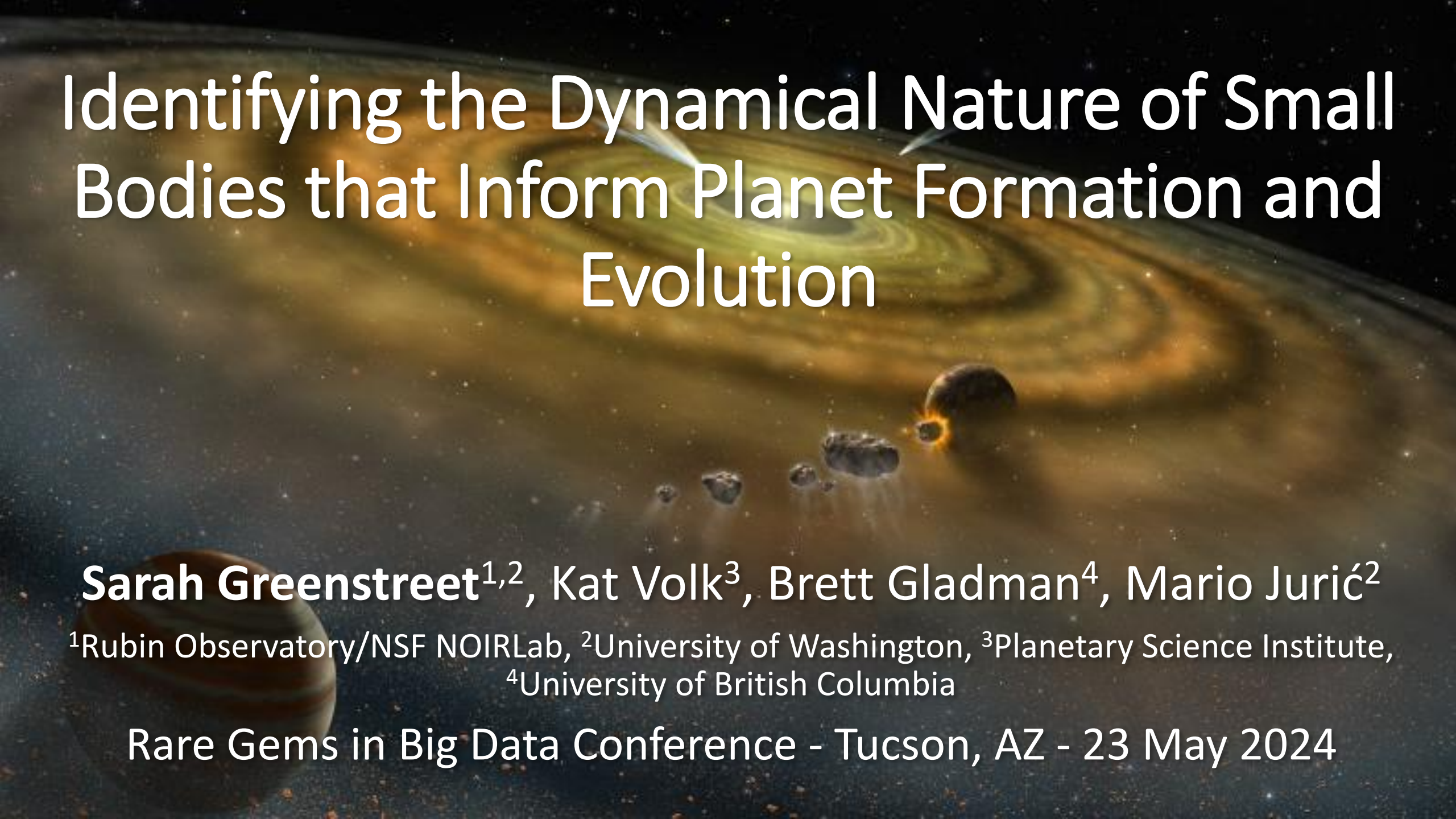
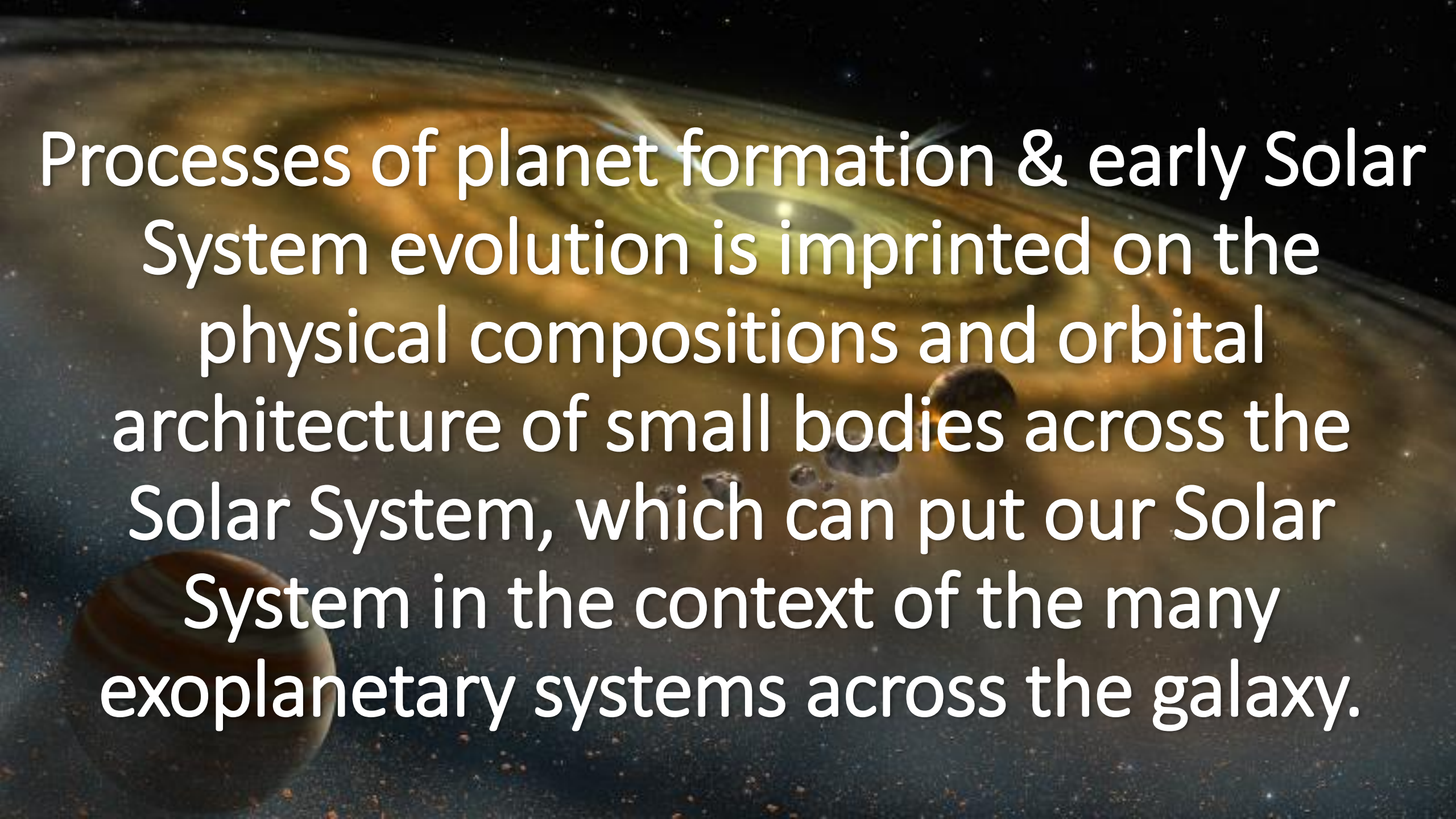
Identifying the Dynamical Nature of Small Bodies that Inform Planet Formation and Evolution



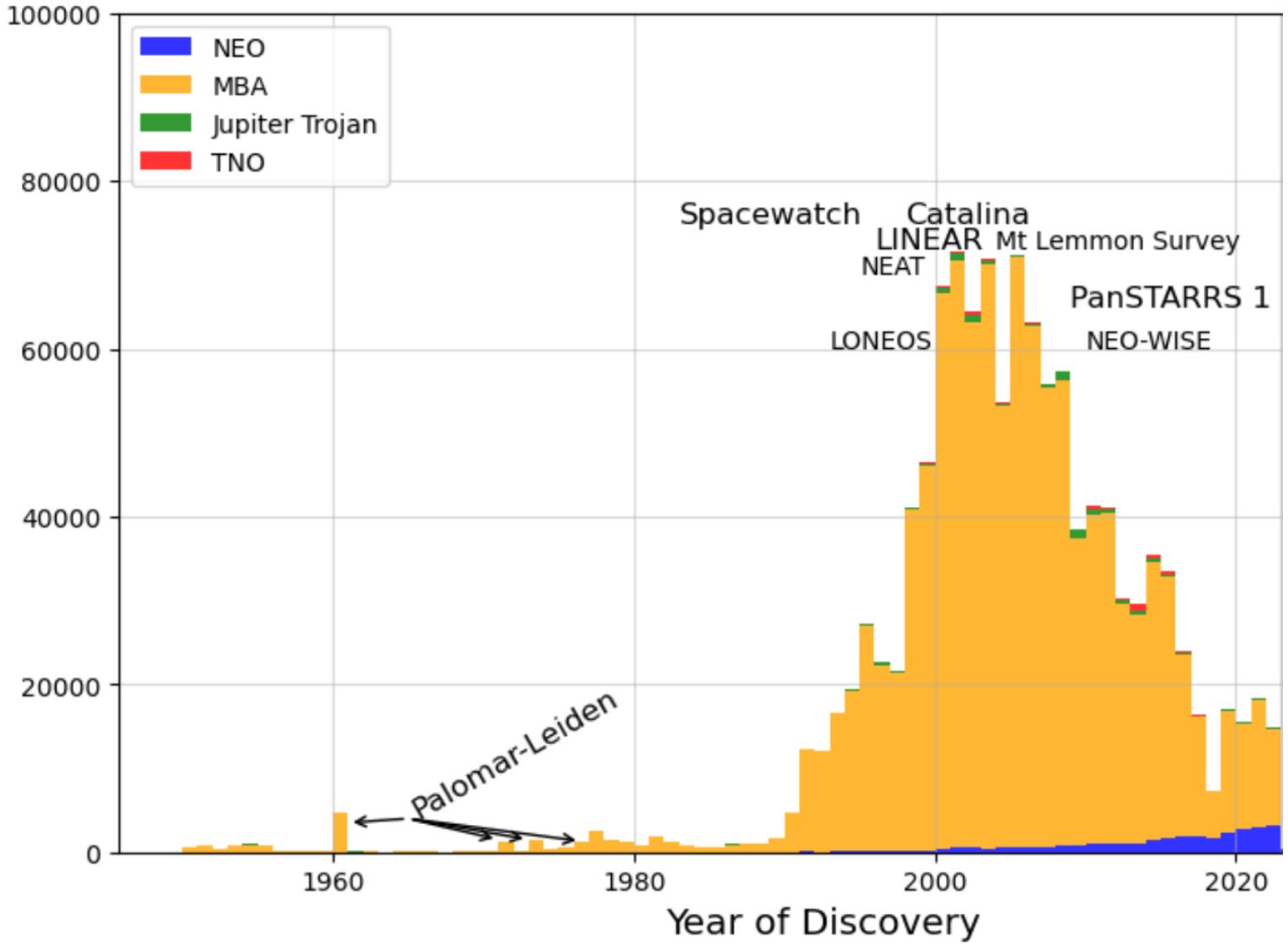
Sarah Greenstreet[1,2], Kat Volk[3], Brett Gladman[4], Mario Jurić[2]

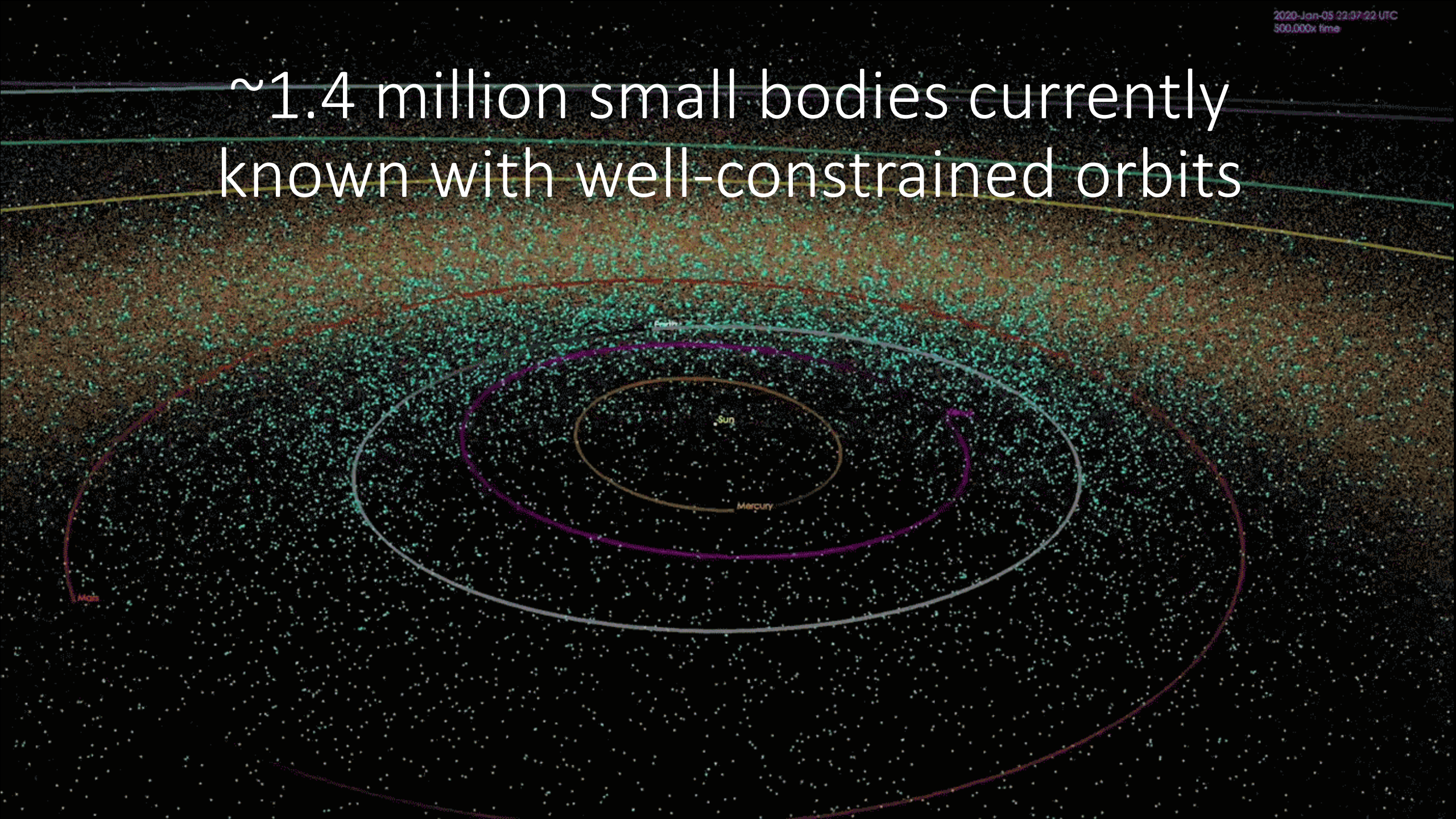
[1]Rubin Observatory/NSF NOIRLab, [2]University of Washington, [3]Planetary Science Institute, [4]University of British Columbia

Rare Gems in Big Data Conference - Tucson, AZ - 23 May 2024


Processes of planet formation & early Solar System evolution is imprinted on the physical compositions and orbital architecture of small bodies across the Solar System, which can put our Solar System in the context of the many exoplanetary systems across the galaxy.

