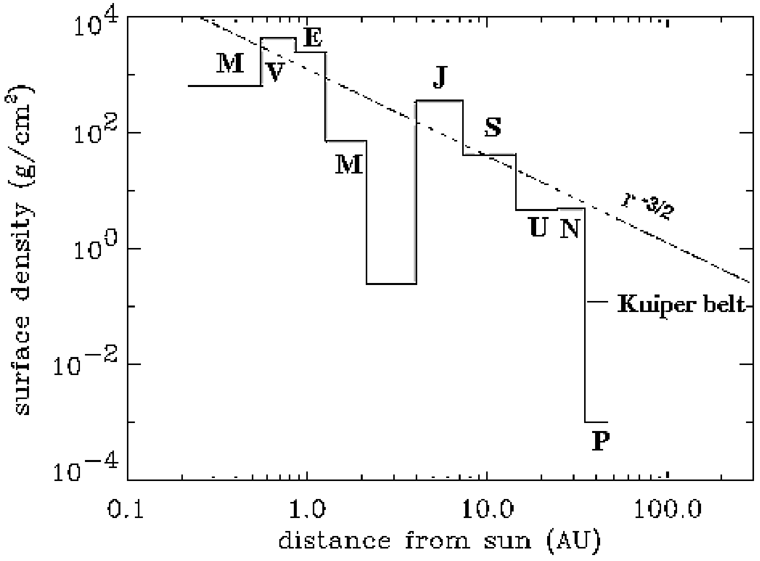
30 Earth masses are expected to exist in the primordial 30-50 AU region because of:

I. Extrapolation of the surface density of solids incorporated in the giant planets

II. Necessity to grow the KBOs in a reasonable timescale

(Stern, 1996; Stern and Colwell, 1999; Kenyon and Luu 1998, 1999; Weidenshilling, 2003)

The current mass is estimated to be 0.03-0.3 M_E



SUMMARY OF INTRIGUING ASPECTS THAT NEED TO BE EXPLAINED

1. Origin of 2000 CR105 (and other ESD bodies)
2. Existence of the resonant Kuiper belt population
3. Eccentricity distribution of classical KBOs (and weird a,e shape)
4. Outer edge of the classical belt
5. Co-existence of HOT and COLD classical populations with different physical properties
6. The mass deficit of the Kuiper Belt

CAUTION!:

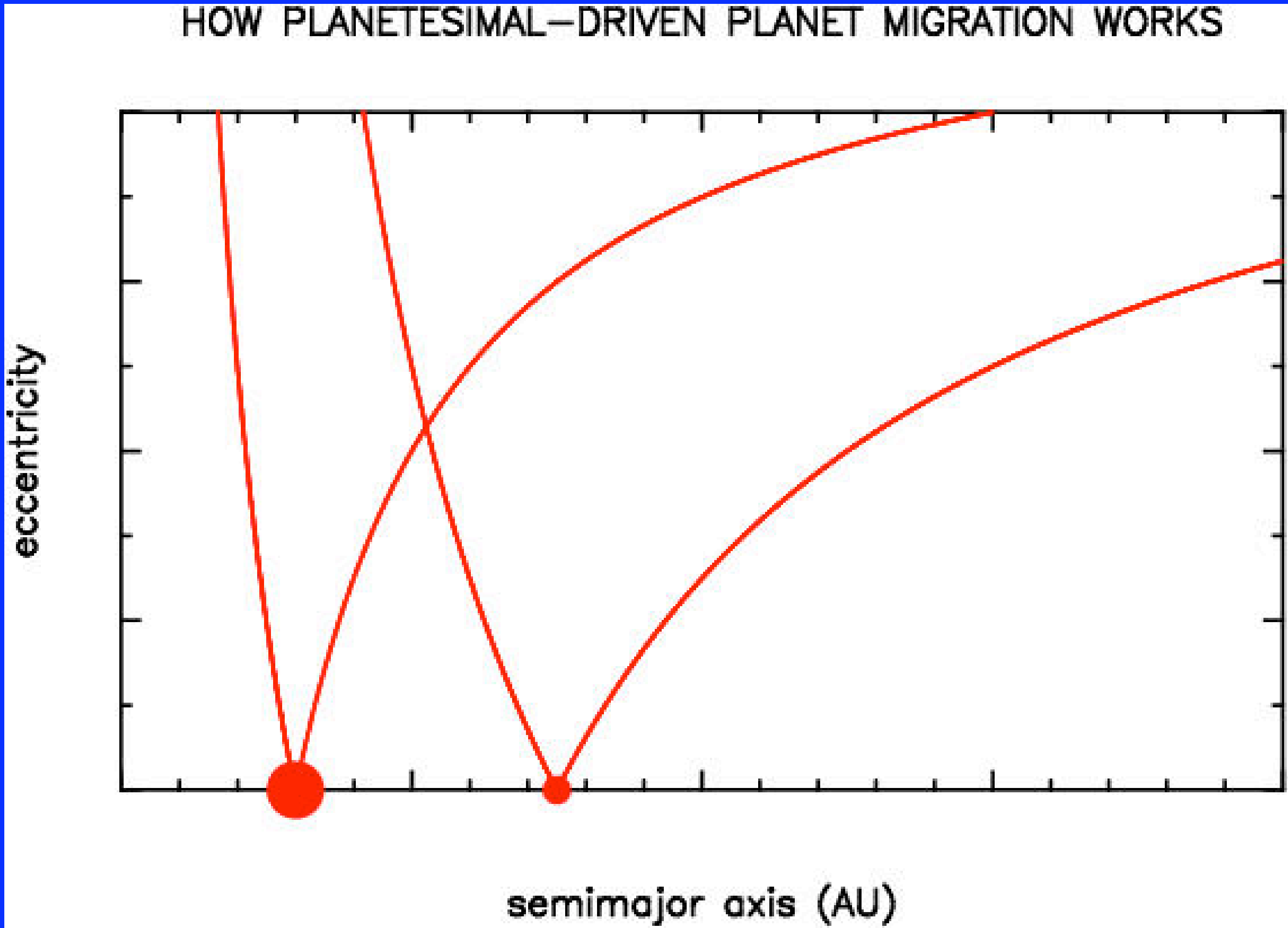
CELESTIAN MECHANICIANS AT WORK!!:

_..A PORTFOLIO OF MODELS

Guideline:

Discuss the sculpting of the Kuiper Belt from the issues that we think to understand the best to those that we understand the least__.

Planets had to migrate as they depleted the disk of planetesimals around them.



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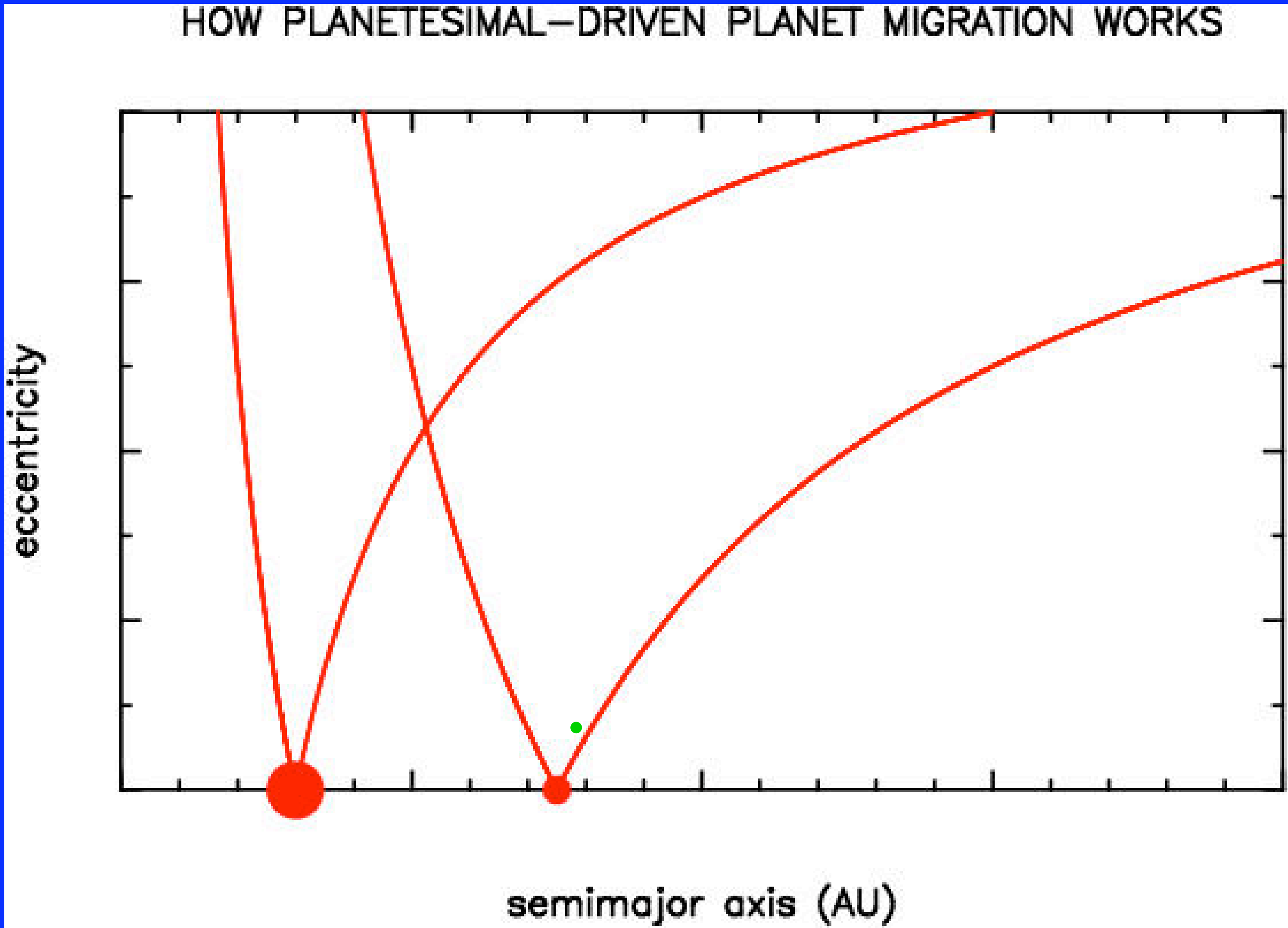

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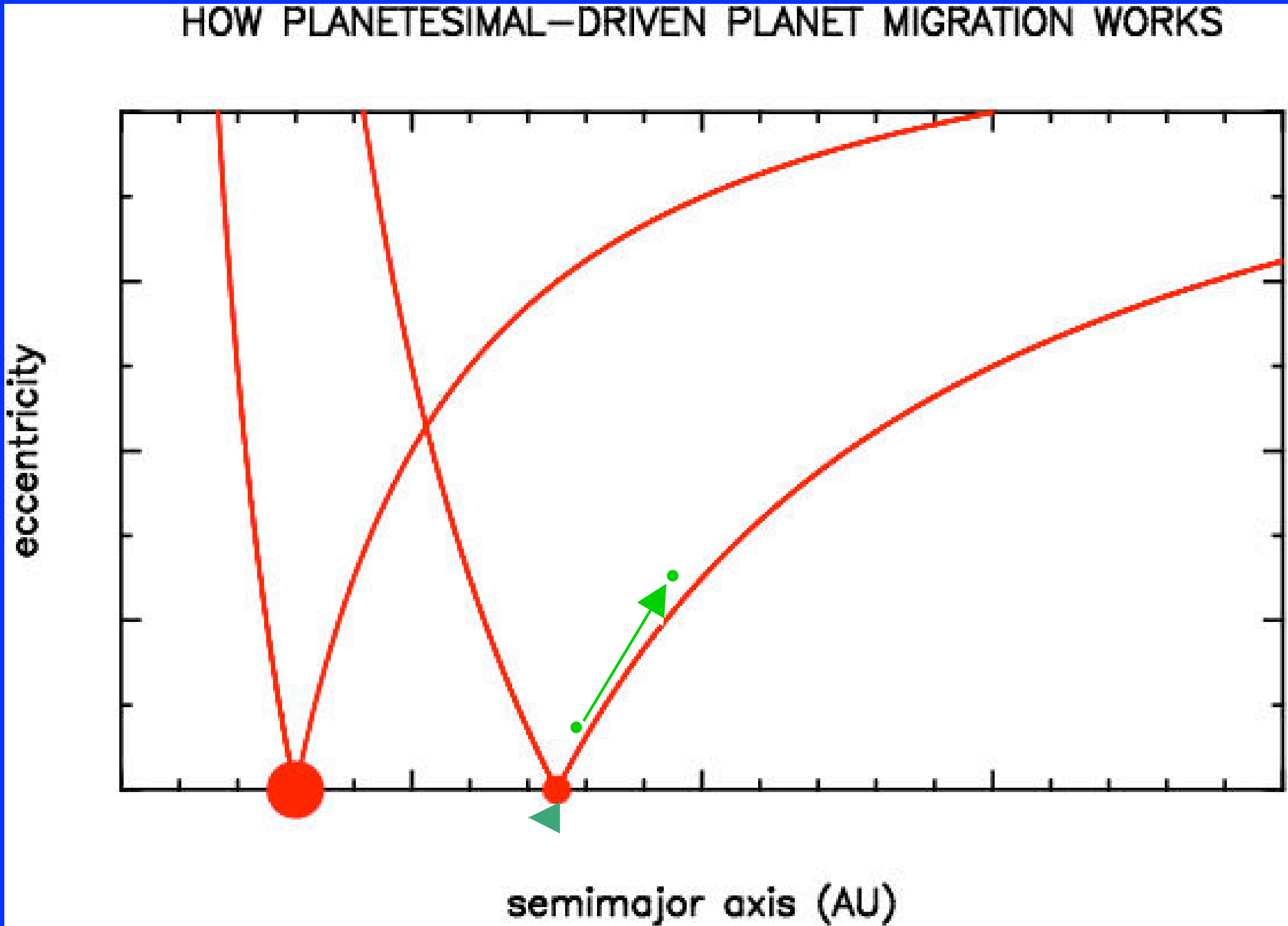

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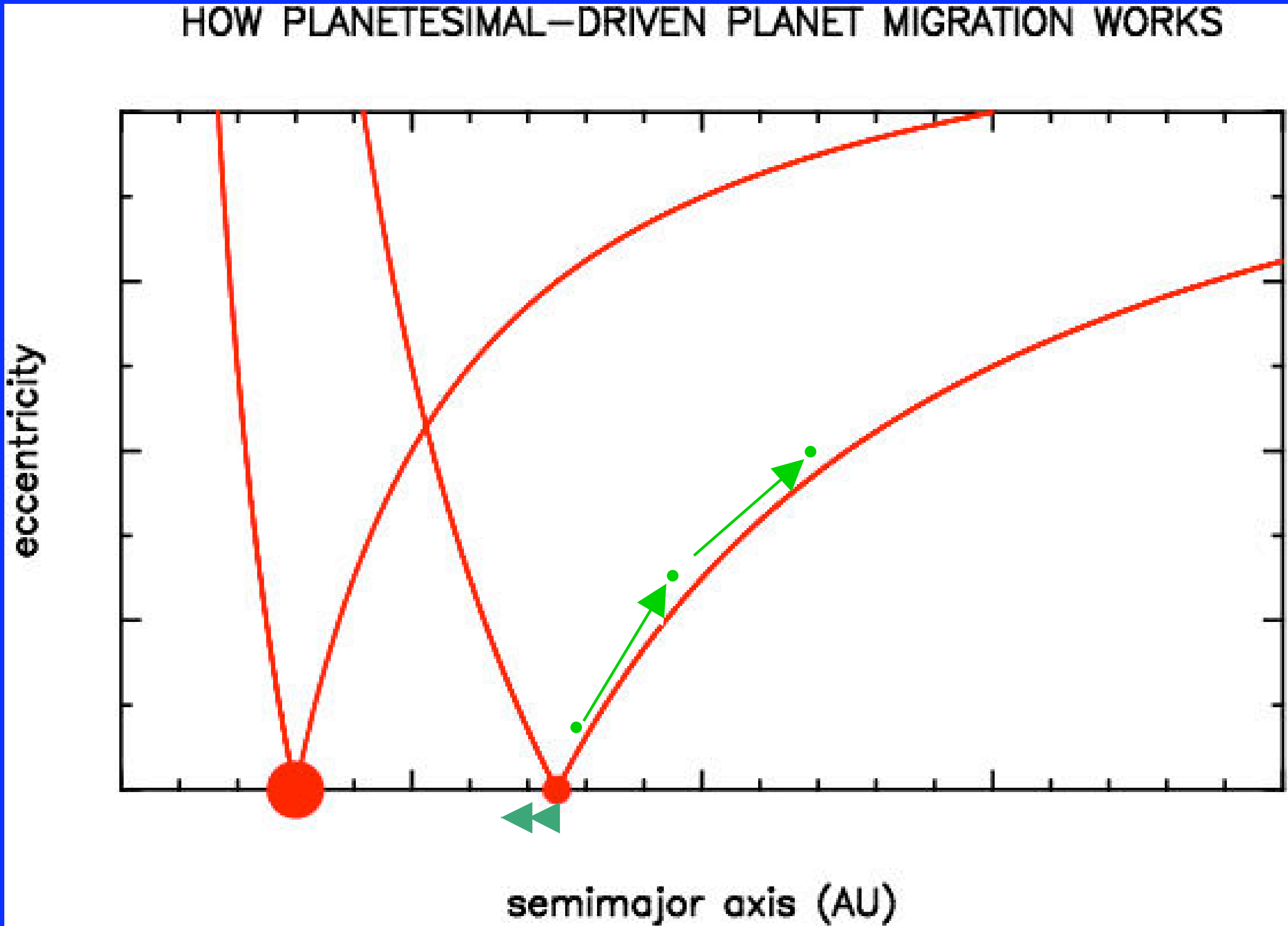

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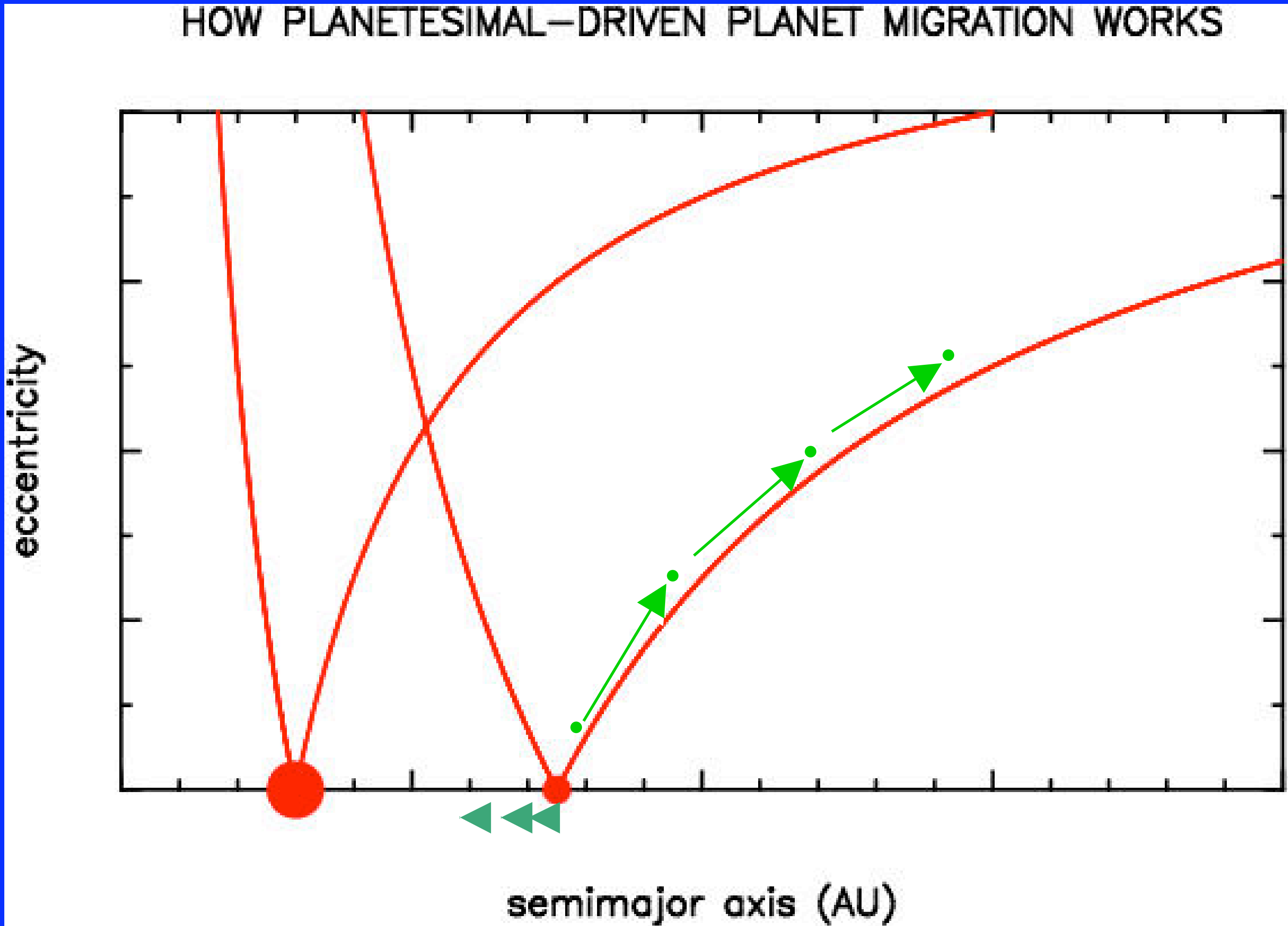

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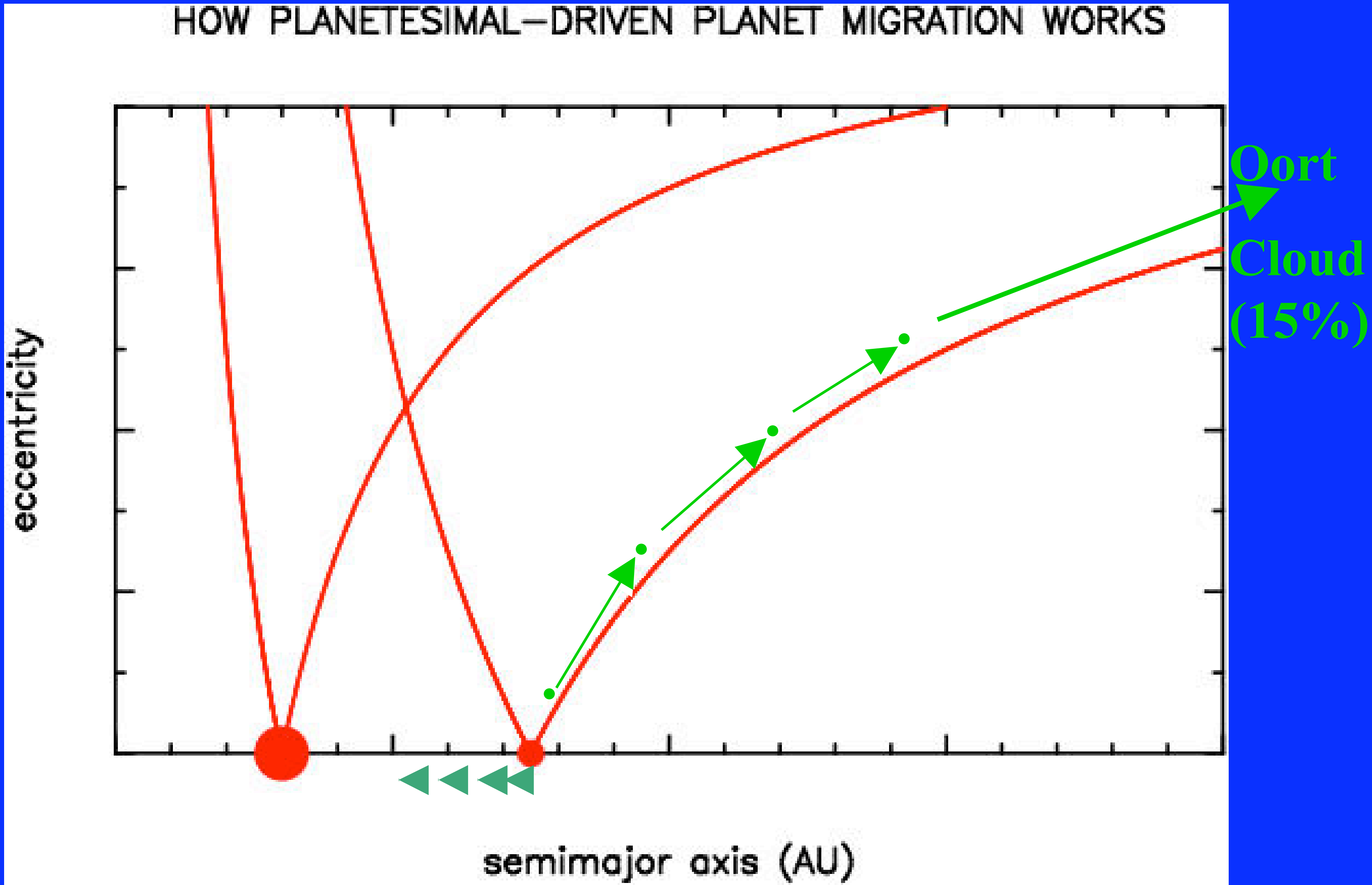

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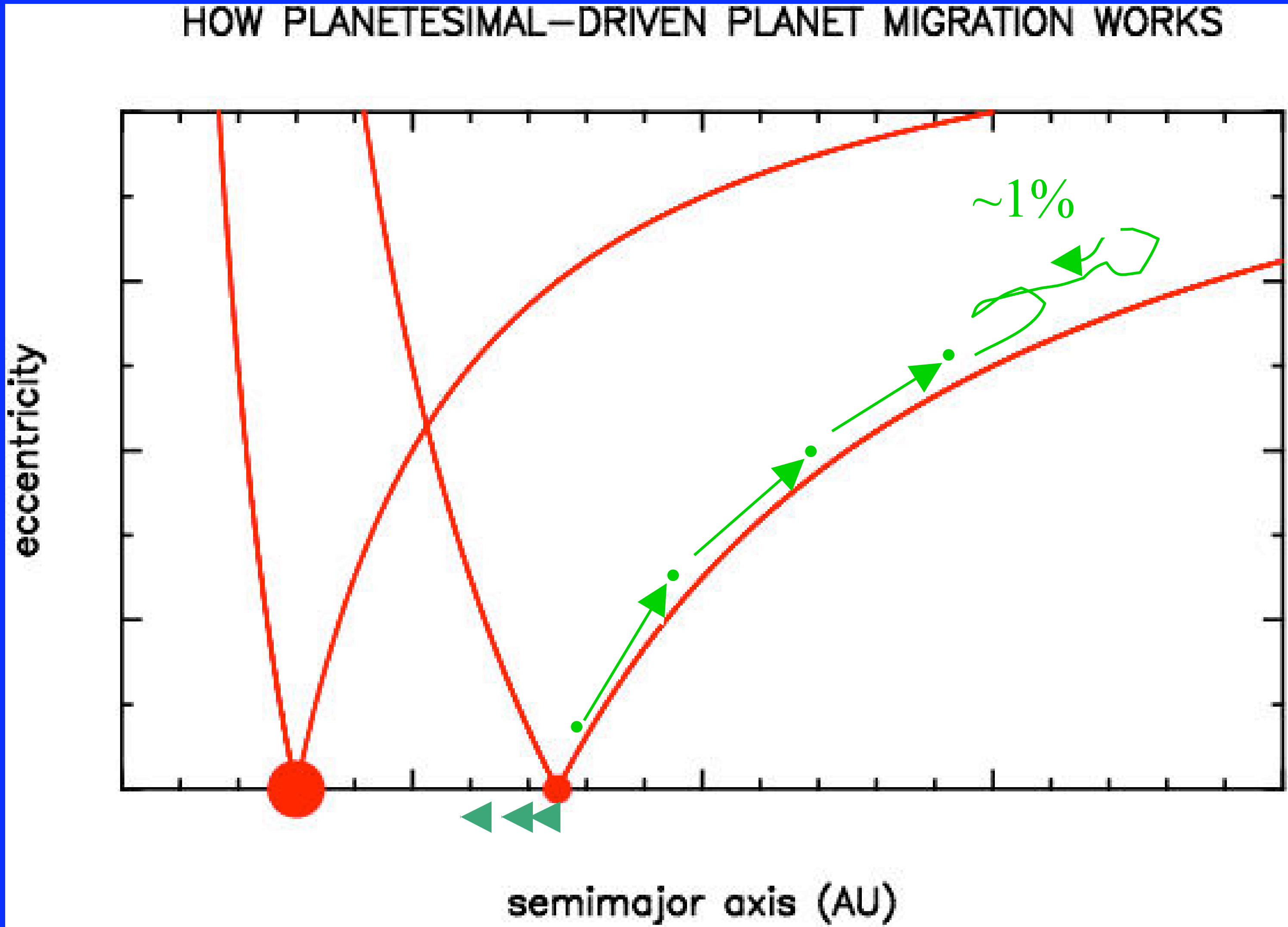

