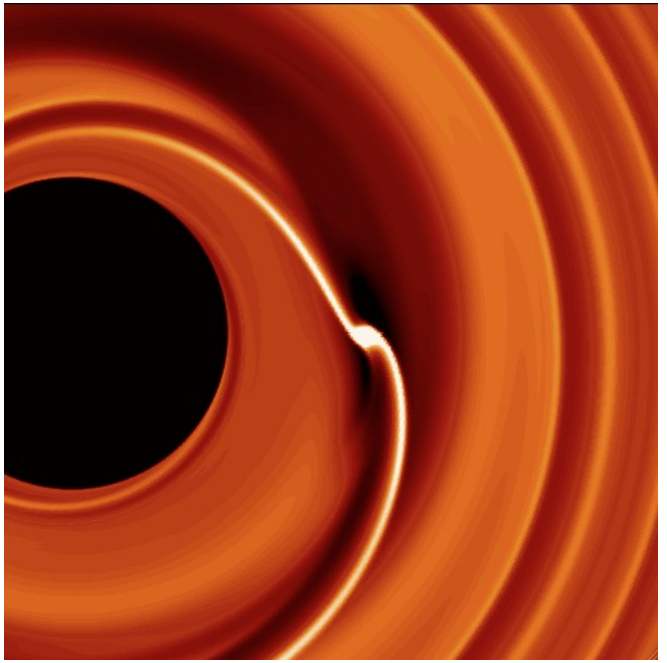
Trojans, TNOs and the migrating planets.

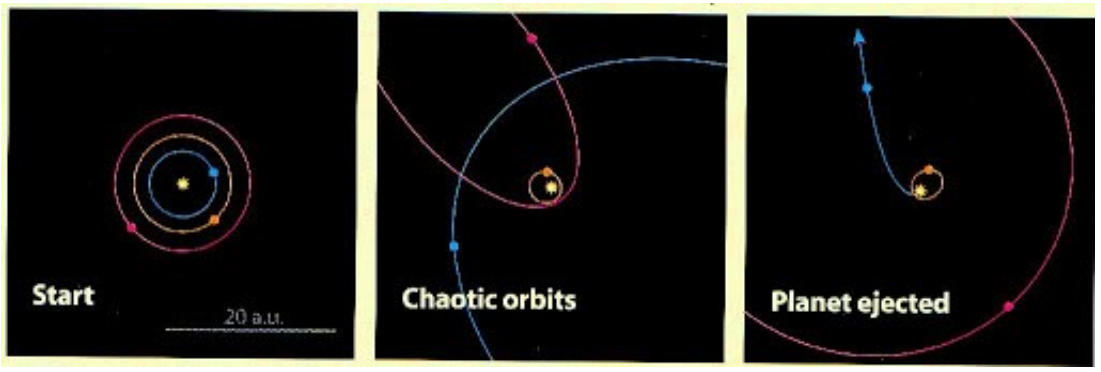
...at the beginning the Solar System was stationary...then God said…let there be exoplanets...
..than all planets started to migrate and scatter..
….and everything changed….

Two main mechanisms for the dynamical evolution of planets:

1) Migration by interaction with the disk



2) Planet-planet scattering possibly coupled to Tidal interaction (Kozai, secular...)



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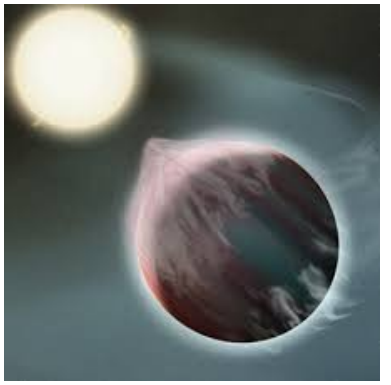
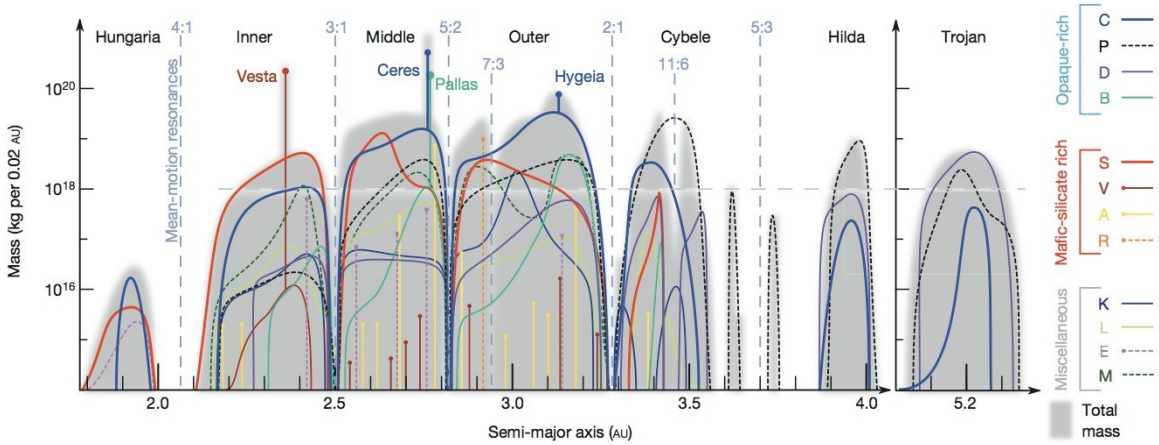


In exoplanetary systems, the evidences of planet migration are Hot/Warm Jupiters and STIPS. They orbit very close to their star. **And in the Solar System? Do we have evindence of planet migration?**

Possible tracers are the population of small bodies, in 2 ways:

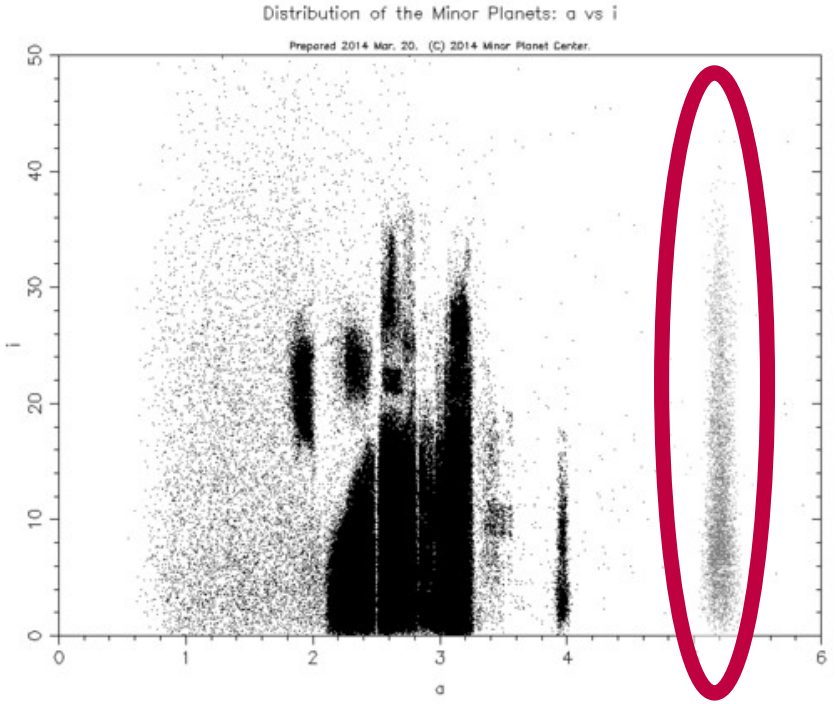
1) Compositional gradient
2) Dynamical features

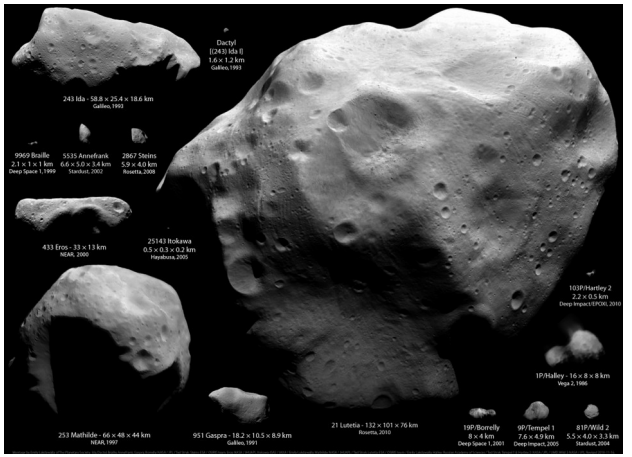


Small-body populations:

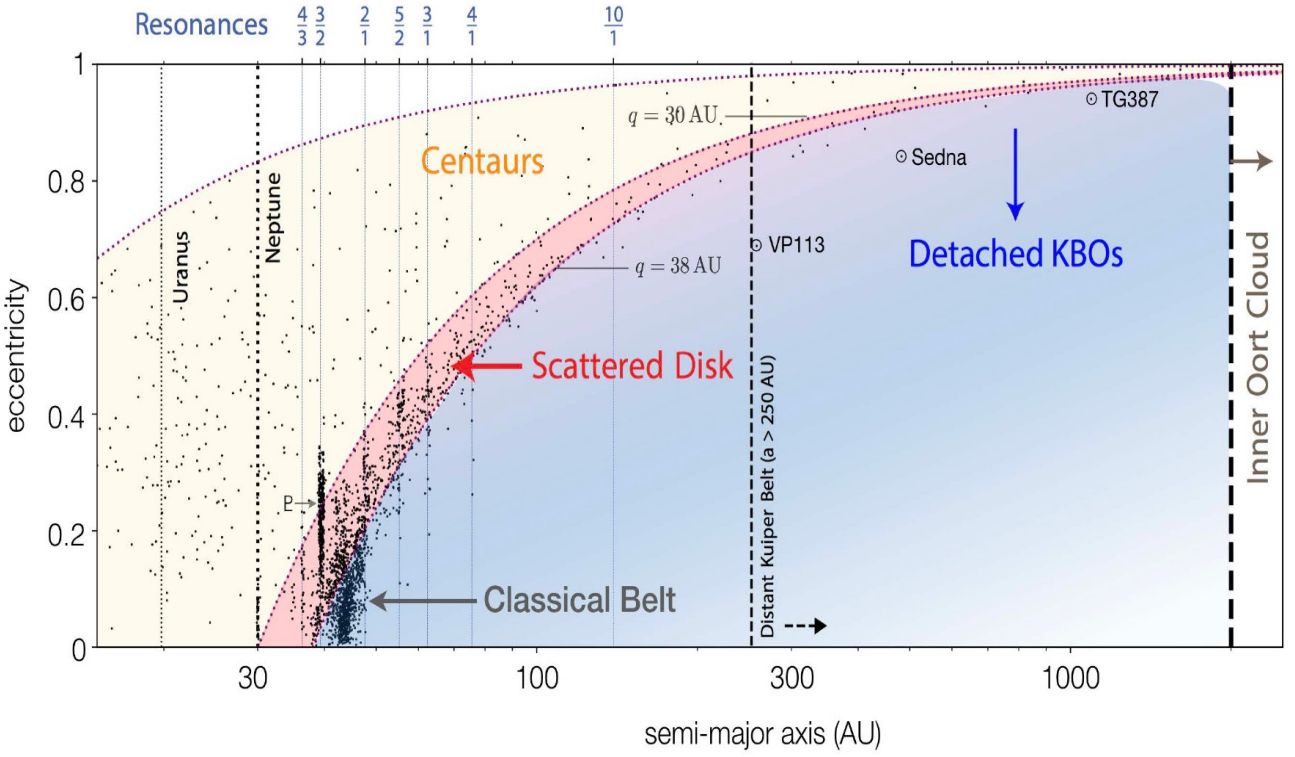
1) NEO
2) Main Belt Asteroids (Hildas in the 3:2 resonance)
3) Trojans
4) TNOs
5) Centaurs
6) Comets
7) Oort cloud

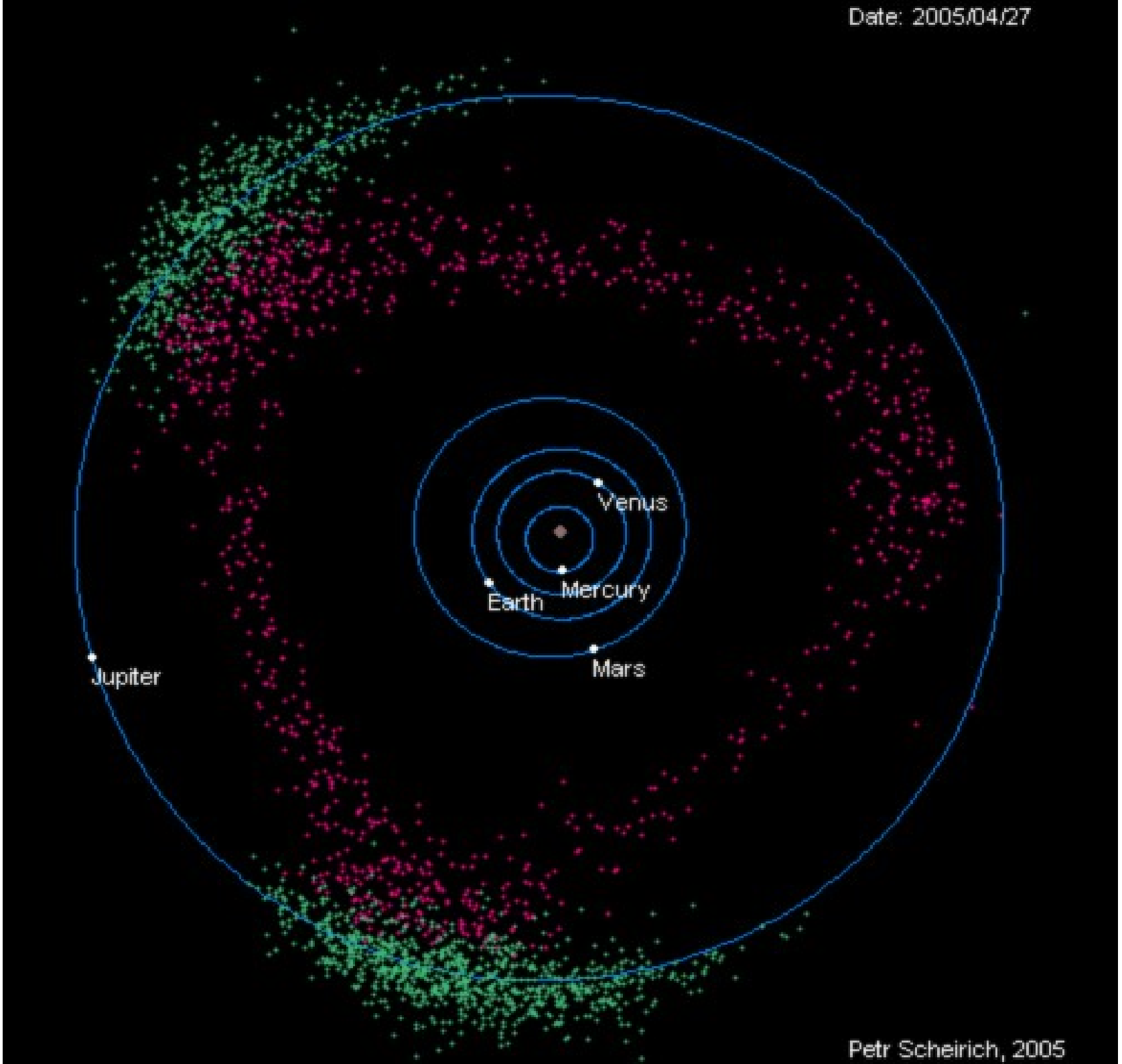
Trojans and KB: features that must be explained by the early solar system evolution.