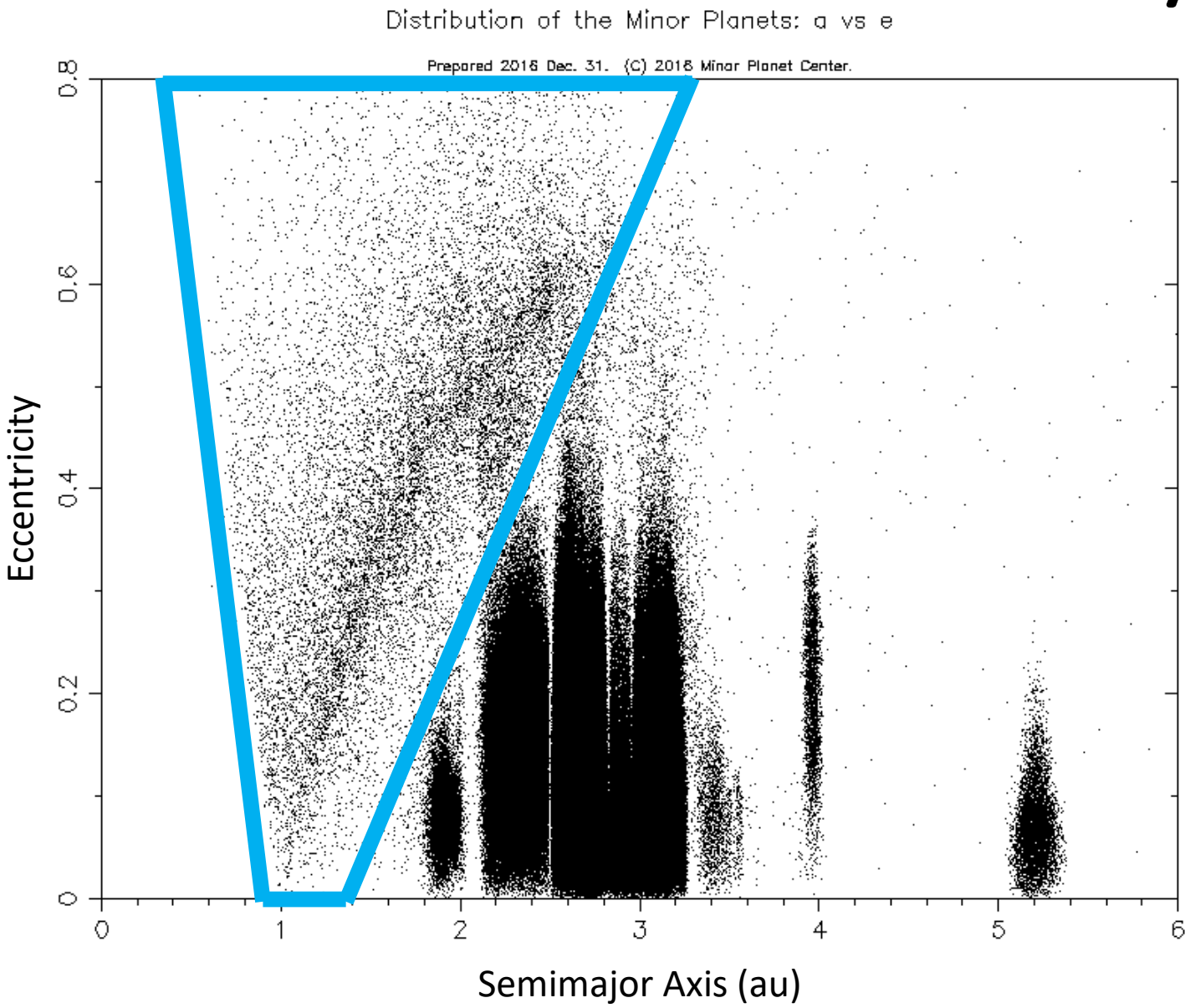
Surveys discover 10,000s of small bodies each year



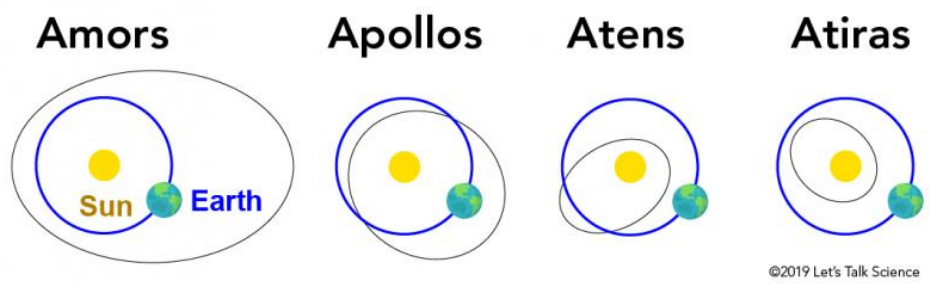


~1.4 million small bodies currently known with well-constrained orbits

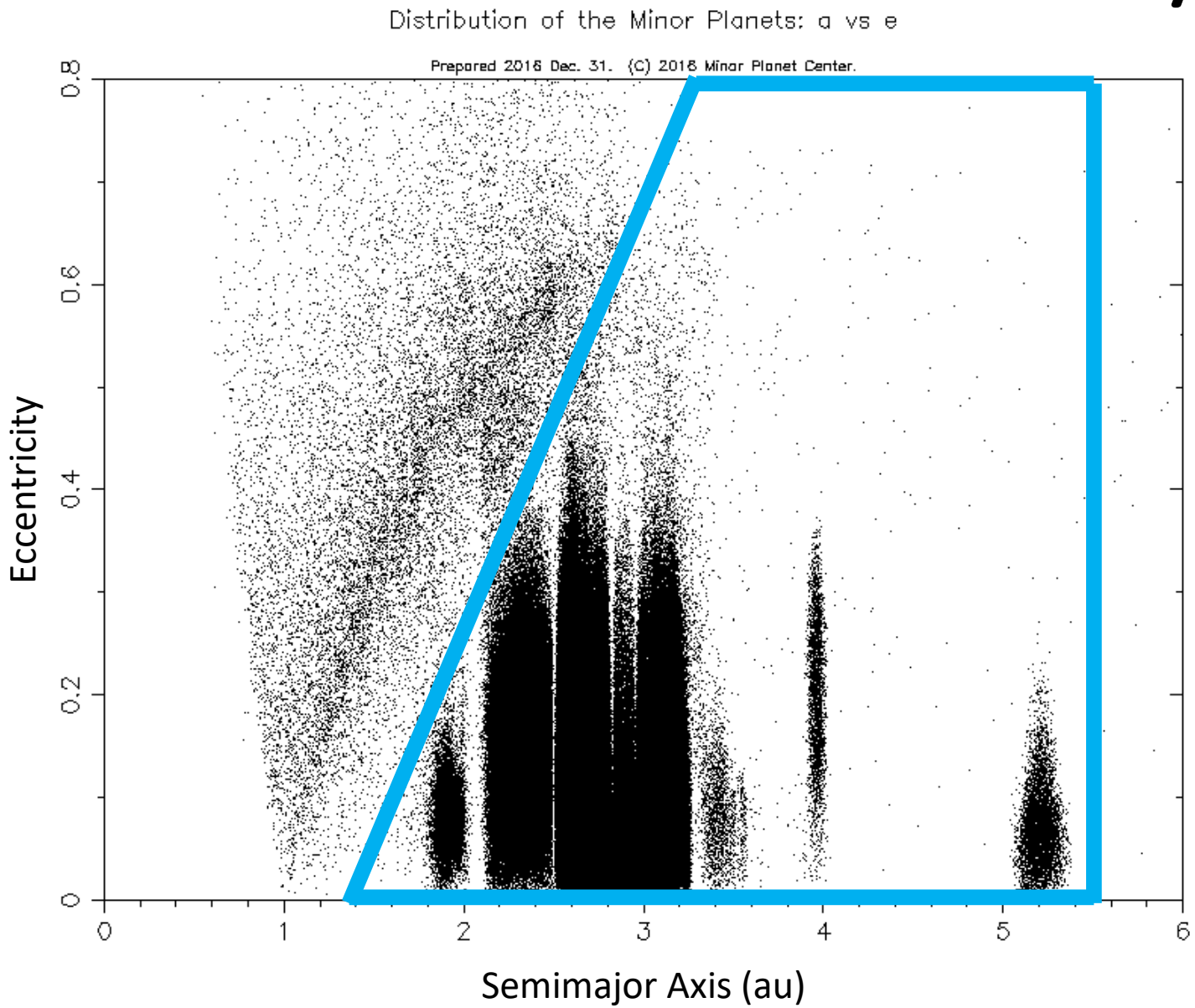
Inner Solar System



Near-Earth Objects



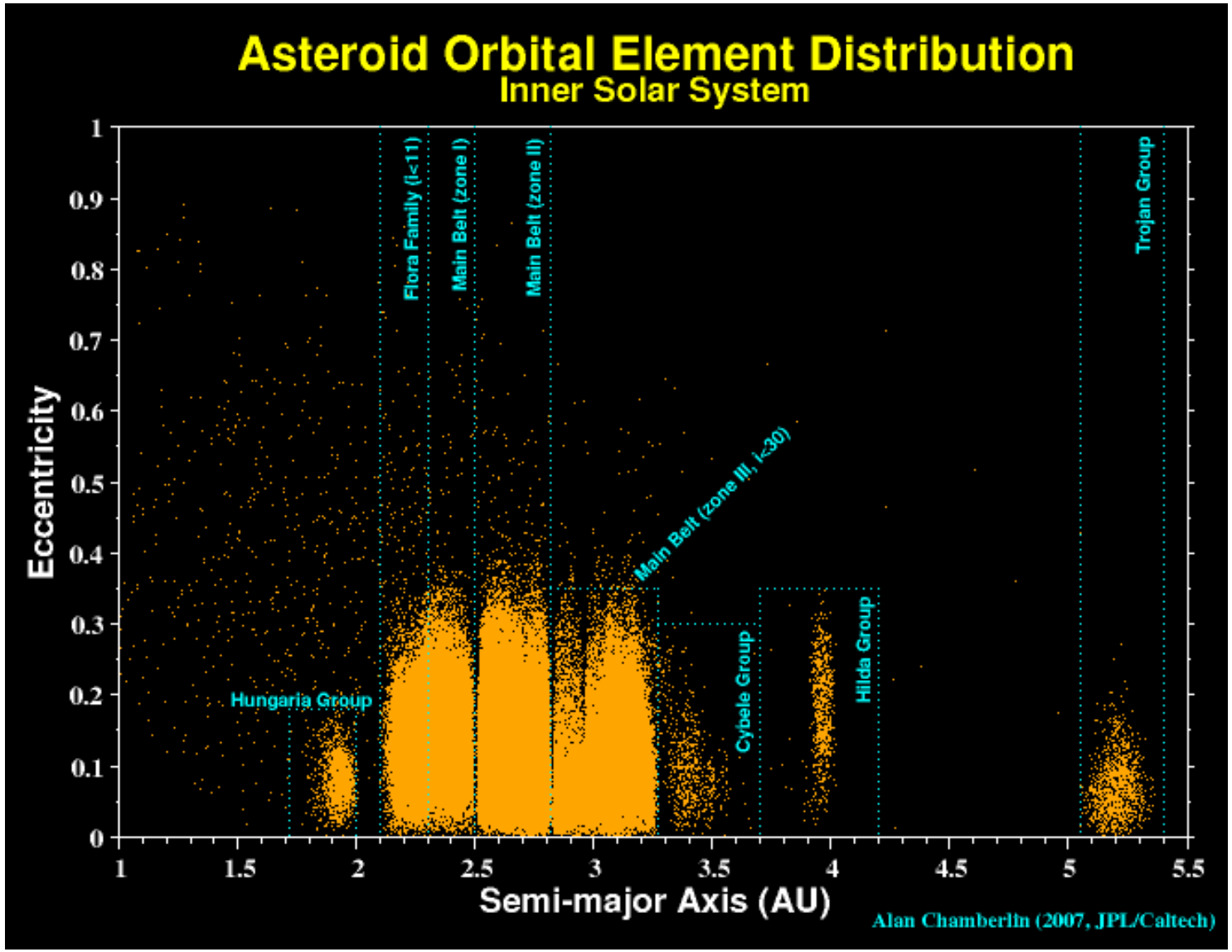
Inner Solar System



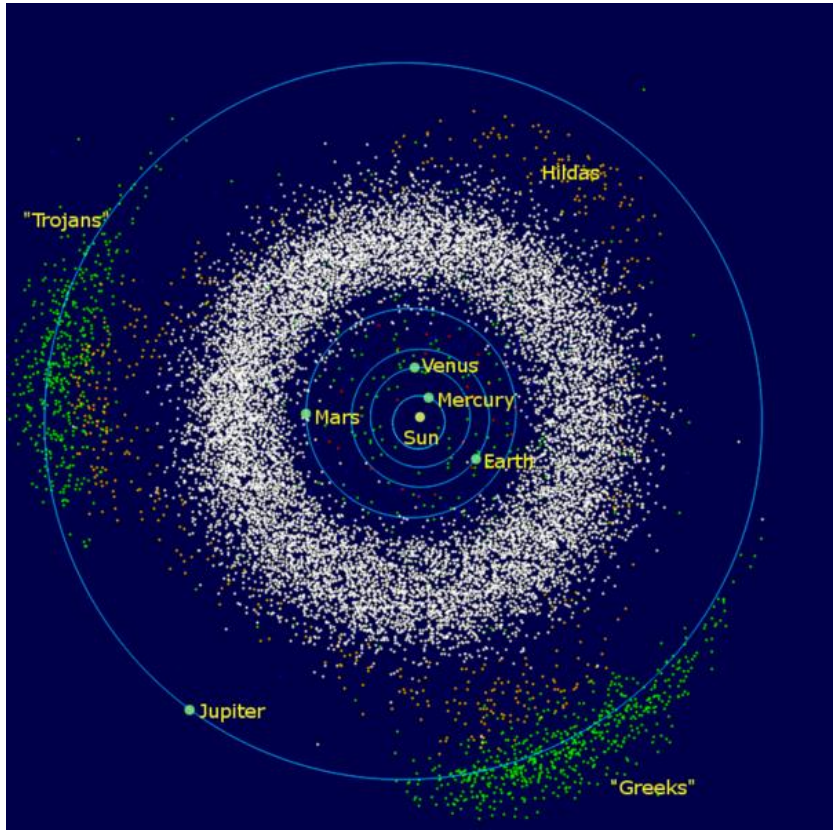
Main-Belt Asteroids & Jupiter Trojans

Inner Solar System

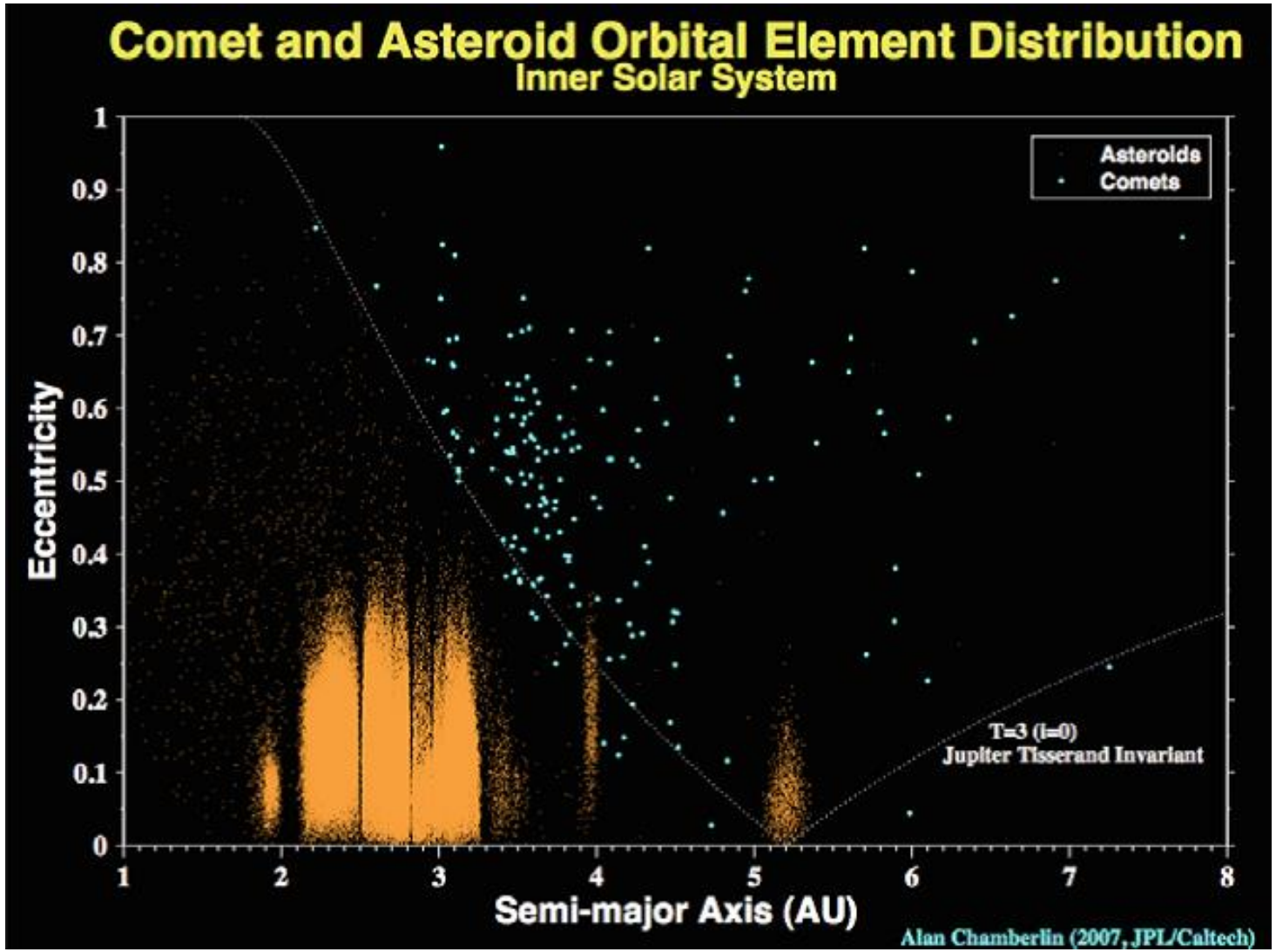
Distribution of the Minor Planets: a vs e