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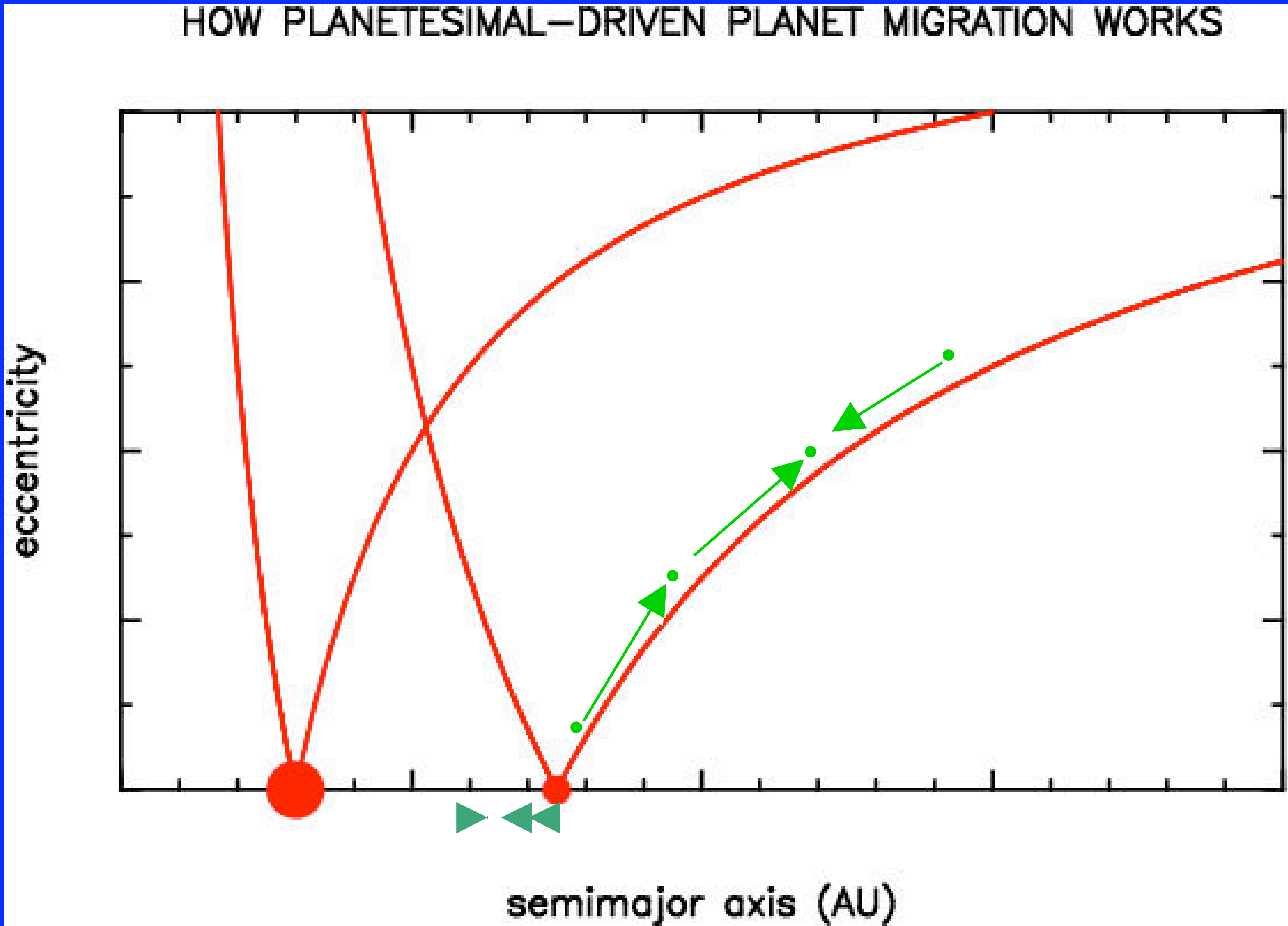

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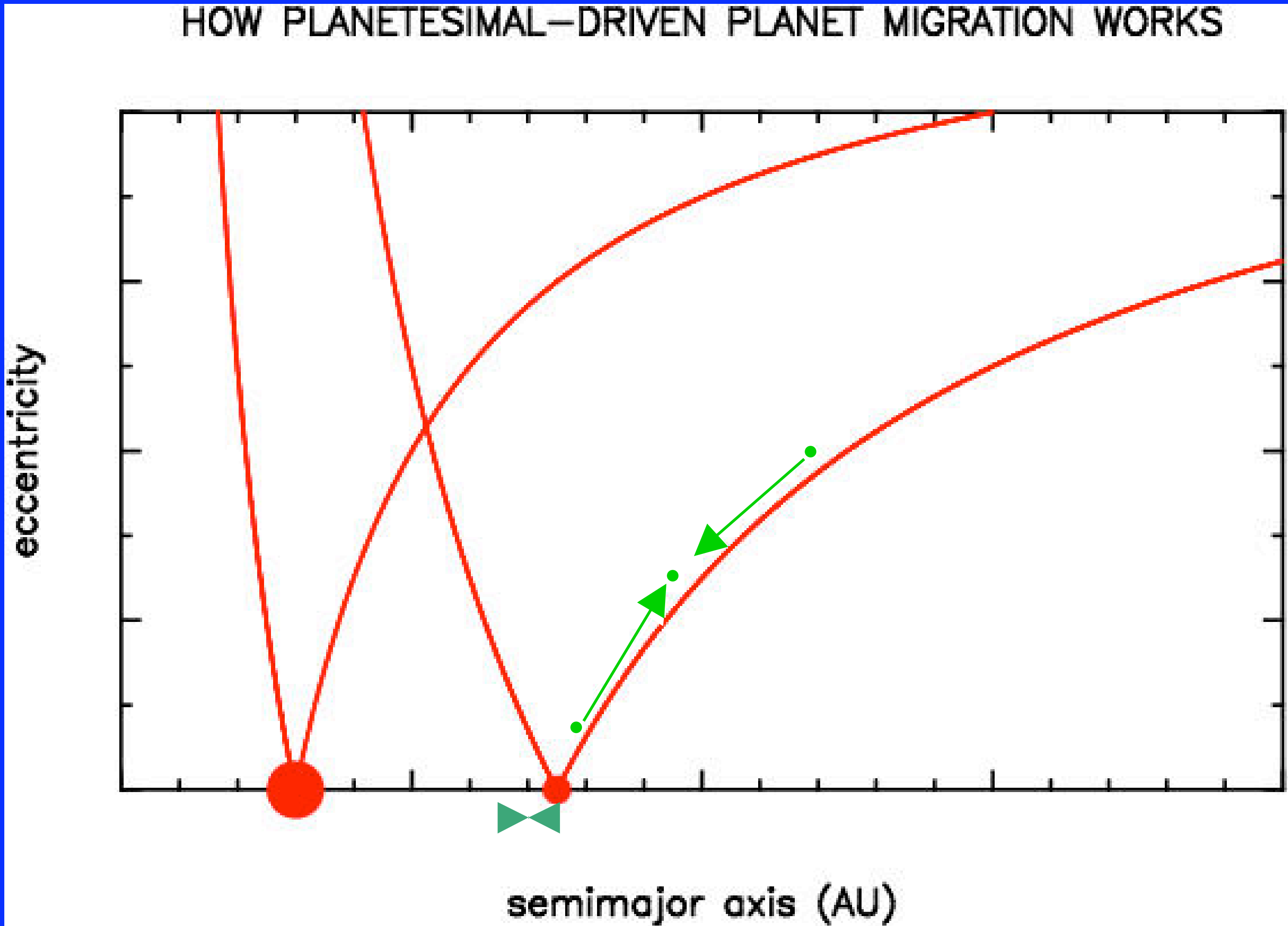

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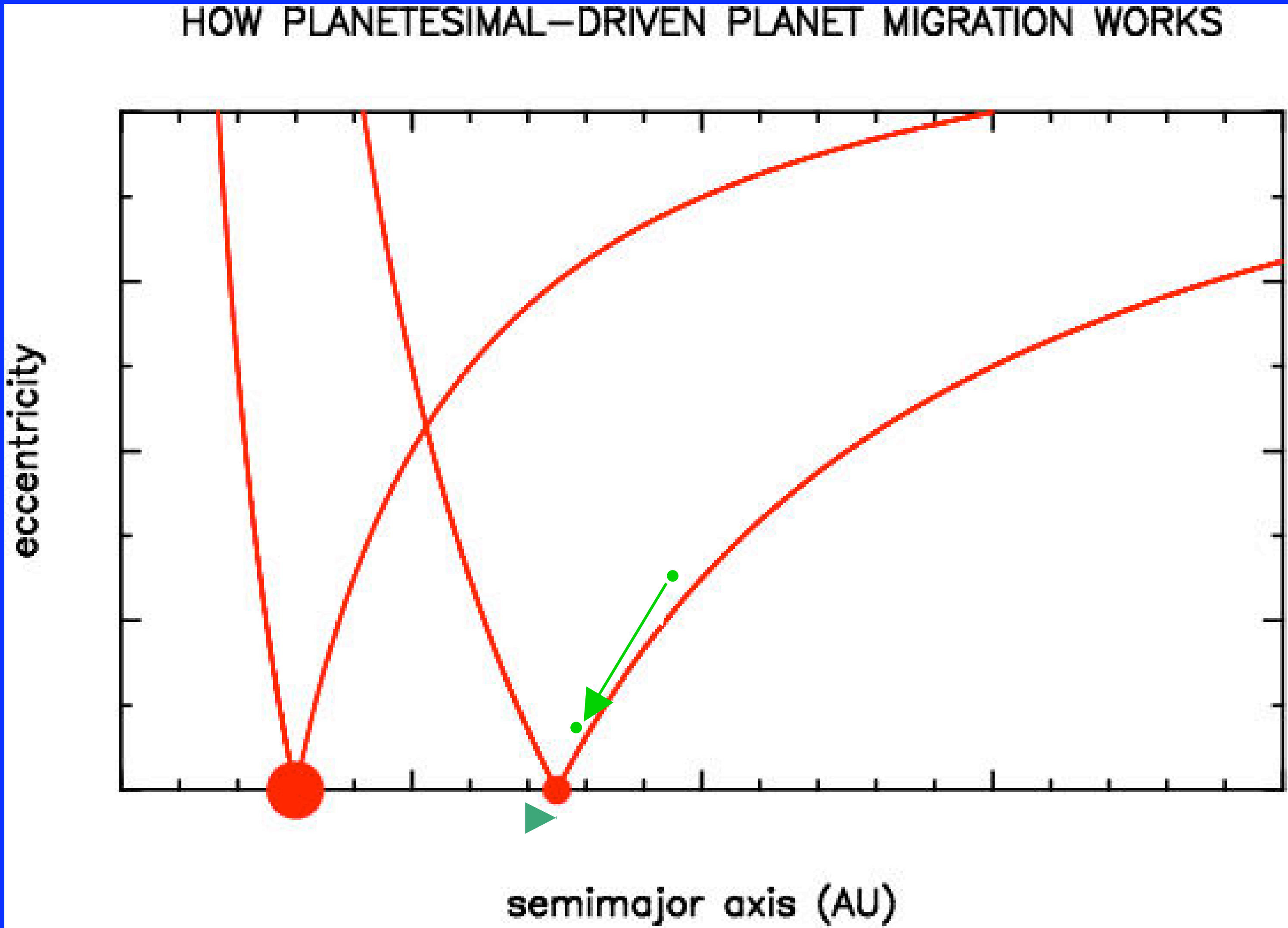

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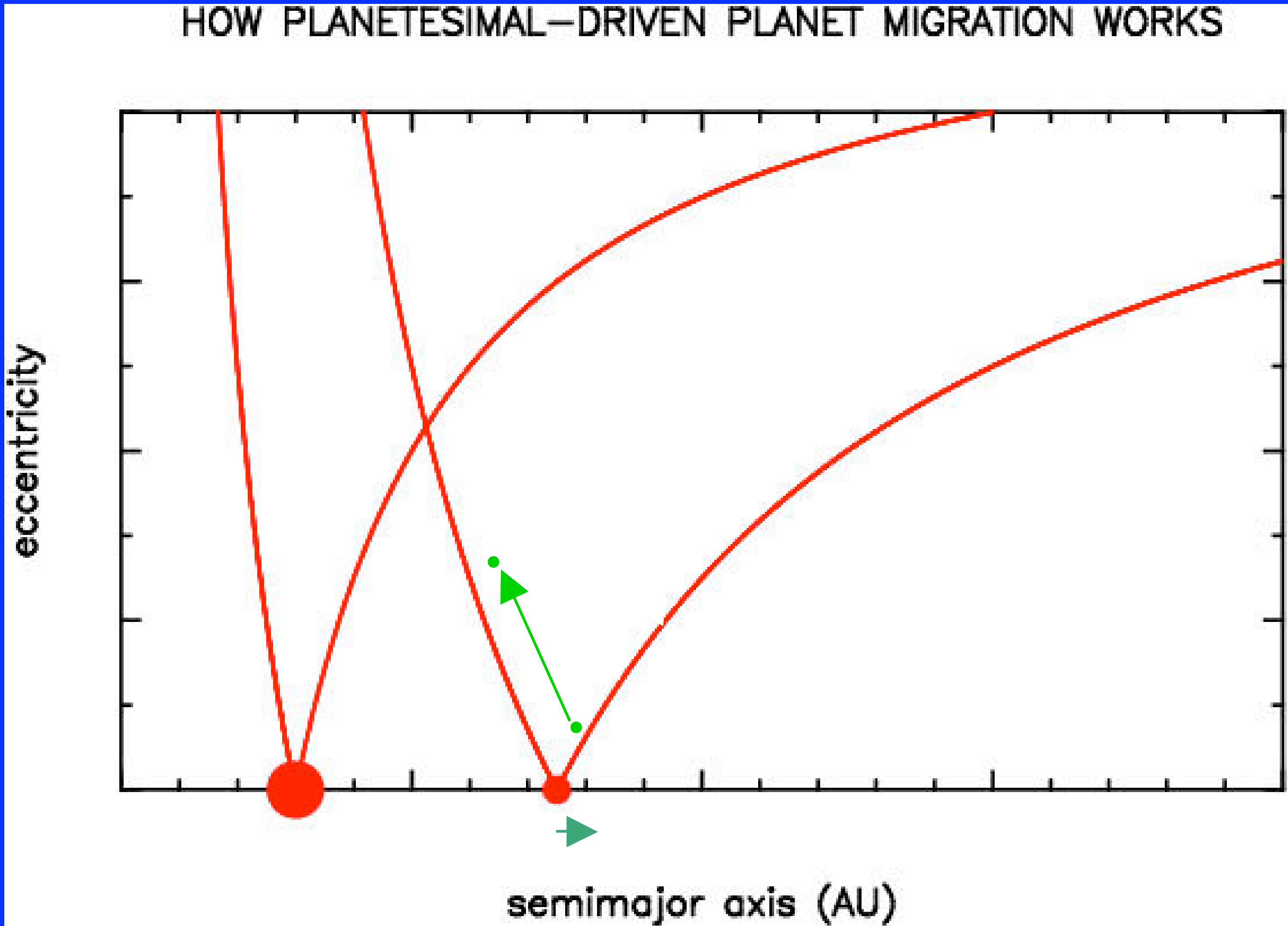

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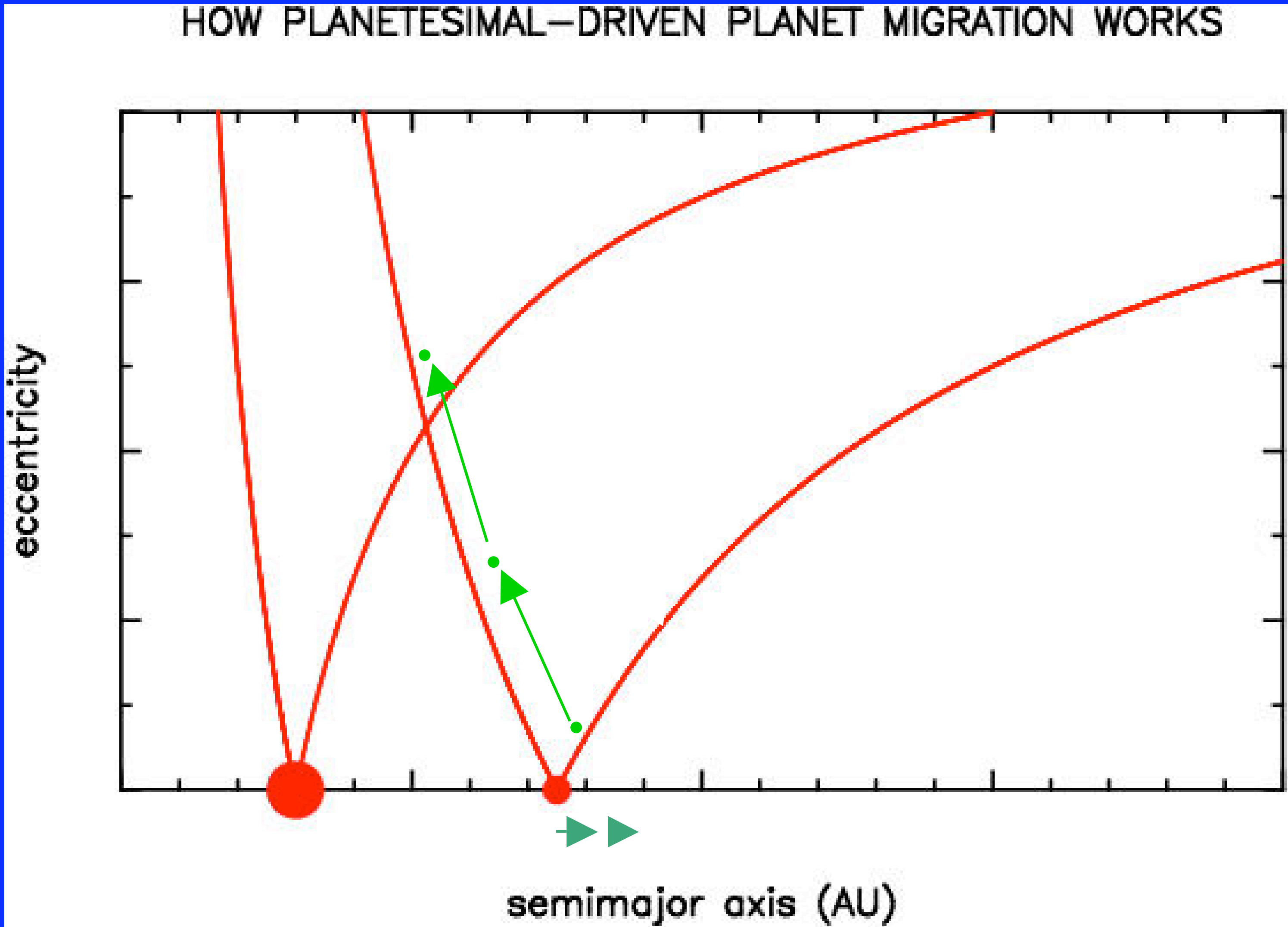

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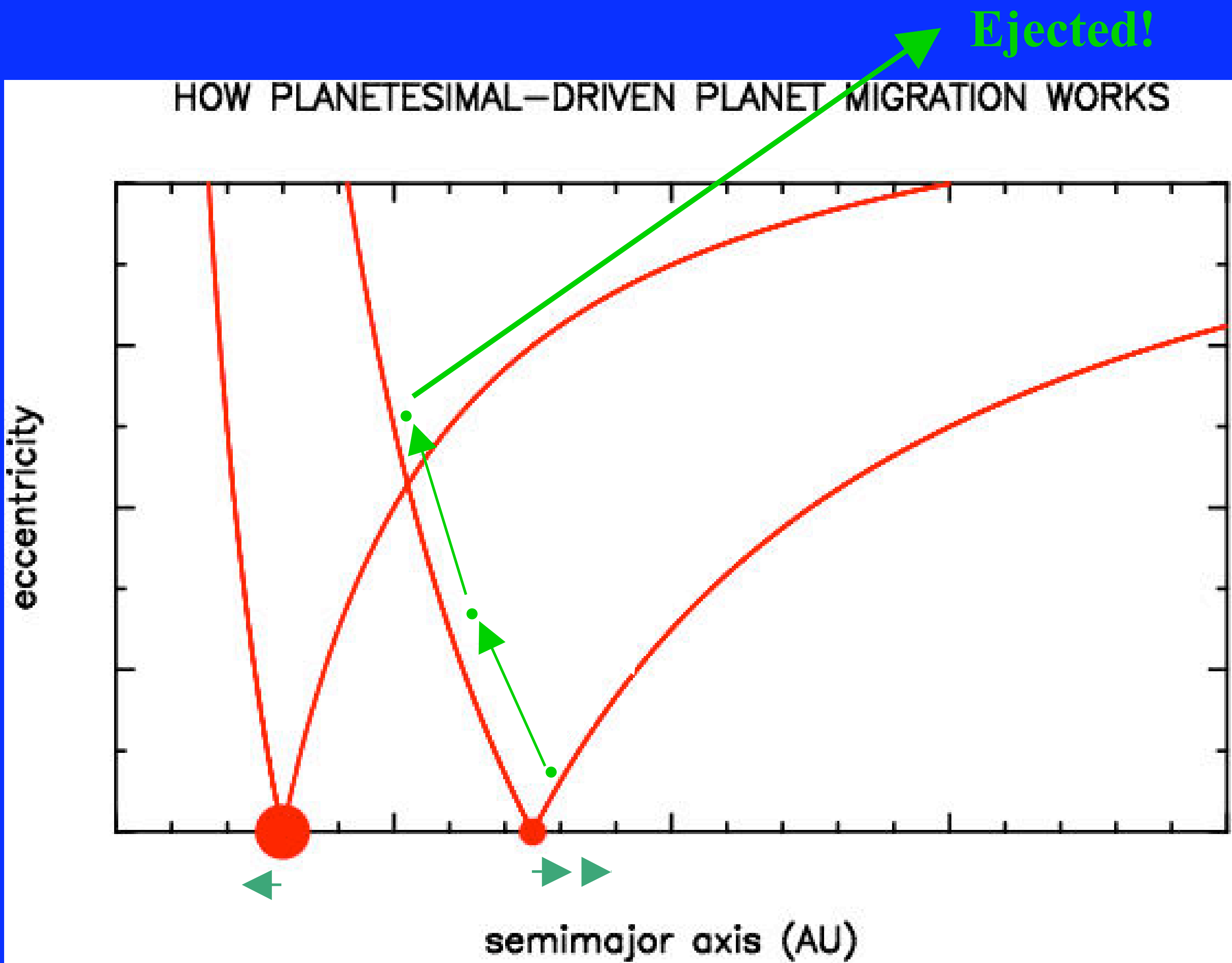

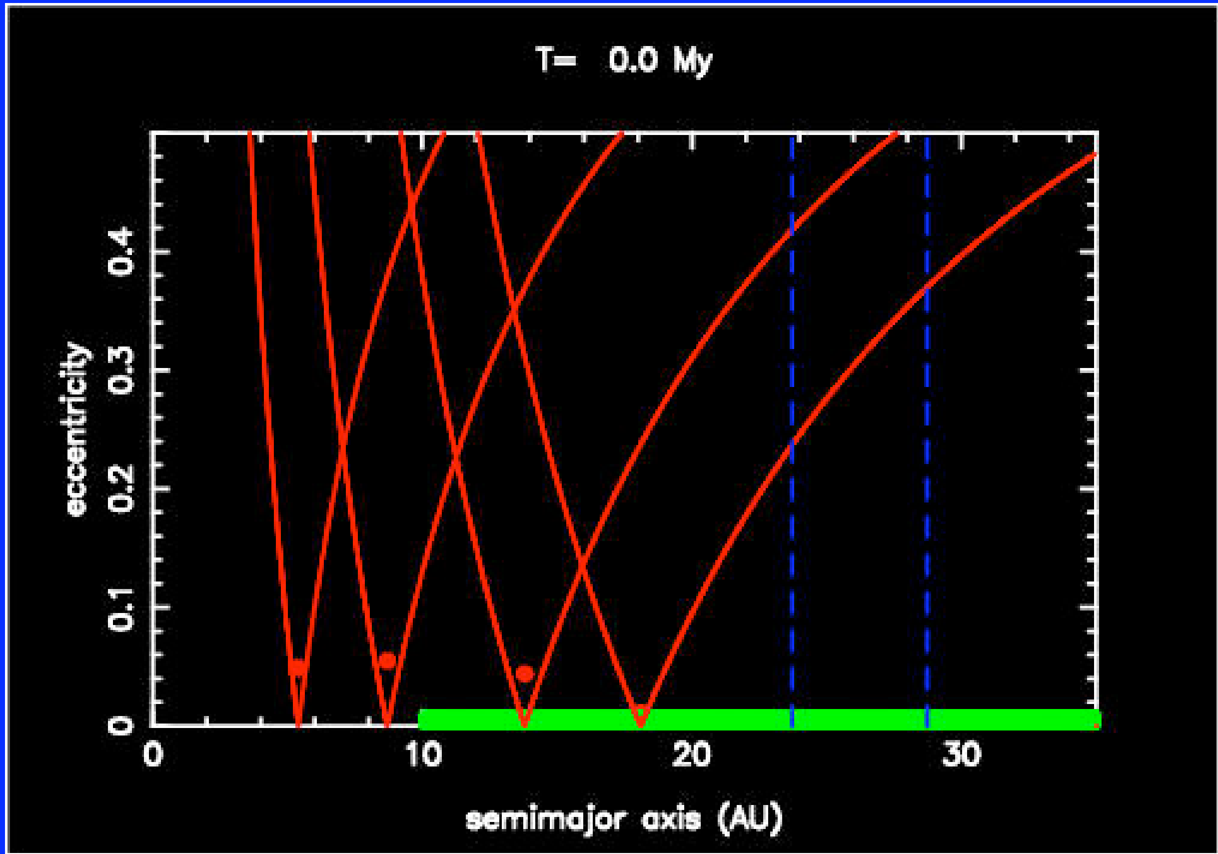
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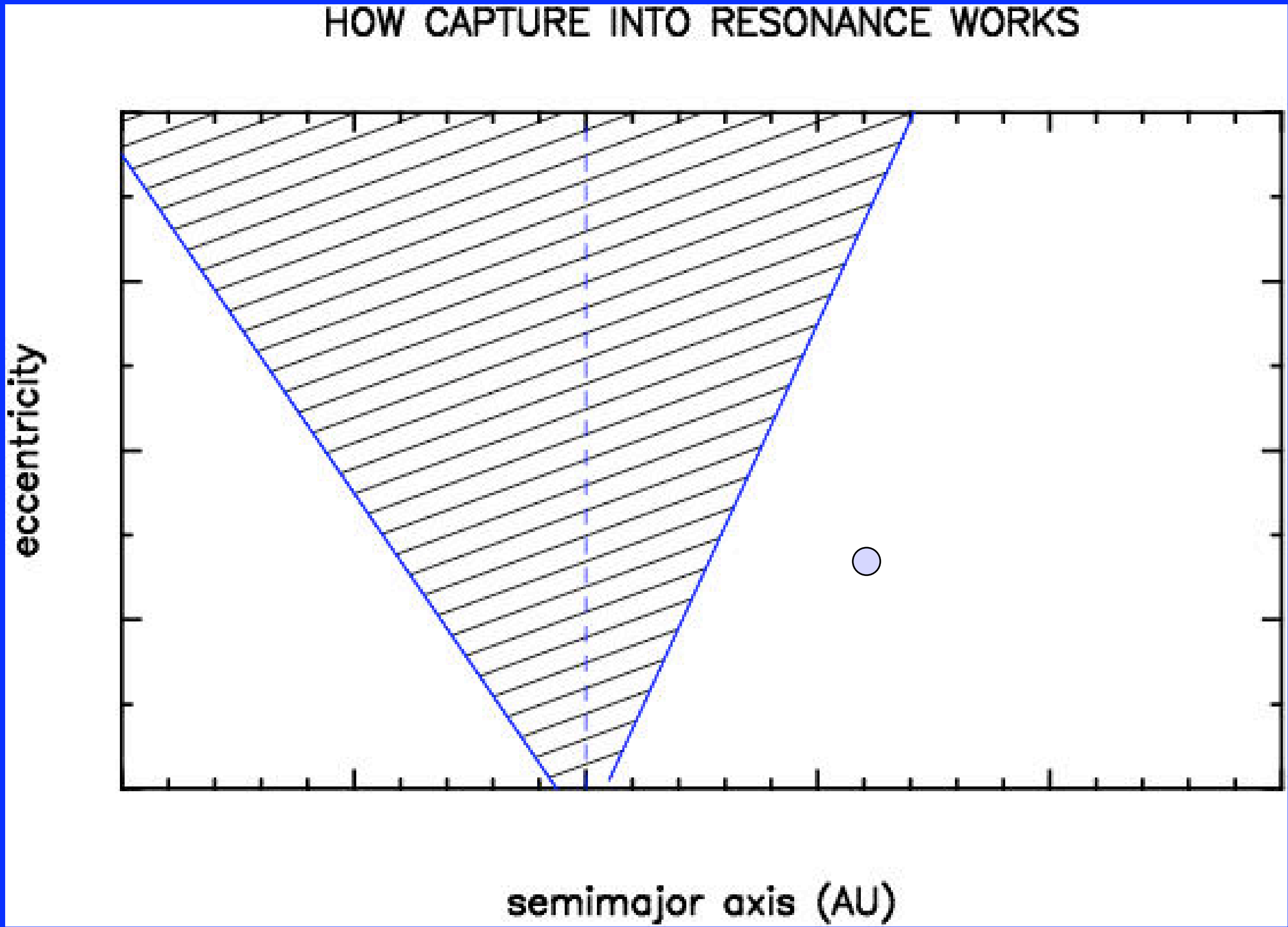
eccentricity
0 0.1 0.2 0.3 0.4
0 10 20 30
semimajor axis (AU)