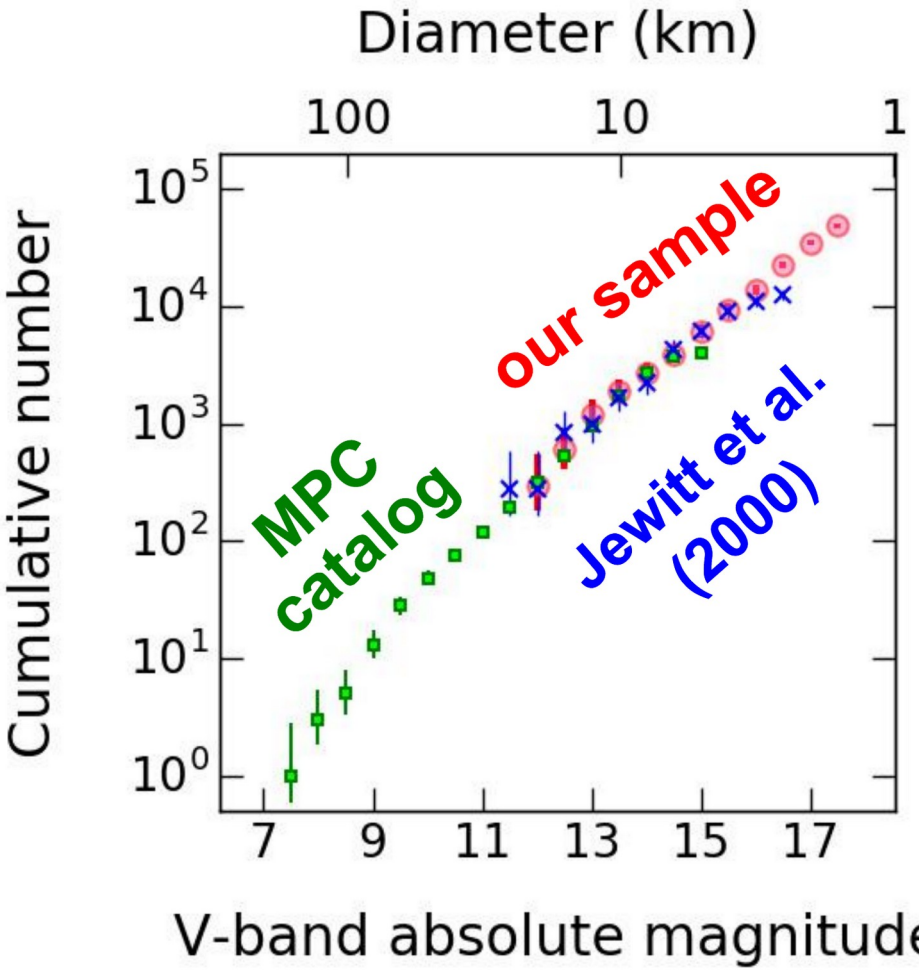
KB: complex dynamical and compositional structures (lack of cold Plutinos, excess of 5:2 resonant, the detached KBOs…..etc...)



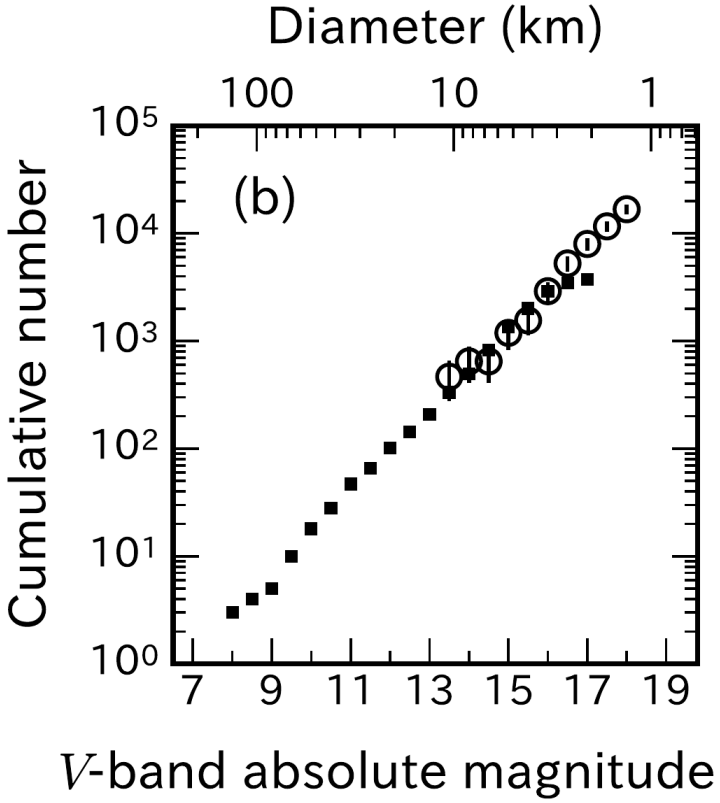

Date: 2005/04/27
Venus
Earth
Mercury
Mars
Jupiter
Petr Scheirich, 2005

Jupiter Trojans:

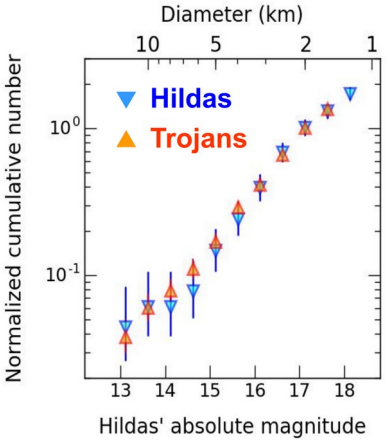
More than 7000, Size distribution: bimodal power law: b=-2.39, -1.84 (~-2.1 for the MB from SDSS)



Hilda Asteroids



At the small size end the two populations have similar slope.



Normalized size distribution similar to Hildas (3:2 MMR) (normalized since Trojans are thought to be 5-times more numerous than Hildas down to 2 km in diameter).

Capture mechanisms for Trojans:

1) Static: a) gas drag (Yoder 1979)
b) collisions close to the border (Schoemaker et al. 1989)
c) mass growth (Marzari & Scholl, 1998)

2) Dynamic: a) chaotic trapping during MMR superposition (Morbidelli et al. 2005)
b) steep jump in *a* during P-P crossing (Nesvorny et al. 2013)
c) Mass growth during migration (Pirani et al. 2019)

Neptune Trojans: 25 L4 and 4 L5. Observational bias, L5 is towards the galactic center (Sheppard & Trujillo, 2010) .
Capture during outward migration due to MMR crossing of U/N (chaotic trapping, Lykawka & Horner 2010). Inward migration and mass growth (Pirani et al. 2019)

Saturn & Uranus Trojans regions unstable due to secular resonance crossing, only transient bodies (Uranus 2), a few Mars Trojans (9) and an Earth Trojan, but that is another story….

First models for Solar System planet migration:

1) The Nice model
2) The Grand Tack model

Not exclusive but complementary….

The Nice Model: original version

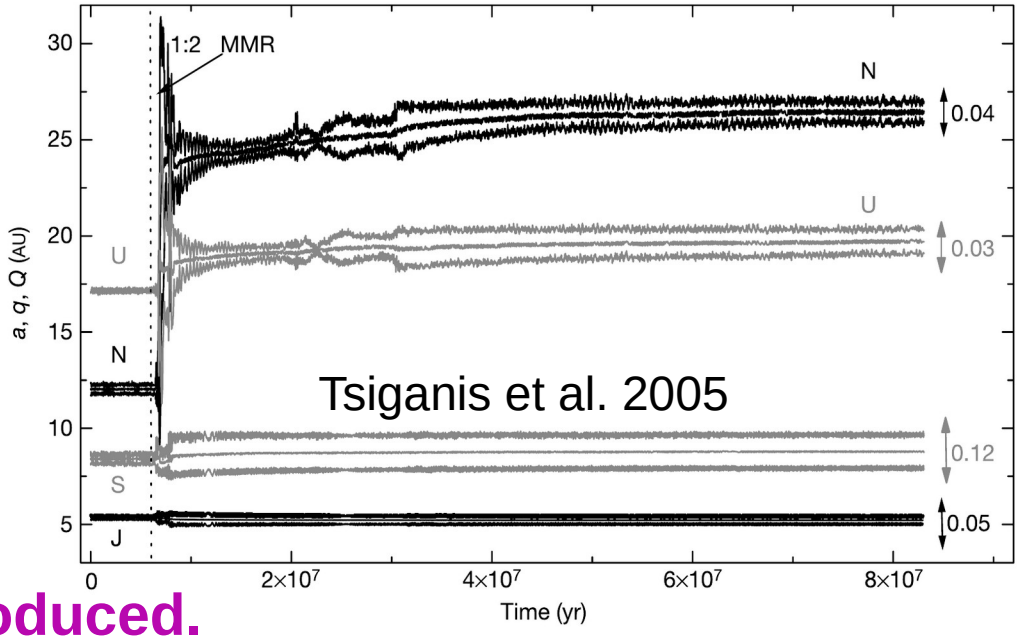
1) Jupiter and Saturn closer than present, Uranus & Neptune on inverted orbits

2) Due to planetesimal scattering, Jupiter and Saturn cross the 2:1 MMR

3) Neptune and Uranus experience a period of chaotic evolution and exchange orbits.