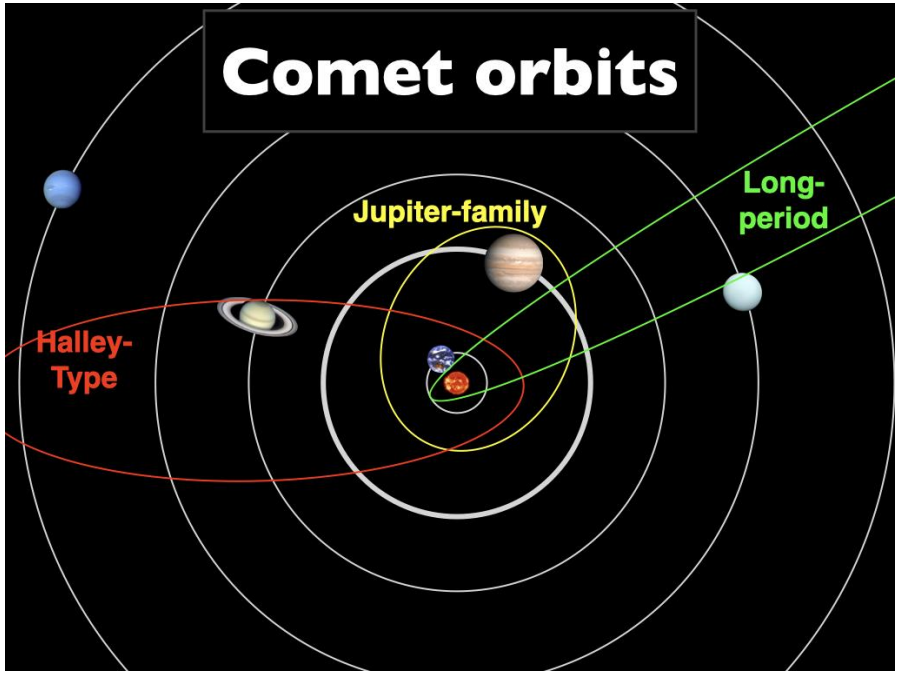
Main-Belt Asteroids & Jupiter Trojans



Outer Solar System

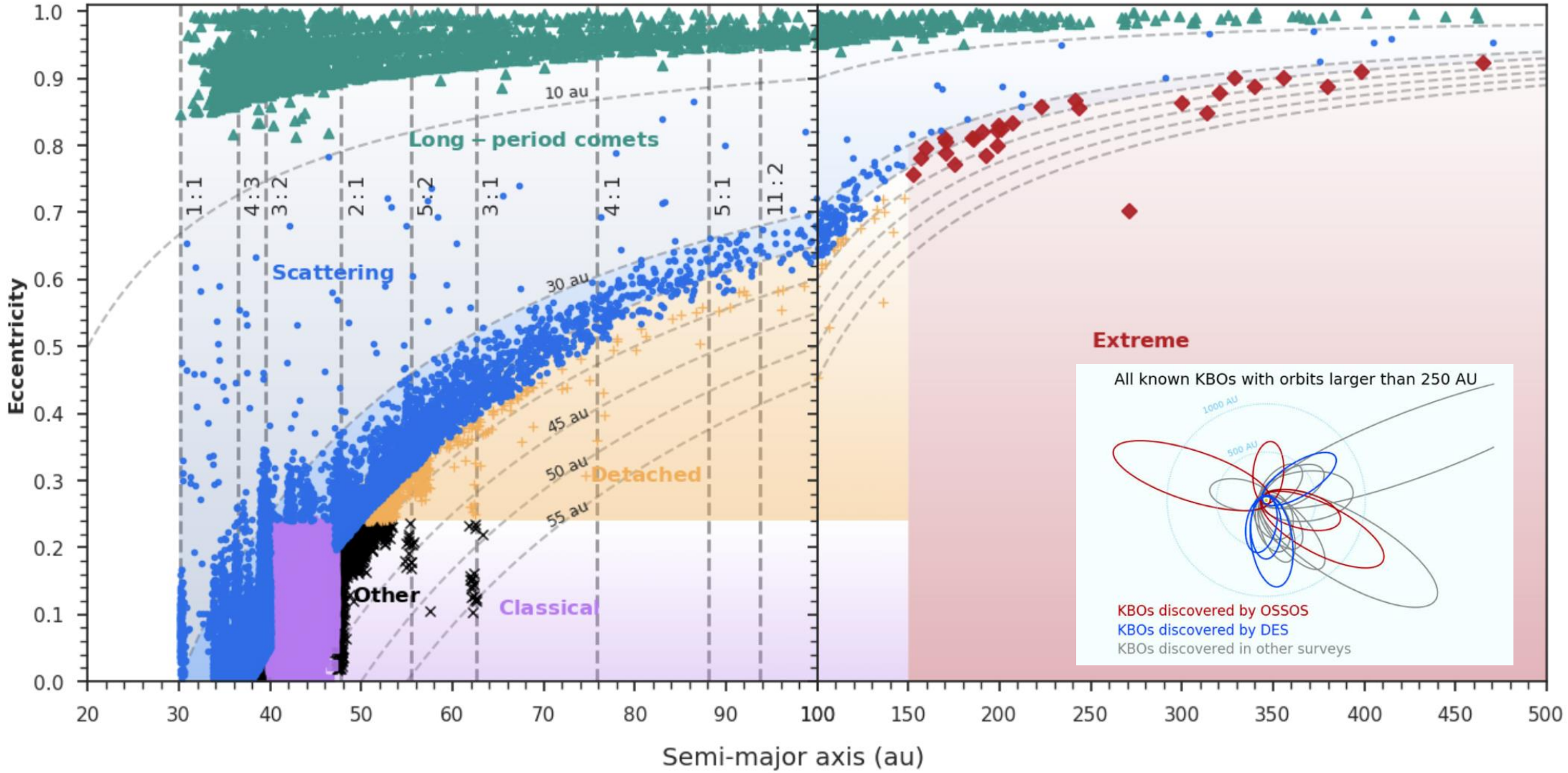


Comets



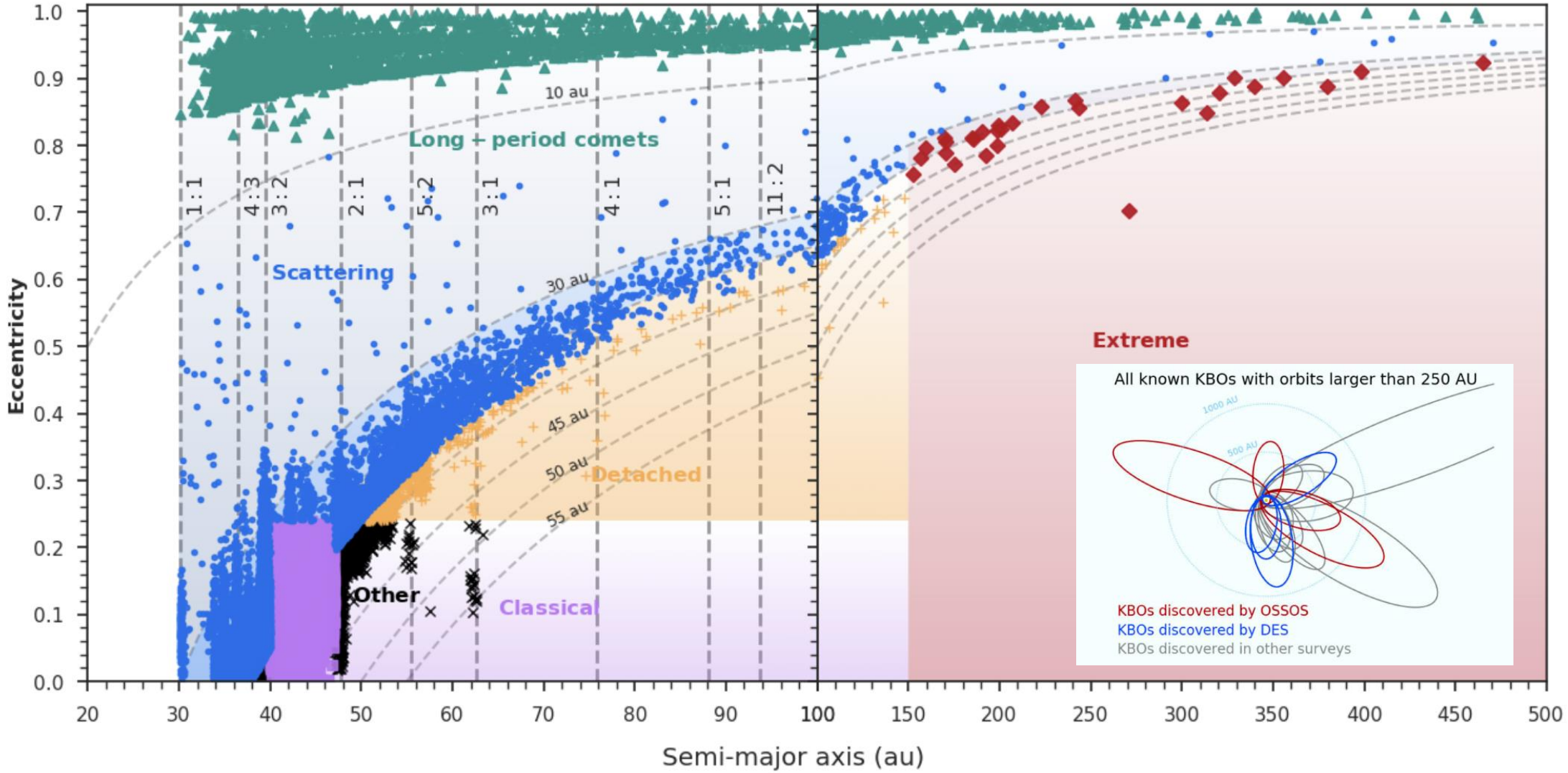
Outer Solar System

Transneptunian Region



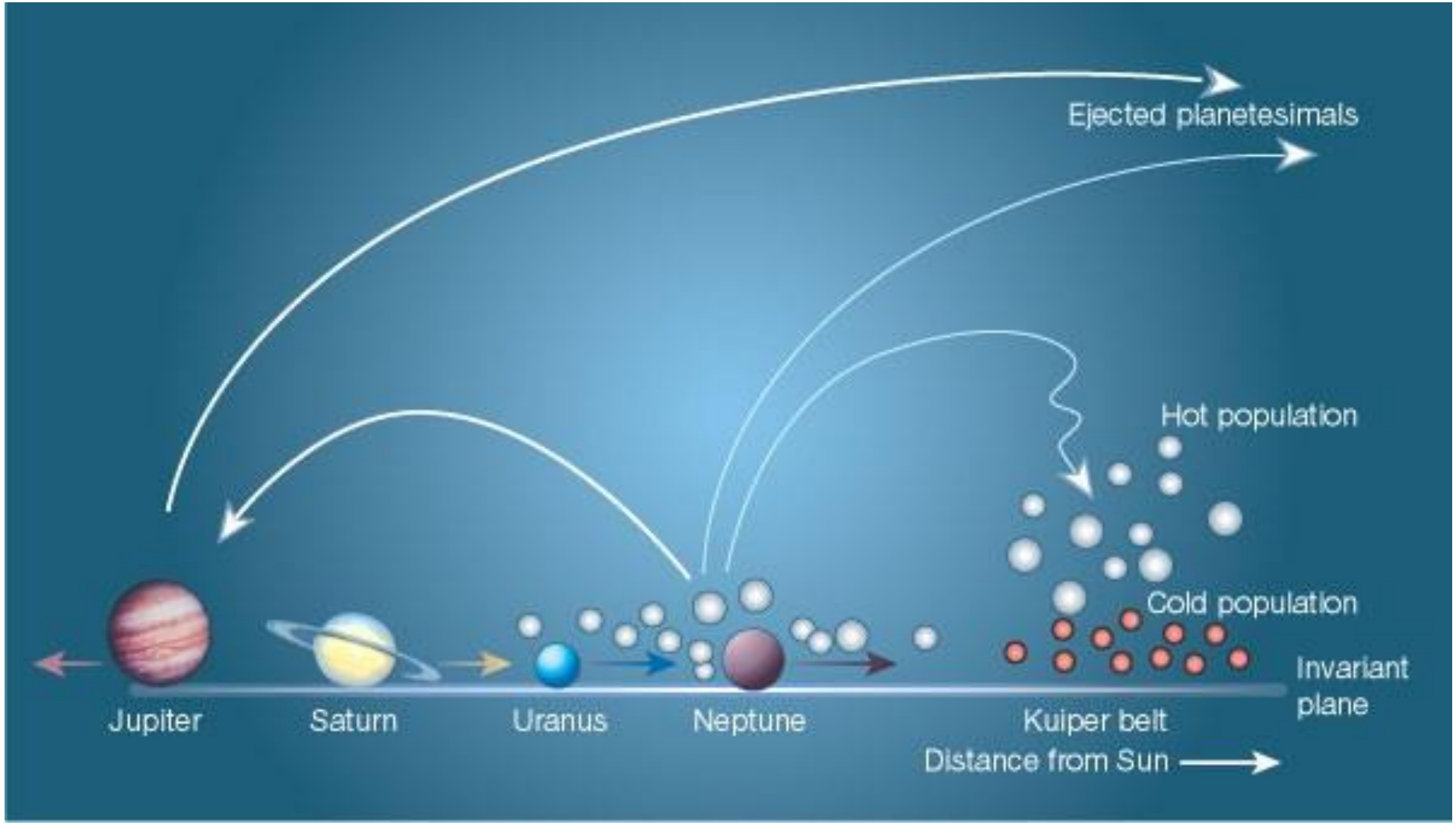
Outer Solar System

Structure Informs Early Solar System Evolution



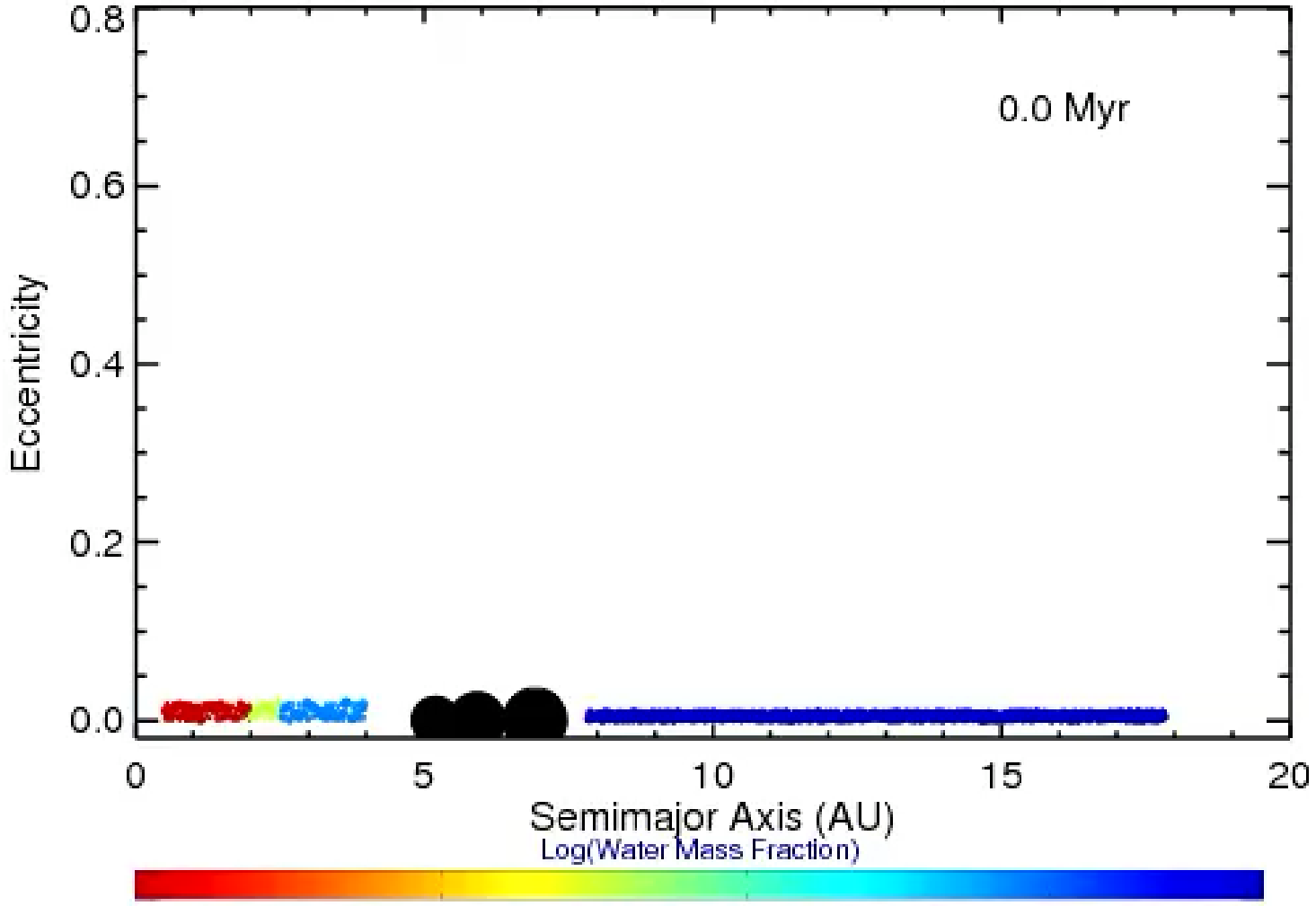
Outer Solar System

Early Giant Planet Instability



Outer Solar System

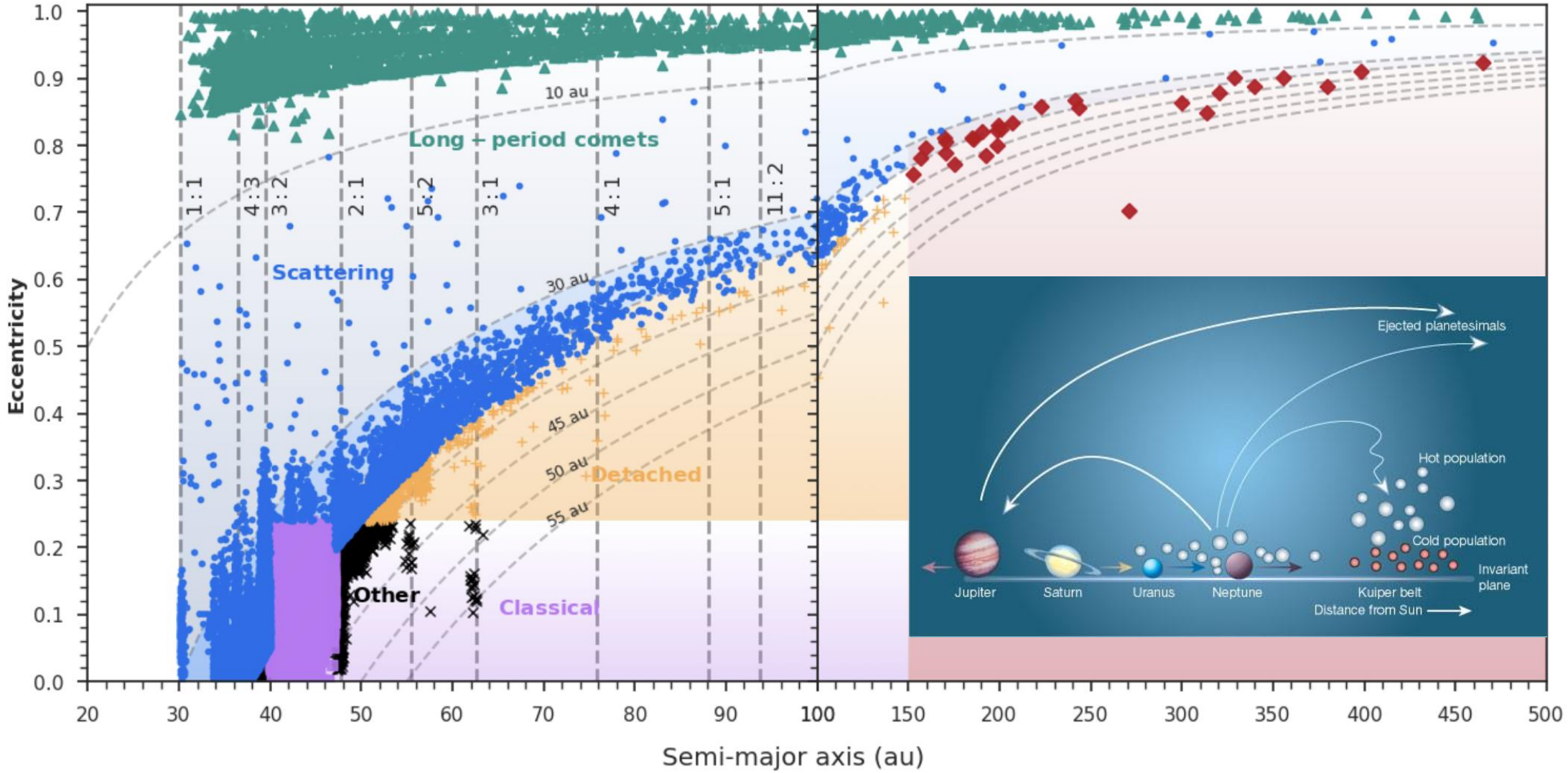
Early Giant Planet Instability



Raymond et al. (2012)