HOW CAPTURE INTO RESONANCE WORKS
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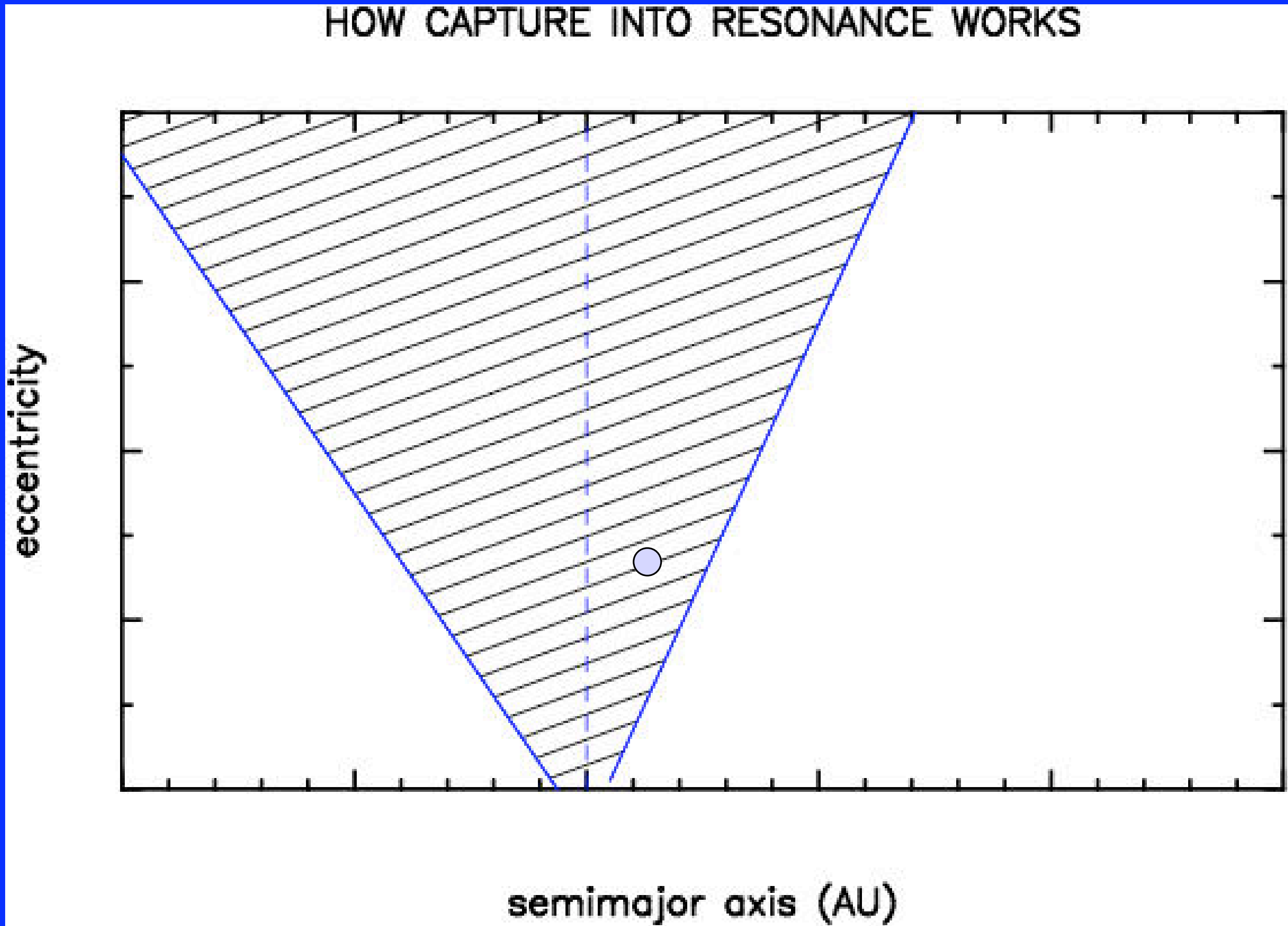
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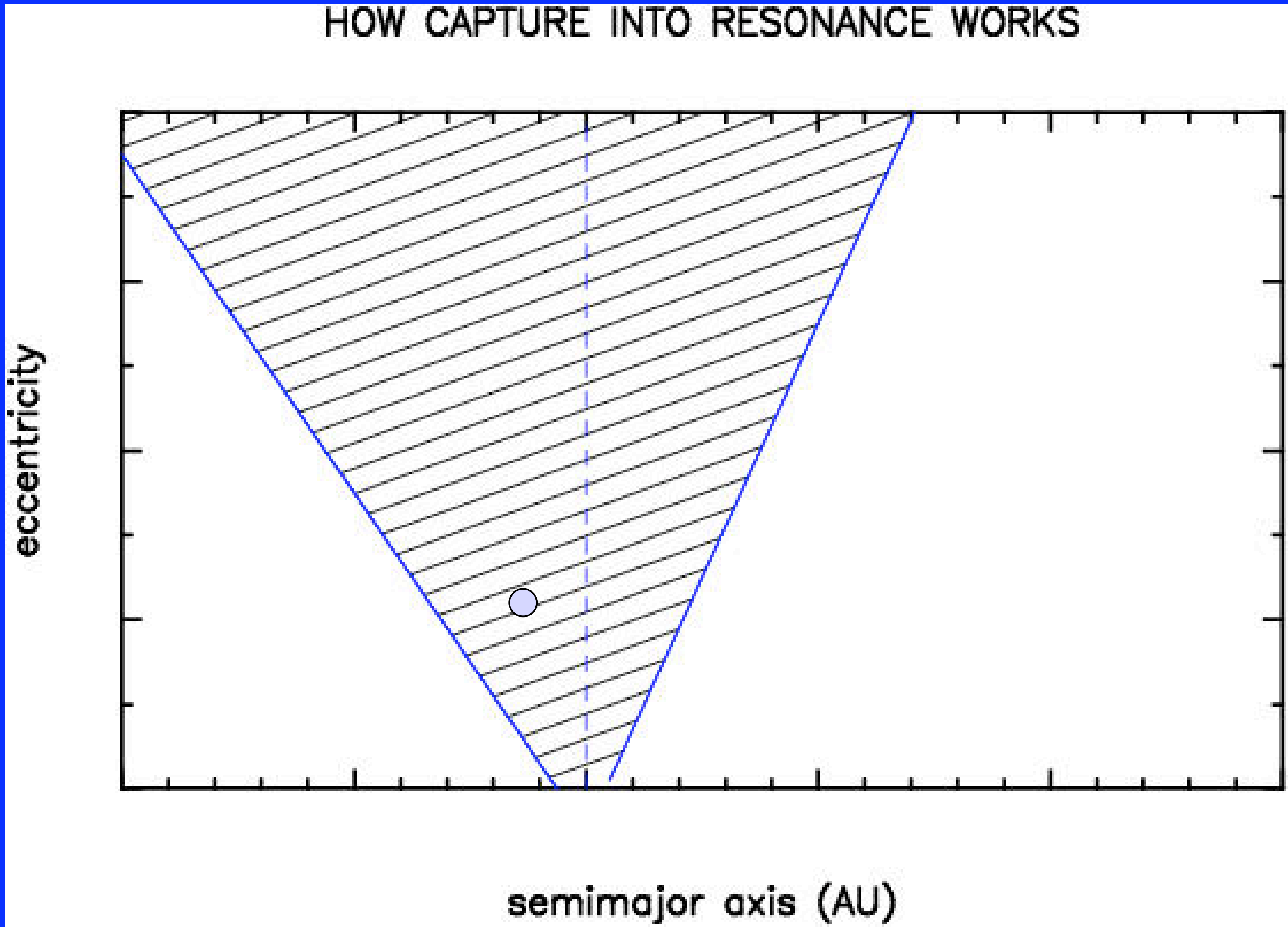
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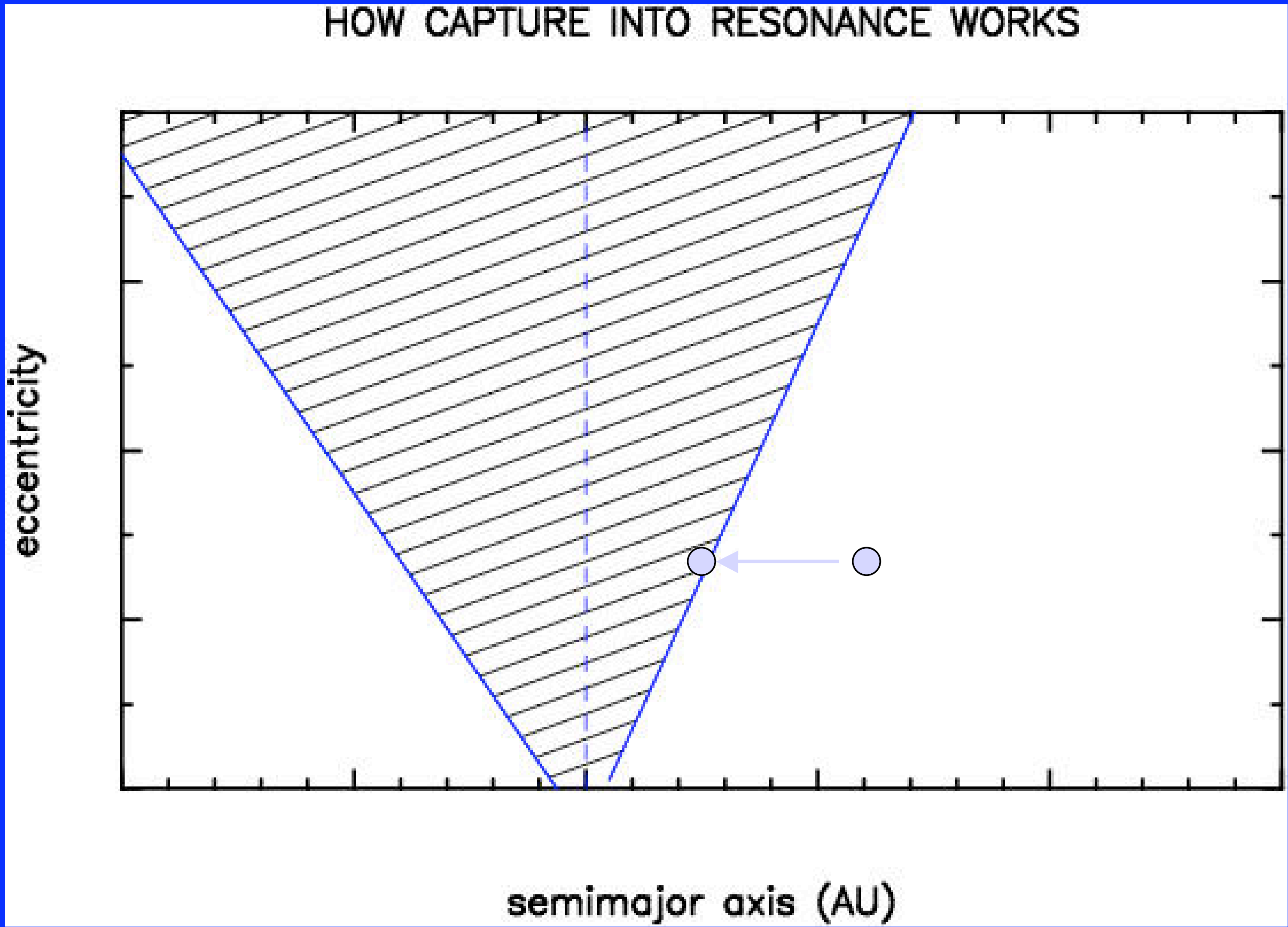
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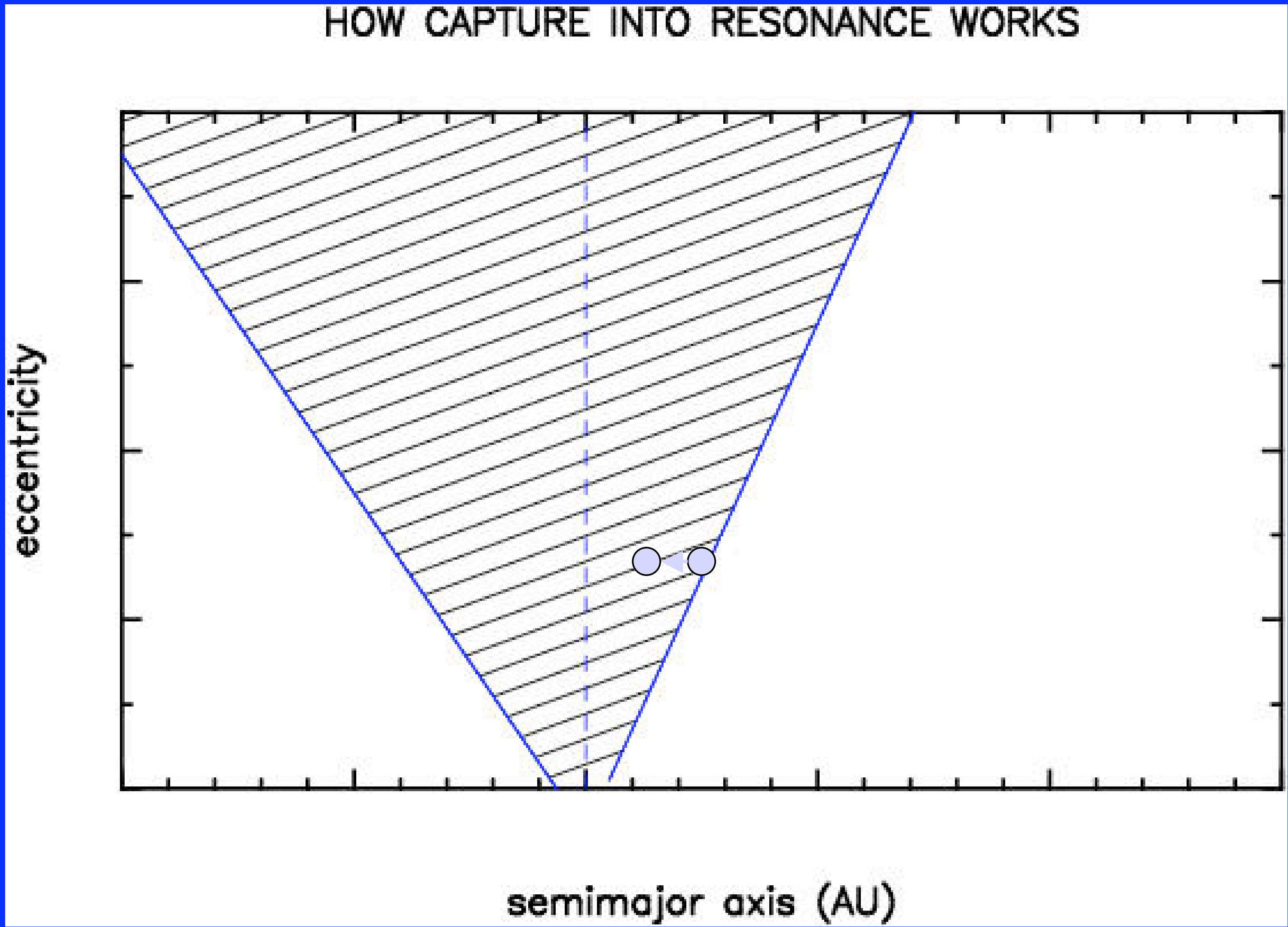
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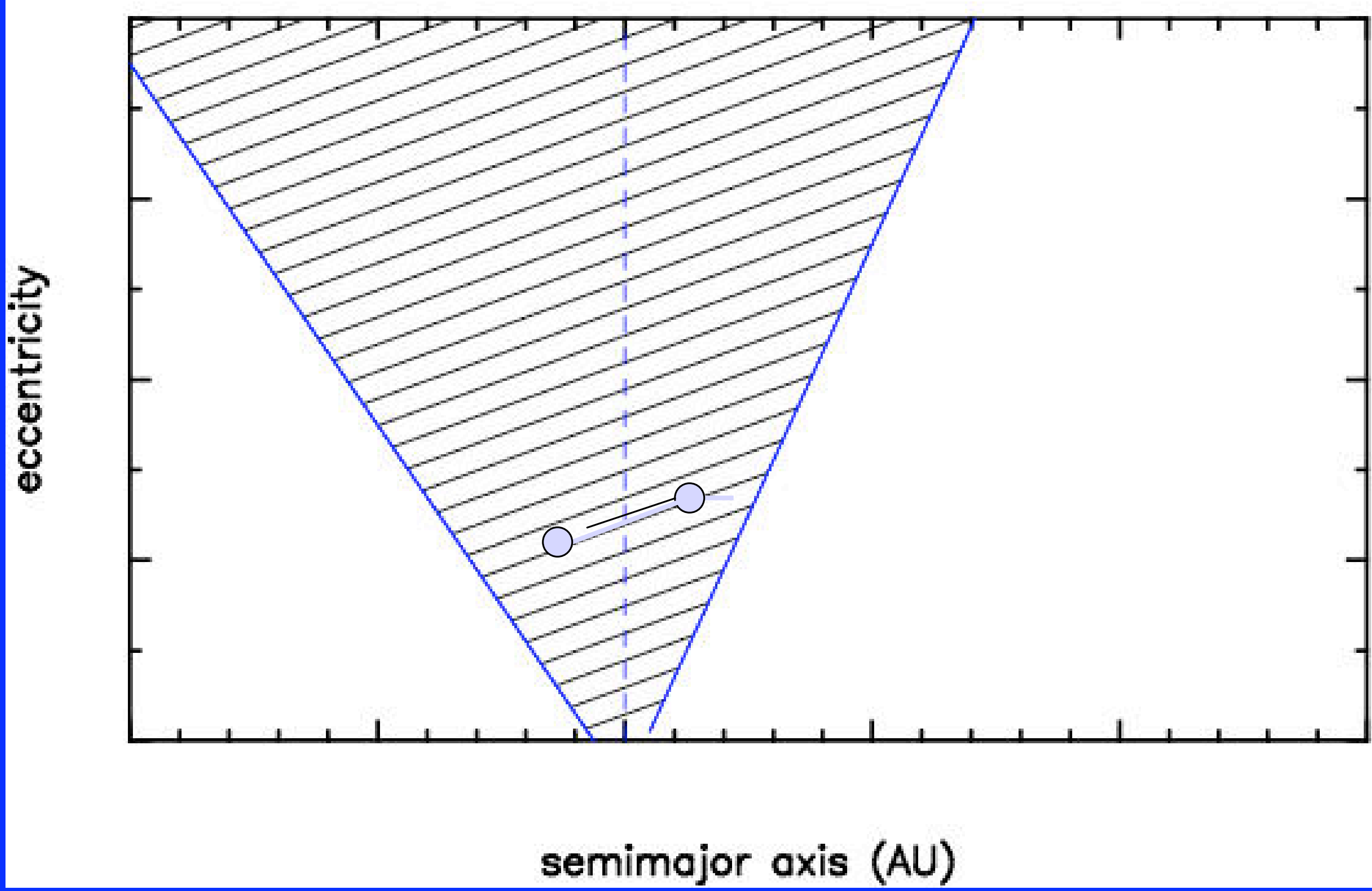

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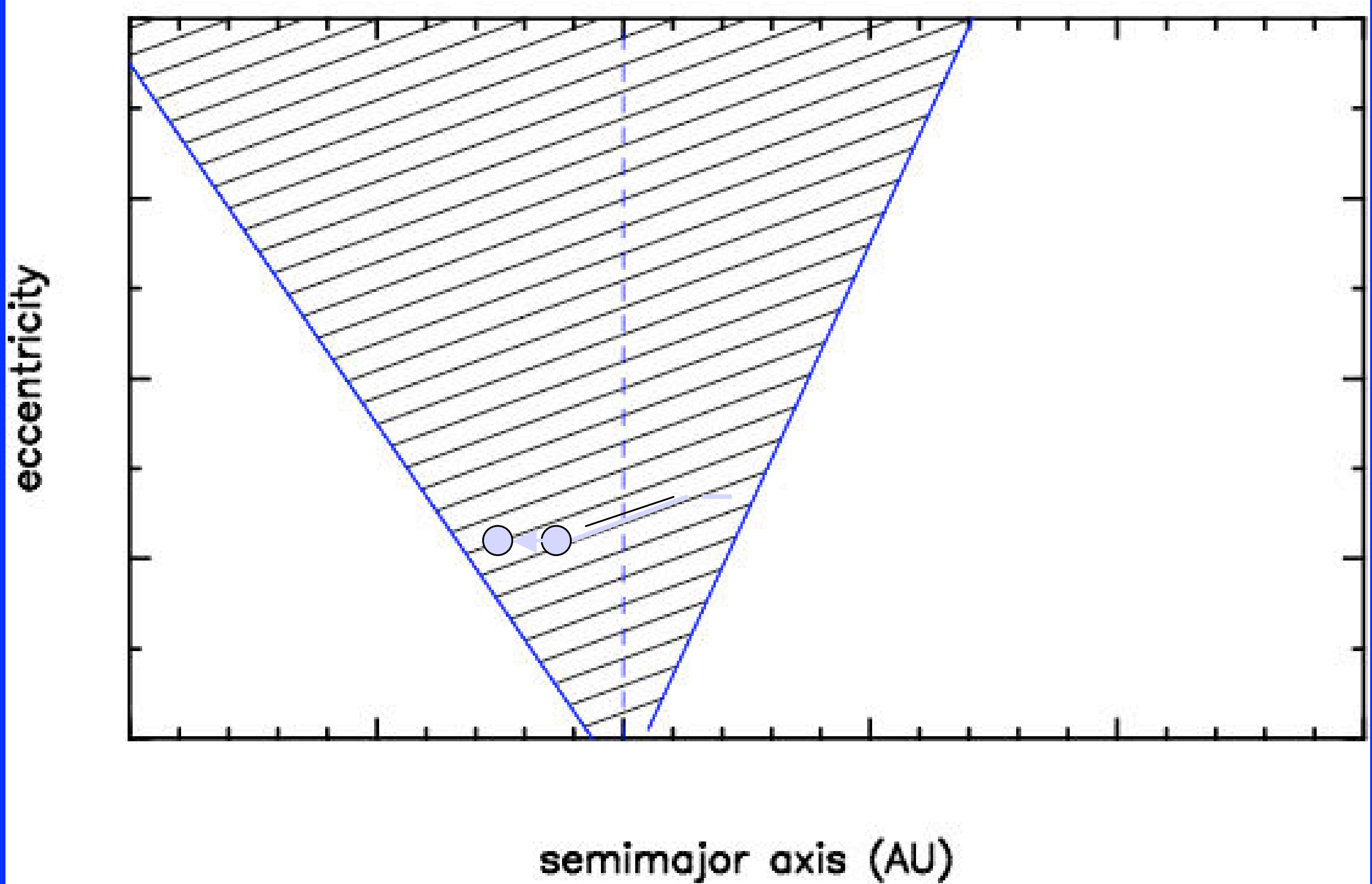

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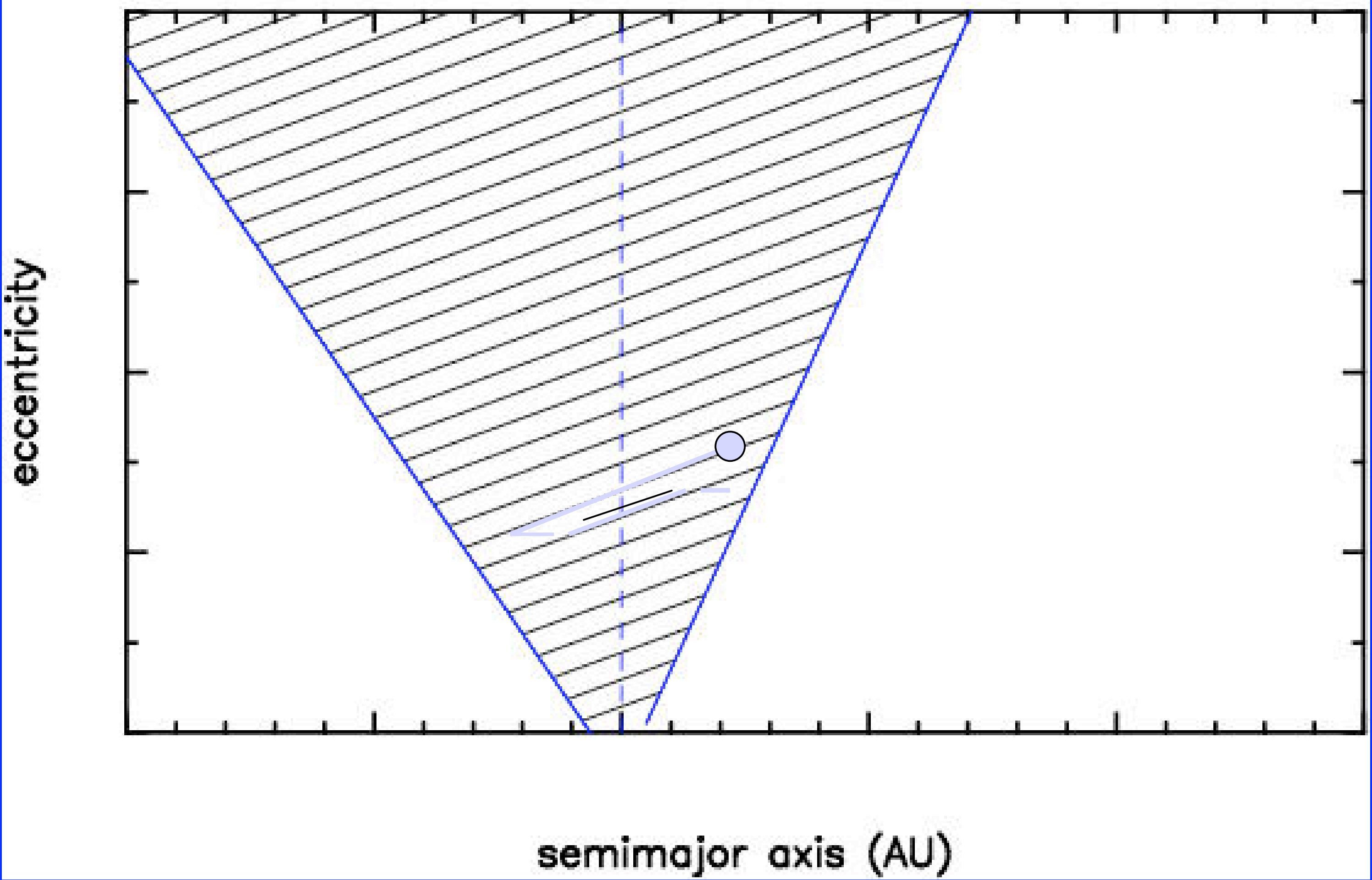