4) They migrate outwards and excite the Kuiper Belt (LHB). Their eccentricity is finally damped by planetesimals and they became dynamically detached

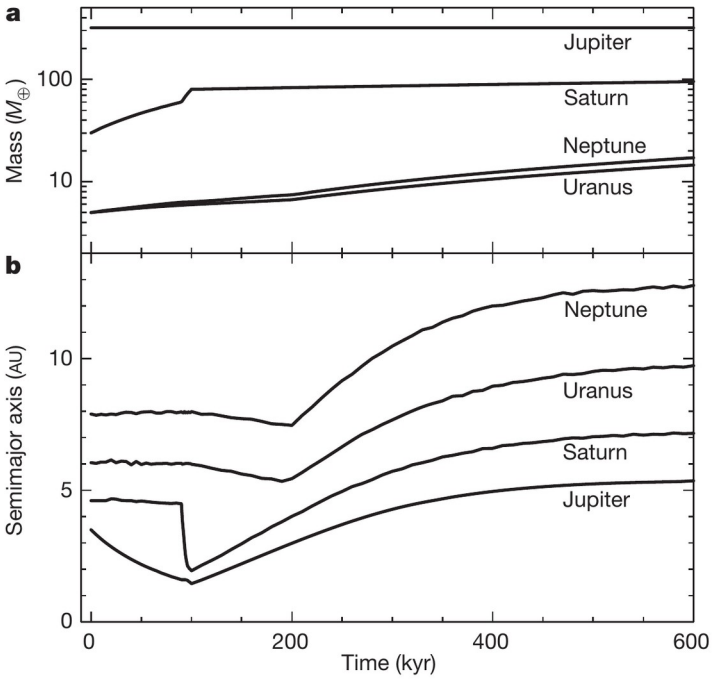
4) Jupiter Trojans are trapped during the 2:1 crossing of Jupiter and Saturn (previous population destabilized, new population captured)



5) The Kuiper Belt is excited and the different populations are produced.

The Grand tack model (Nice model antecedent stage….)

1) Convergent migration: Saturn approaches Jupiter which is migrating inwards till 1.5 (2 in the latest version) au
2) The planets get trapped in the 3:2 (2:1 in the latest version) MMR
3) They reverse the migration due to the formation of a common gap
4) They migrate outwards and trap Uranus and Neptune in MMR resonances
5) The gas dissipates, the resonances are broken by planetesimal scattering….from there on the Nice model….
6) It well explains the Mars problem and the asteroid belt compositional radial mixing



‘New’ Nice model with planet-planet scattering

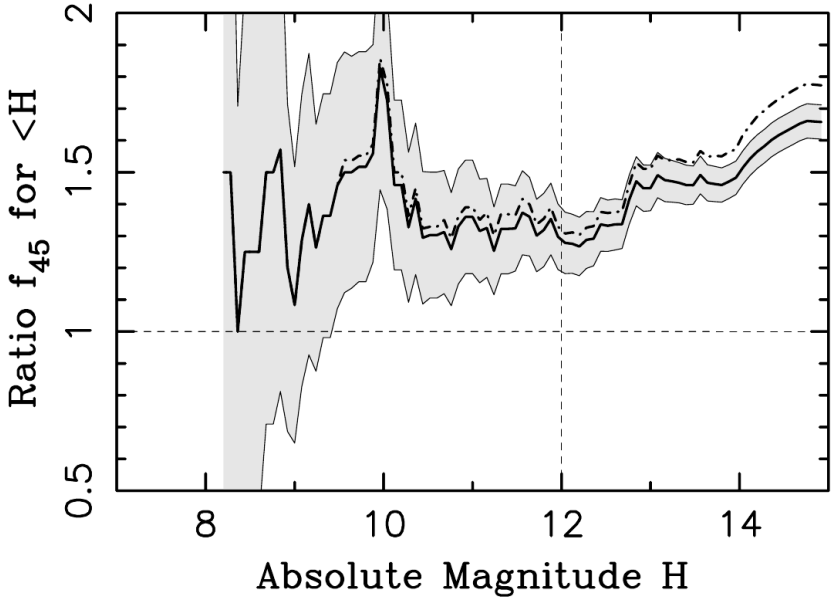
1) Previous Nice model did not predict asymmetry in the L4/L5 population

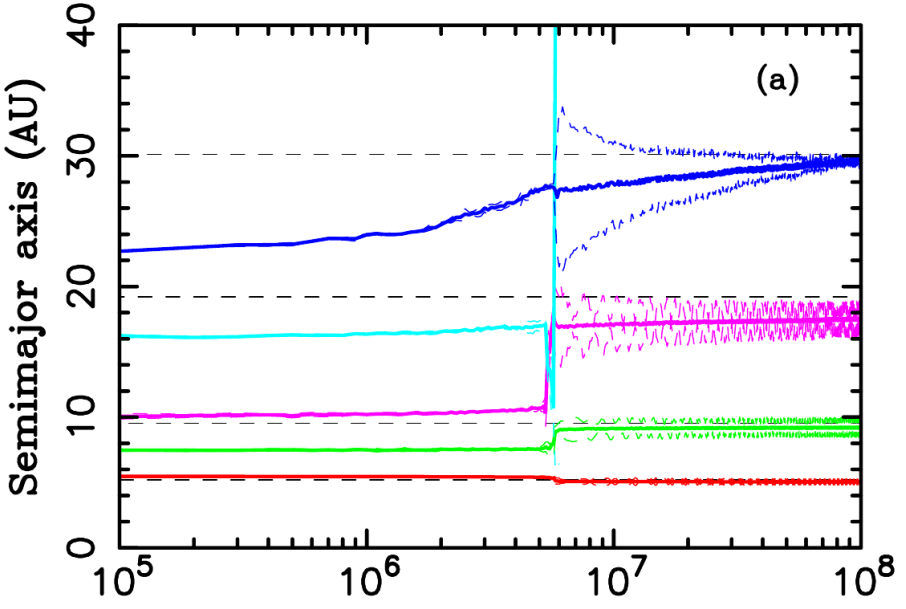
2) In the new model J,S,U, N and an **additional icy planet** migrated inward until a resonant chain is produced.

3) After the gas dissipation, a period of dynamical instability follows.

4) Finally, the 5th planet is ejected and the system relaxes to its present architecture.

5) Trojans are captured during the jumps of Jupiter. L4/L5 asymmetry retrieved (Nesvorny et al. 2013) but it can be either around L4 or L5.