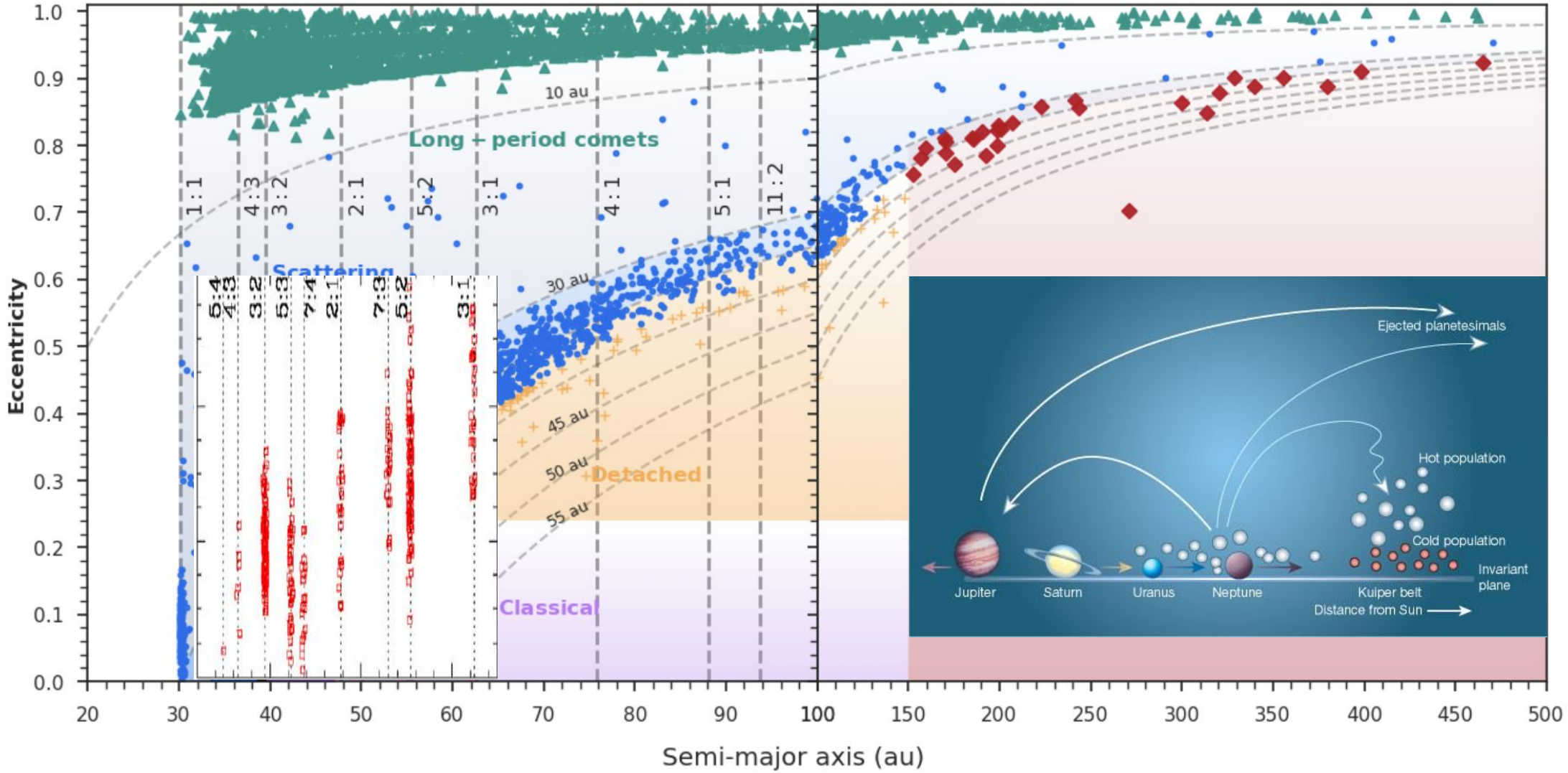
Outer Solar System

Structure Informs Early Solar System Evolution



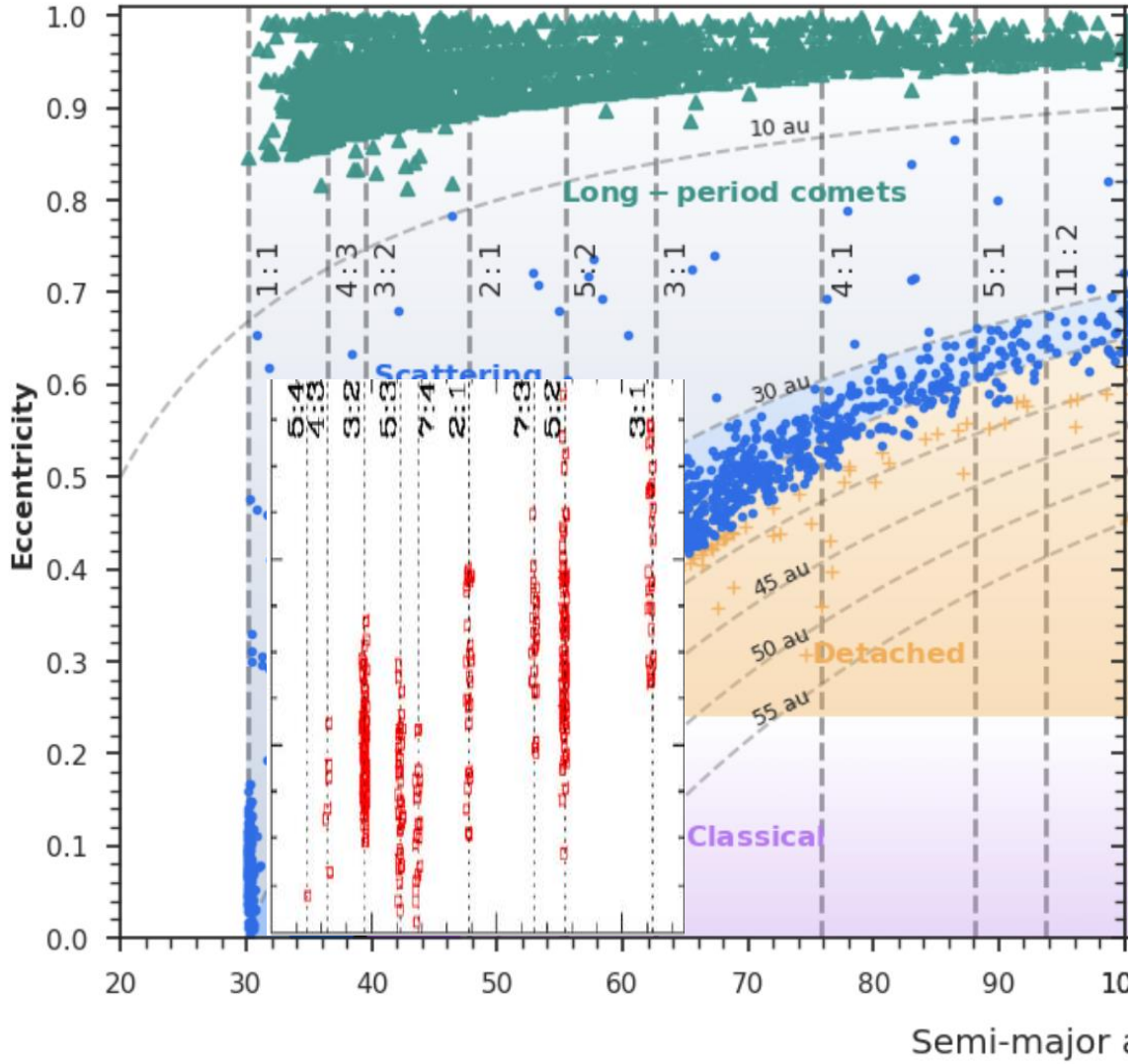
Outer Solar System

Objects Swept Up Into Moving Resonances



Outer Solar System

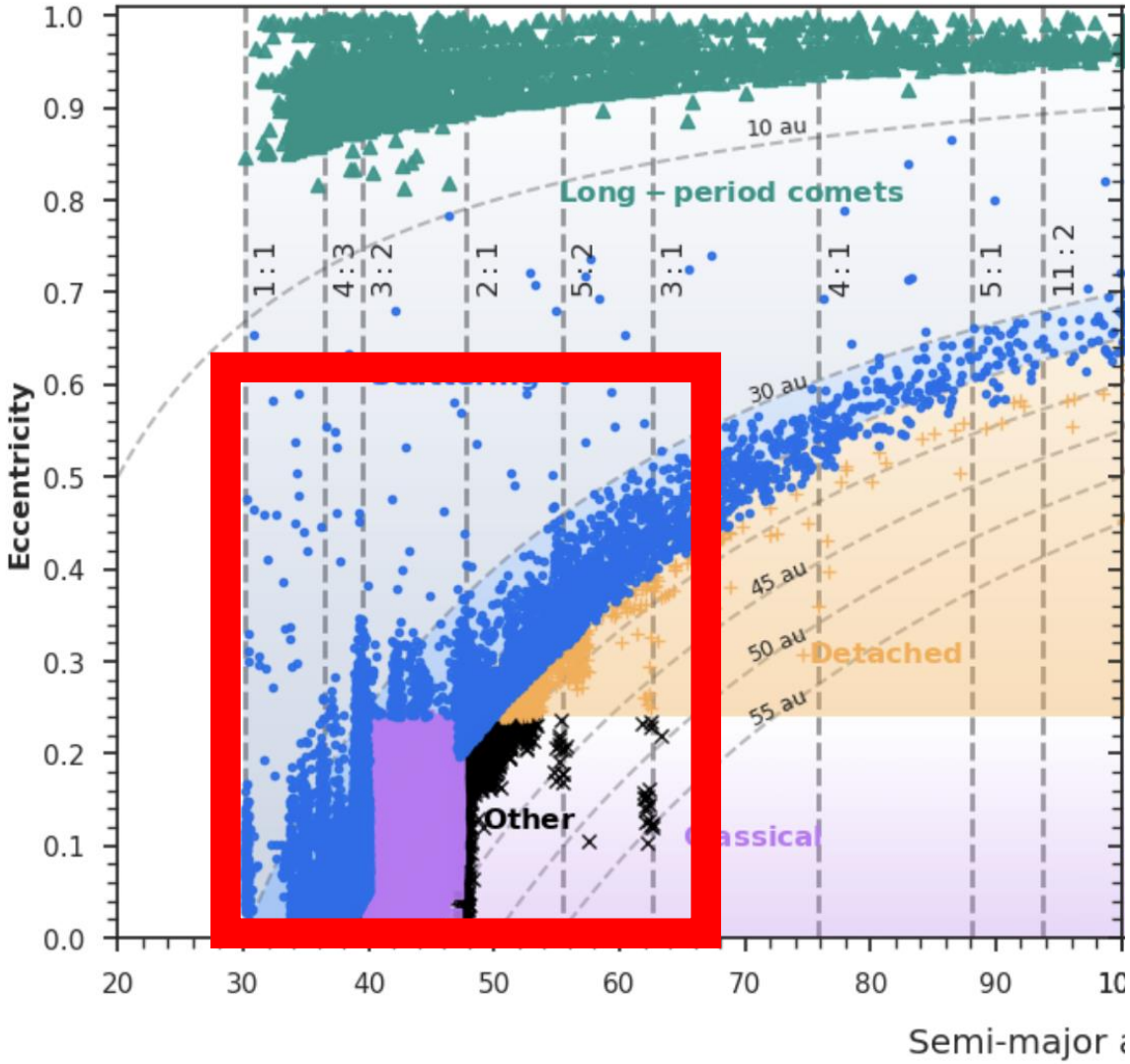
Objects Swept Up Into Moving Resonances



How many objects are in resonances places constraints on planetesimal disk mass, speed & timing of giant planet migration

The Challenge:

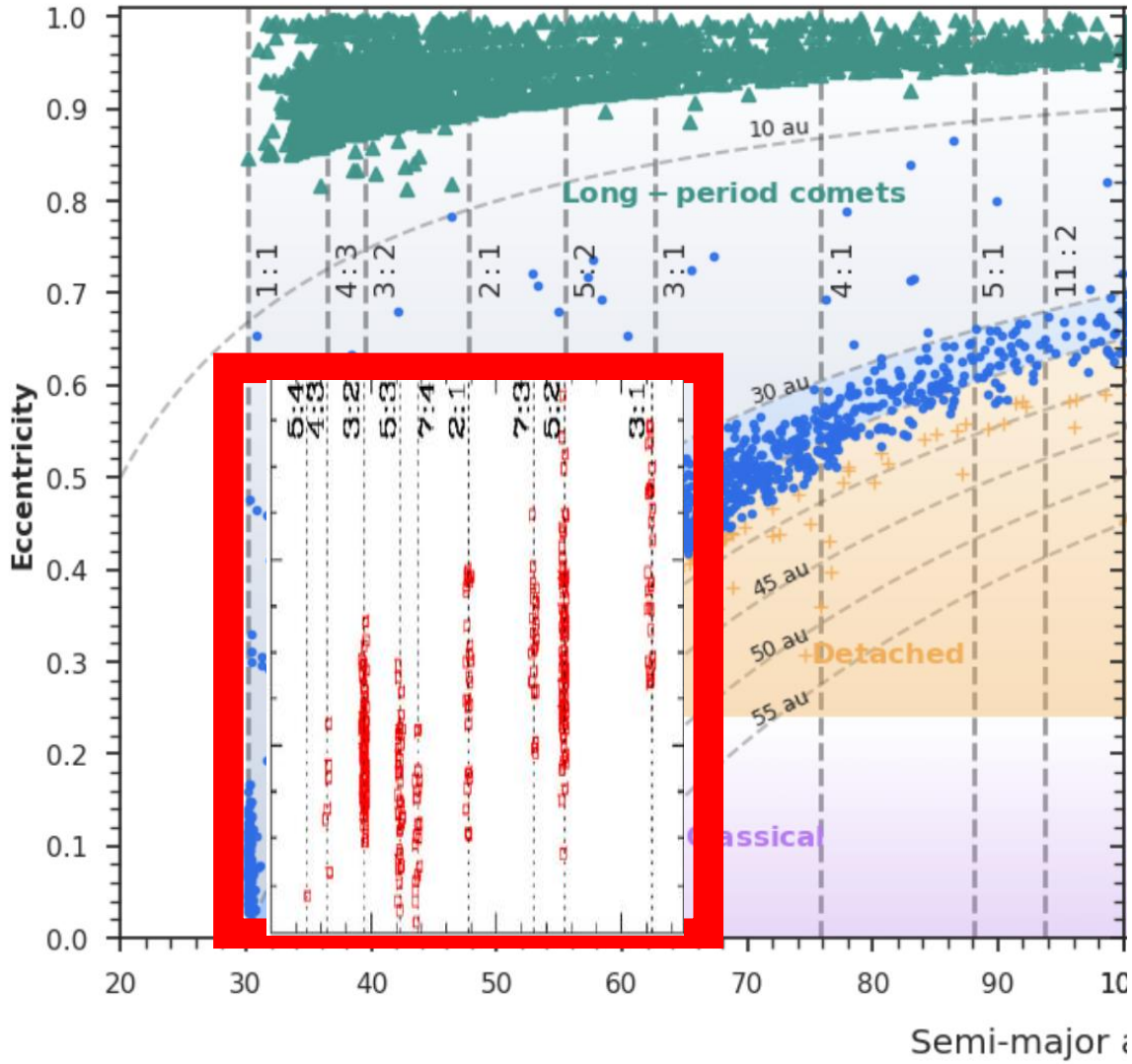
Finding which objects are in resonances



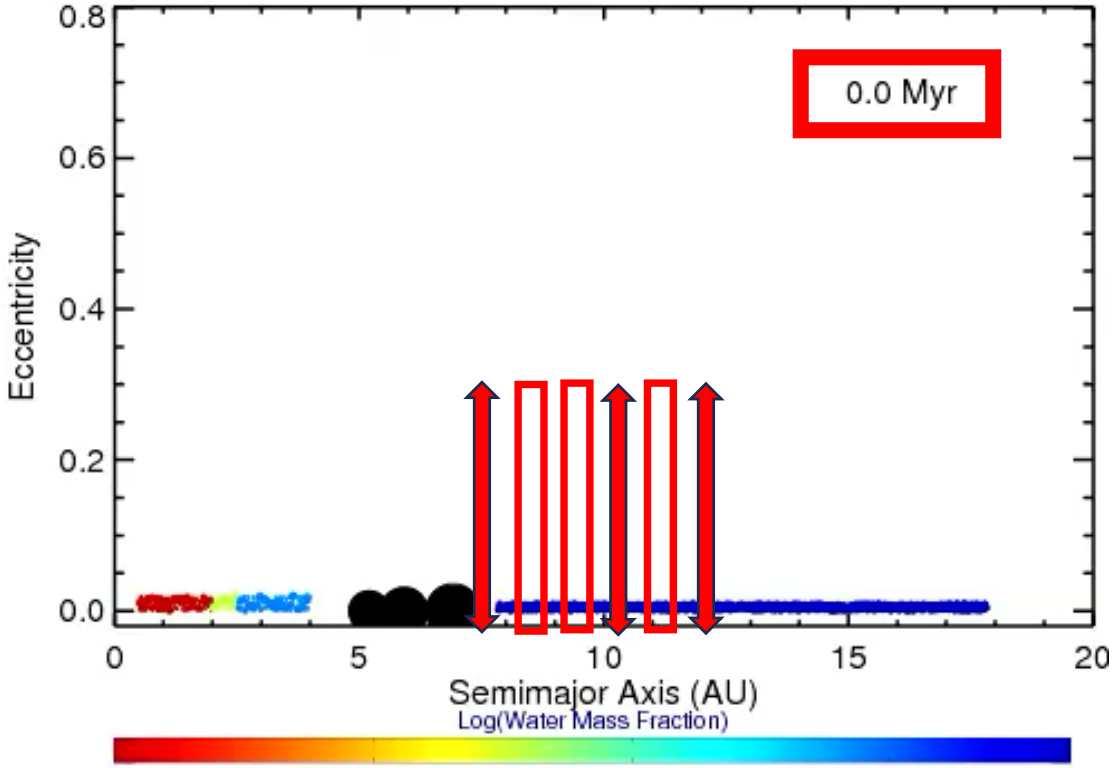
Current orbital elements aren't enough

The Challenge:

Finding which objects are in resonances

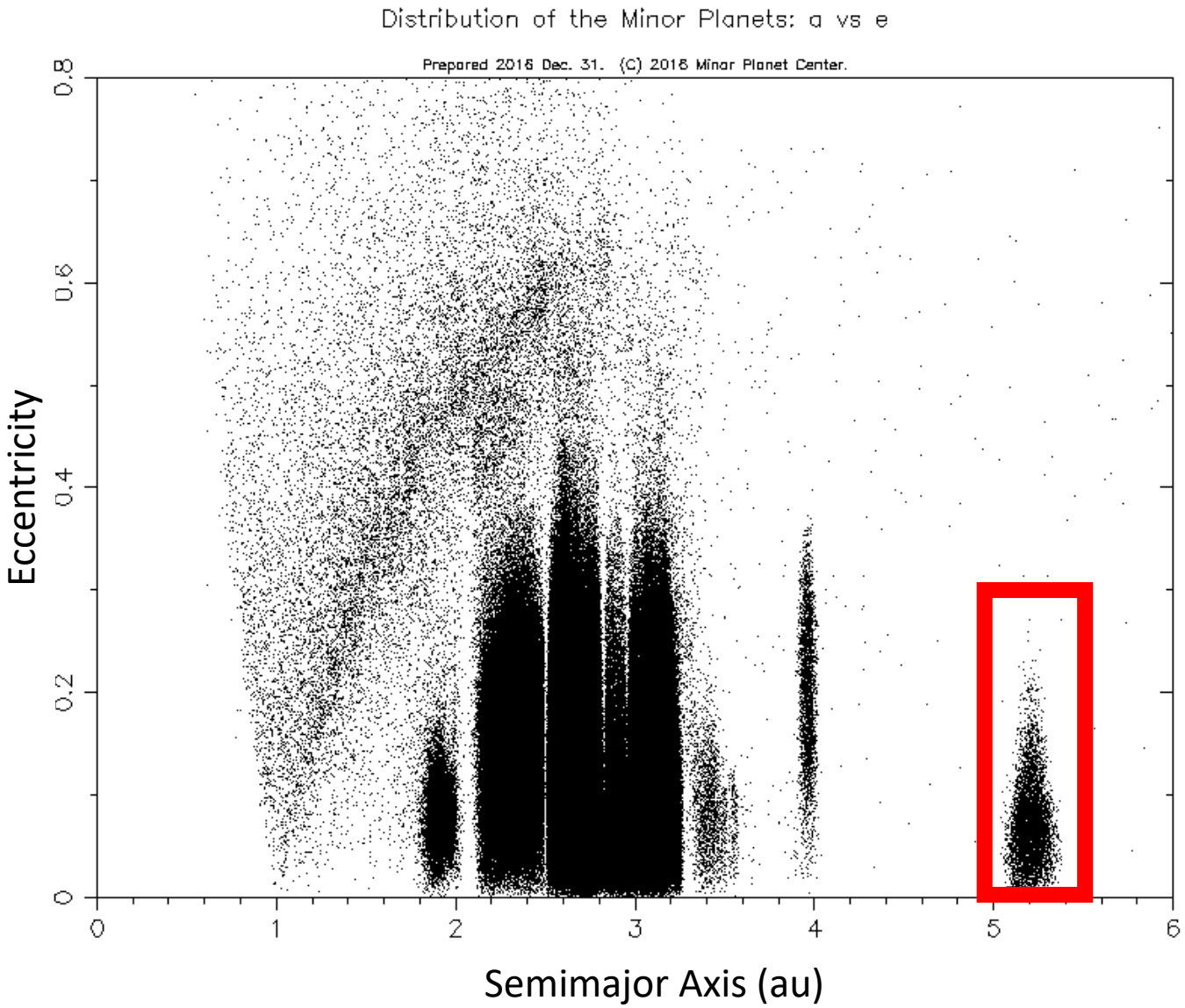


Need time variability

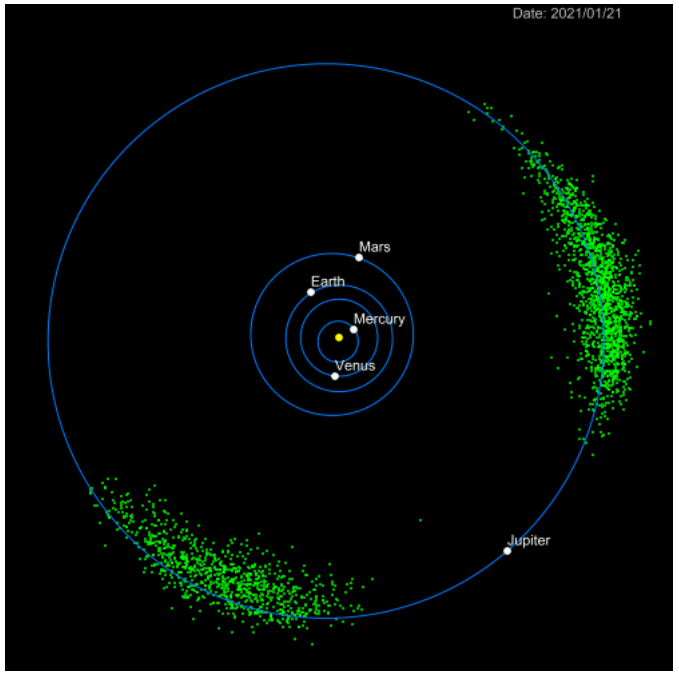


Raymond et al. (2012)

Jupiter Trojans

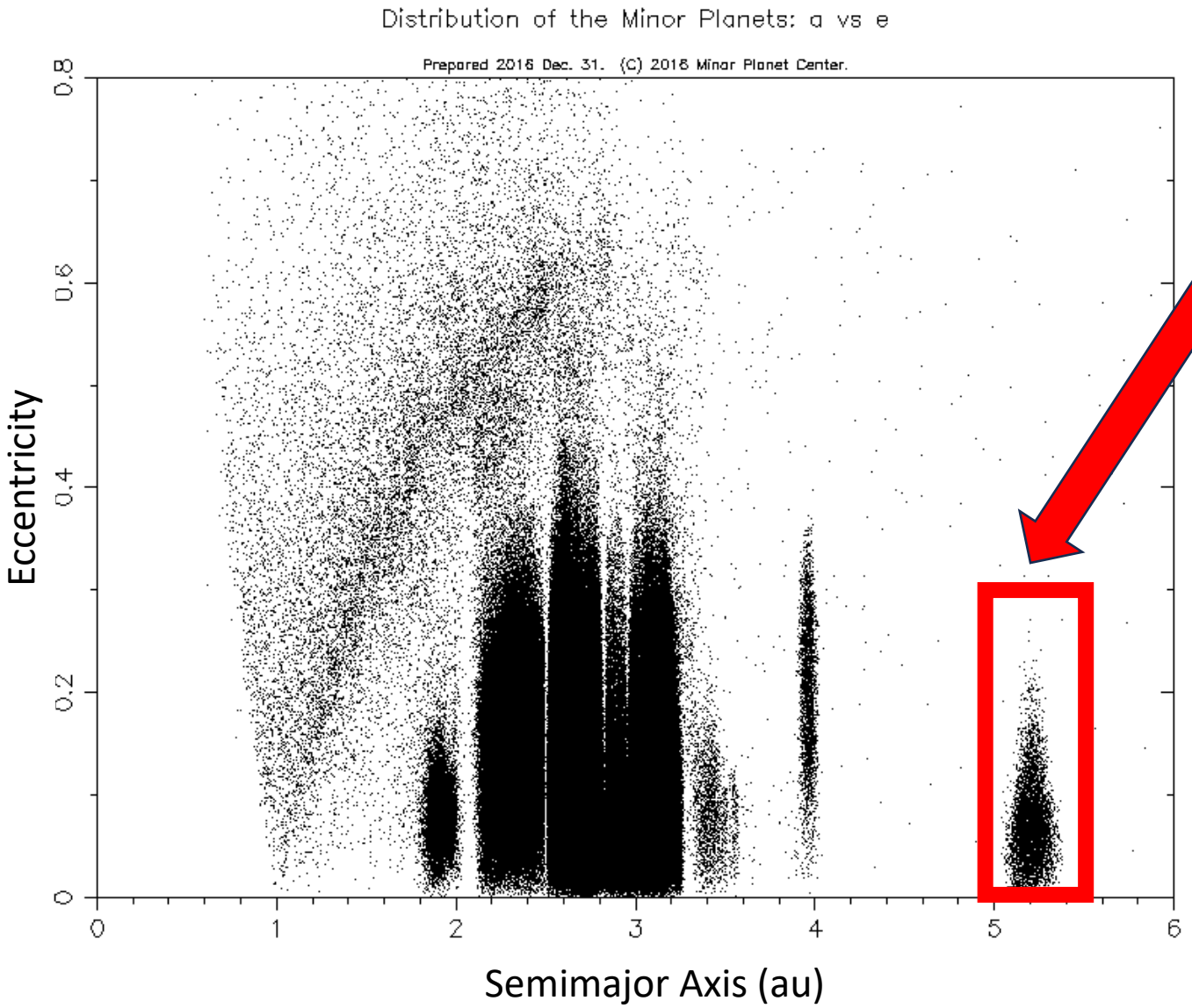


- ~12,000 known Jupiter Trojans
- Stable dating to planet formation
- Constrain early evolution models

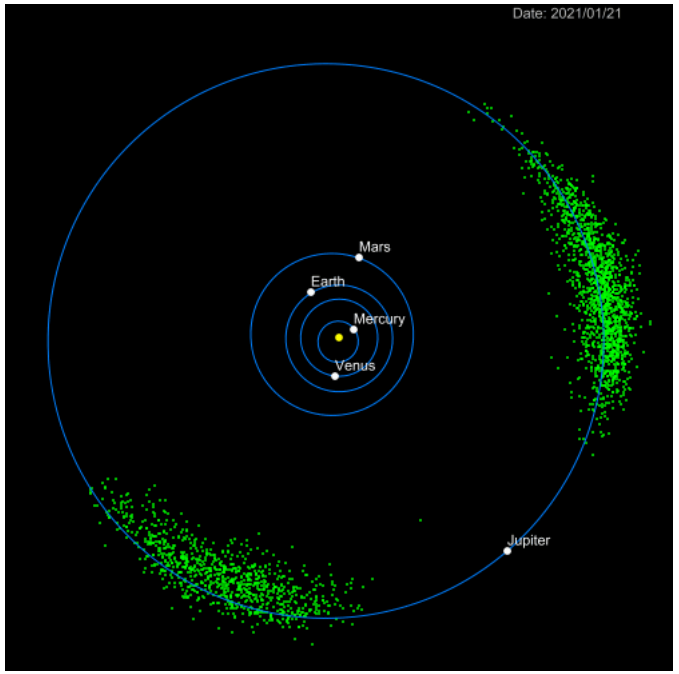


Petr Scheirich (Astronomical Institute of the Czech Academy of Sciences)

Jupiter Trojans



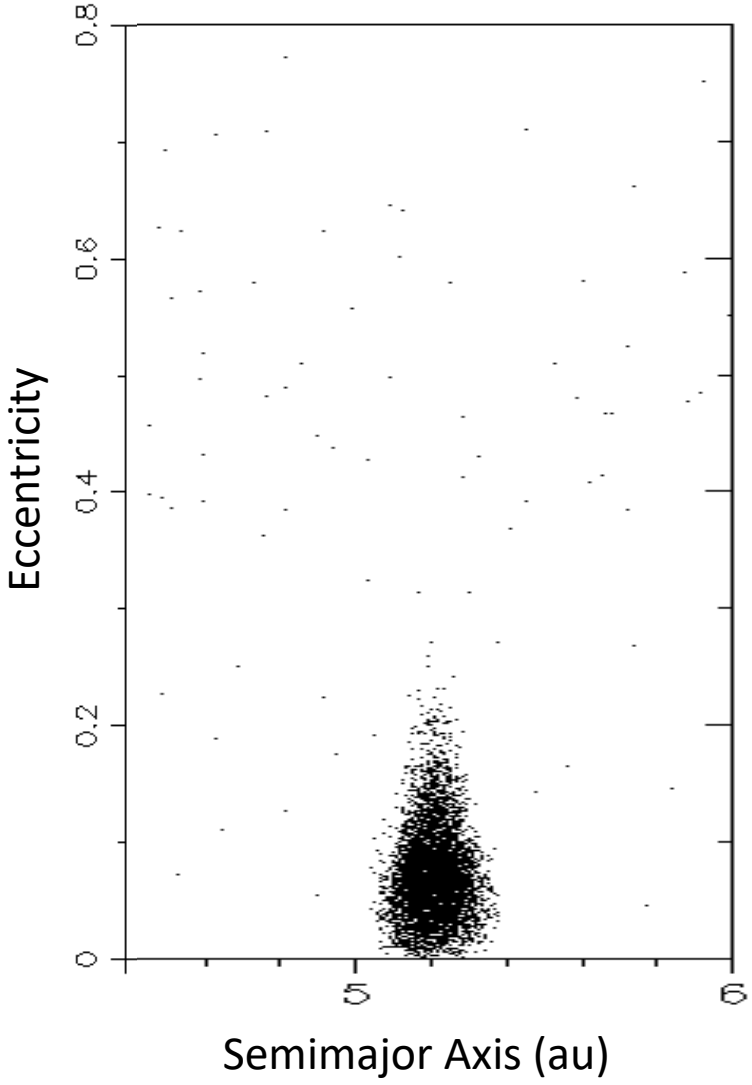
Are all of these objects primordial?



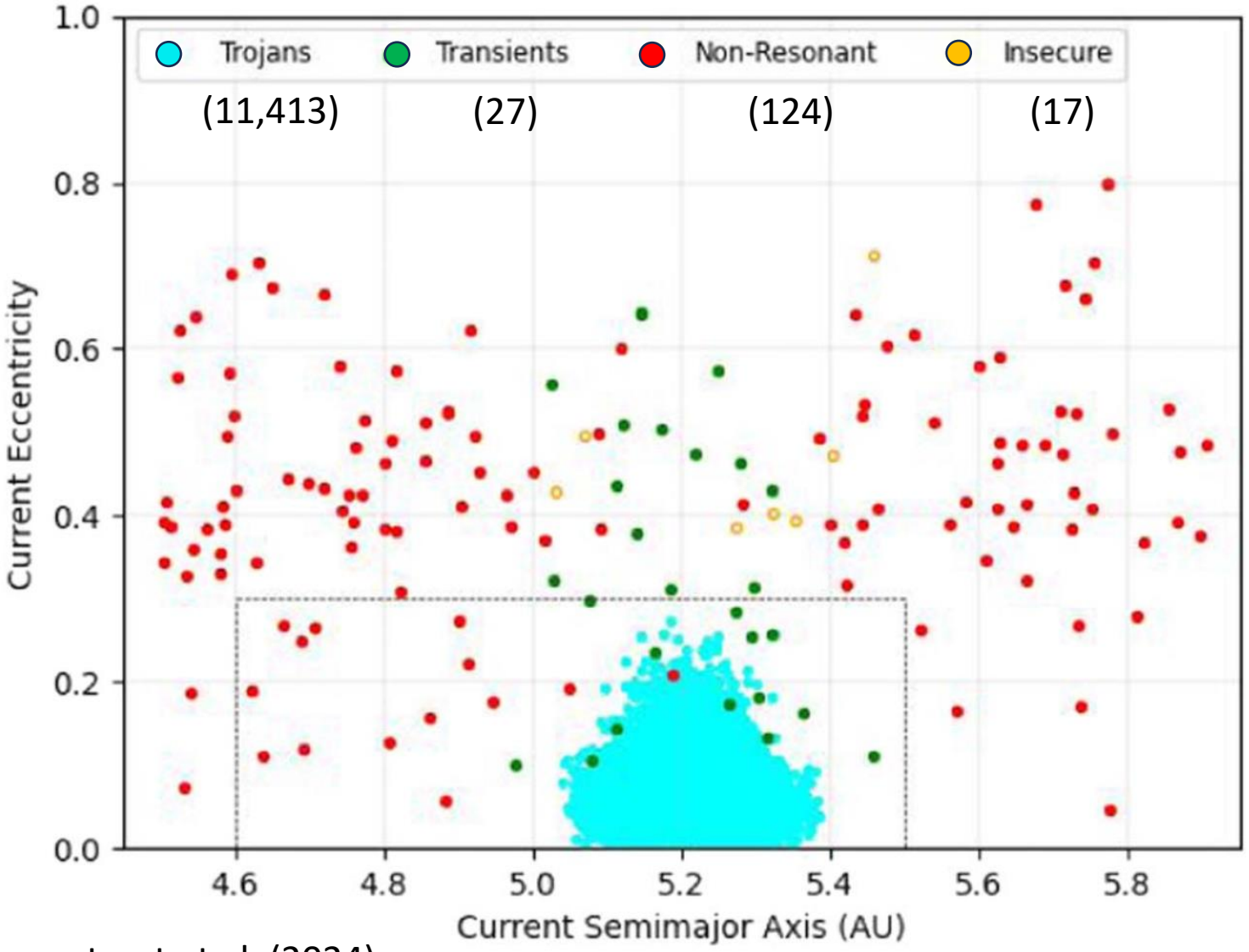
Petr Scheirich (Astronomical Institute of the Czech Academy of Sciences)