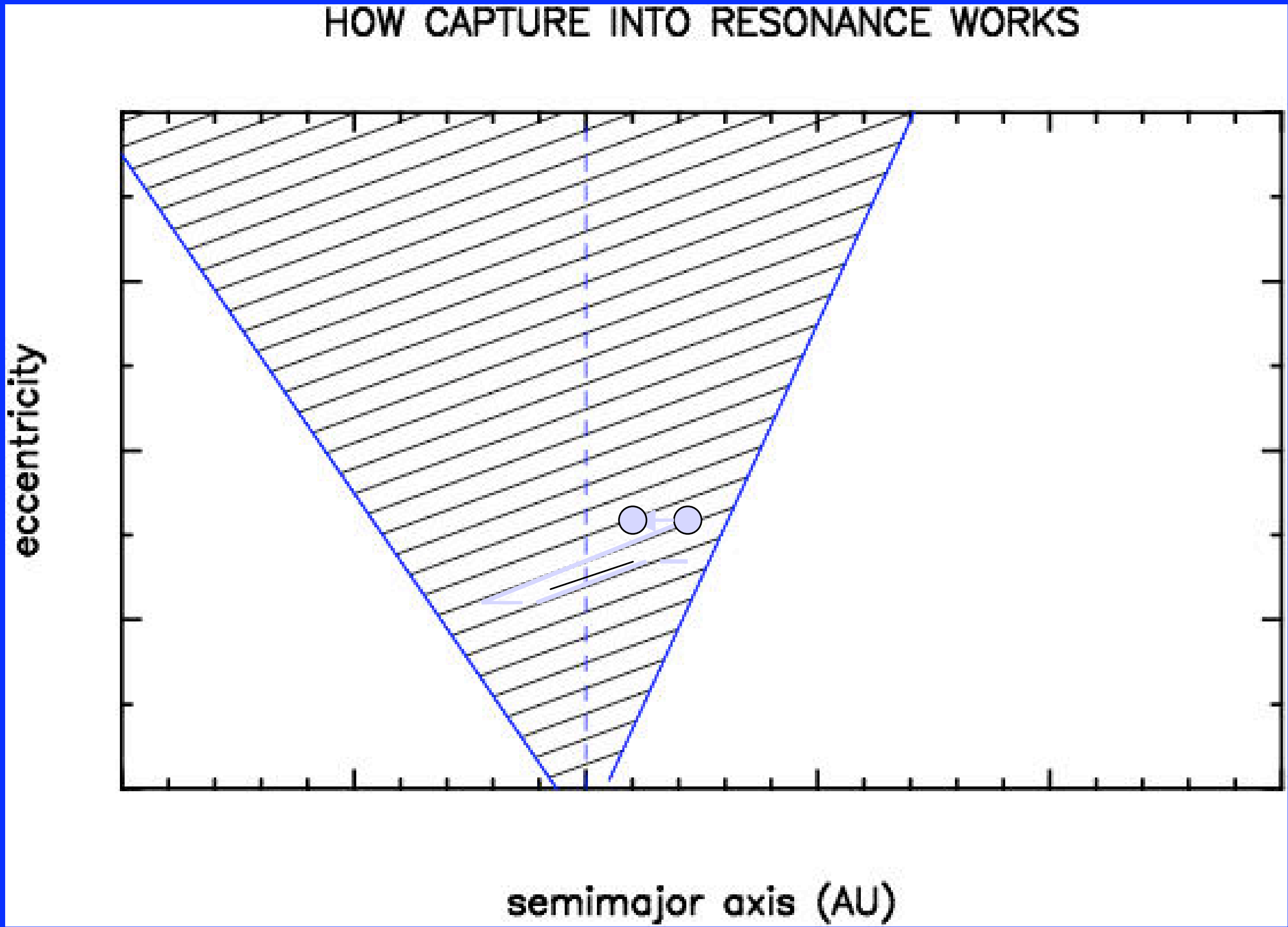
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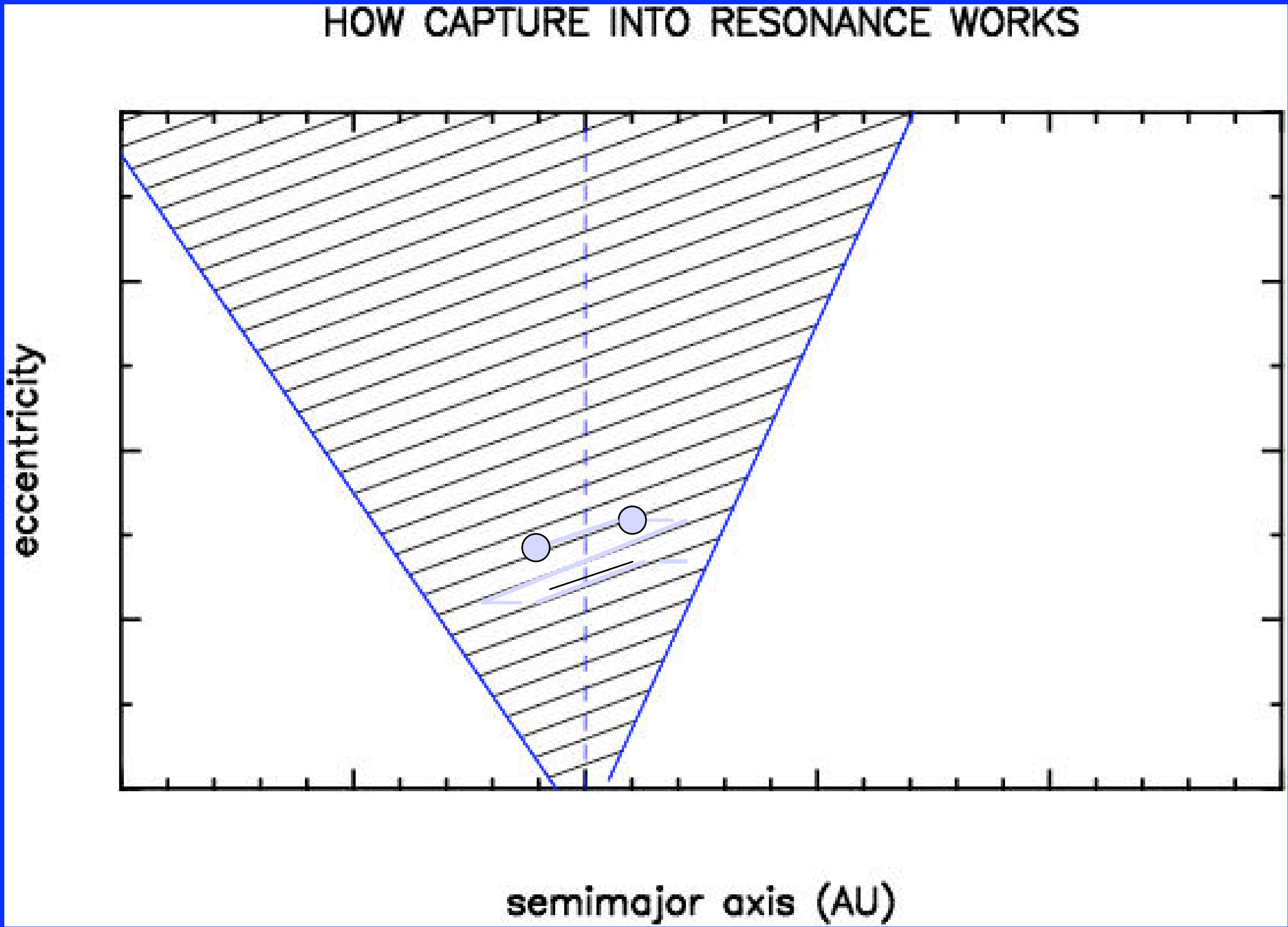
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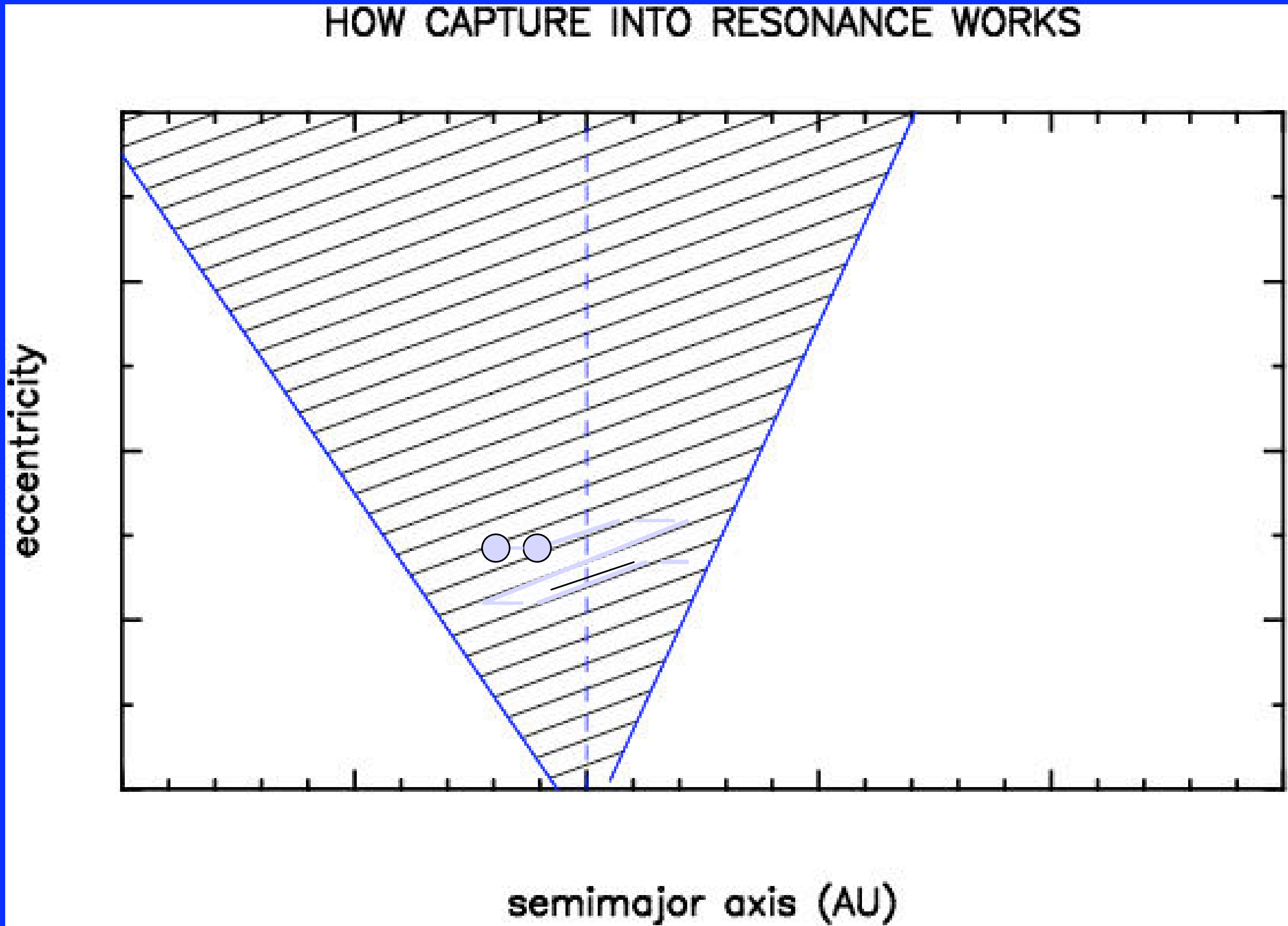
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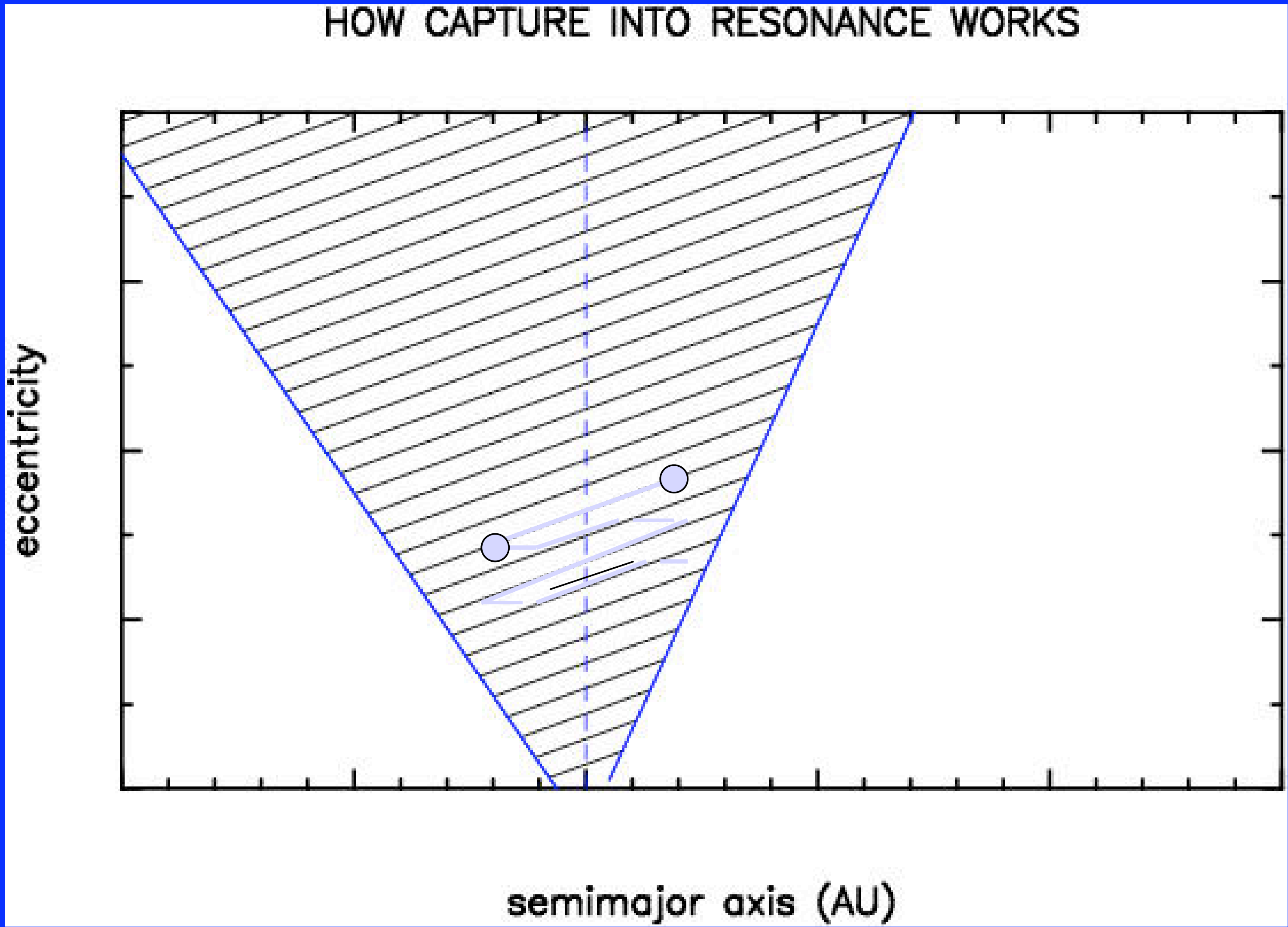
HOW CAPTURE INTO RESONANCE WORKS
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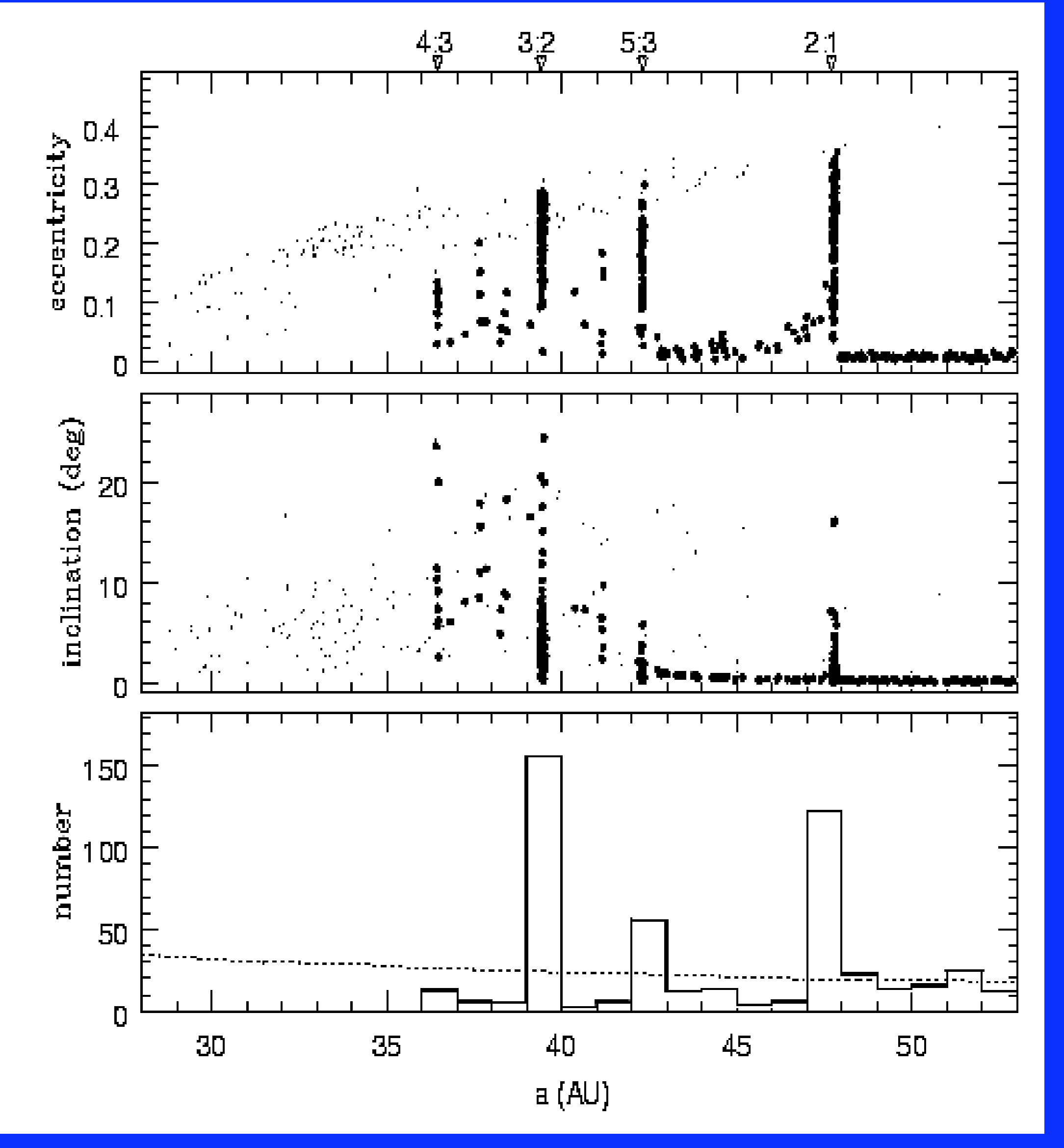
Origin and orbital distribution of the resonant population

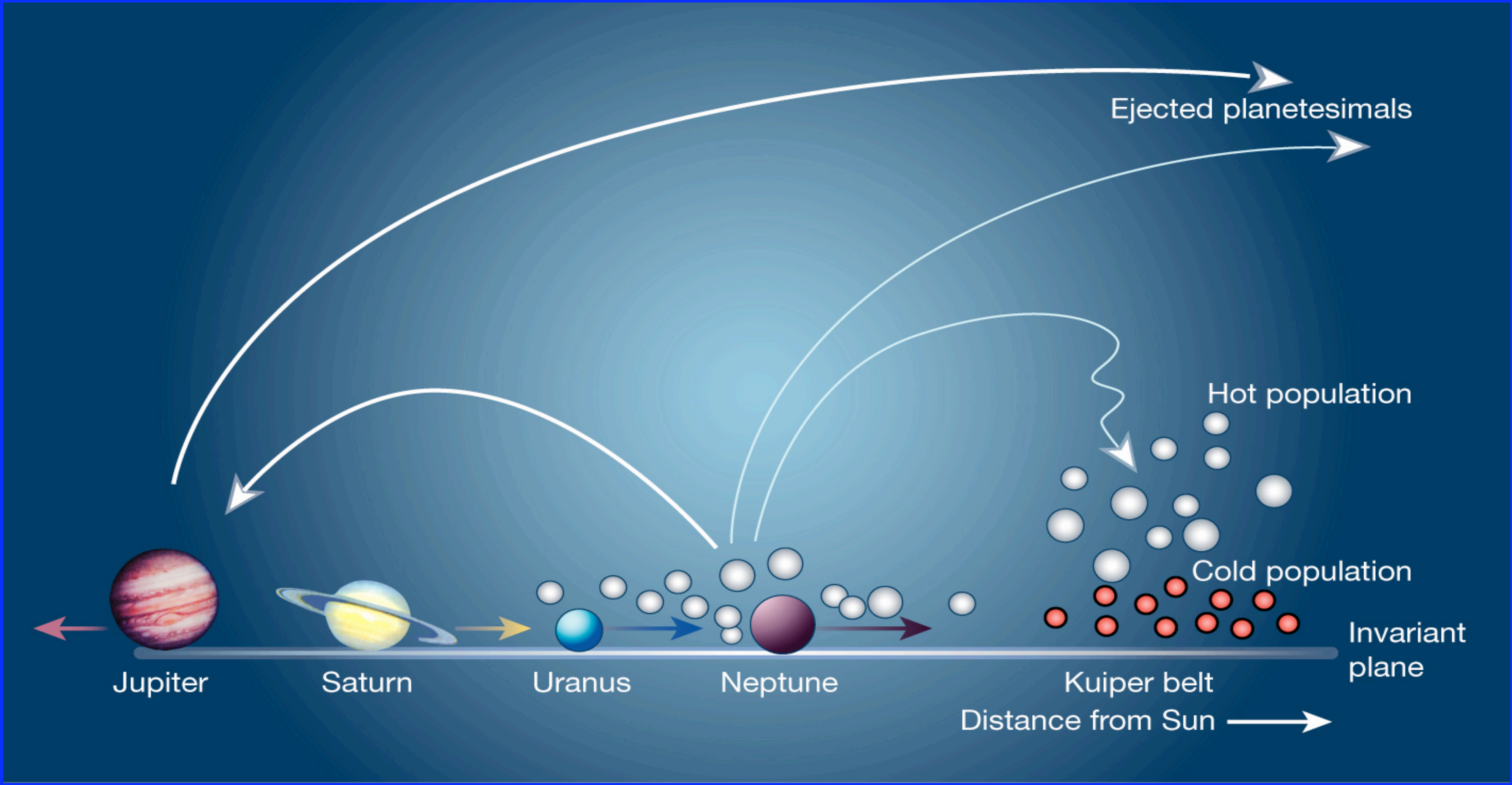
Mean motion resonance sweeping during Neptune migration des explain the existence of the resonant populations and their e,i distribution (Malhotra, 1993, 1995; Hahn and Malhotra, 1999; Ida et al., 2000; Gomes 2000)

But it cannot explain all the rest (e,i distribution of the classical belt, outer edge, mass deficit)

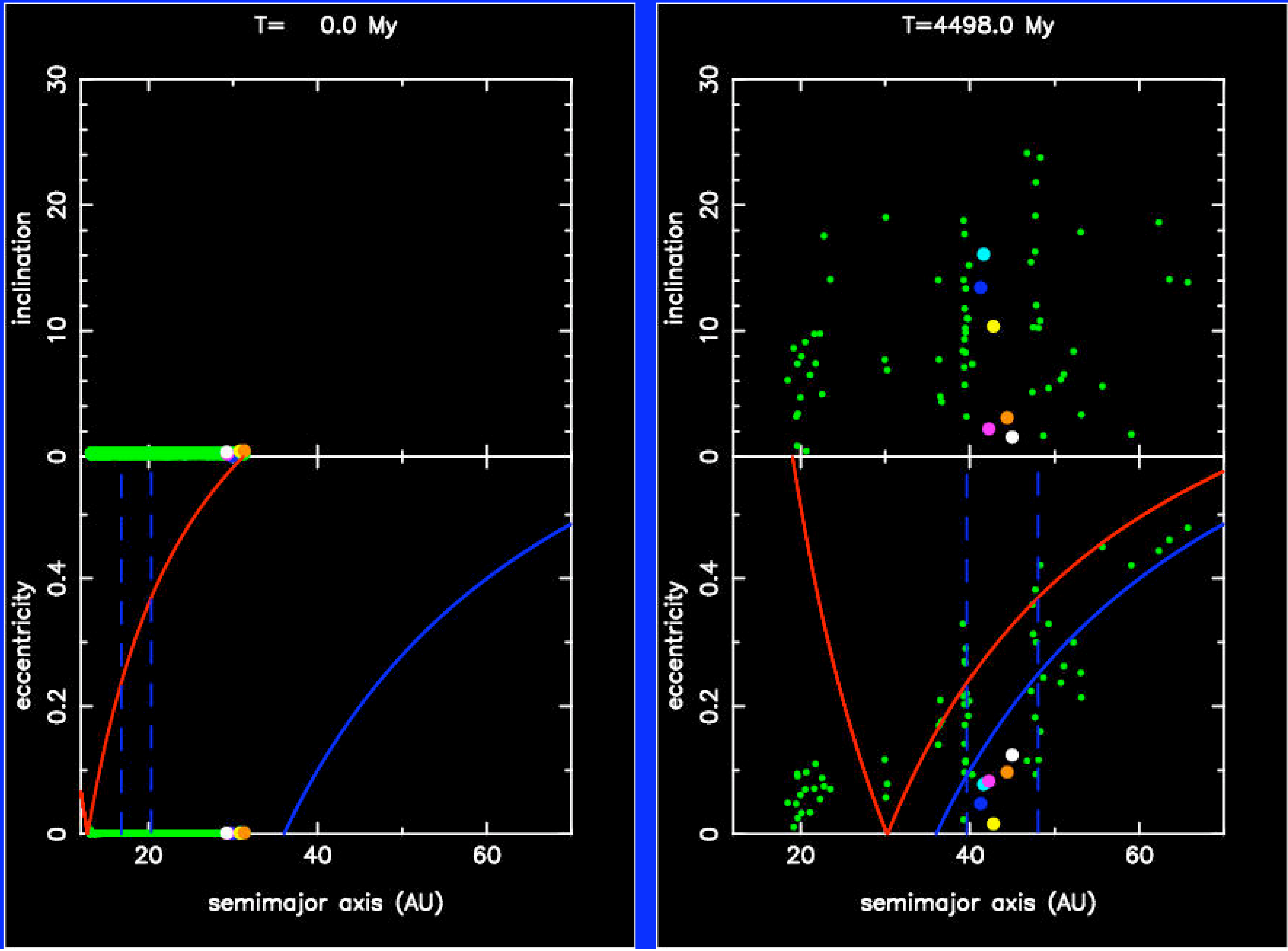


Origin of the HOT population

Again based on planet migration (Gomes, 2003)



Implanting the hot population in the Kuiper belt… (Gomes, 2003)

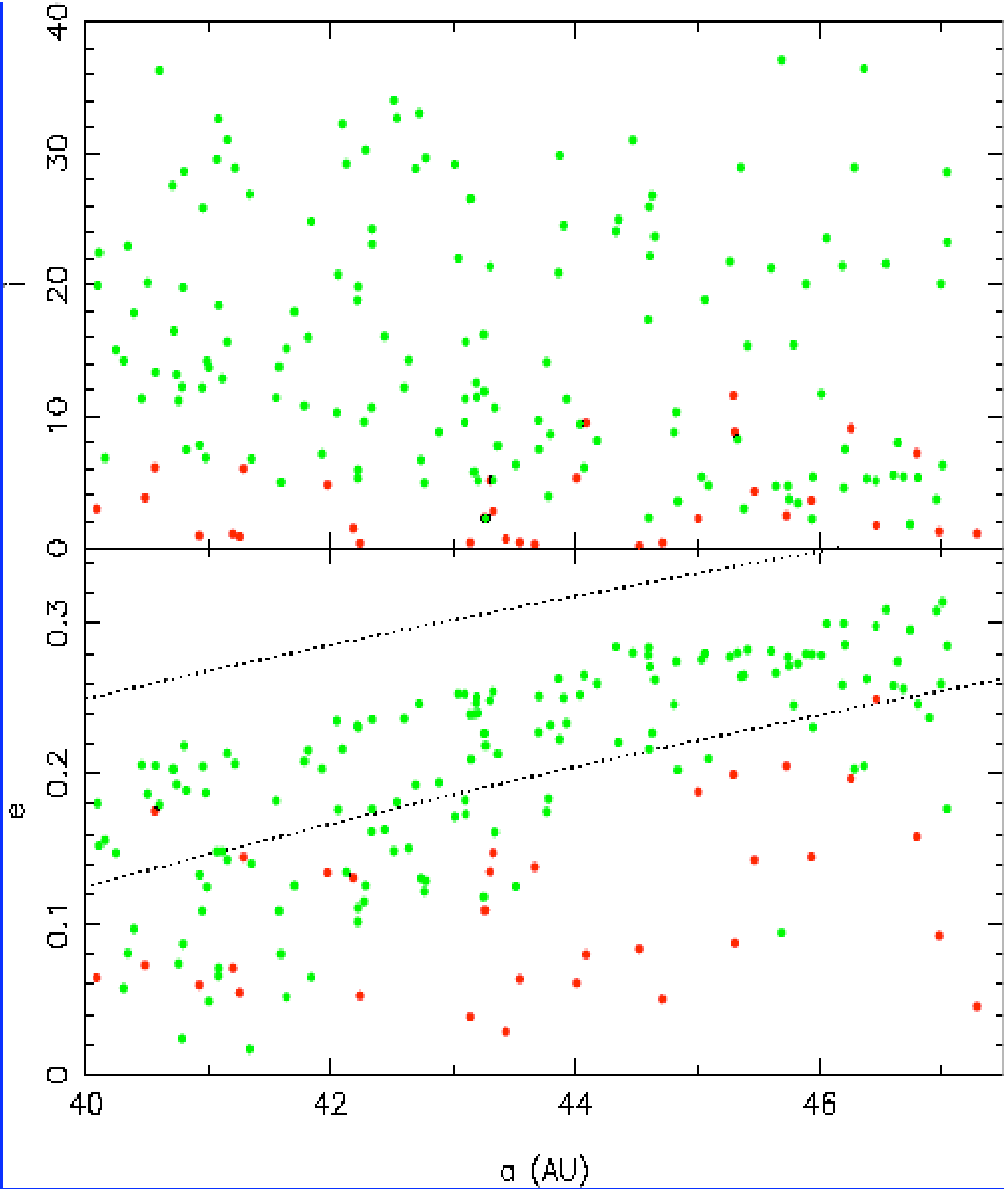


Gomes, 2003:

Red dots represent the local population, originally in the 40-50 AU zone

Green dots represent the population coming from Neptune_s region

Explains most of what we see_
_but why is the cold population not massive?
Why an edge at 50 AU?



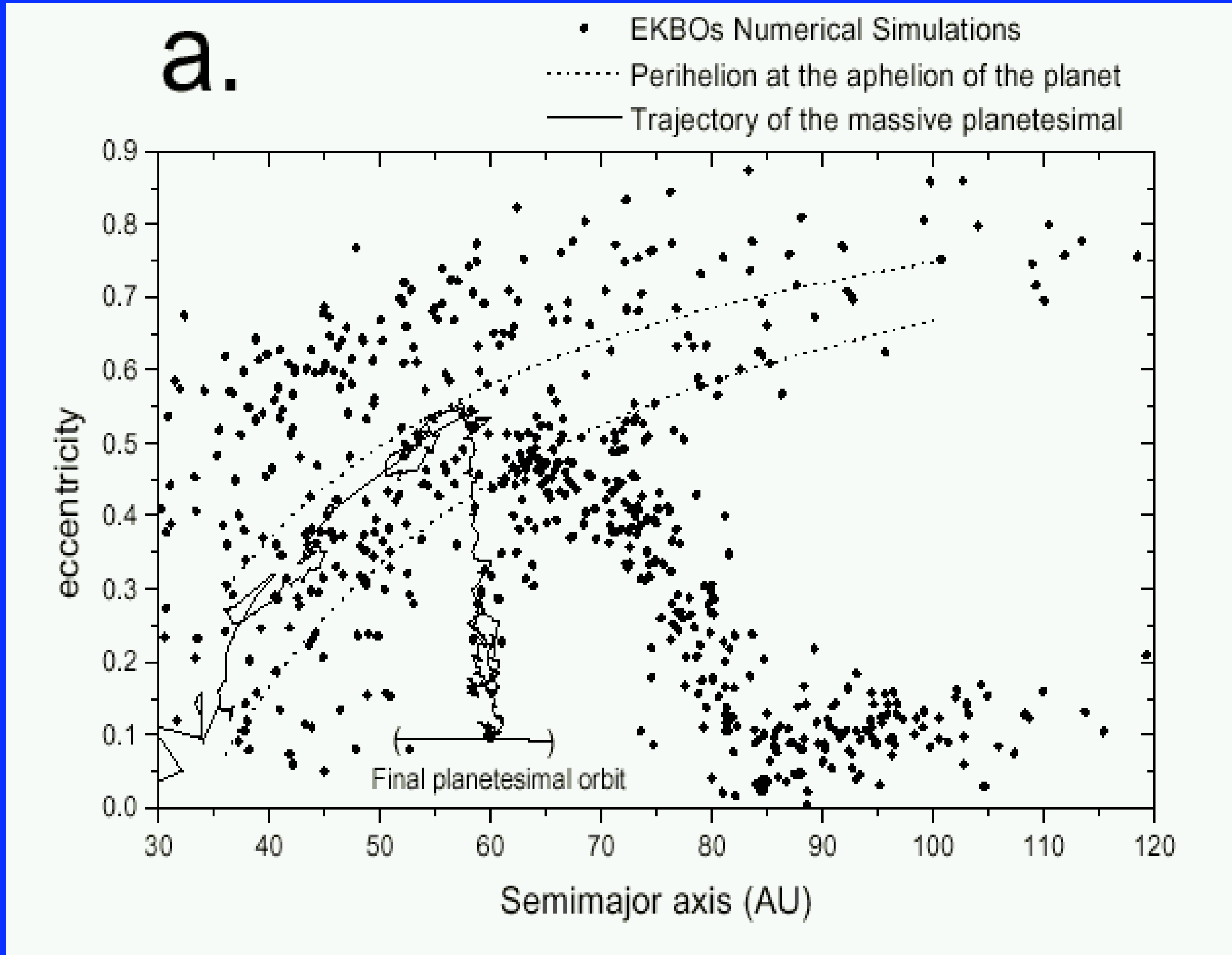
Origin of the outer edge

Five models proposed:

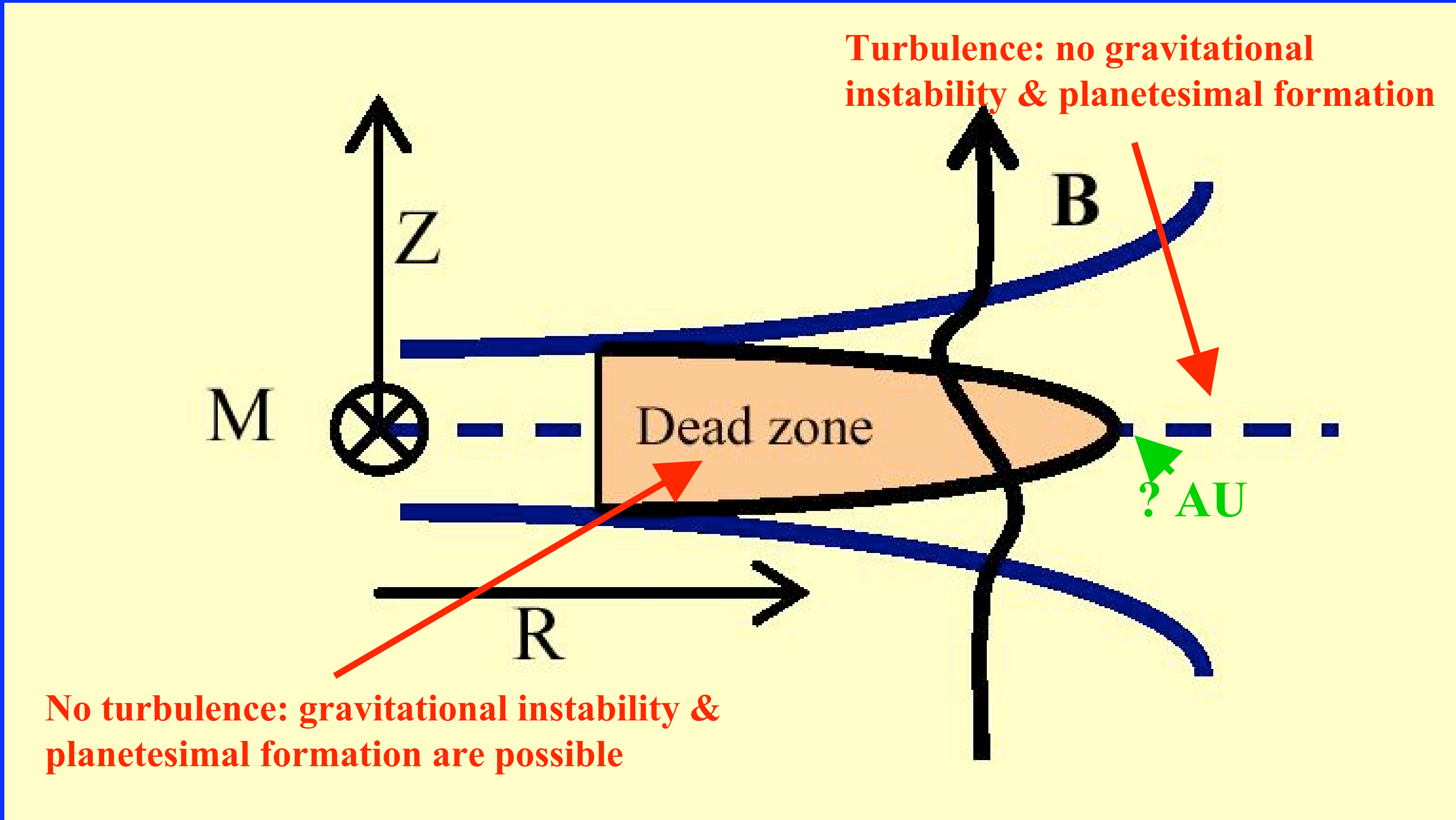
1. The existence of a yet undiscovered Martian-mass planet orbiting in the 50-70 AU range (Brunini and Melita, 2002)
2. Prevention of planetesimal accretion beyond 50 AU due to MRI turbulence (Balbus et al.)
3. Gas-drag migration that moved all growing planetesimals from beyond to within 50 AU (Weidenschilling)
4. Photo-evaporation of the disk due to nearby OB stars (Hollenbach et al.)
5. A close stellar passage (Ida et al., 2000)

Forming a 50-70 AU gap with a planet

The planet should still be there, and we should have already found it !