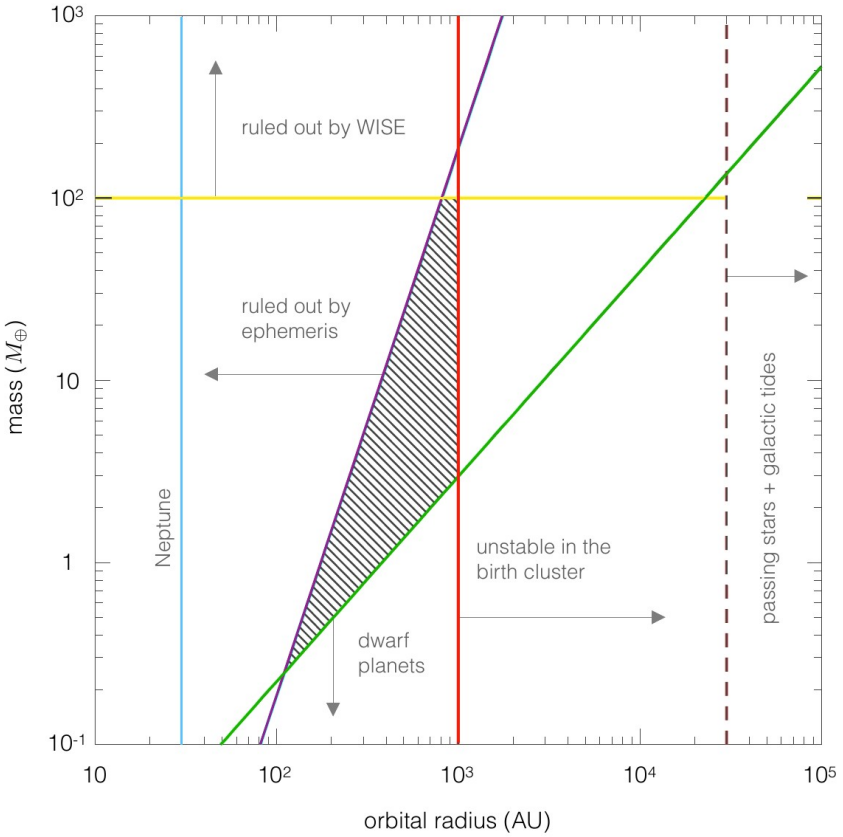


Second additional planet recently invoked to explain some of the TNOs features (periodic idea, Nemesis, planet X, planet nine, Brunini & Melita 2002, Lykawka & Mukai 2008, Trujillo & Sheppard 2014, more recently Batygin…) either trapped during the cluster phase (Mustill et al. 2016) or scattered outward and then damped:

1) Alignment of some highly eccentric orbits (perihelion clustered ~ 0º)
2) Common values of inclinations
3) Detached from Neptune orbit (example, Sedna and Sednoids)
4) Highly inclined and retrograde orbits

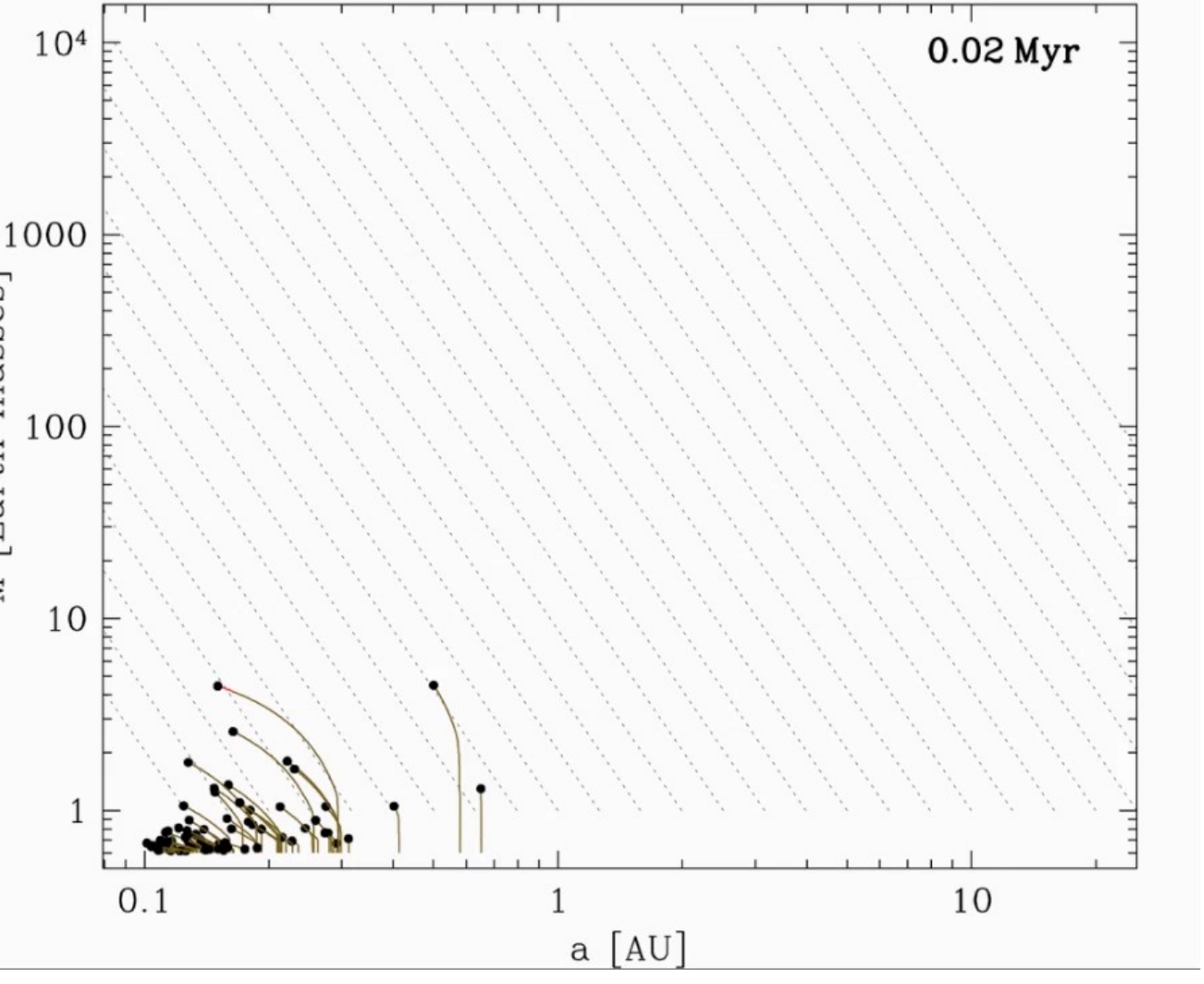
Hatched region: potential distance where an additional planet can orbit without being detected by observations and perturbations on other planets.
(green line, minimum mass needed, red line speculative…)

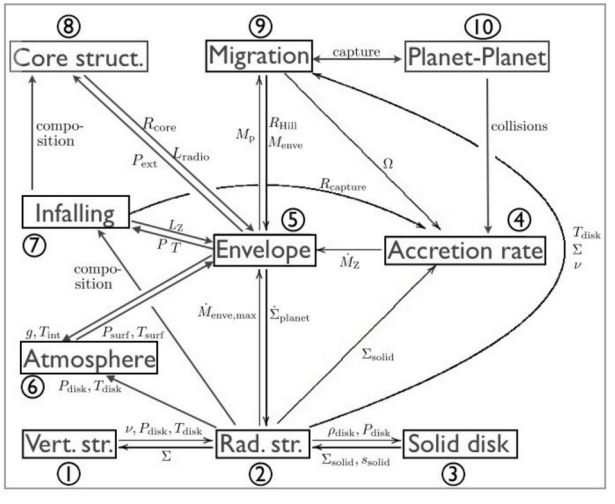
Alternative explanations: passing stars (Sun born in a cluster?), galactic potential...