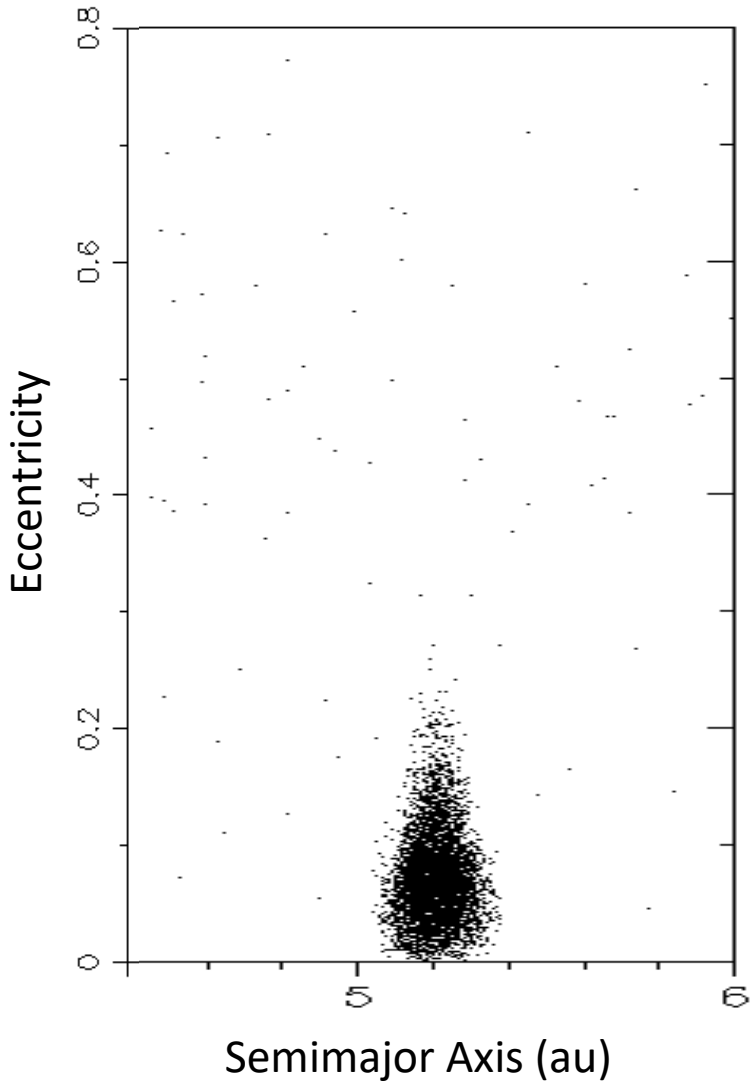
Temporary Jupiter Trojans

- Most planets have temporarily-resonant “Trojans”
- Jupiter expected to have ~1 – 100 temporarily-resonant “Trojans” with $d < 1$ km that remain resonant for ≤10 Myr timescales (Greenstreet et al. 2020)
- Greenstreet et al. 2024 looked for temporarily-resonant “Trojans” among known Jupiter Trojan population
- Ran numerical integrations of orbital evolution of all ~12,000 near-Jupiter objects for 0.5 Myr
- Looked for objects that leave the resonance or that aren’t in resonance



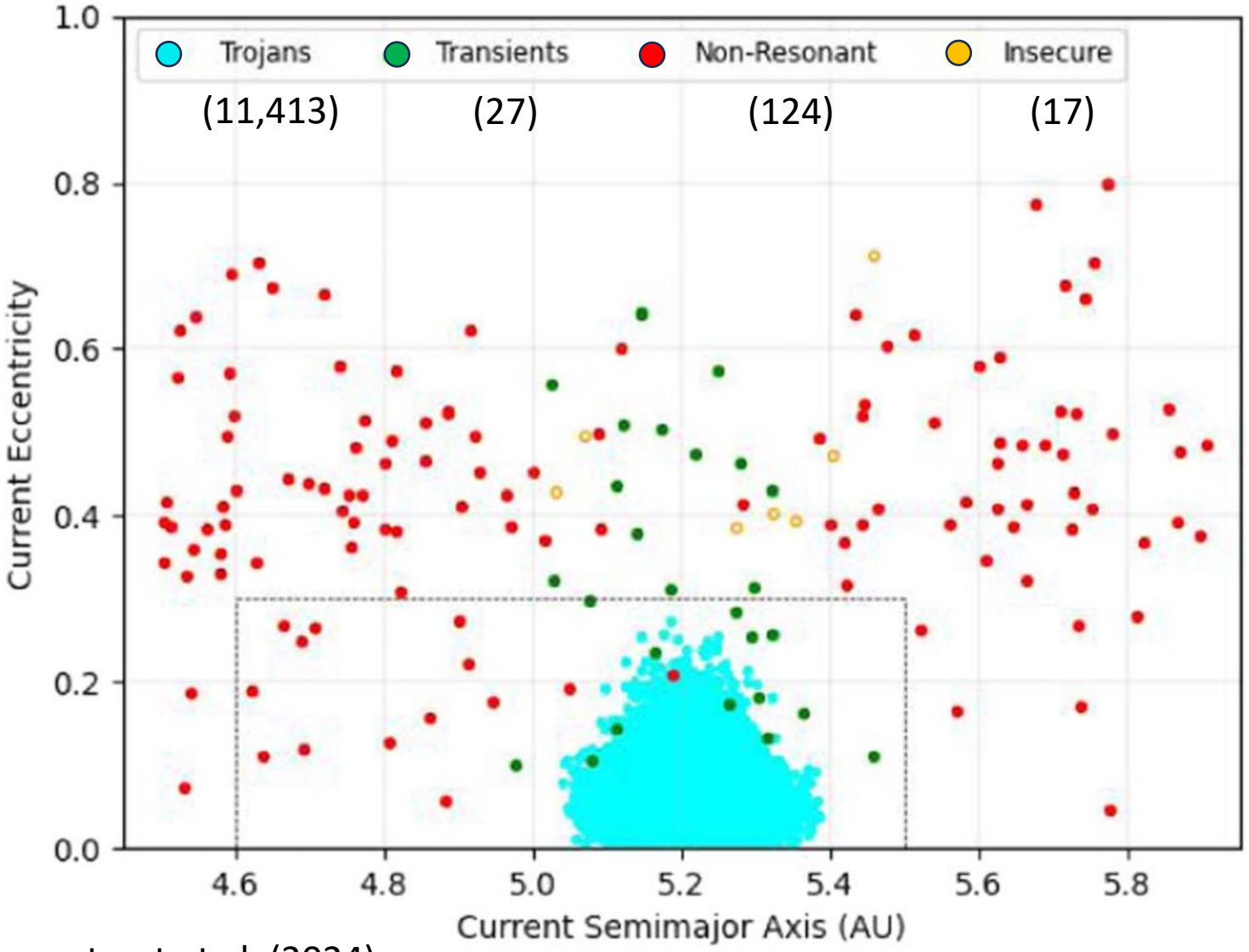
Temporary Jupiter Trojans



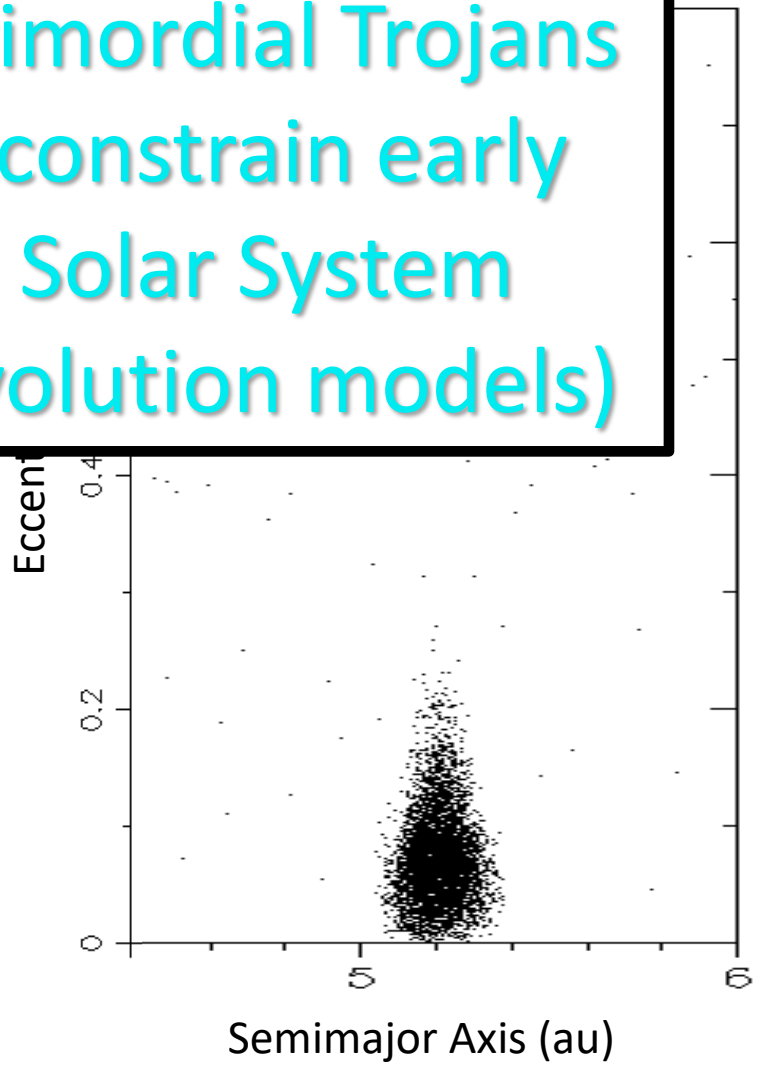


Greenstreet et al. (2024)

Temporary Jupiter Trojans

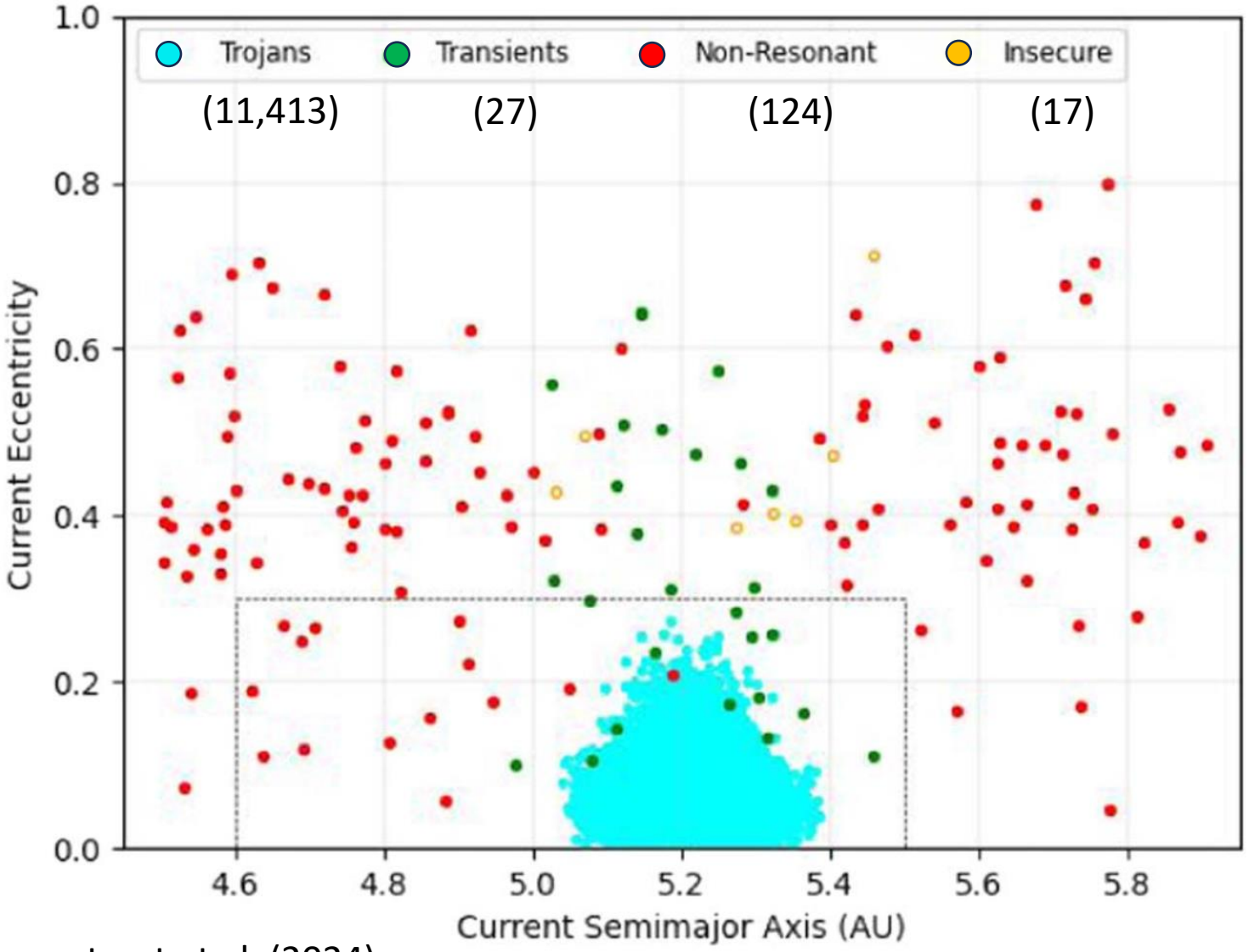


Primordial Trojans (constrain early Solar System evolution models)

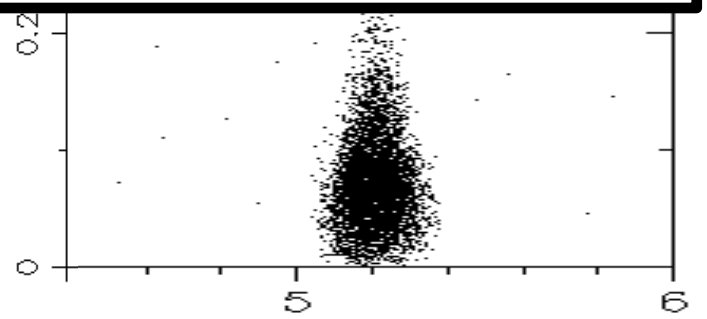


Greenstreet et al. (2024)

Temporary Jupiter Trojans



Temporarily-resonant
and
Non-resonant
(*cannot* constrain early Solar System evolution models)



Greenstreet et al. (2024)

What can temporarily-resonant or non-resonant objects near Jupiter tell us?

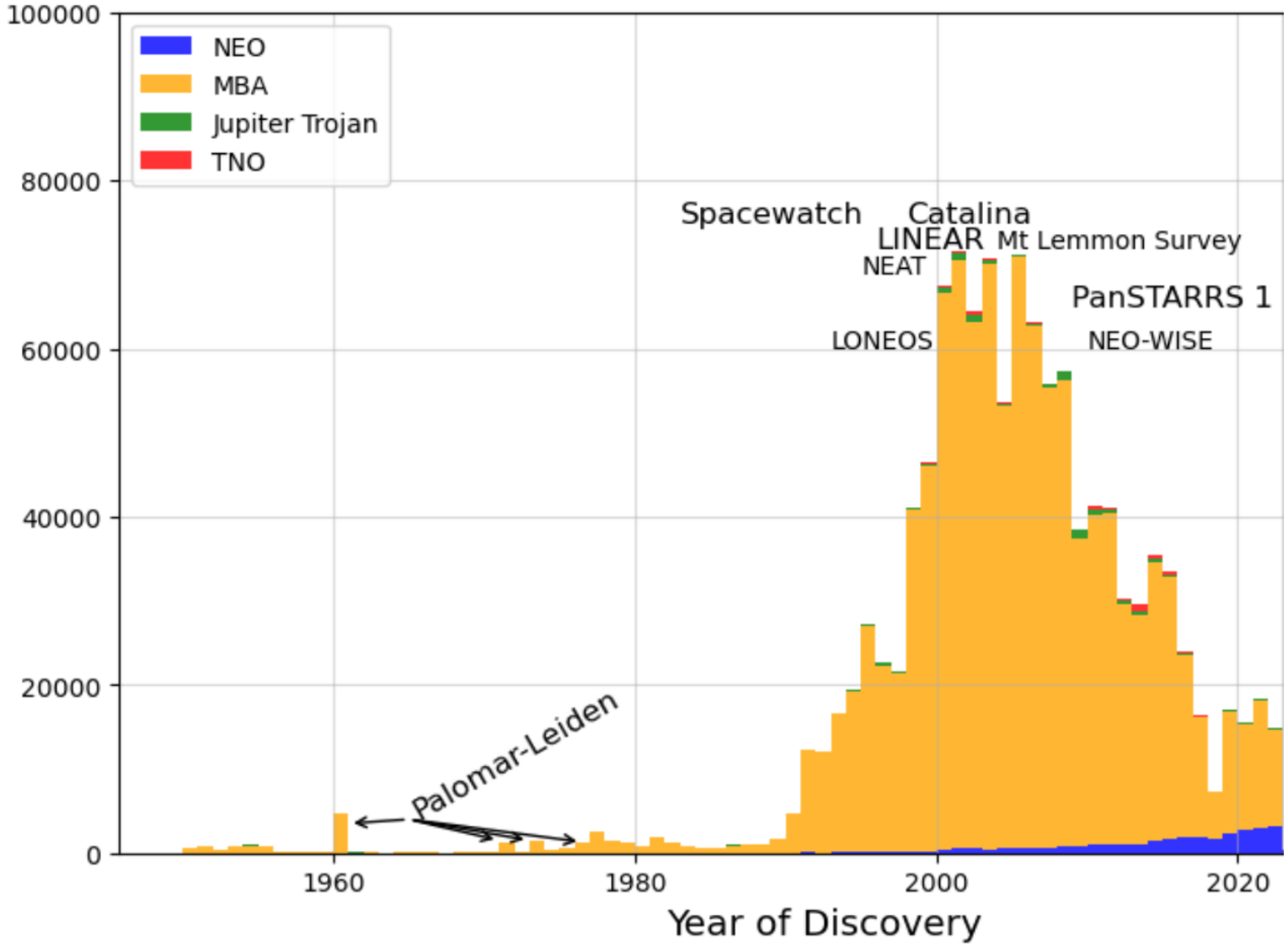
- Very likely formed farther from Sun than Trojans, so should have physical properties more like Centaurs
- Closer proximity to Earth than typical Centaurs could aid spacecraft rendezvous for first time to study object formed in giant planet region
- Could be pristine comets that could become active for the first time
- Example: 2019 LD2 initially thought to be first Jupiter Trojan to have cometary activity, but numerical studies of orbital evolution determined Jupiter Family Comet fortuitously near Jupiter (Kareta et al. 2020; Steckloff et al. 2020)
- Better understand nature & frequency of outburst process & activity evolution
- Determine distribution of volatiles across Solar System

Challenge: Finding These Rare Gems

- Dynamically new comets near Jupiter (volatiles across Solar System)
  - Inform planet formation
- Centaurs temporarily-trapped into “Jupiter Trojan” resonance (outer Solar System objects brought closer to Earth)
  - Inform planet formation
- Objects in transneptunian resonances (captured with giant planet migration)
  - Inform early Solar System evolution
- And others…

Need time evolution of orbits to determine their rare gem nature, and in era of large surveys, requires new tools to extract them!