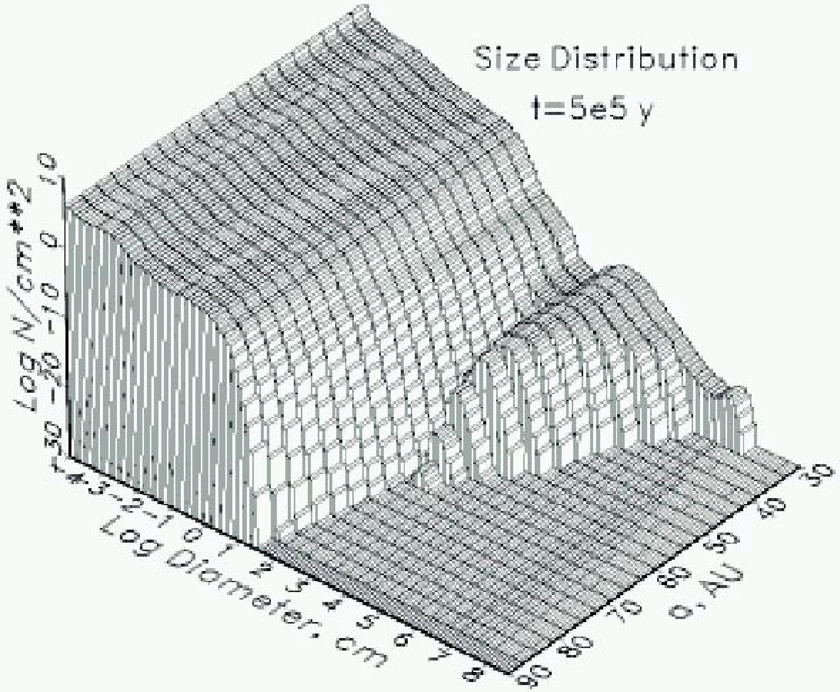


MRI turbulence preventing planetesimal accretion

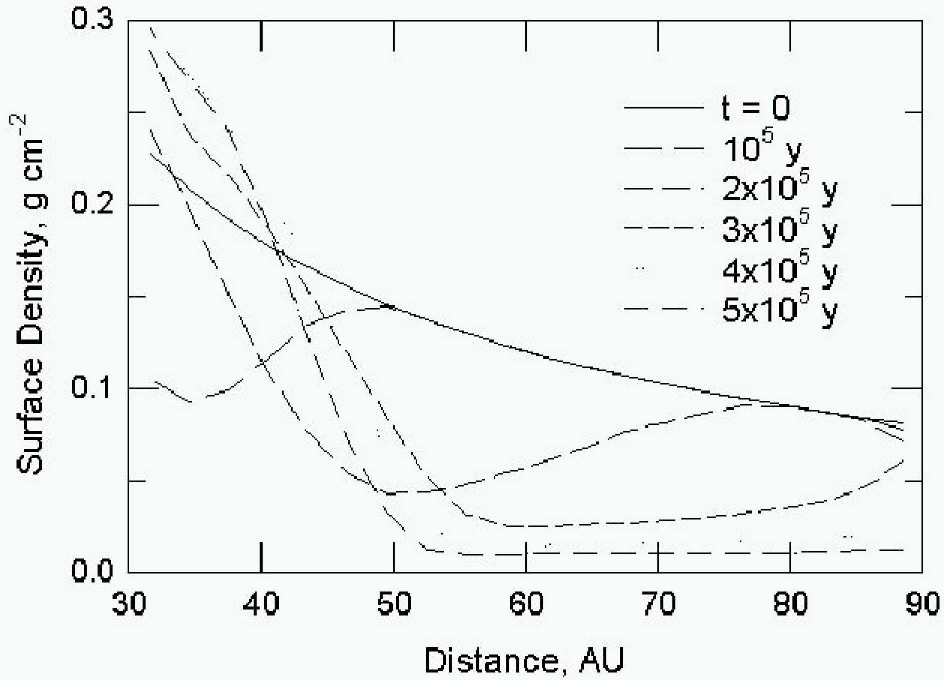


Balbus et al.

Drifting growing planetesimals from the distant disk



From Weidenschilling

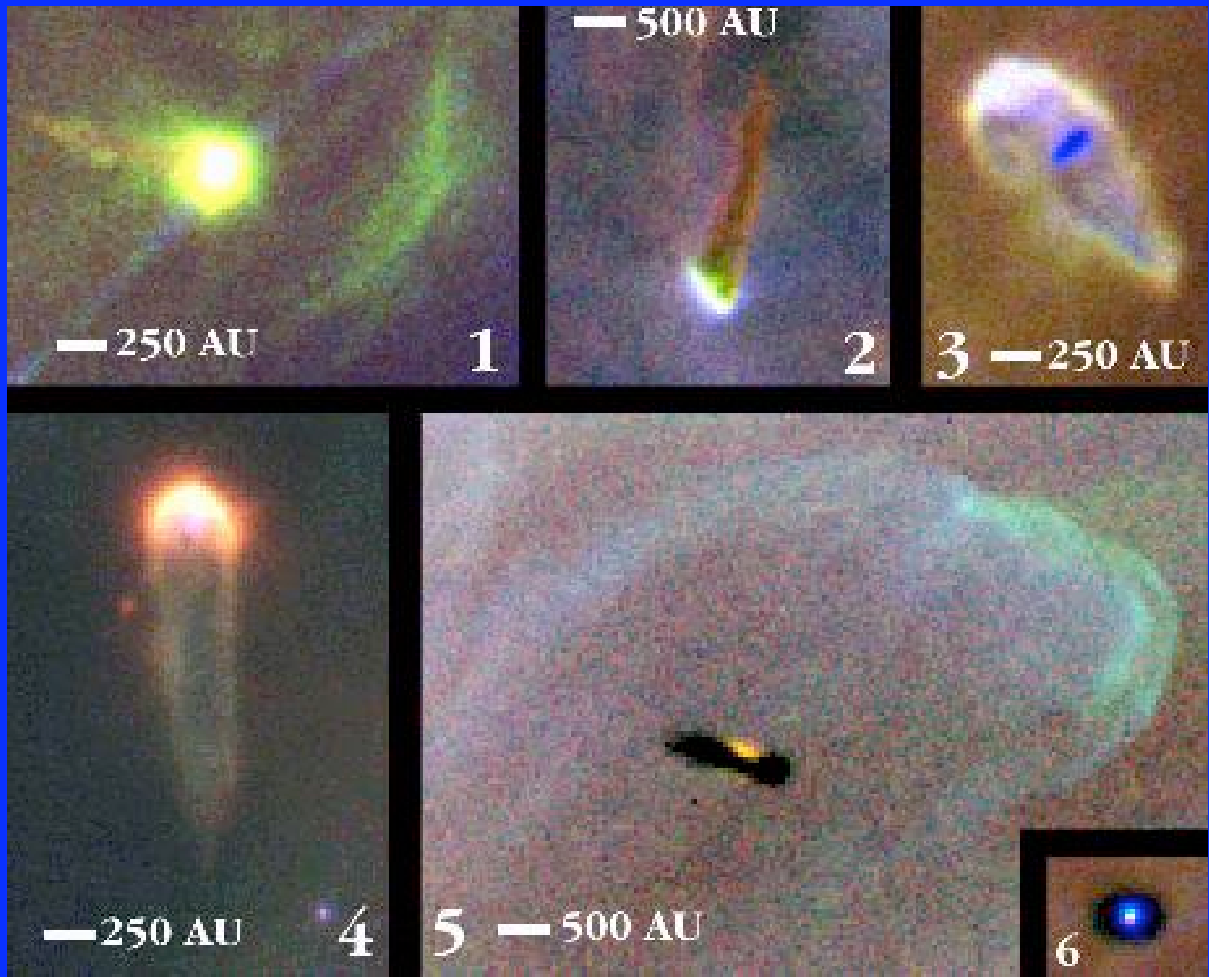


The competition between accretion and gas-drag induced migration prevents the formation of sizeable planetesimals beyond ? AU

Photo-evaporation of the distant disk

Narrow proplyds (disks around new born stars) are observed in many young stellar associations

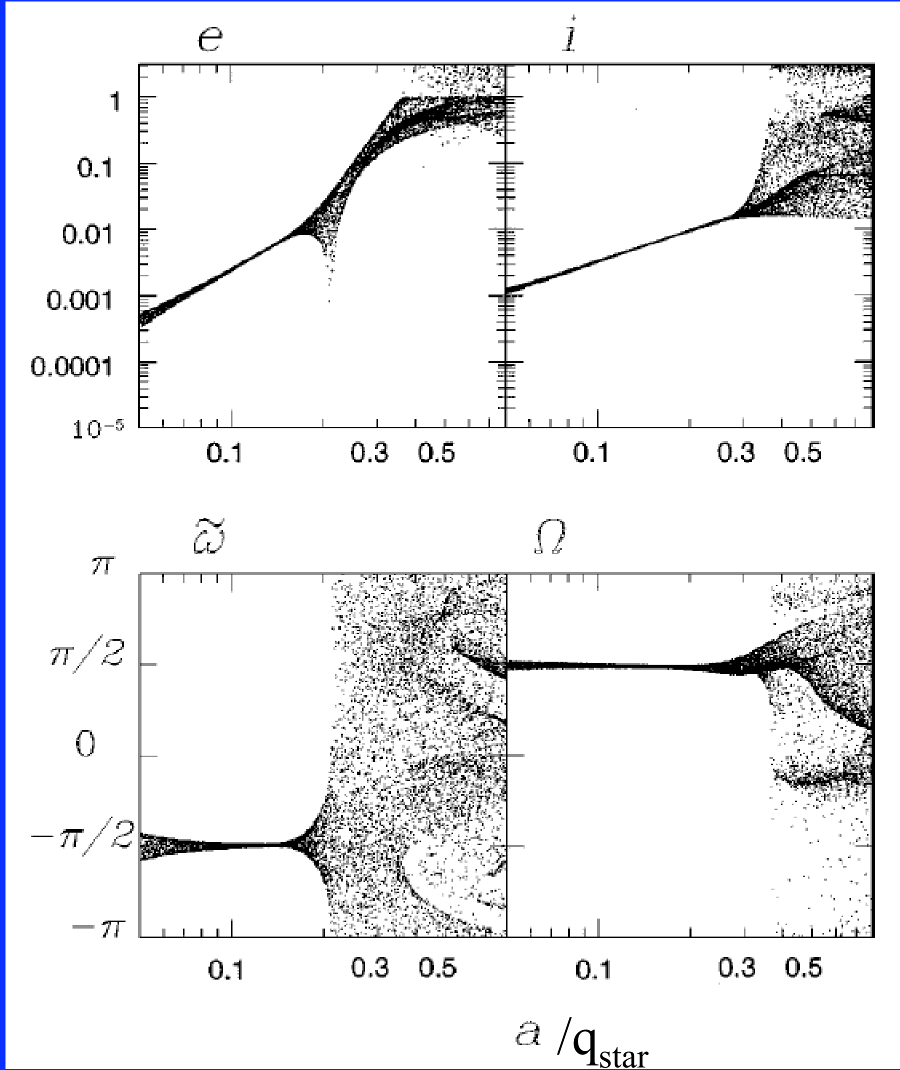
Their small sizes are believed to be due to the photo-evaporation of the distant disk due to the radiation of nearby OB stars



Hollenbach et al

Forming the outer edge by a passing Star

The passage of a star at 150-200 AU would have produced the sharp edge of the Kuiper belt at ~ 50 AU (Ida et al., 2000; Kobayashi and Ida 2001; Melita et al. 2002)

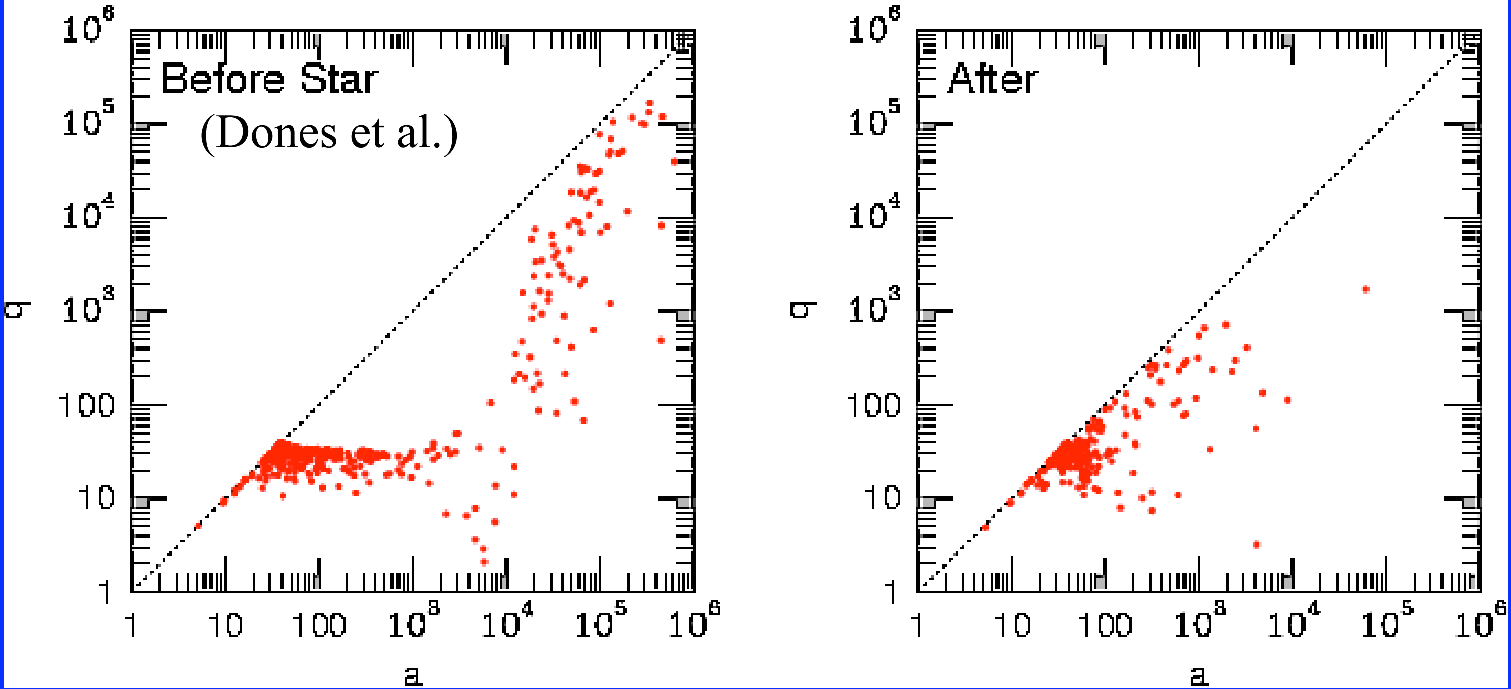


However, severe constraints on the time of the encounter are provided by the preservation of the Oort Cloud

Forming the outer edge by a passing Star

At $t=10^8$ yrs

A late stellar encounter would strip off the already formed Oort cloud_



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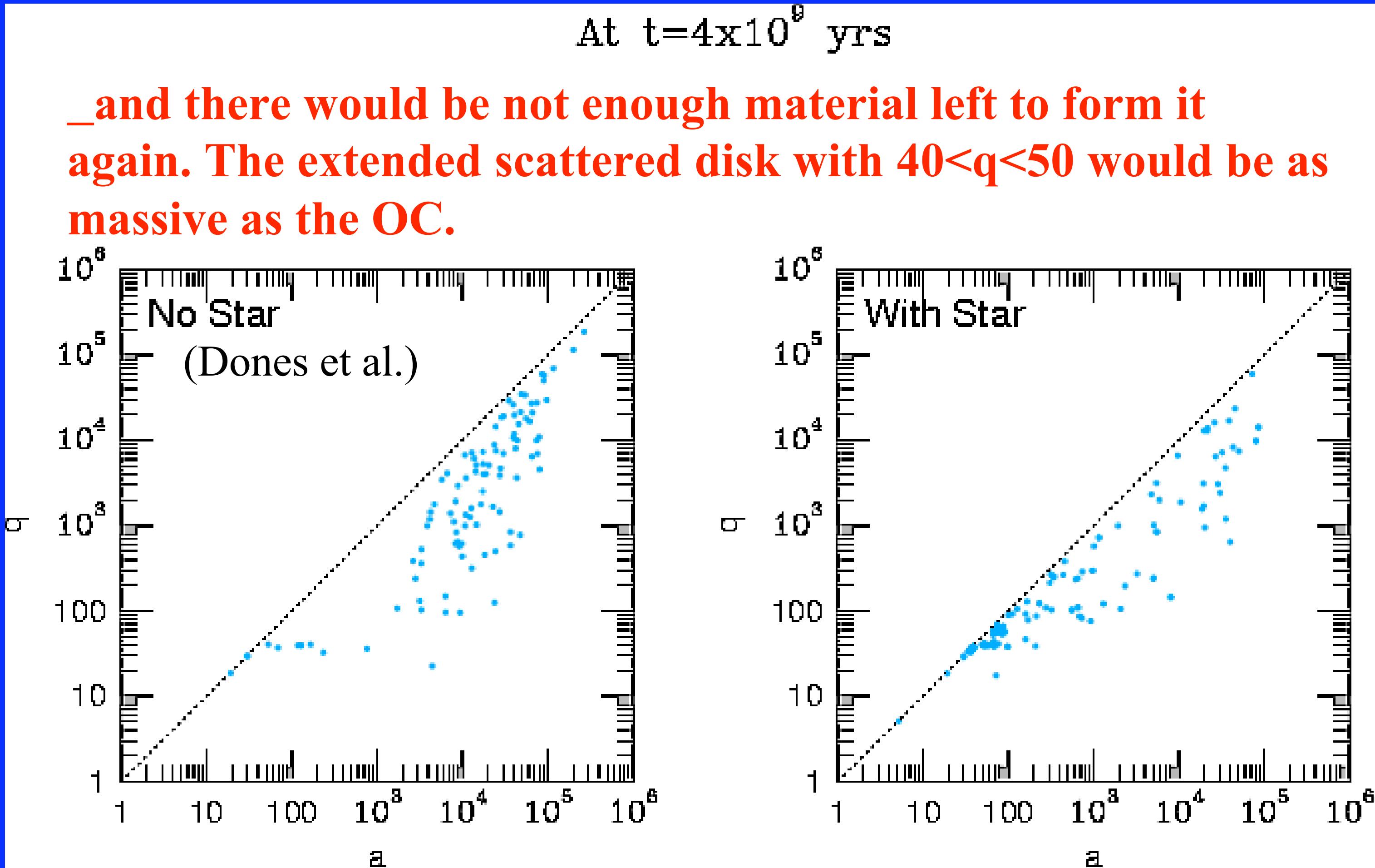
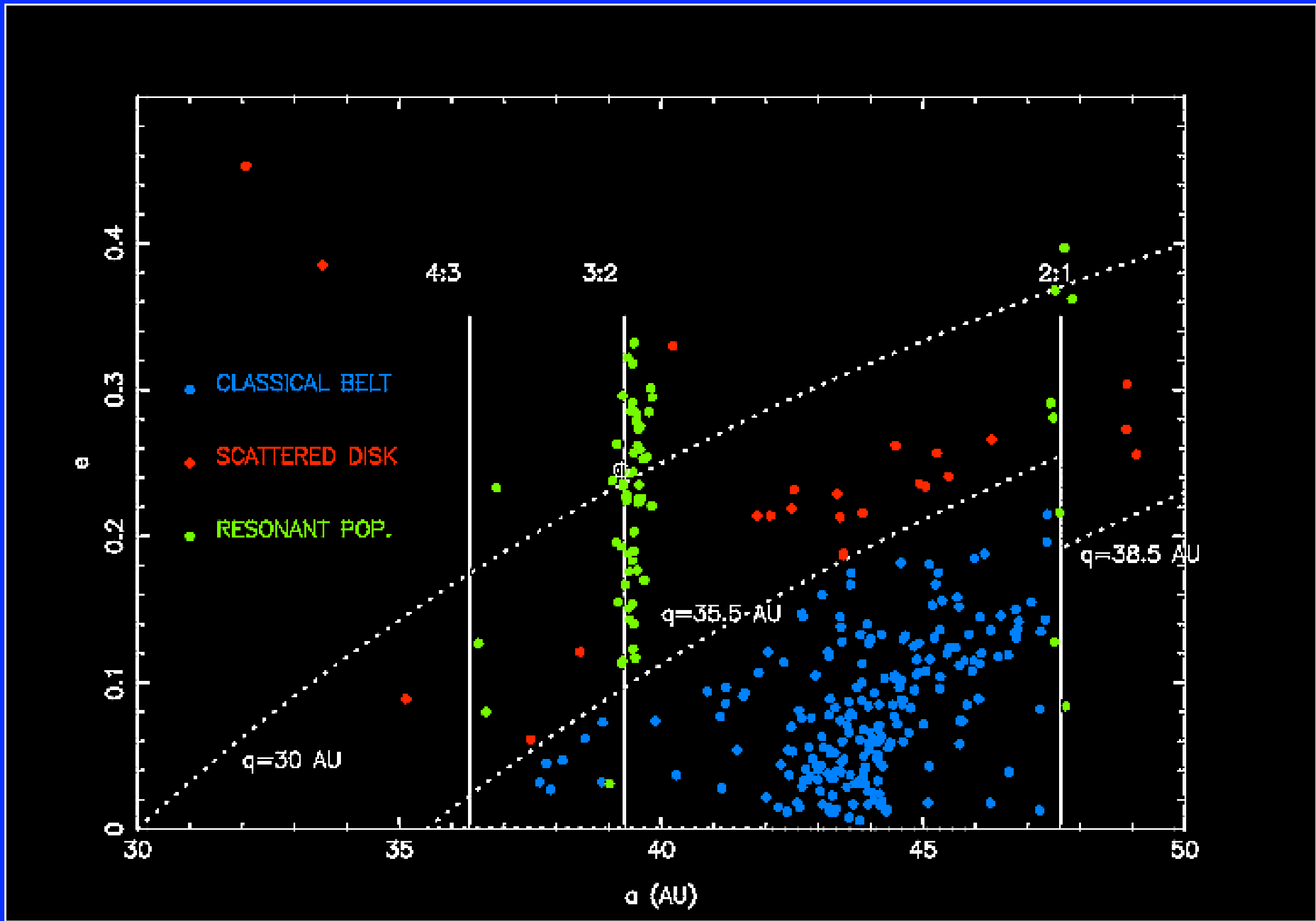


A stellar encounter truncating the KB must have occurred not later than 1 My after the beginning of Oort cloud formation. Possible/probable in a stellar cluster?

But_. Why is the edge at the location of the 1:2 resonance?