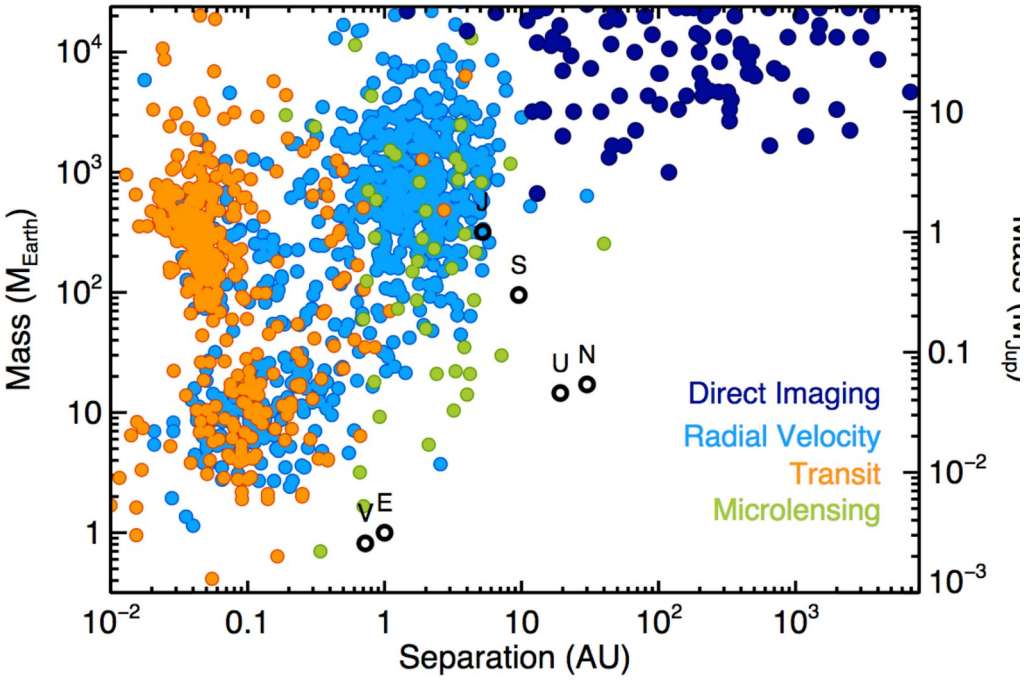
More complete models of planet evolution from exoplanet statistics: from the protostellar disk to the final planetary system. Population sysnthesis models (core accretion).

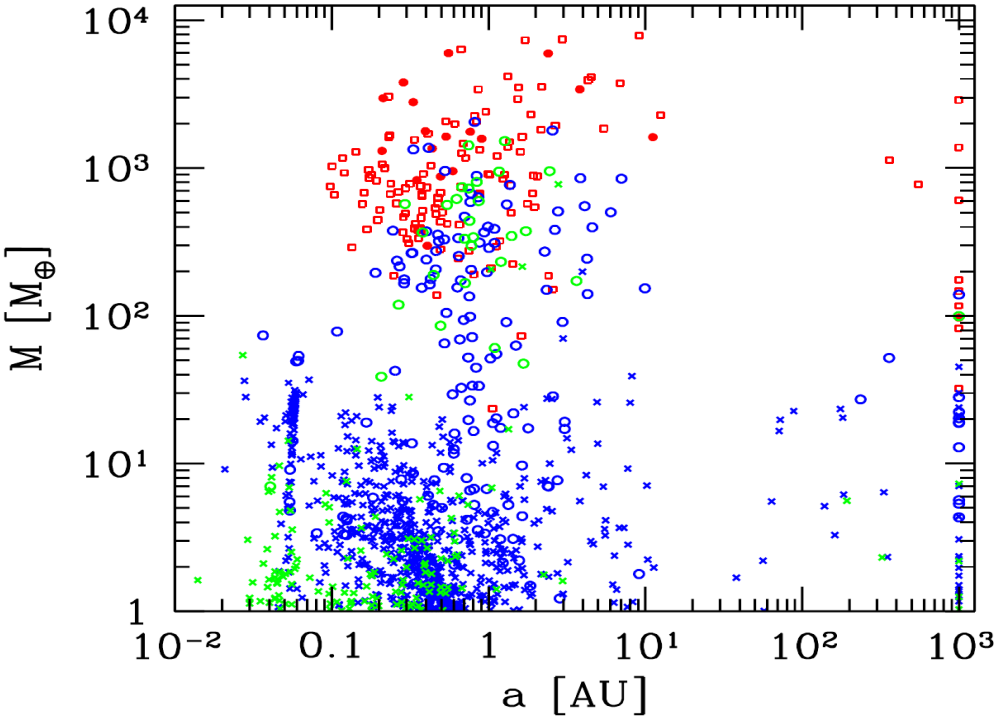
Pioneers: the Bern group i.e. Benz, Mordasini & Alibert and Lin & Ida (2004).





Difficulty in comparing with observations due to observational biases: different detection methods...

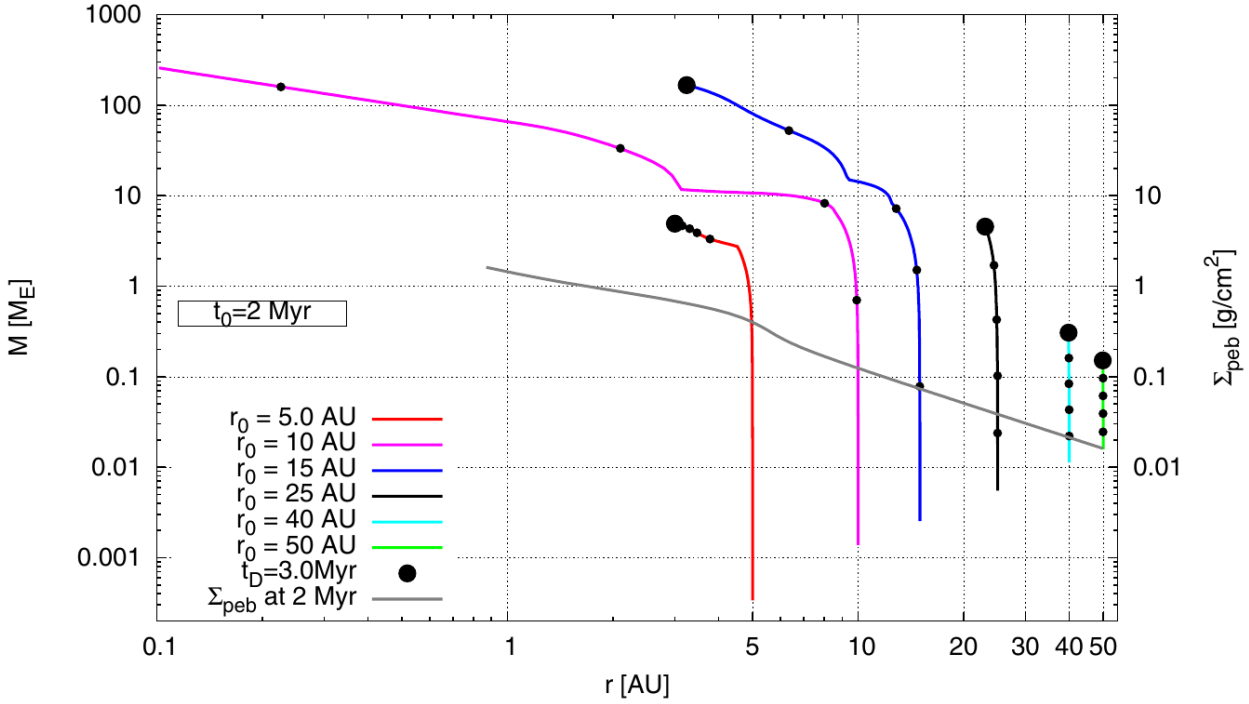




Additional models:

1) Coleman & Nelson (2016)
2) Bitsch et al. (2015)