LSST Will Discover ~6 million Solar System Objects



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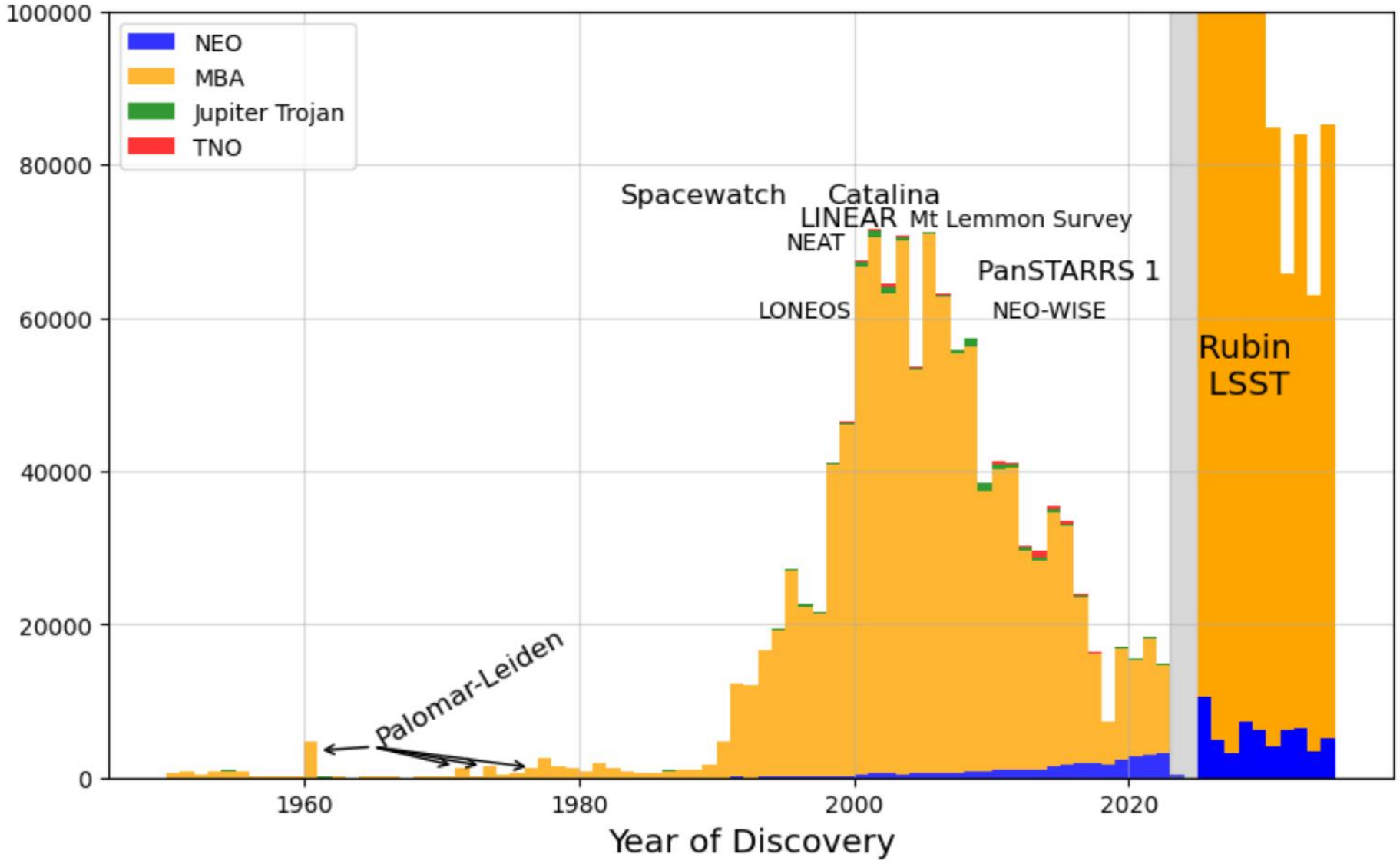

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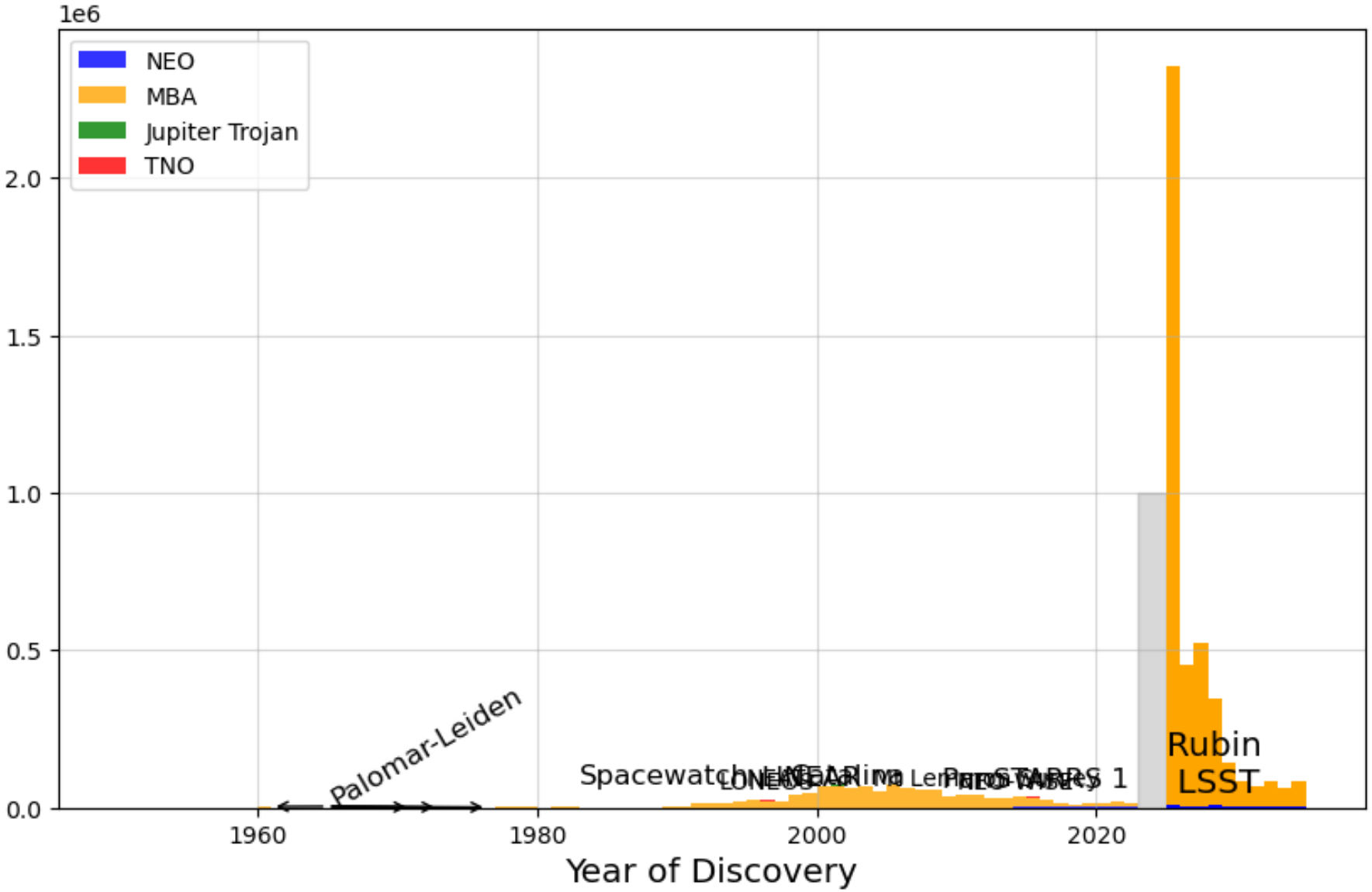


Small Body Dynamics Tool

SBDynT

A user-friendly python tool to characterize solar system small bodies

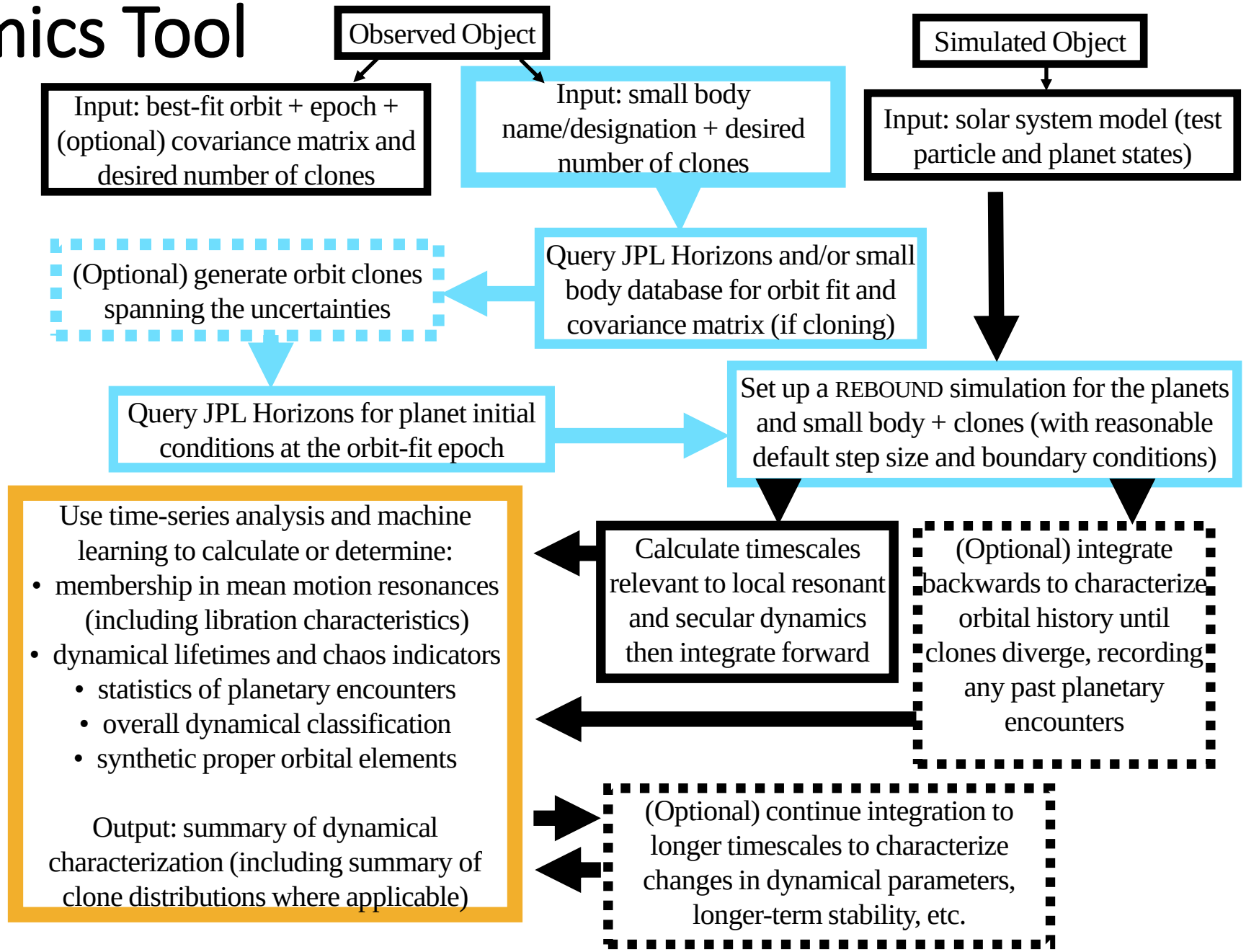
Our goal: make integrating and analyzing an object's basic orbital evolution easy, with just a few lines of python code!

We are on GitHub: https://github.com/small-body-dynamics/SBDynT

Tool coming to the main repository:

- A machine learning classifier for outer solar system objects (TNOs)

Developed by Kat Volk (PSI) & Dalin Spencer (BYU).



Every object in the Solar System has the details of planet formation and early Solar System evolution imprinted on it.

However, some objects, due to their current locations and dynamical nature within the Solar System, are likely to have higher scientific value for unlocking the answers to the open questions about how planets and small bodies were formed and how the Solar System has evolved over the past 4.6 billion years, which can help to place our Solar System within the context of the vast number of exoplanetary systems across the Milky Way and beyond.

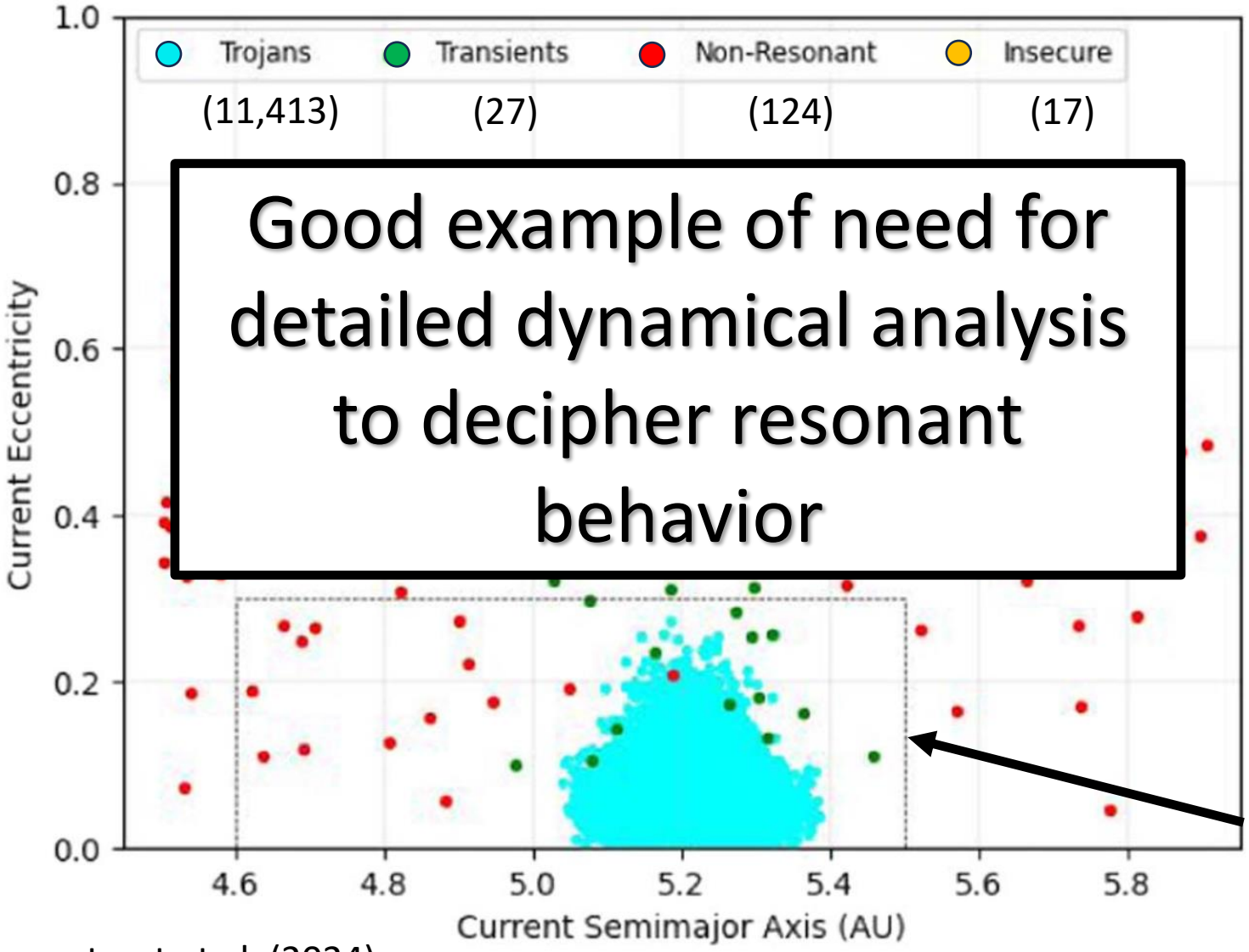
In order to find the most valuable rare gems in the Solar System, we need tools that can be used to identify the dynamical nature of the objects in the vast data sets the era of large surveys will provide.