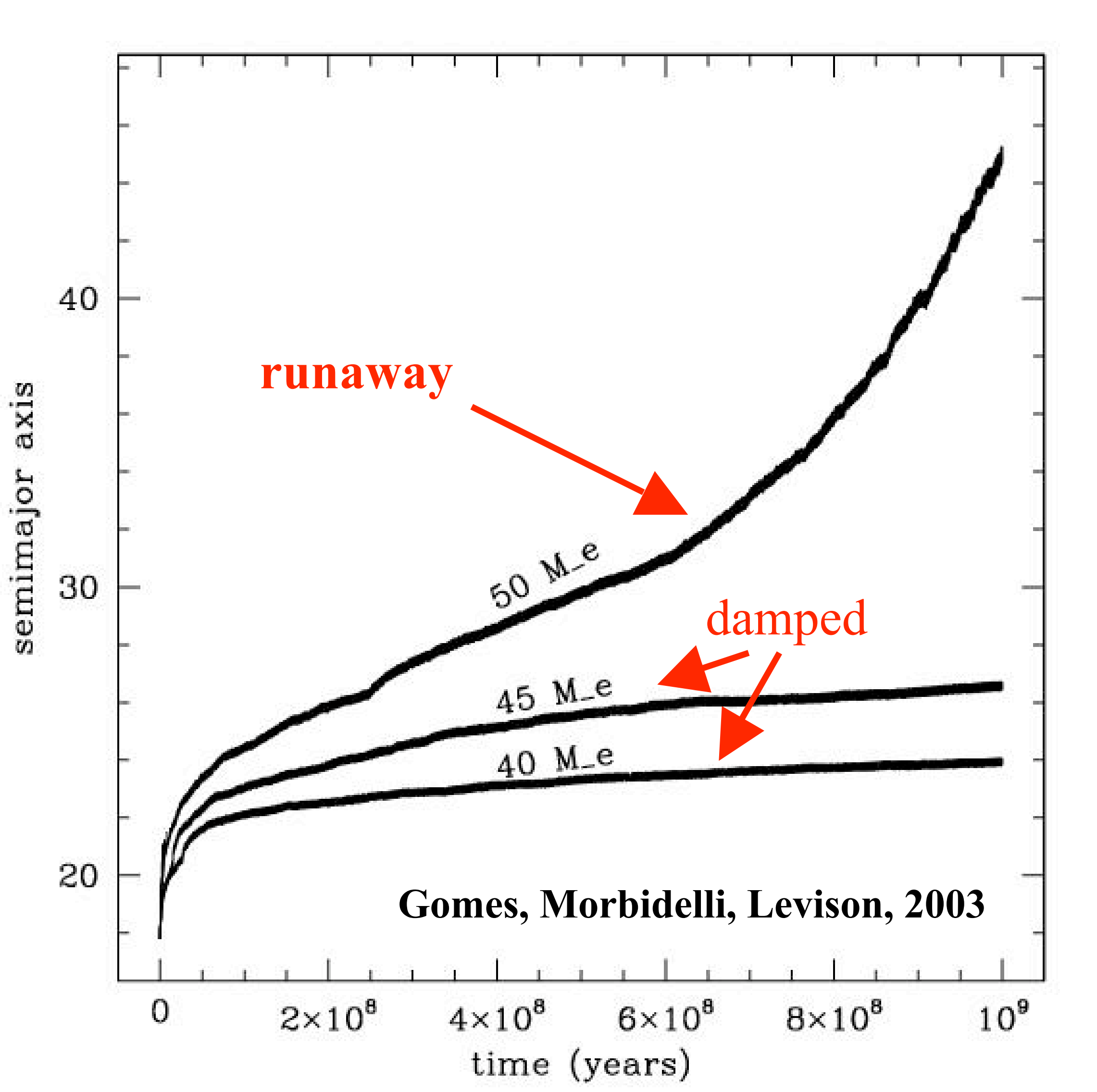
The mass depletion problem

Related to the problem of why Neptune stopped at 30 AU

Two migration modes:

DAMPED _ the planet stops after creating a gap around itself, leaving a massive disk outside its final position

RUNAWAY _ the planet accelerates up to the disk outer edge



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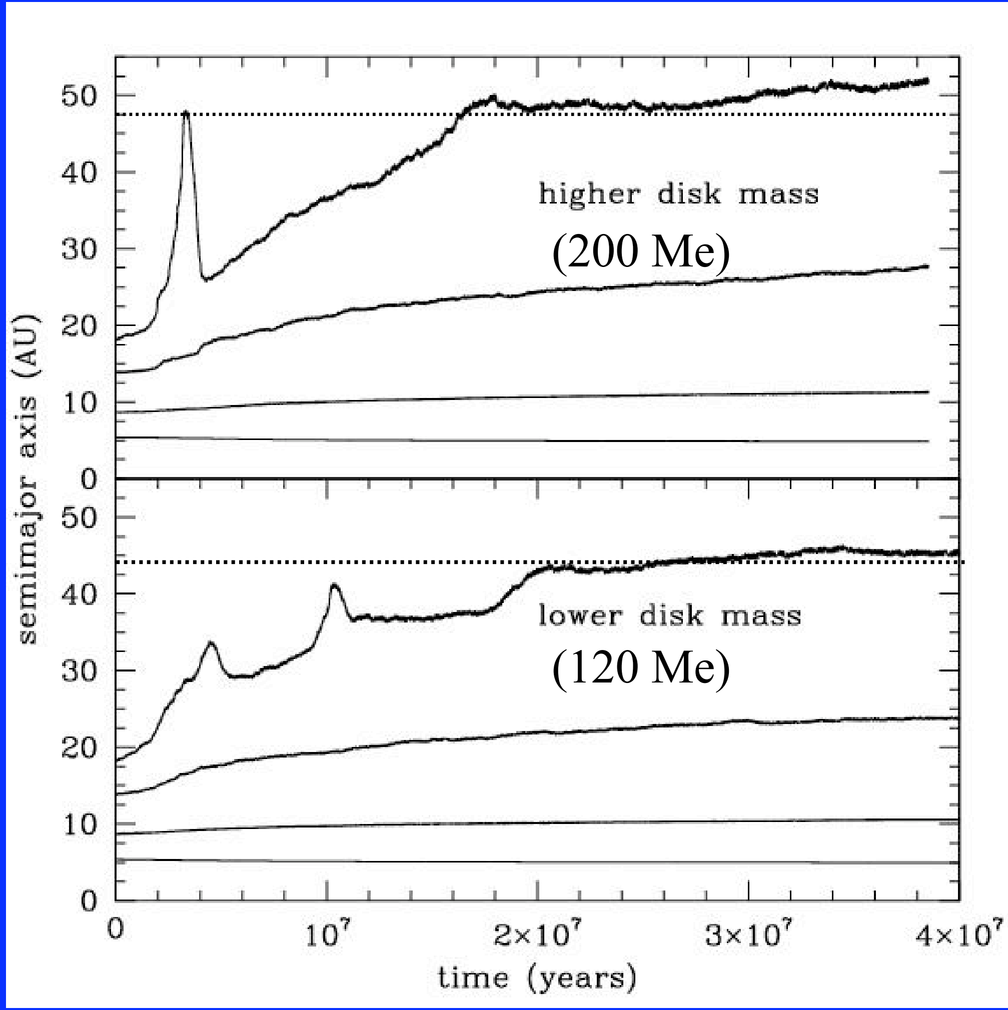


Gomes, Morbidelli, Levison, 2003

The mass depletion problem

The fact that Neptune stopped at 30 AU seems to indicate that

- The planetesimal disk had to have a moderate mass (<50 Me) so to produce a damped migration
- Neptune had to start around 23-24 AU (how did it form so far?)
- The disk beyond 35 AU (i.e. the cold population) remained massive

The mass depletion problem

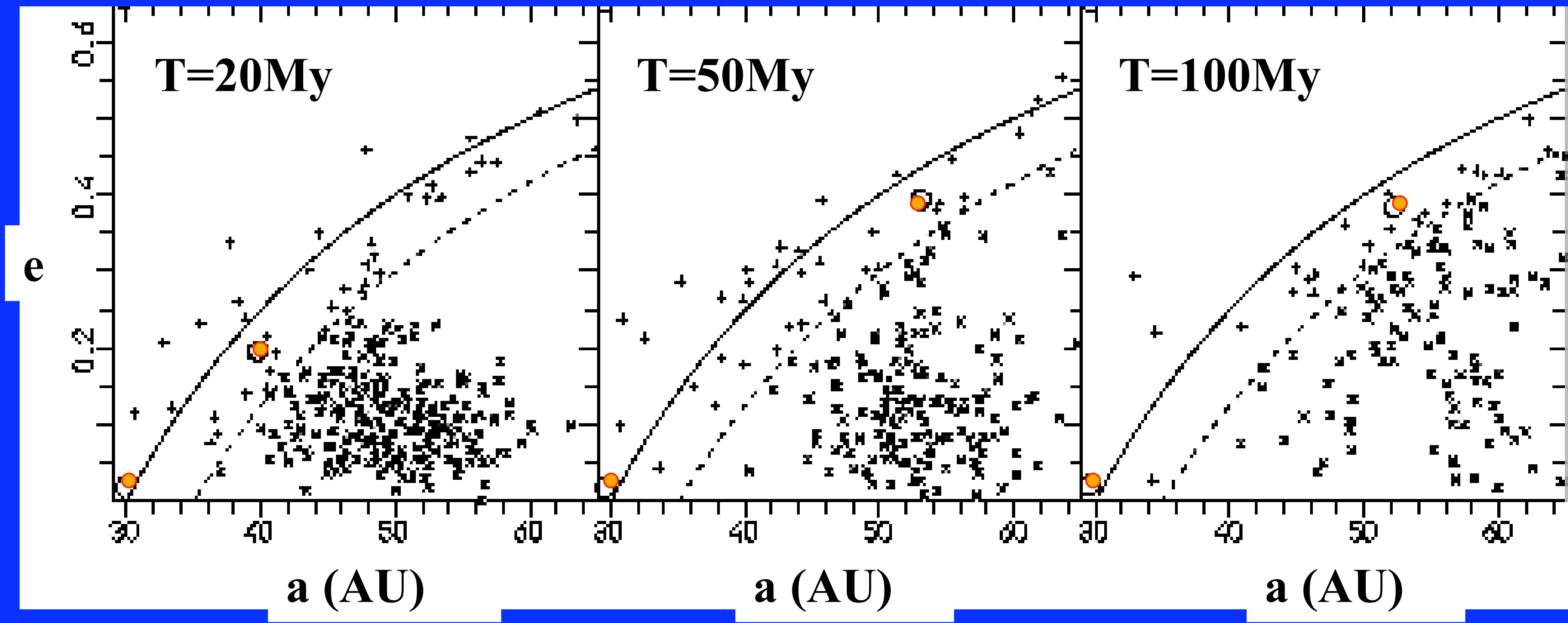
What depleted the mass of the cold classical population in the 40-50 AU region?

Two possible ways:

1 **Dynamical way, by exciting the eccentricity of most of the objects up to Neptune-crossing values**

2 **Collisional grinding and evacuation of dust by radiation pressure**

Depletion by dynamical excitation

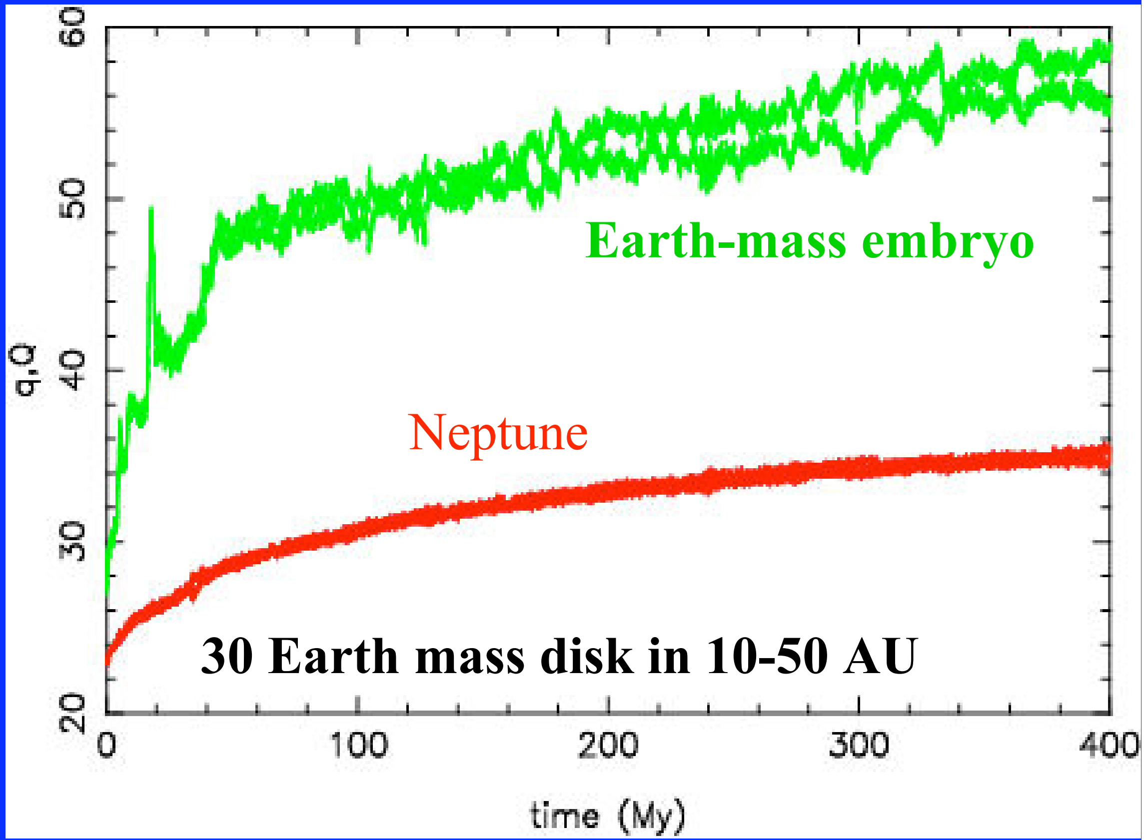


A massive planetary embryo scattered by Neptune through the Kuiper belt can explain the mass depletion and the KB e-distribution (Morbidelli and Valsecchi, 1997; Petit et al., 1999)

Depletion by dynamical excitation

The bodies scattered by the embryo to Neptune-crossing orbit would have forced Neptune to migrate well beyond 30AU

To stop Neptune at 30 AU the total mass of the 10-50AU disk had to be < 15 M_E :TOO SMALL!



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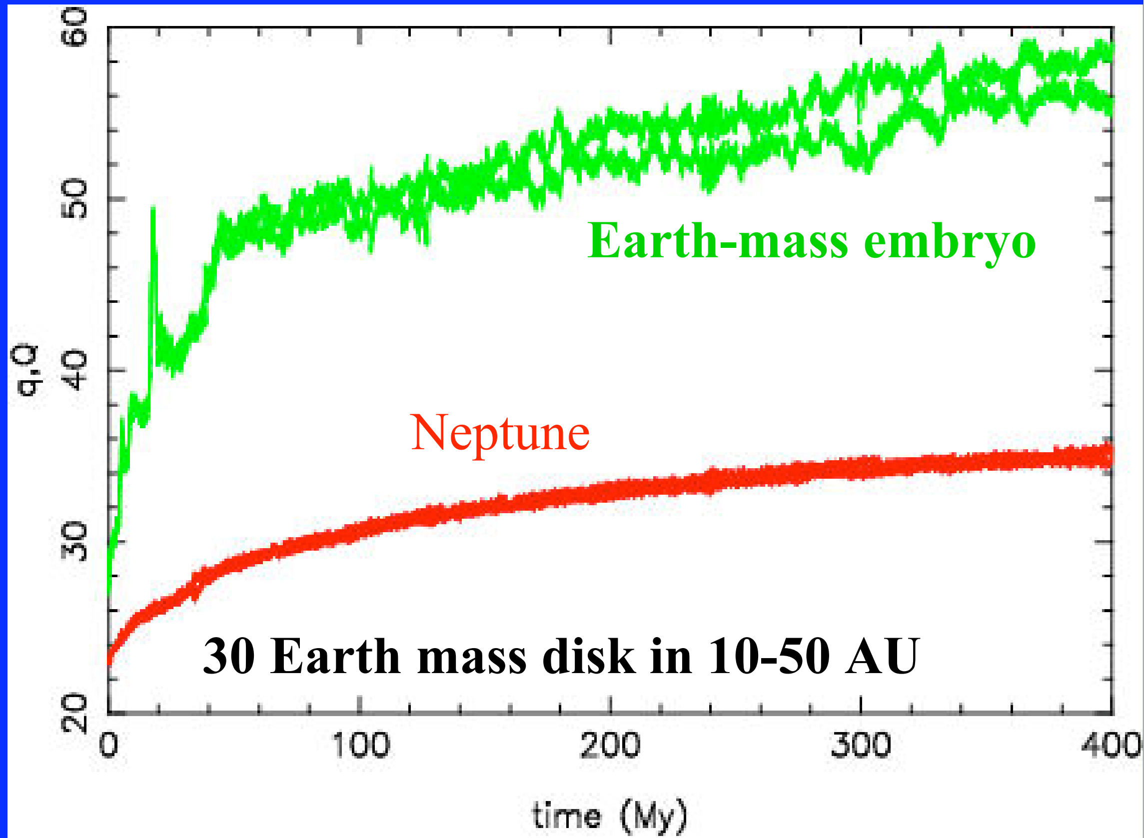
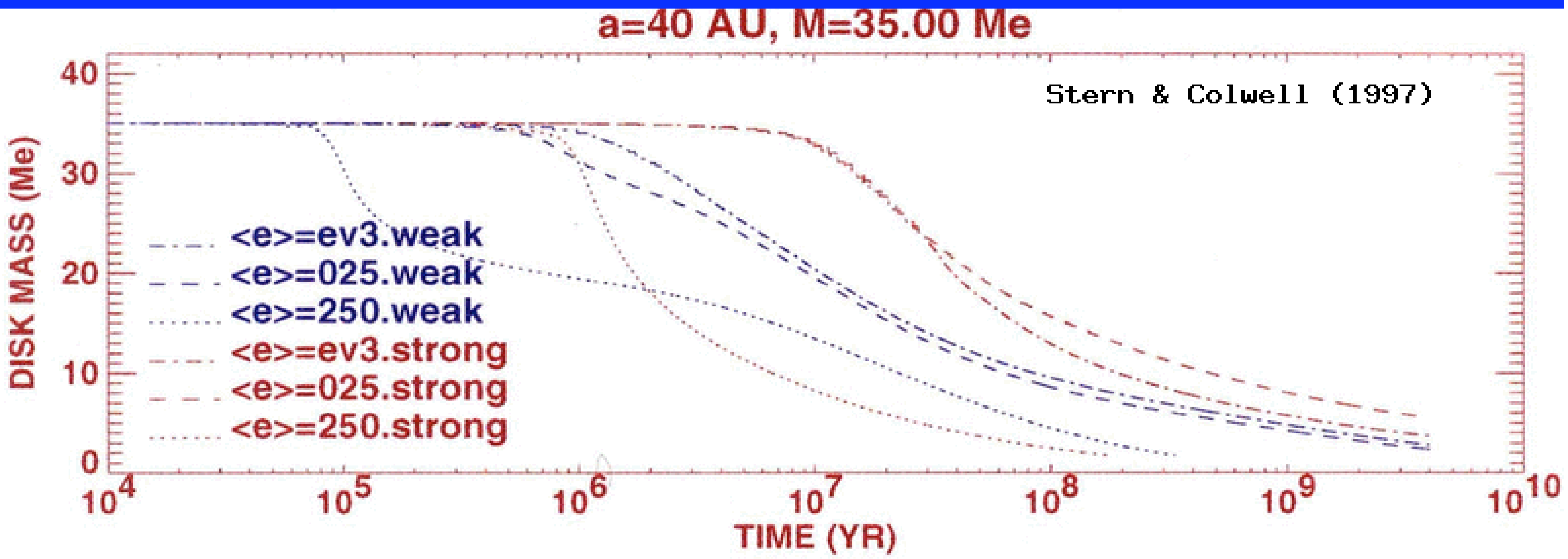


GENERAL HUGE IMPLICATION:

It is not possible to deplete the belt by ejecting most of its objects to Neptune-crossing orbit, otherwise Neptune would have migrated well beyond 30 AU !

Depletion by collisional grinding



Collisional grinding can get rid of most of the mass provided the eccentricity excitation is large

Stern and Colwell, 1997b

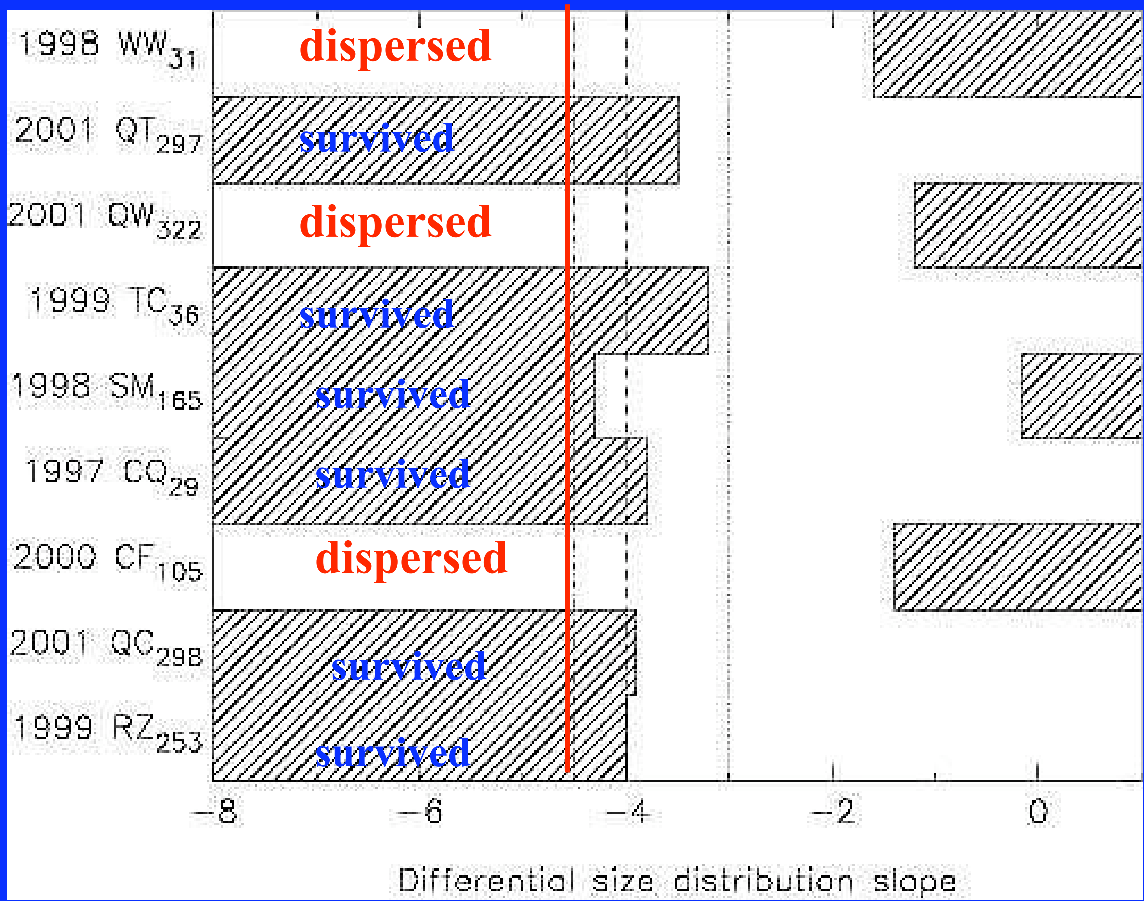
but.

3 potential problems:

1) To work, the scenario requires a weird size distribution

2) The excitation of the cold belt may not be enough for an effective collisional grinding

3) Some TNO binaries would have not survived the intense collisional process: collisions would have given the satellites an impulse velocity > escape velocity (Petit and Mousis, 2004)



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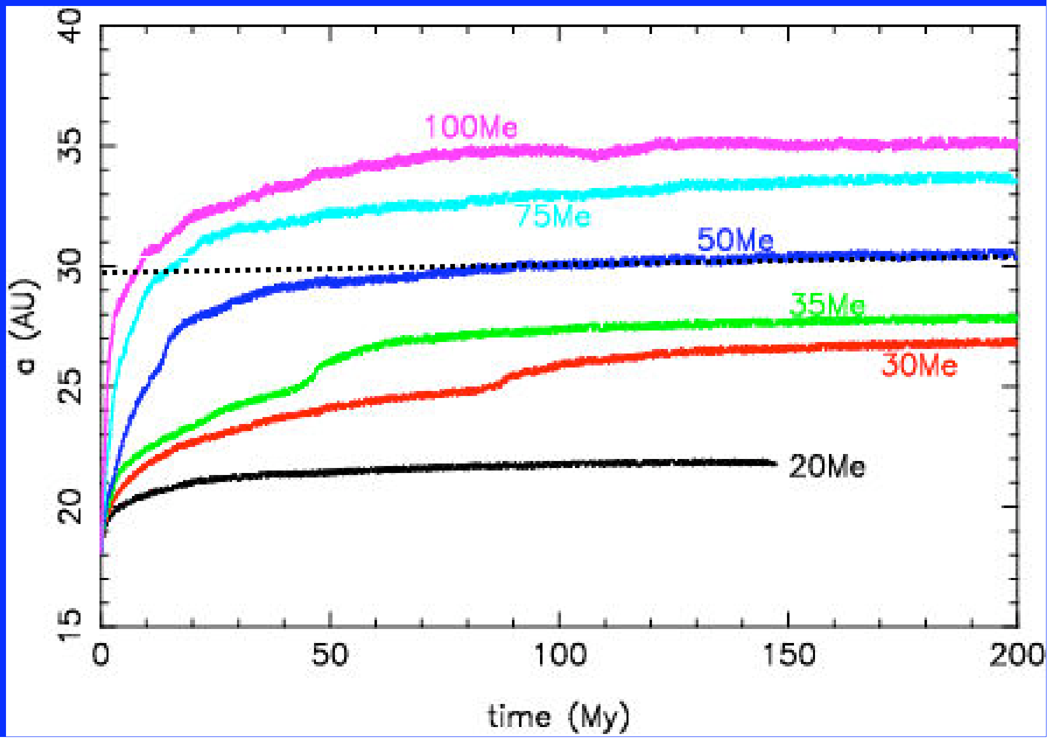
ADVANTAGE I:

The edge forces the planet to stop in its vicinity for a wide range of disk masses (whatever the initial planet position).



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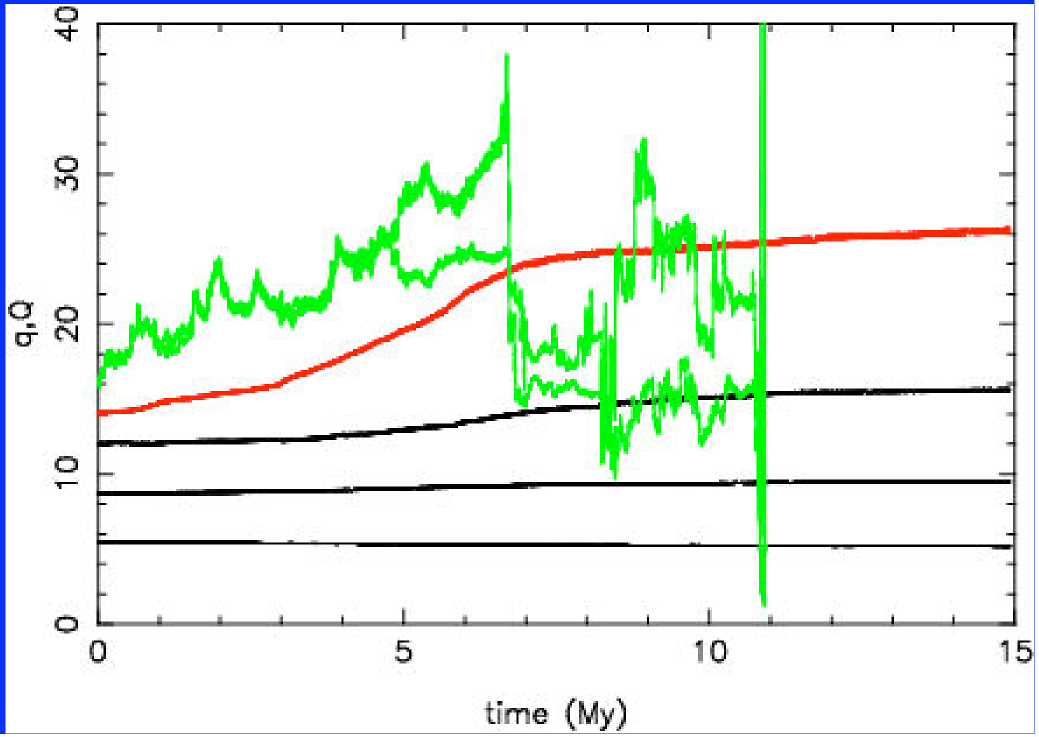
ADVANTAGE II:

Massive embryos would have been catched by Neptune at the disk's edge and dynamically eliminated.



.we need a change of perspective concerning the mass depletion problem. **(Levison, Gomes, Morbidelli):**

_the Kuiper belt was never massive.

_The outer edge of the massive proto-planetary disk was somewhere at 30-35 AU.

_The bodies that are currently observed in the cold population formed within this limit and were pushed to their current location.

The push-out mechanism for the cold population must be different from that of Gomes (2003) but not in contradiction with it _ it has to preserve the initial small inclinations.

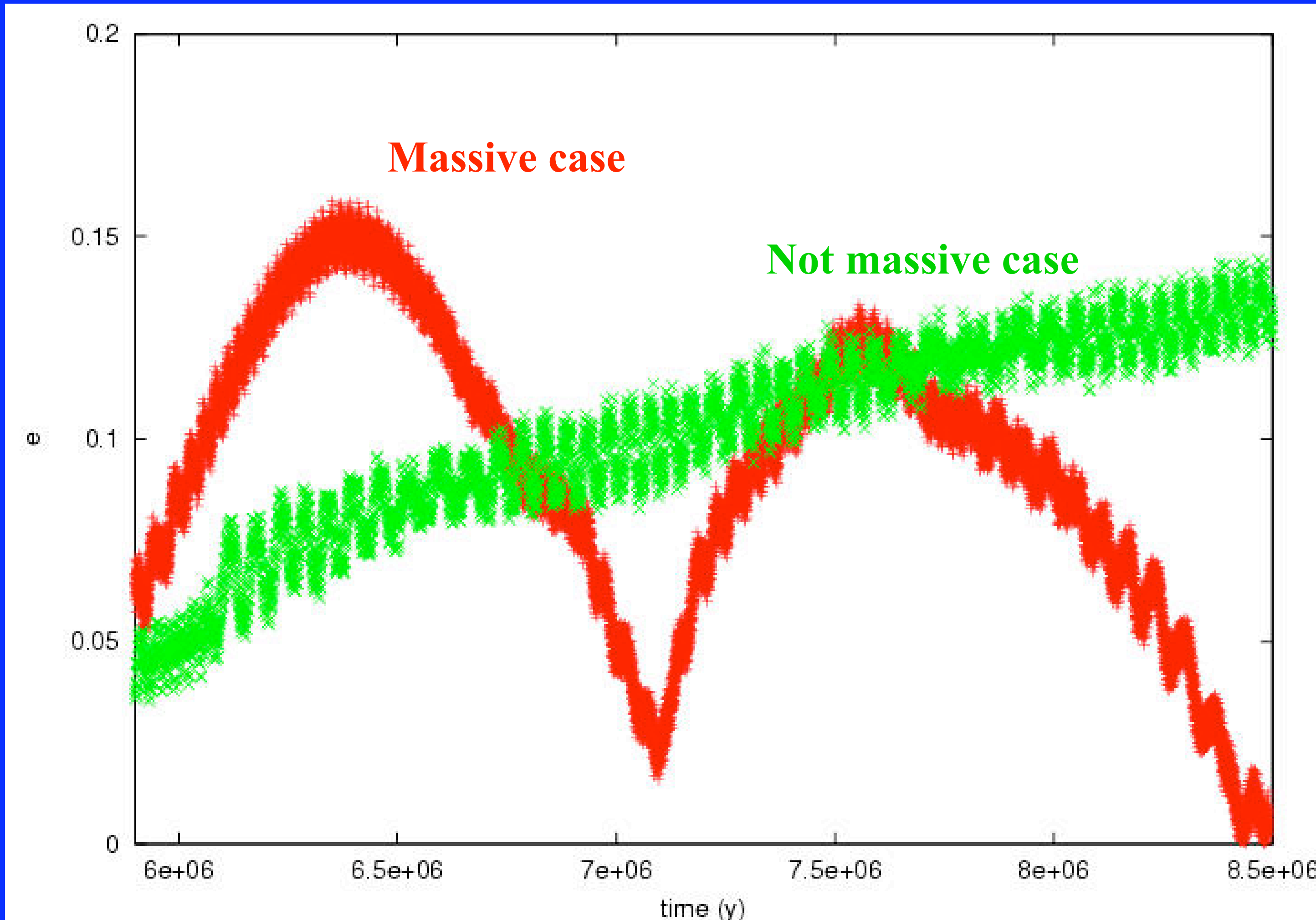
Levison and Morbidelli_s mechanism:

_The current cold-belt bodies were captured in the 1:2 mean motion resonance with Neptune during the migration of the planet

_They moved outward with the resonance while Neptune moved

_They were progressively released from the resonance due to the non-smoothness of Neptune_s migration, thus populating the 40-48 AU region

Q: Why doesn_t the eccentricity of the resonant particles increase as predicted by the adiabatic theory?