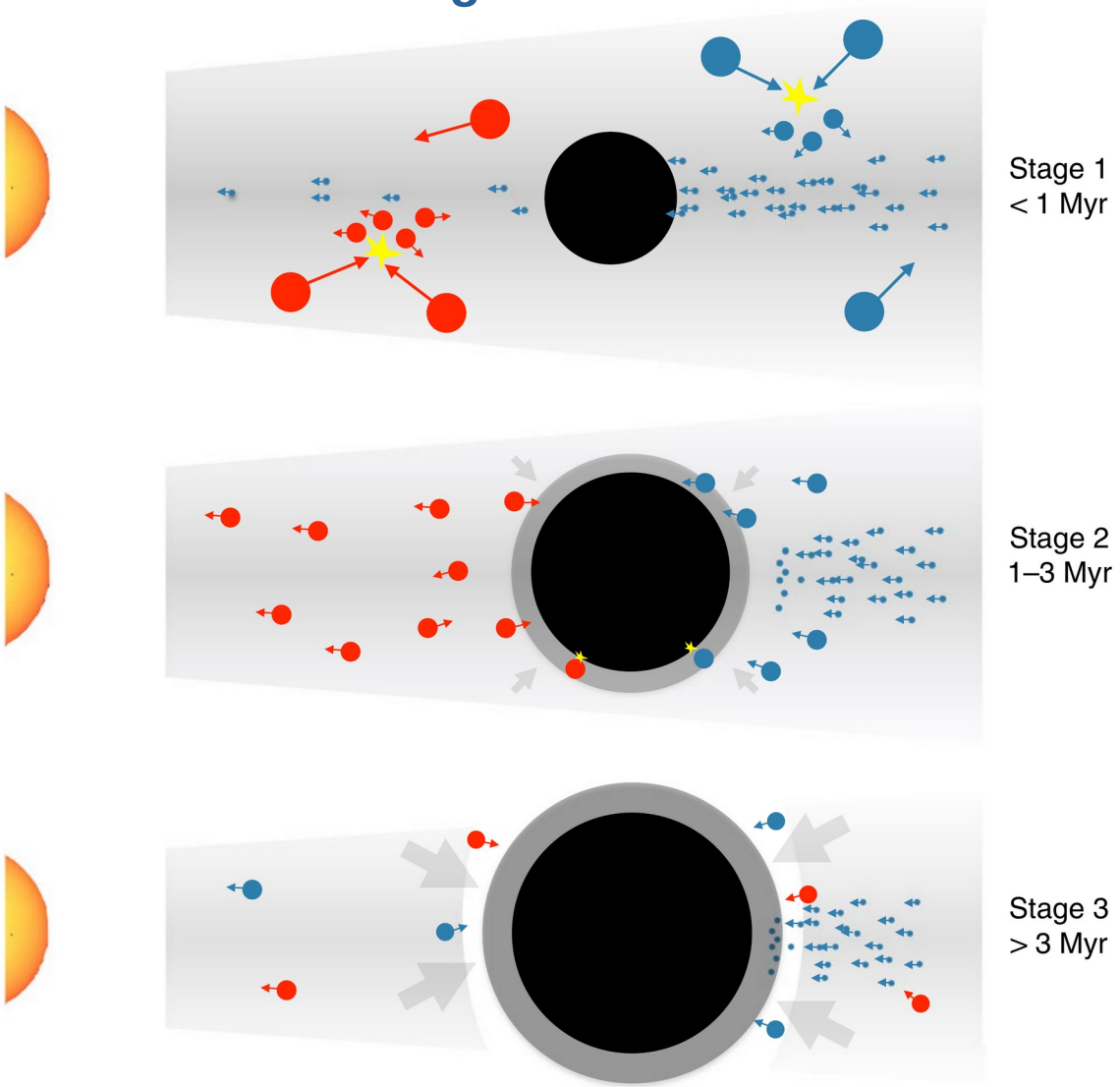
Improved disk models and planet-disk interaction, planet growth via pebble and planetesimal accretion…..and additional effects.

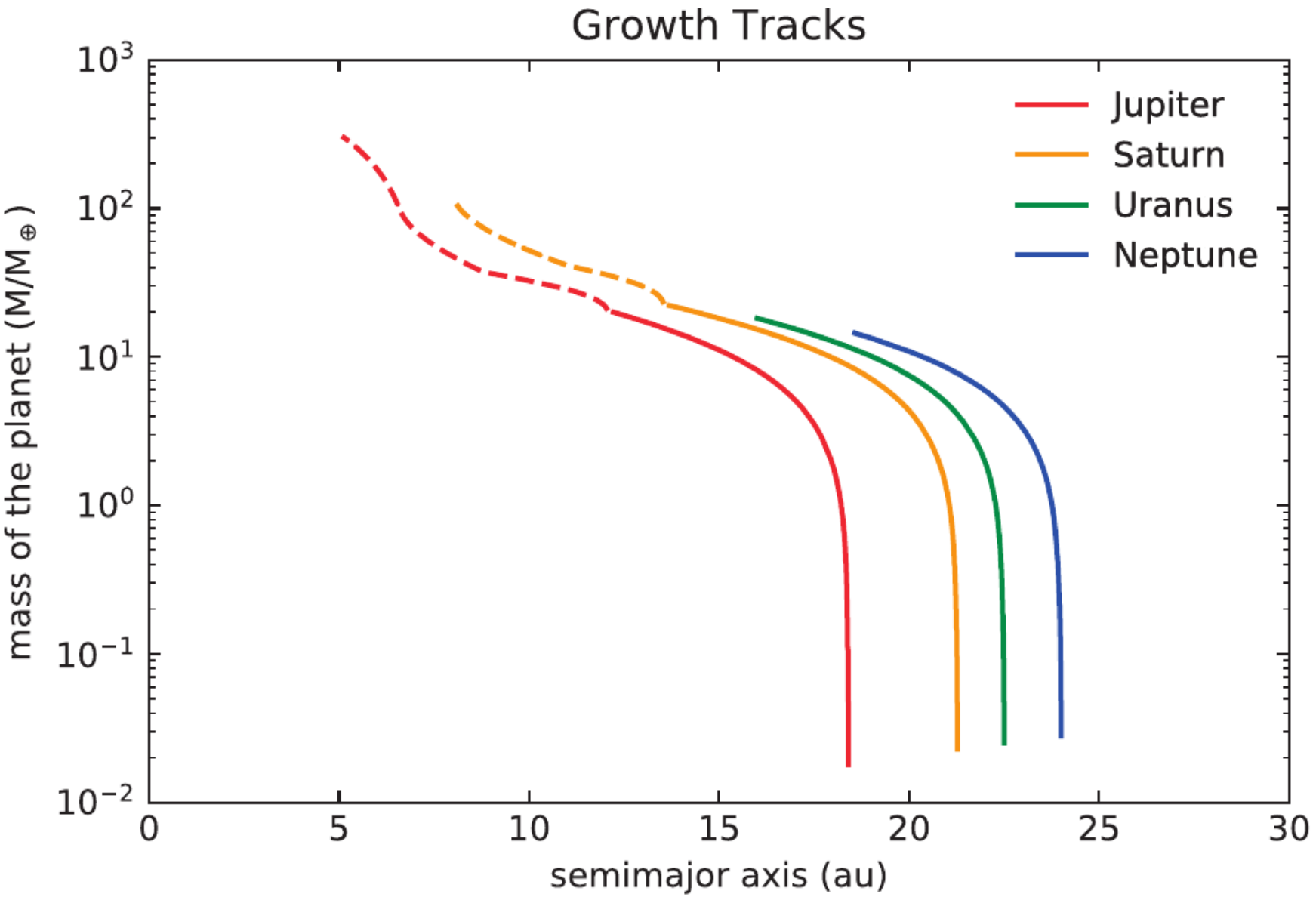


Oberg et al. 2019, Jupiter core formed beyond N_2 and Ar snow lines (~20-30 au)

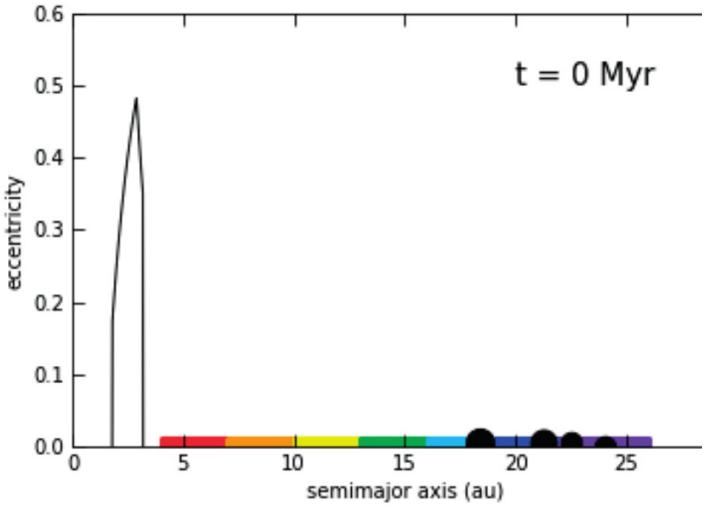
Pirani et al. (2019)

Refined stationary models: Alibert et al. 2018, to explain costraints from meteoritic data, divide the accretion process of Jupiter (in situ) in two stages. In the first Jupiter grows by pebble accretion to 10 ME in 1 Myr. Then, pebble isolation occurred and Jupiter accumulates planetesimals for 2 Myr and gas infall occurs. Fresh pebbles are produced by planetesimal collisions. New old pebbles from outside are scattered back inside when Jupiter is fully formed and massive. Compatible with some migration but what about other constraints?