A: Because of the total non-negligible mass of the resonant particles

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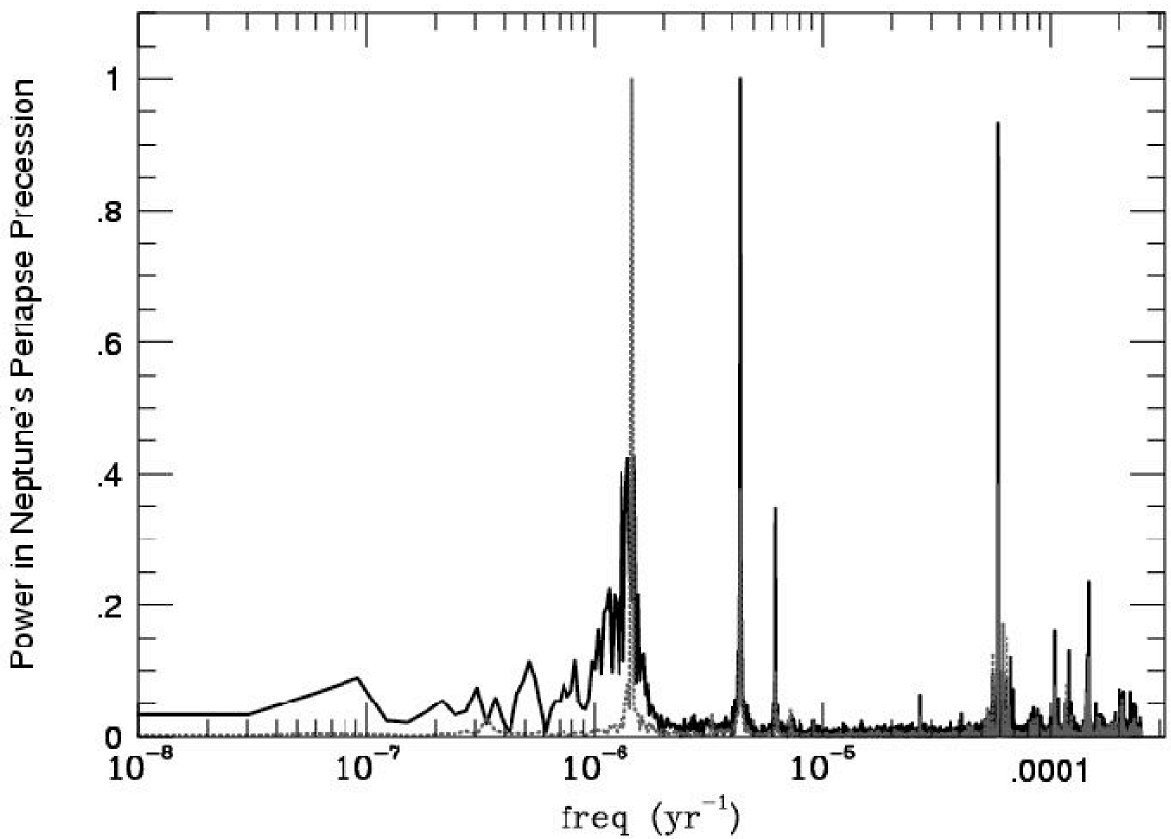

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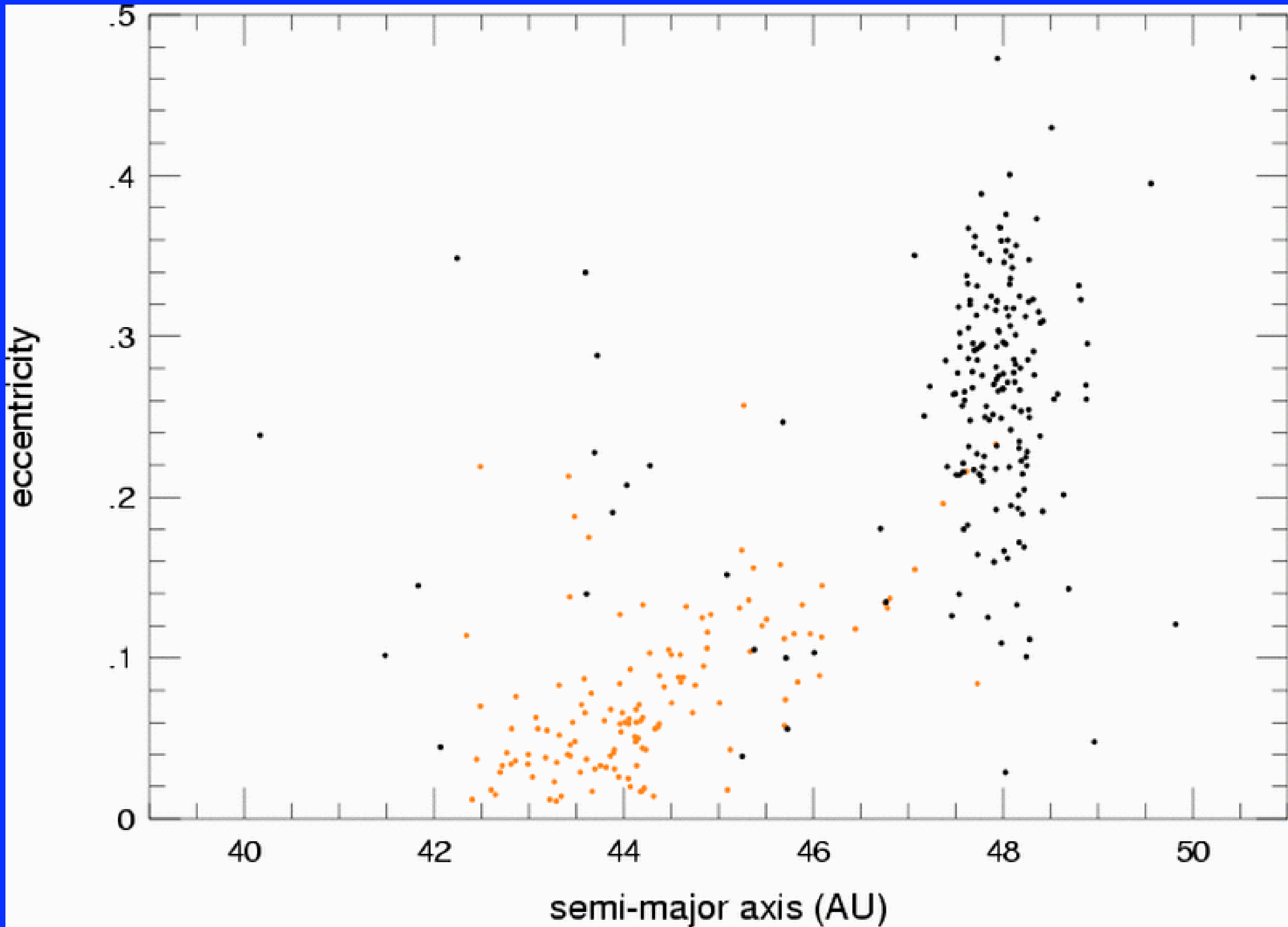
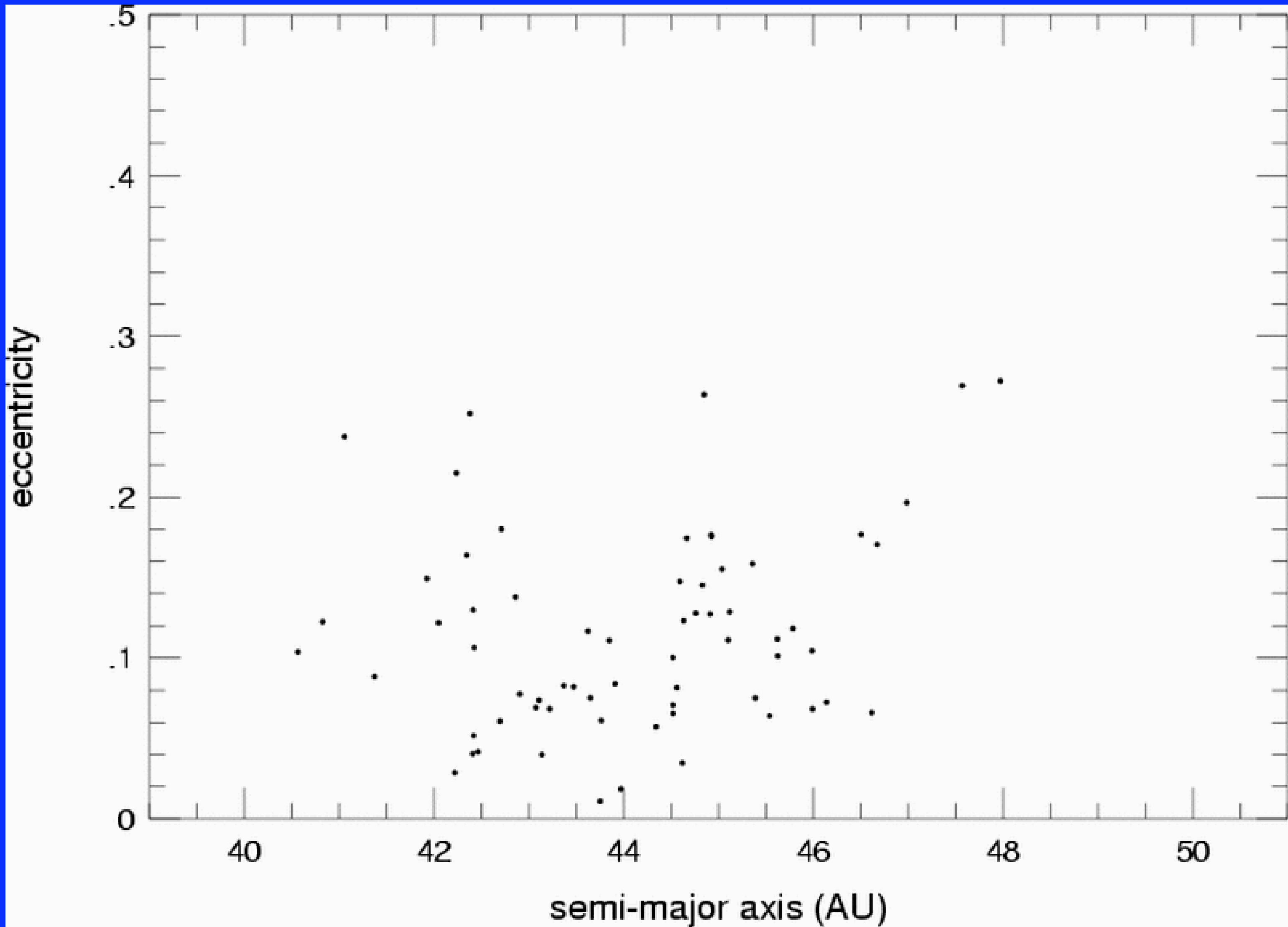
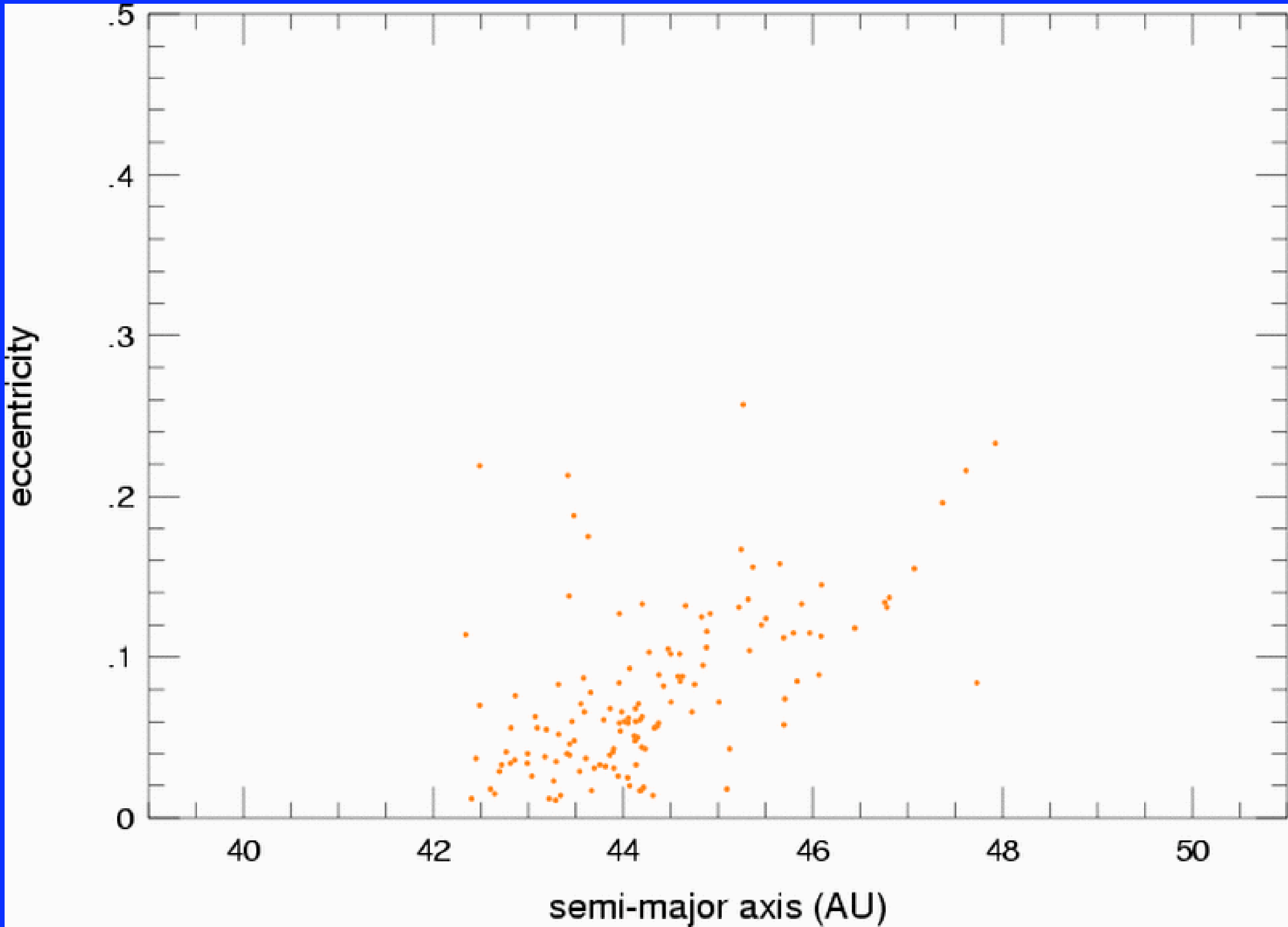


.5
.4
.3
.2
.1
0
eccentricity
40
42
44
46
48
50
semi-major axis (AU)

Final (a,e) distribution in Levison and Morbidelli scenario



Final (a,e) distribution in Levison and Morbidelli scenario



ADVANTAGES OF THE MODEL:

1 It circumvents the mass depletion problem

2 It explains why the border of the Kuiper belt coincides with the 1:2 resonance

3 It reproduces the (a,e) distribution of the KBOs

4 It_s not in conflict with the survival of the binaries

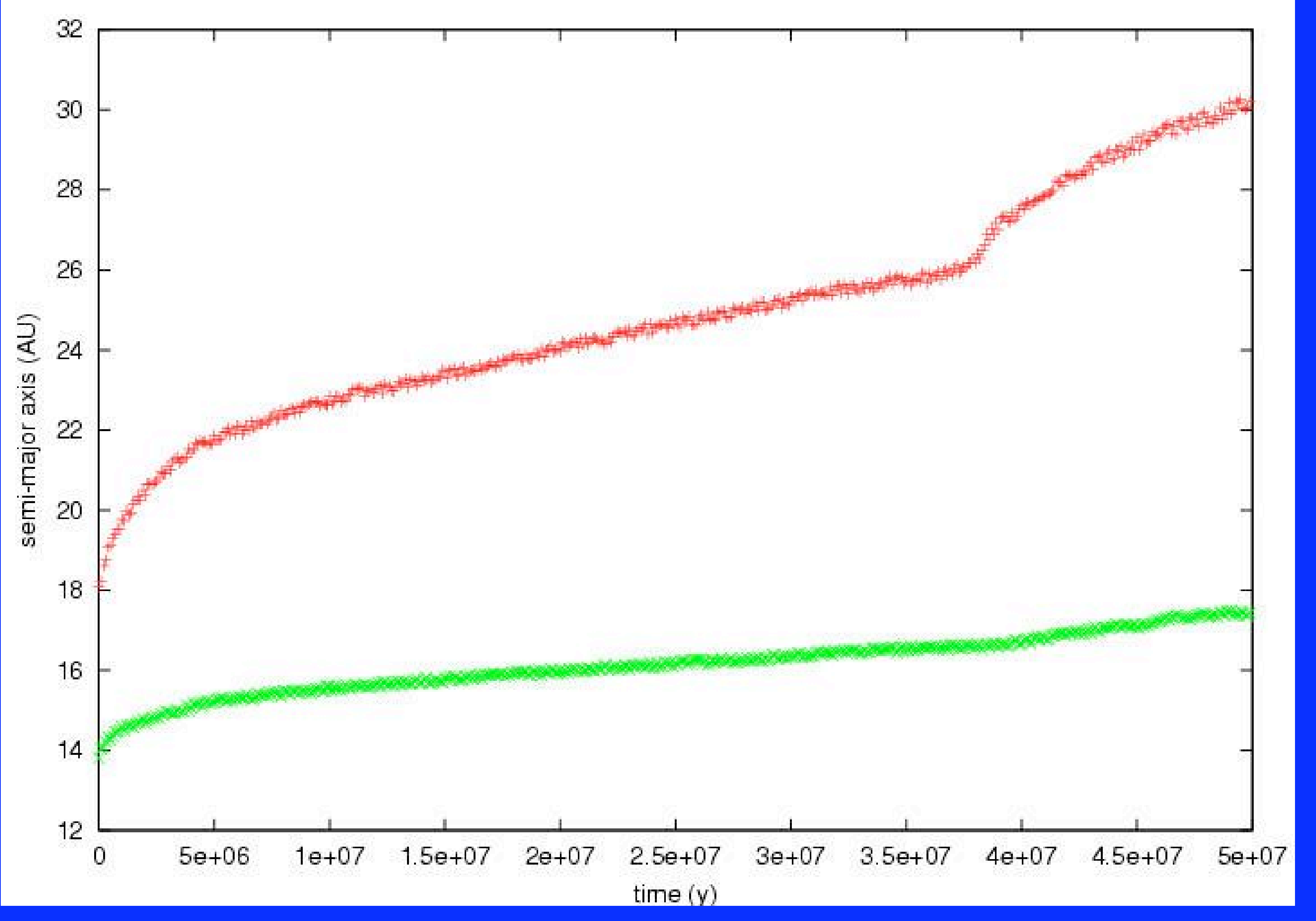
DRAWBACKS:

1 How to explain the physical differences between the cold and the hot population?

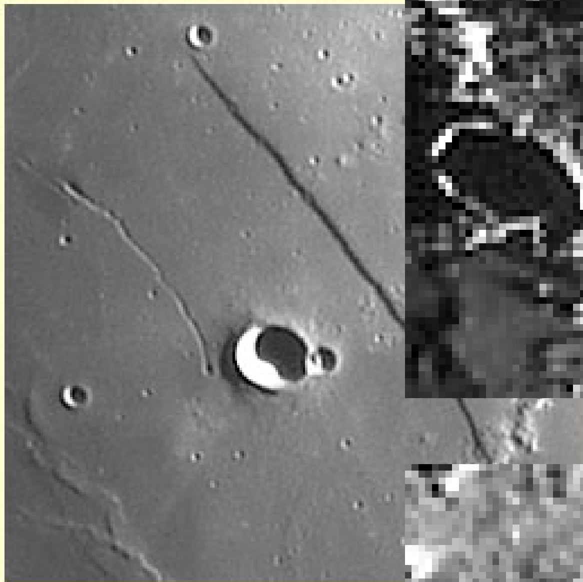
(ALMOST) EVERYTHING SEEMS TO FIT IN A COHERENT SCENARIO

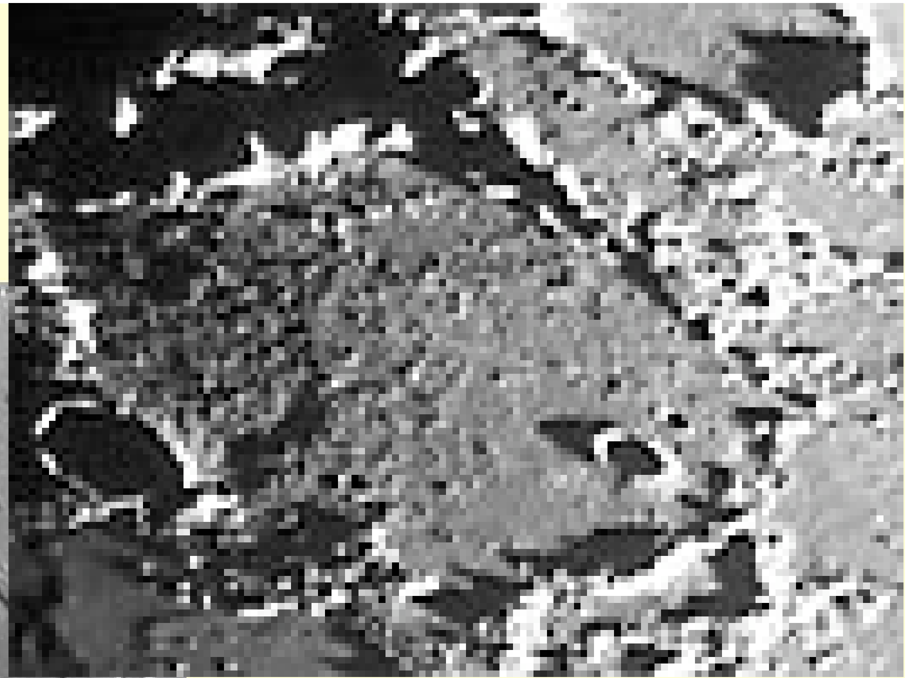
BUT_

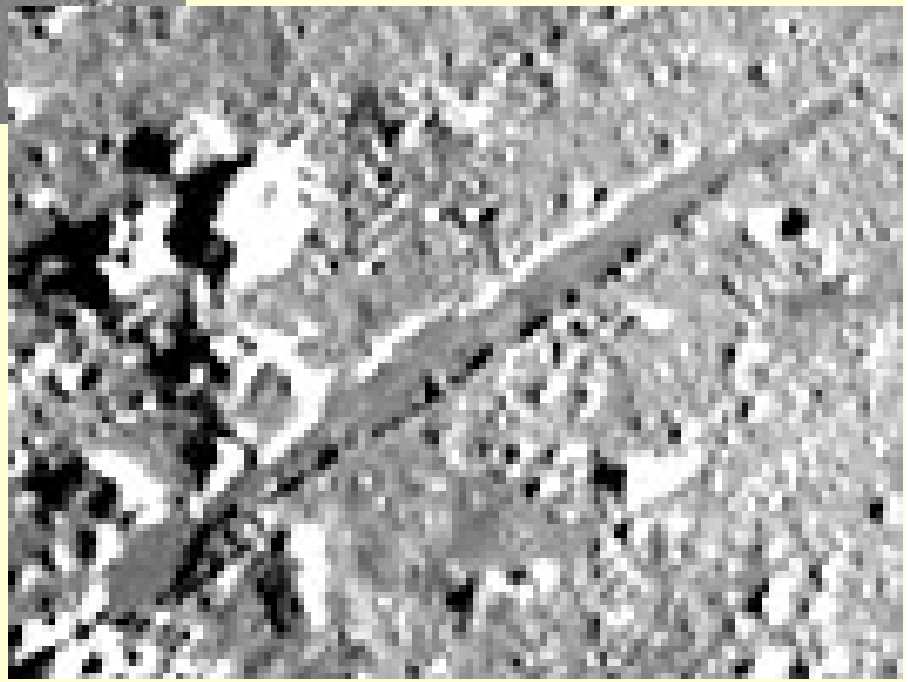
First problem: Uranus does not `follow_; it never reaches 20 AU



Second problem





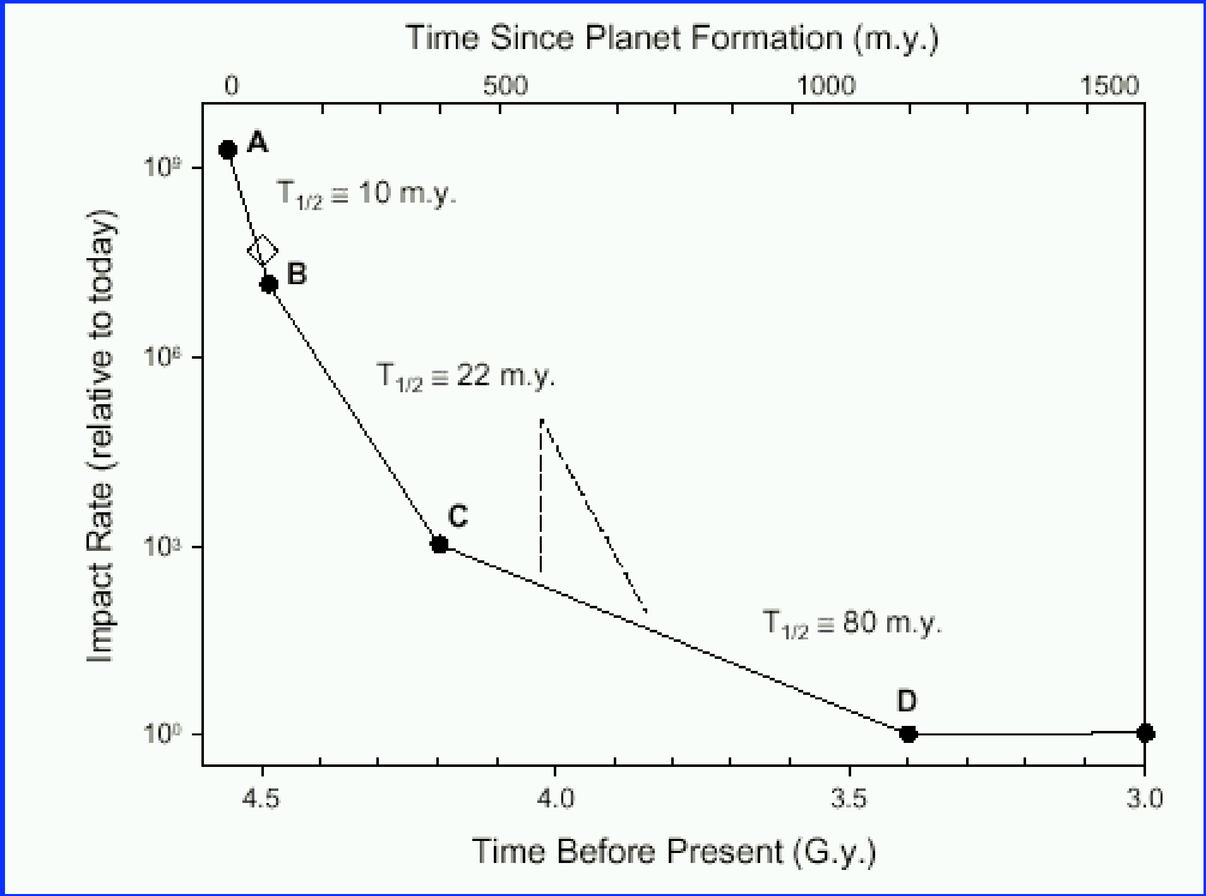


THE LATE HEAVY BOMBARDMENT

The Moon shows that the bombardment was *much heavier* in the past, *until late* after the Moon formation, than at the current time.

Studies of crater densities at sites of known ages (from Apollo samples) give flux data back to 3.9-3.8 Gy ago, and show that the bombardment was ~100 times higher

Problem: What was the evolution of the bombardment before 3.8 Gy ago?



Evidence for a cataclysm ~4.0-3.8 Gy ago:

The ages of the rocks collected on the Moon cluster at ~3.9-3.8 Gy, and rocks older than 4 Gy are extremely rare.

Suggests a disastrous sudden and short-lived cratering episode about 3.9 Gy ago, which distroyed all primoridal rocks, resetting their ages (Tera et al., 1974)

Counter-argument:

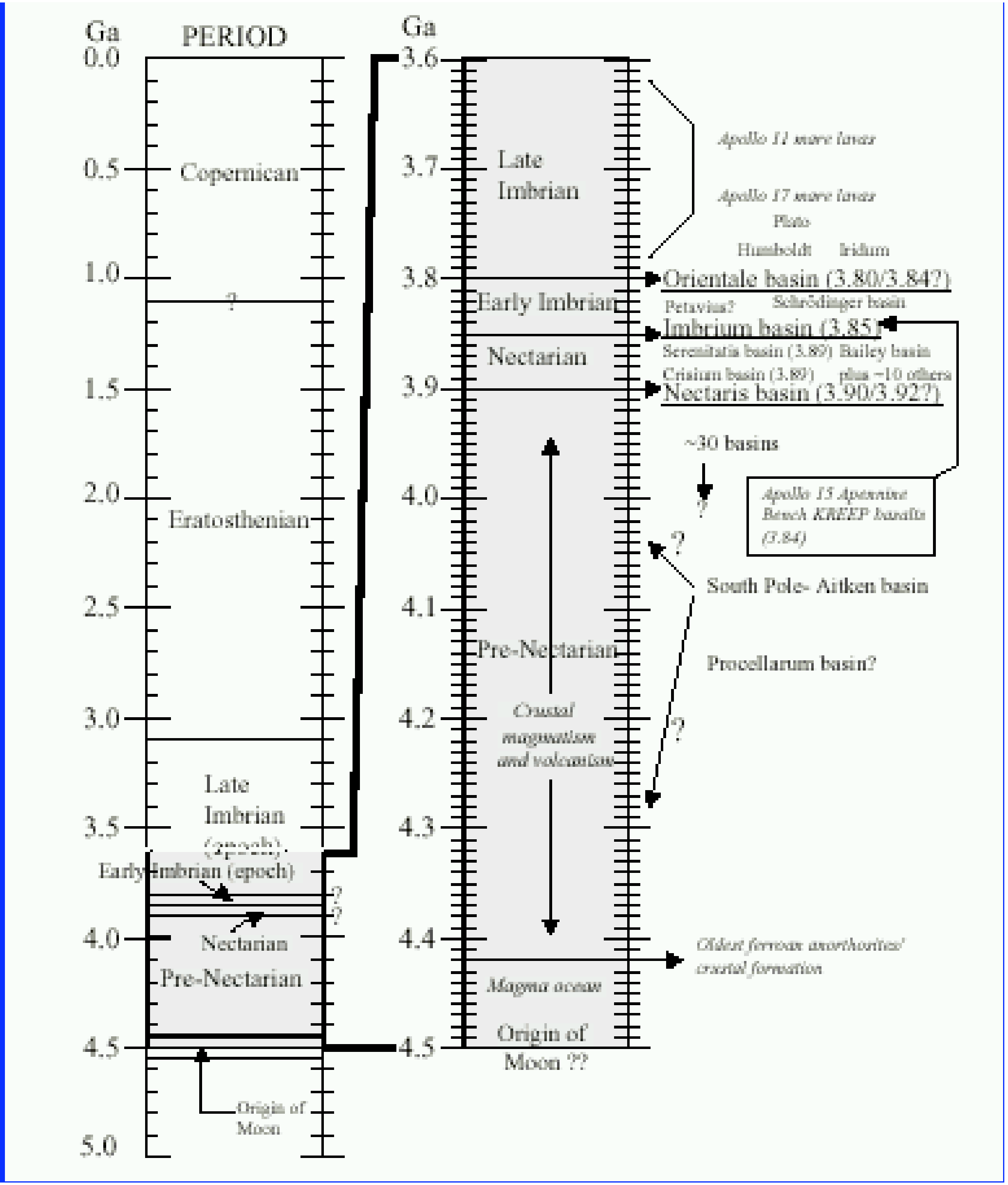
A very heavy, time declining, bombardment, could produce the same effect (Hartung, 1974; Hartmann, 1975, 1980, Grinspoon, 1989)

Evidence for a cataclysm ~4.0-3.8 Gy ago:

The ages of many basins (impact features > 200km) cluster in the 3.9-3.8 Gy period (Wilhelms, 1987; Ryder, 1994)

Counter-argument:

Basins datations are fooled because collected samples are dominated by Imbrium ejecta (Haskin, 1998). Only Imbrium is dated.



Evidence for a cataclysm ~4.0-3.8 Gy ago:

The amount of siderophile elements on the ancient highlands suggest that the amount of interplanetary mass accumulated by the Moon in the 4.4-3.9 Gy period is about the same of that required to form the basins in the 3.9-3.8 Gy period ($5\ 10^{21}$g), 20 times less than suggested by models with a declining bombardment from the time of formation

Counter-argument:

It critically depends on the assumed composition of the early impactors. Was it the same as that of the current meteorites?

What could have caused a huge spike in the bombardment rate 500-700 My after the planetary formation?

What could have caused a huge spike in the bombardment rate 500-700 My after the planetary formation?

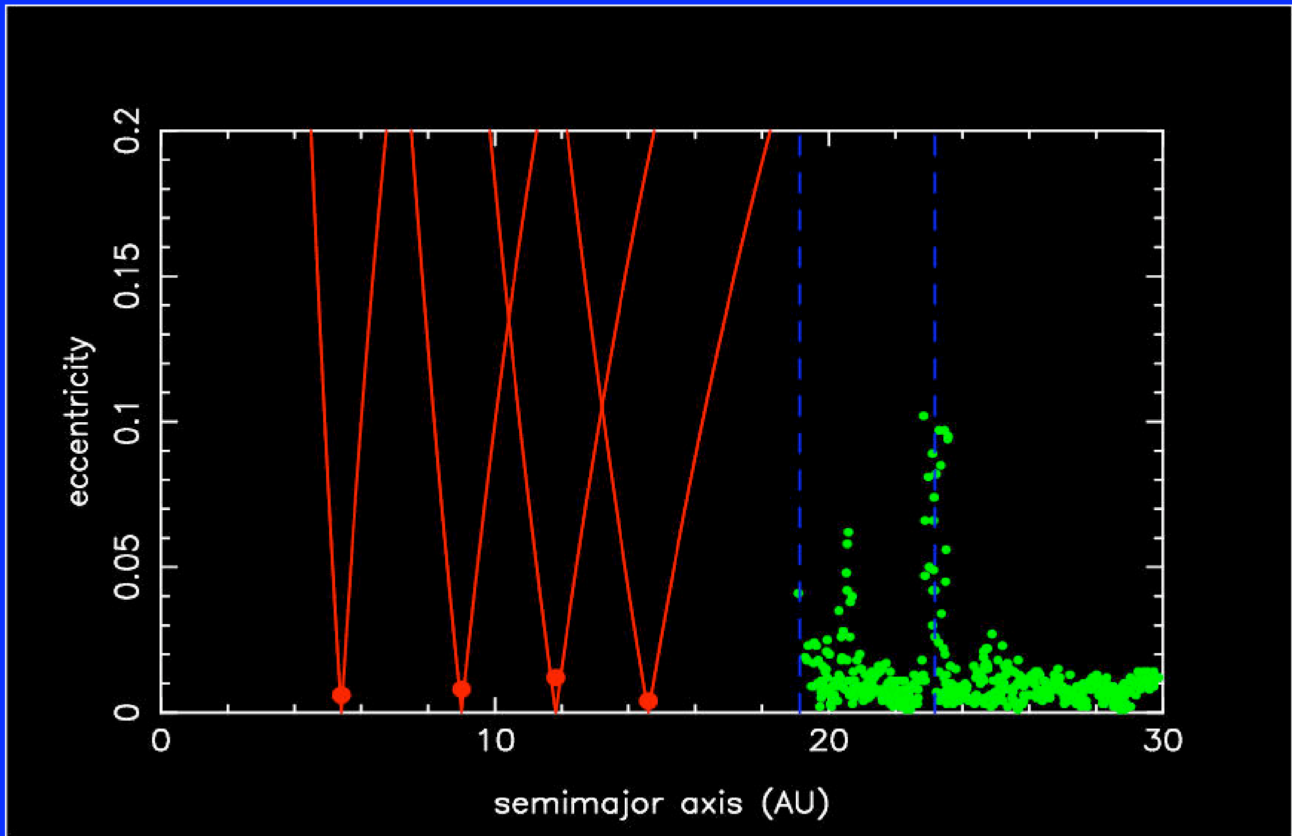
Not the asteroid belt

In the asteroid belt, the survival of Vesta_s 60 km-thick basaltic crust after 4.5 Gy of collisional evolution provides a key constraint on the amount of impact processing that has occurred (Davis *et al*., 1985, *Icarus* 62, 30-35)

The massive phase could last only ~10 My

What could have caused a huge spike in the bombardment rate 500-700 My after the planetary formation?

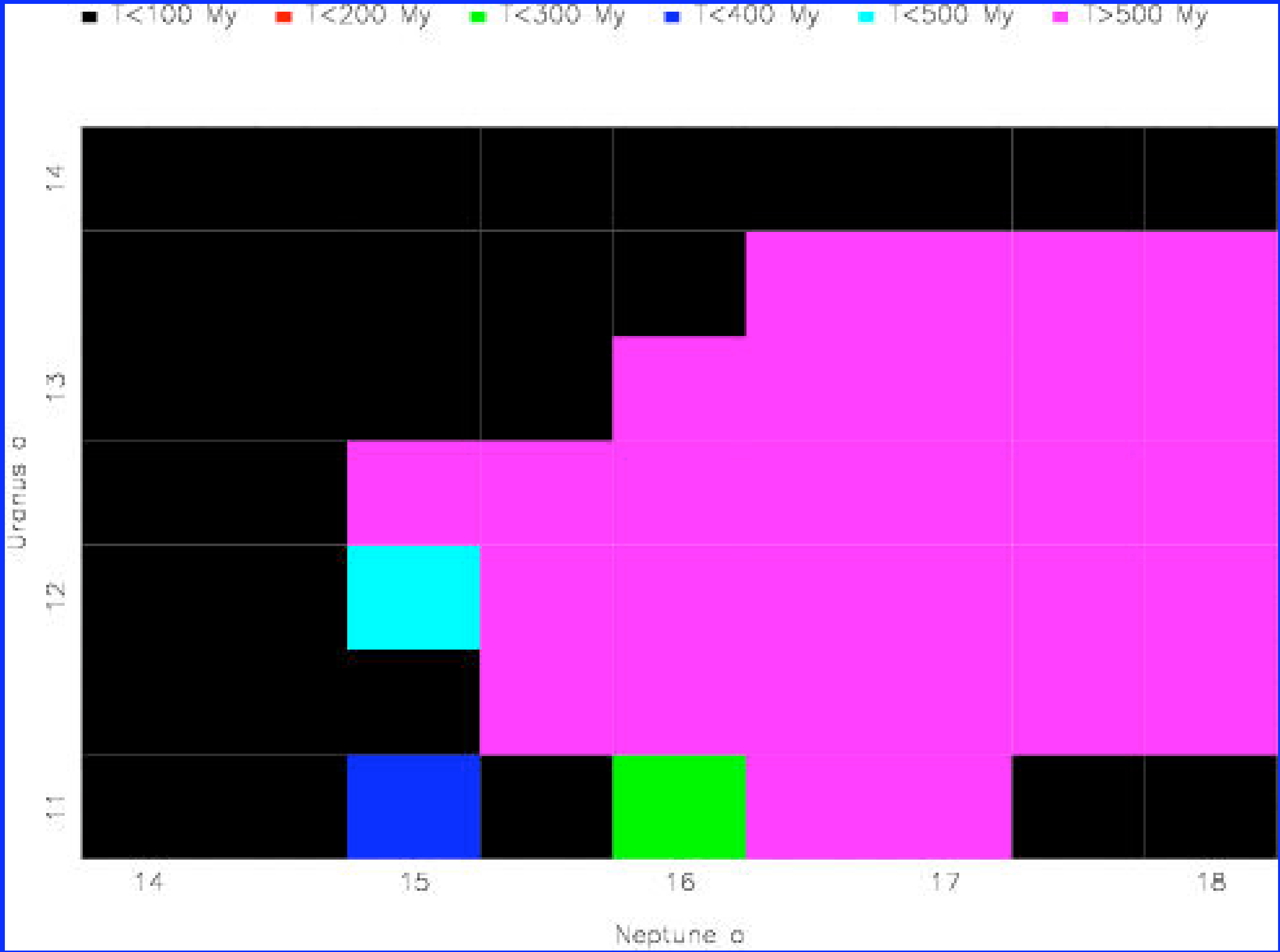
We believe that the most likely explanation is a delay in the beginning of the planetary migration process.



If Jupiter and Saturn had eccentricities and inclinations comparable to the current ones, long-term stability of the planetary system requires that Neptune was at least at 20-21 AU

No space for a disk of planetesimals between Neptune and 30-35 AU.

If Jupiter and Saturn had `zero_ eccentricities and inclinations long-term stability of the planetary system could be achieved with Uranus at ~12 AU and Neptune at ~15 AU.



There is space for a disk of planetesimals between 20 and 30-35 AU.

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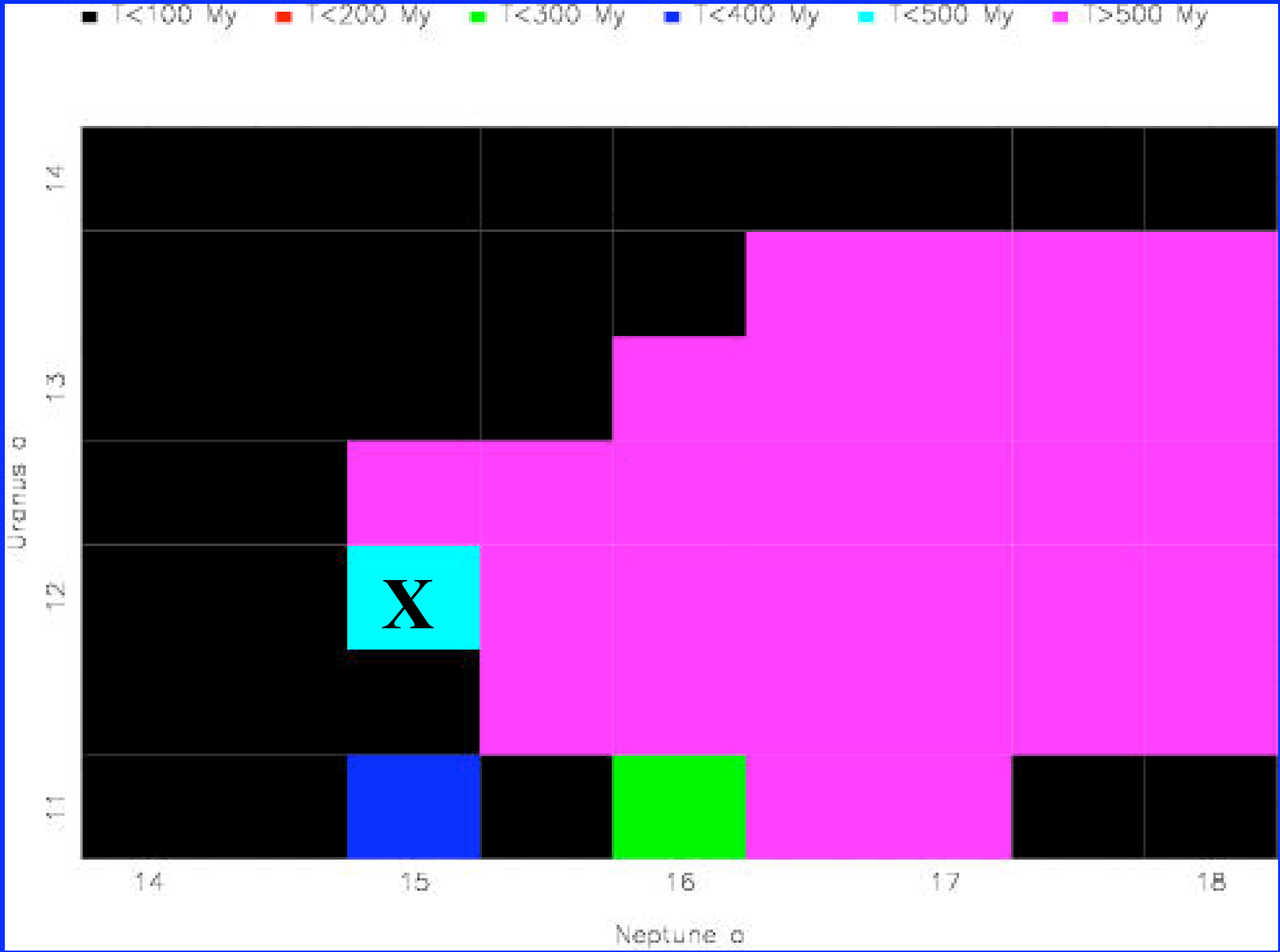
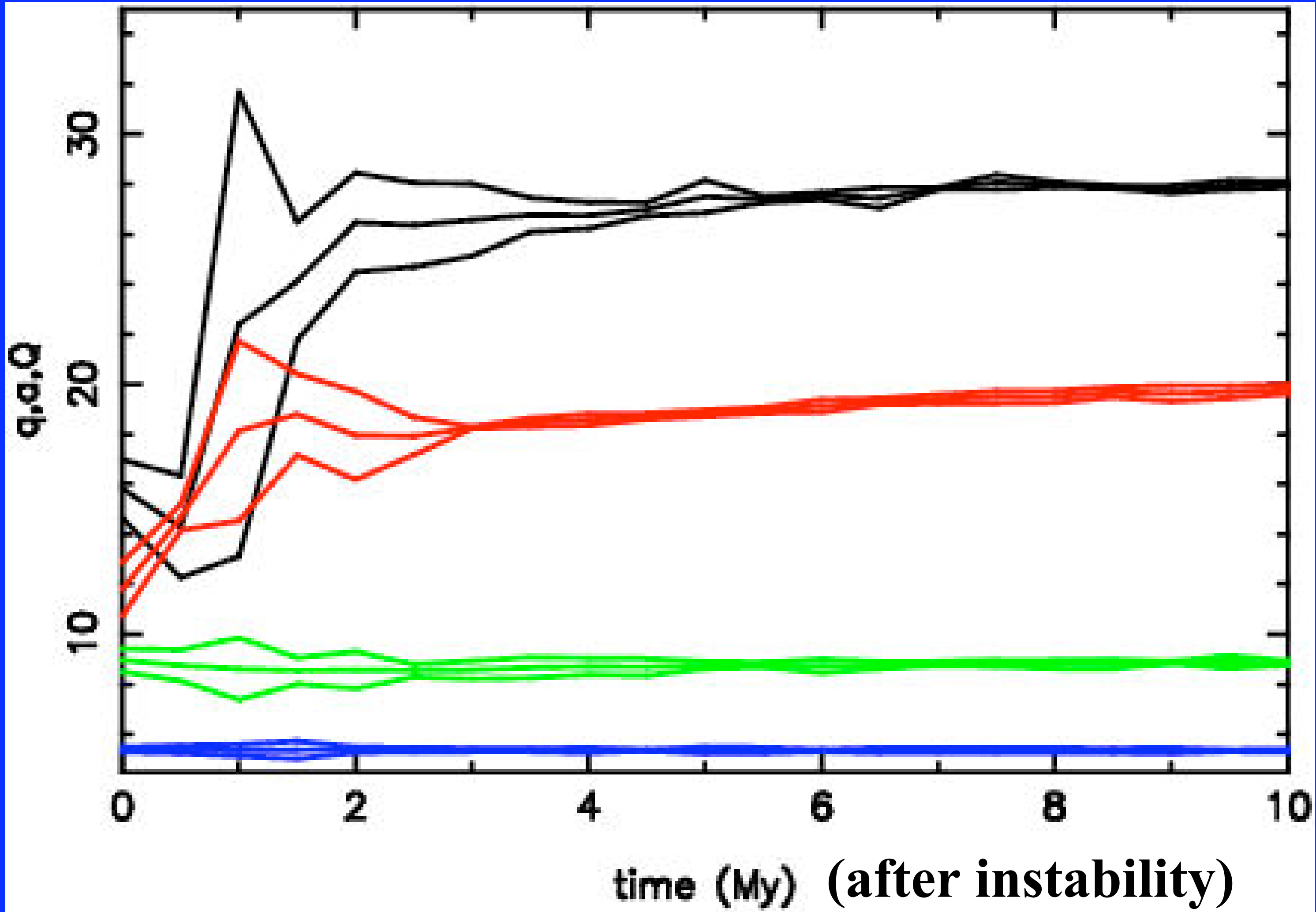


There is space for a disk of planetesimals between 20 and 30-35 AU.

What happens when the system becomes unstable?



(after instability)

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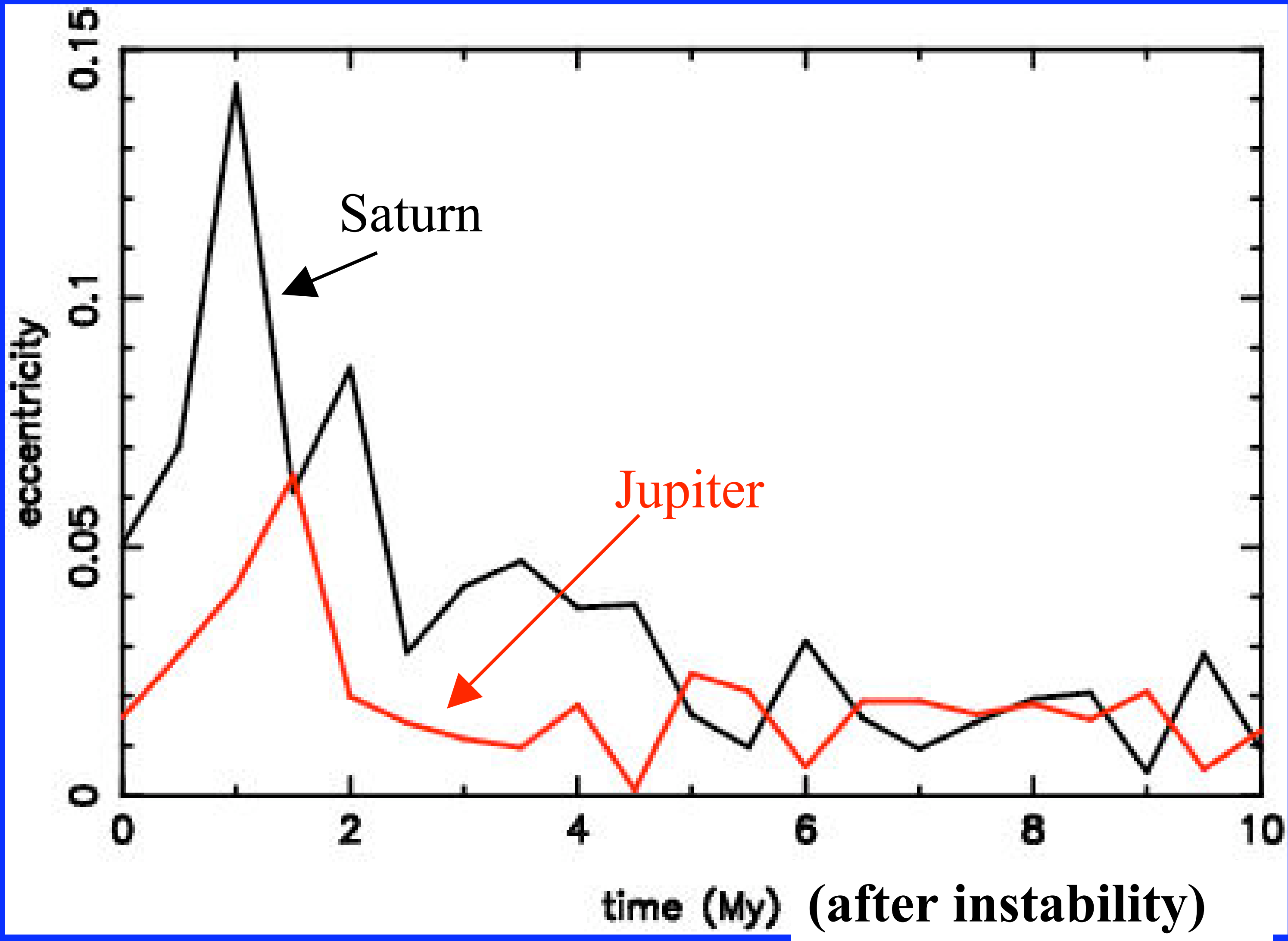

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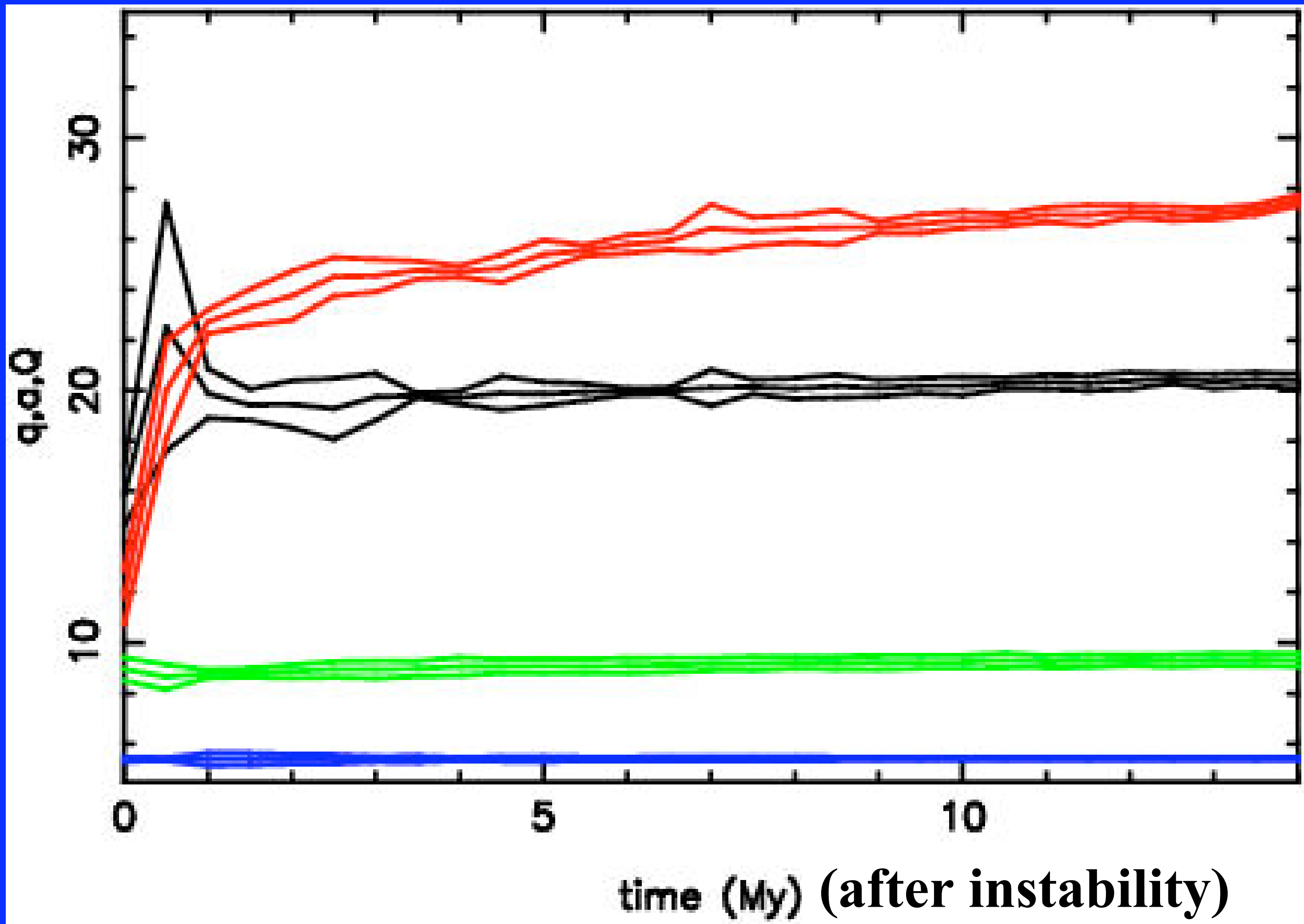
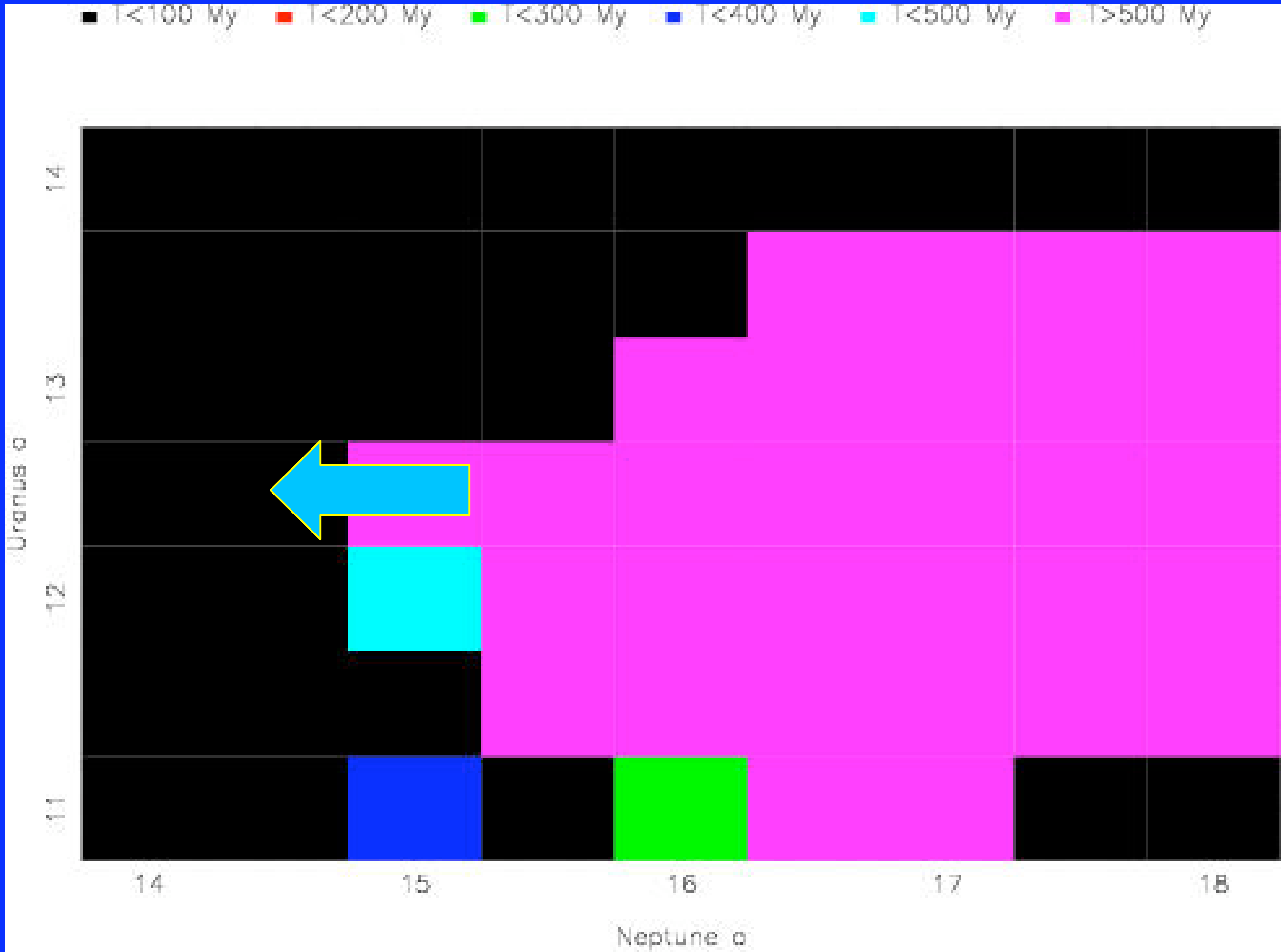


(after instability)

URANUS AND NEPTUNE EXCHANGE POSITIONS!

HOW TO TRIGGER THE INSTABILITY?



CONCLUSIONS

A vision of the late evolution of the Outer Solar System:

- The giant planets formed on quasi-circular & coplanar orbits in the 5-15 AU range
- A disk of planetesimals of 30-50 Earth masses existed between ~20 and ~30 AU
- The system remained stable for 500-700 My, then for some (yet not fully understood) reason the planetary system became unstable
- The instability excited the eccentricities and inclinations of Jupiter and Saturn and pushed outward Uranus and Neptune
- The most distant planet started to interact with the disk and migration began.

CONCLUSIONS

A vision of the late evolution of the Outer Solar System:

- The massive disk of planetesimals was distroyed as Neptune migrated through
- Some 15% of the planetesimals ended in the Oort Cloud
- Some 1% survive now in the scattered disk
- Some 1% was implanted from the scattered disk into the Kuiper belt and constitute what is now identified as the hot population
- Some 1% was pushed outward by the 1:2 resonance and constitute what is now identified as the cold population
- the remaining ~80% of the planetesimals was eliminated, but some (10^{-6} of them) hit the Earth and the Moon, causing the LHB