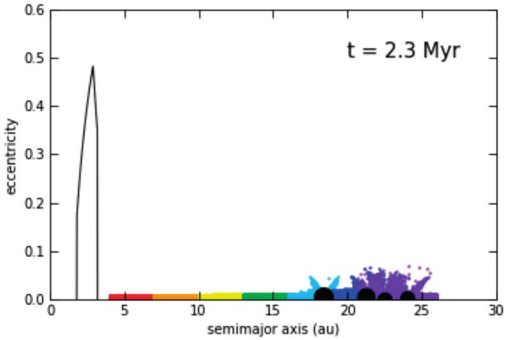


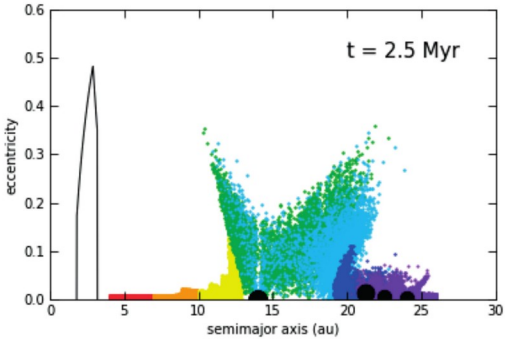


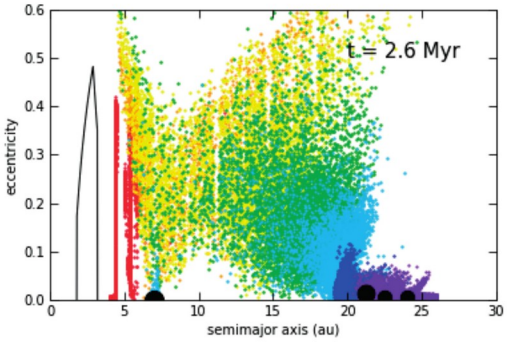
Pirani et al. 2019

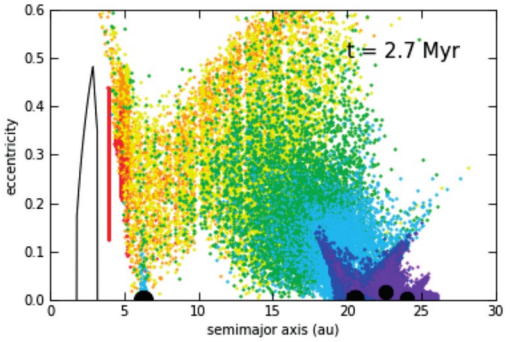


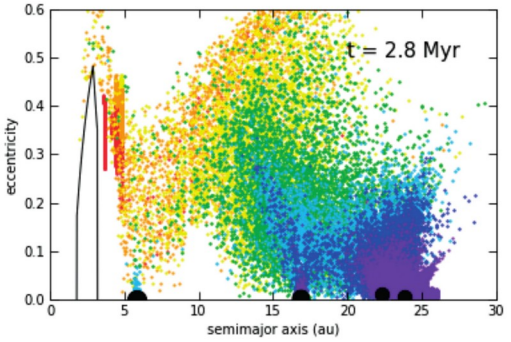
N-body simulations with induced migration on the 4 planets. Trojans are trapped during mass growth and migration. The Kuiper belt is excited.

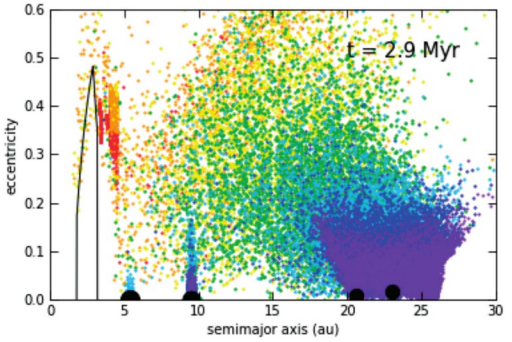


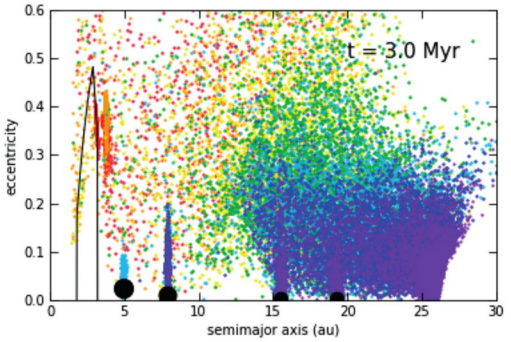


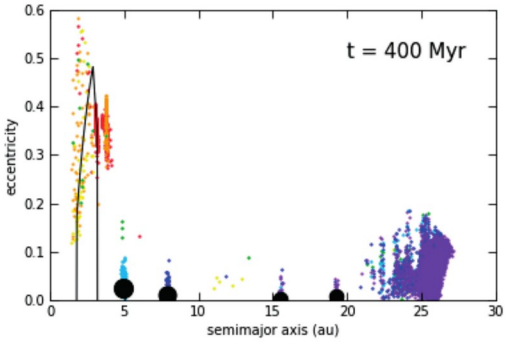


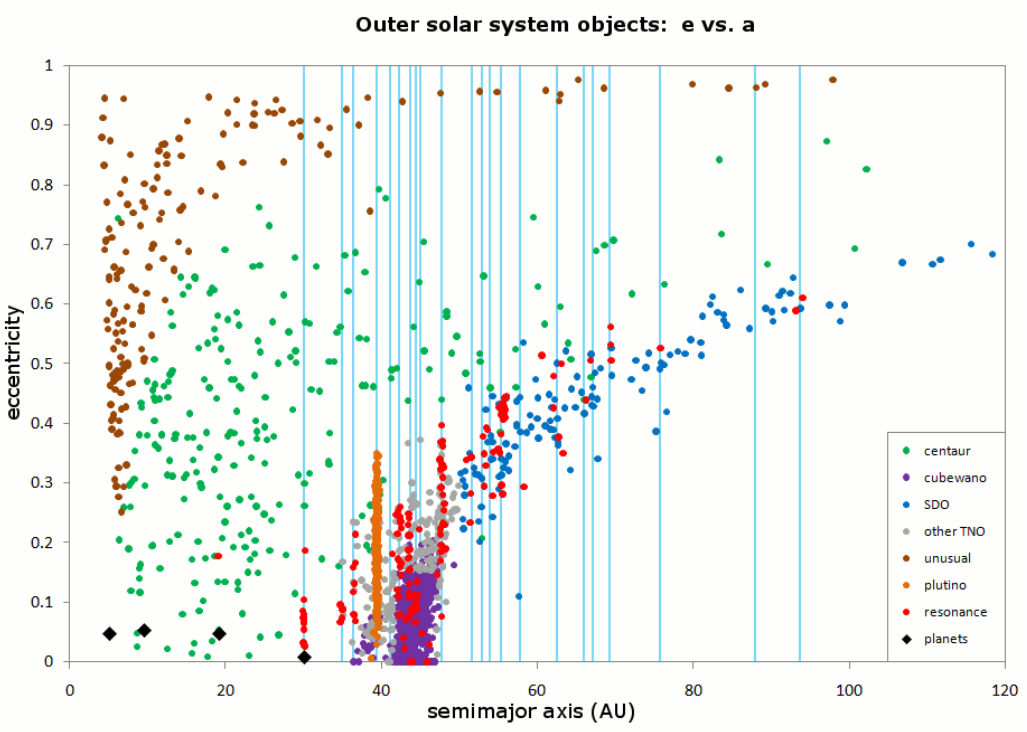











Outer solar system objects: e vs. a
eccentricity
semimajor axis (AU)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
centaur
cubewano
SDO
other TNO
unusual
plutino
resonance
planets