Colors More Like Centaurs than Trojans & Lucy Targets

- Preliminary look at (sparse) SDSS color data (Sergeyev & Carry 2021)
- 2016 TE71, (288282) 2004 AH4, and (163240) 2002 EM157
- All have evidence for redder photometric ($g - r$) and/or ($g - i$) colors relative to most known Trojans (Szabo et al. 2007) and Lucy Targets
  - Expected if recently-trapped Centaurs

Greenstreet et al. (2024)

Temporary Jupiter Trojans



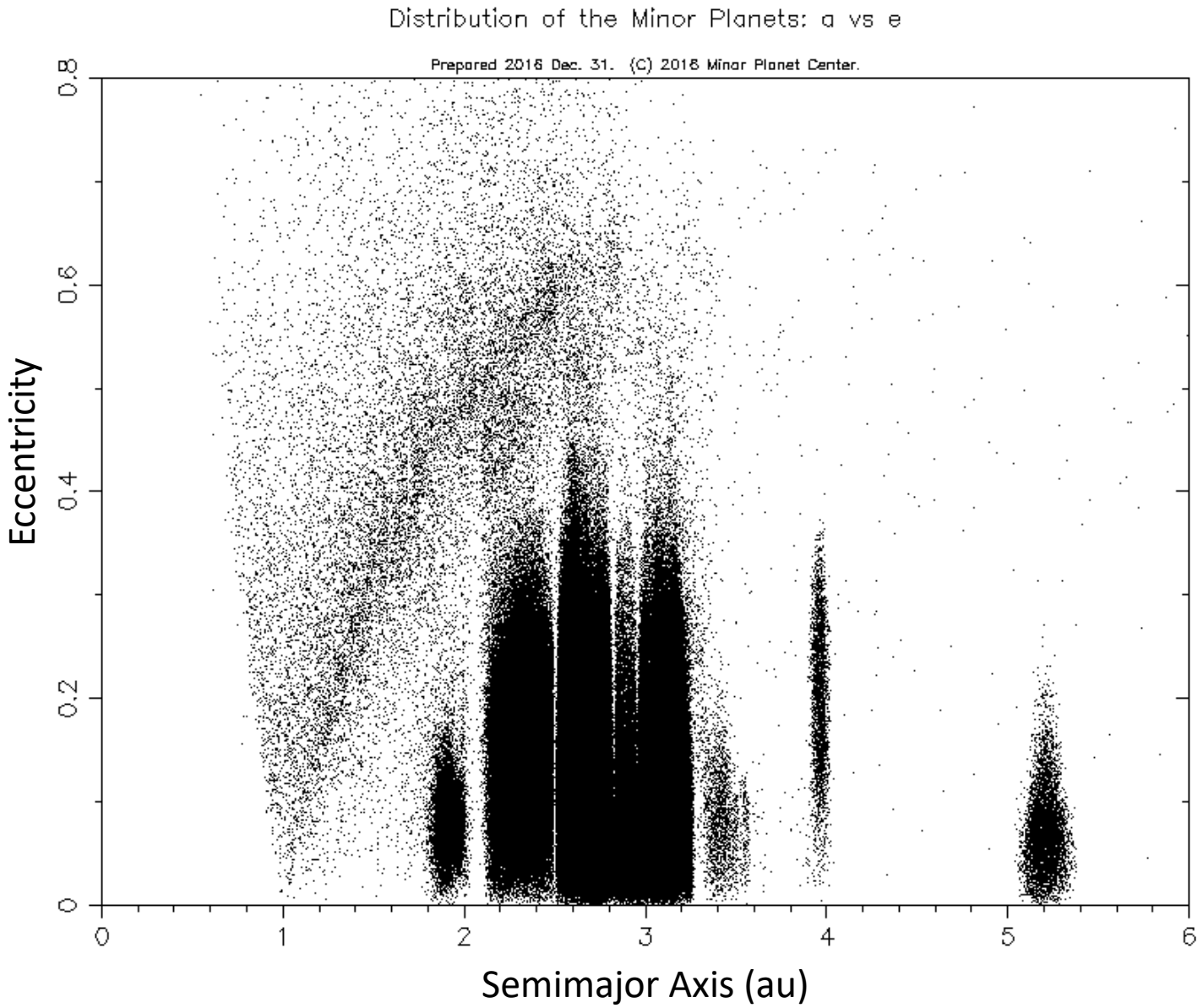
Good example of need for detailed dynamical analysis to decipher resonant behavior

Temporarily-resonant
and
Non-resonant
(*cannot* constrain early Solar System evolution models)

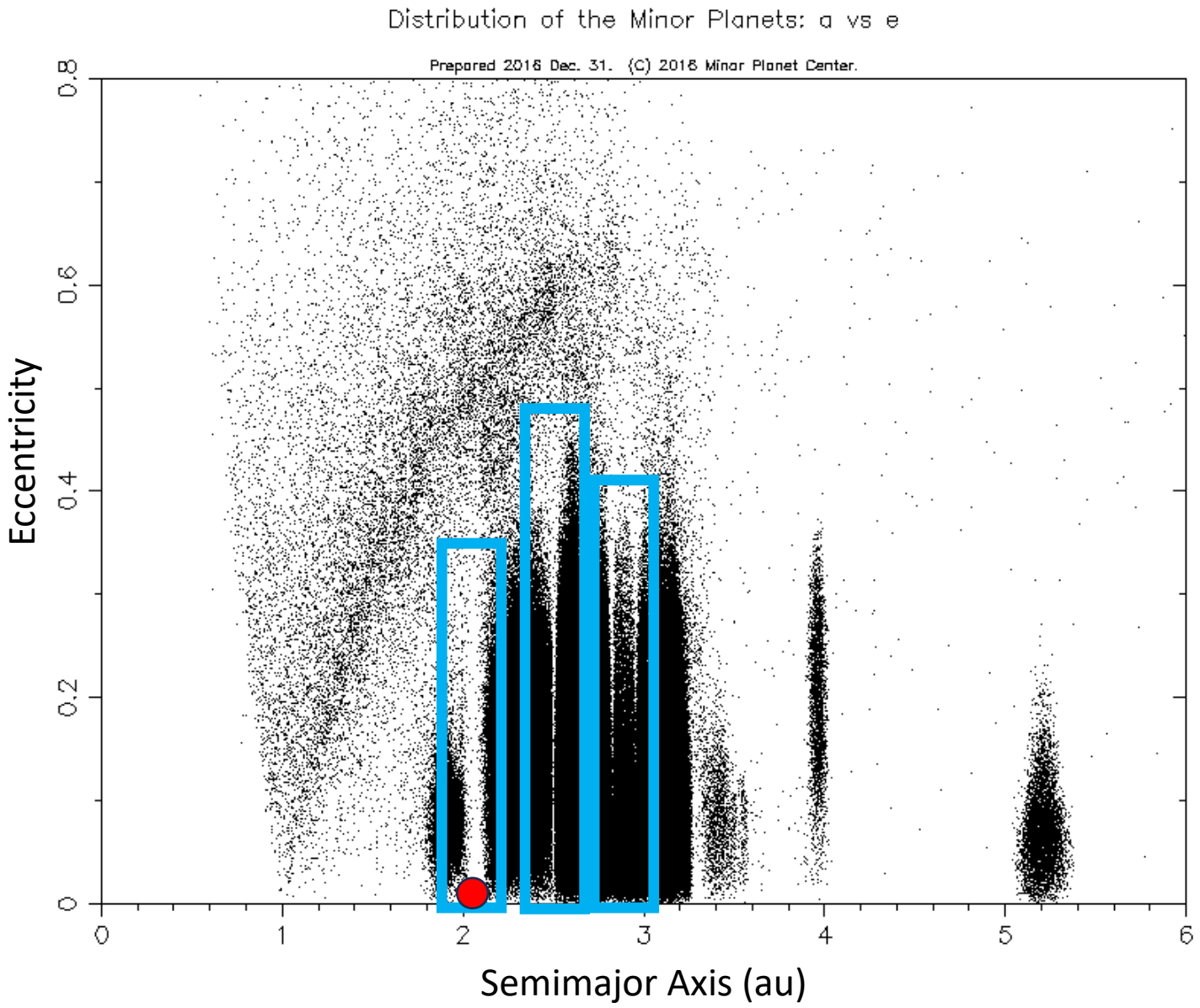
Region defined by JPL Horizons & Minor Planet Center as "Jupiter Trojan" space

Greenstreet et al. (2024)

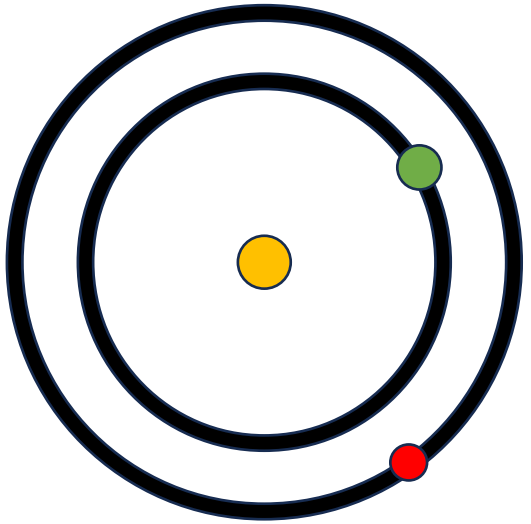
Inner Solar System



Main-Belt Resonances Feed Near-Earth Objects



Gaps in main-belt contain resonances



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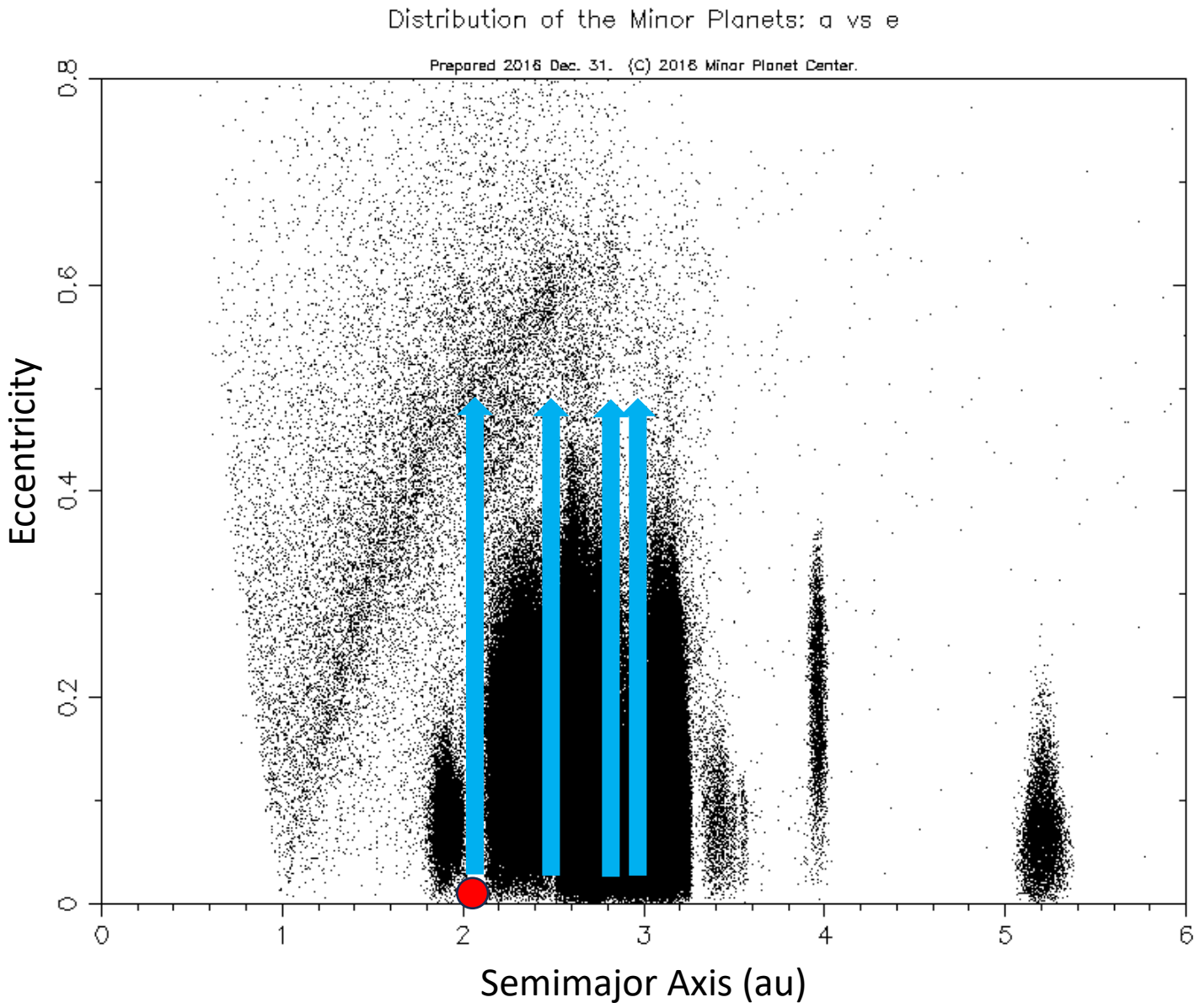
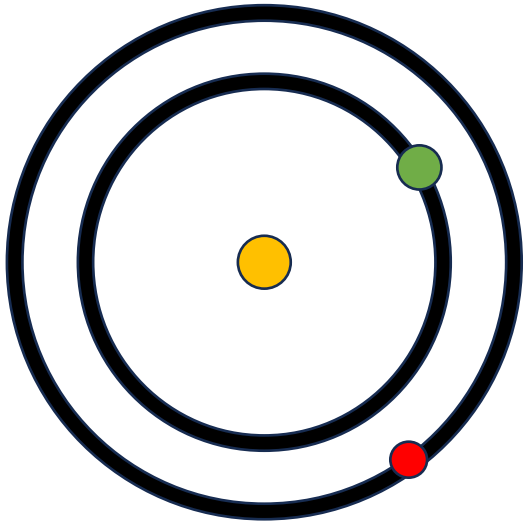
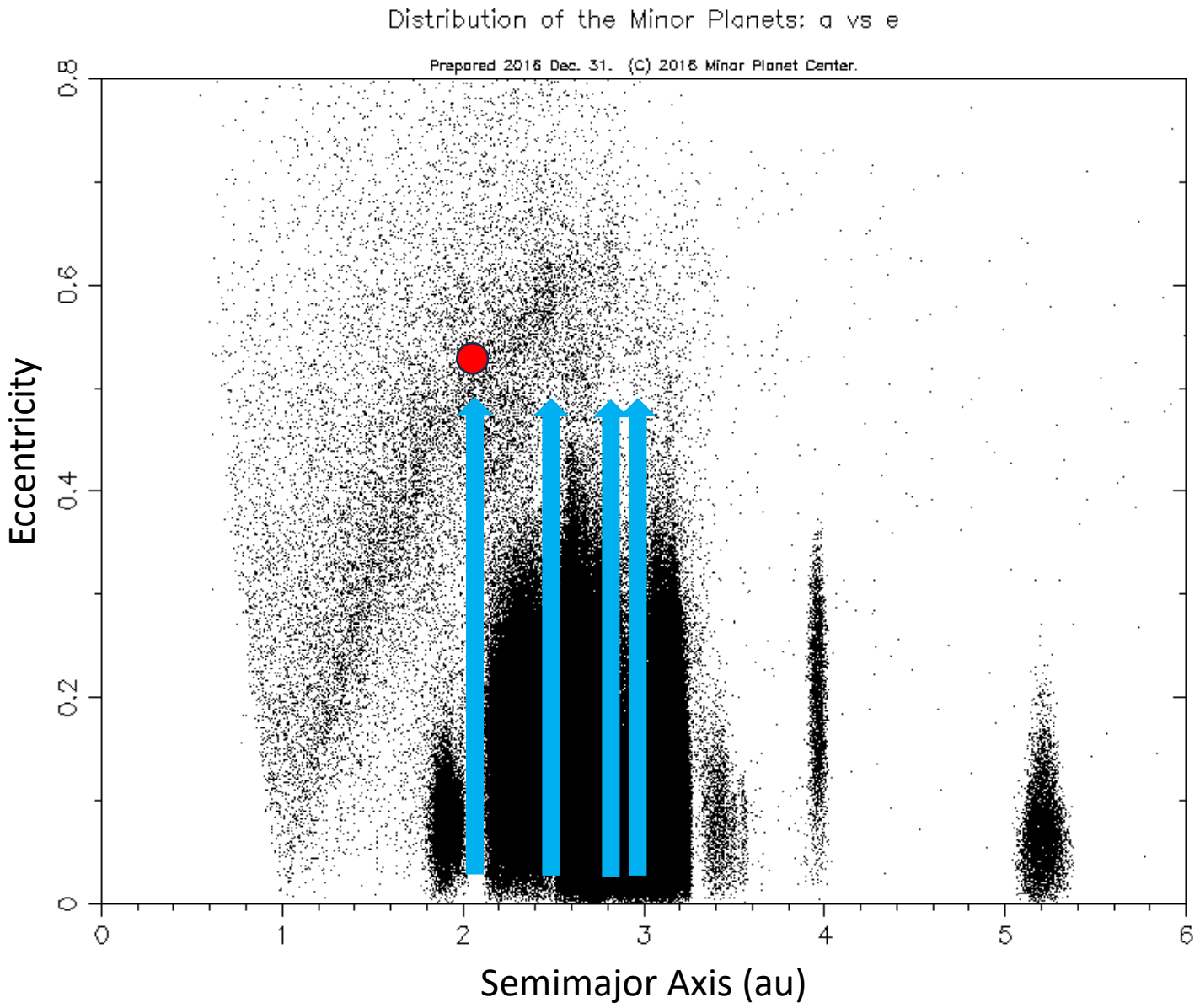


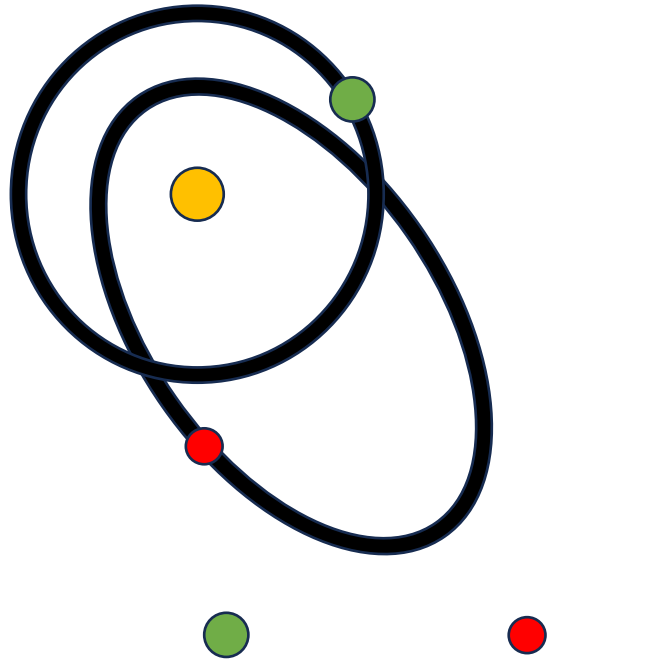
Resonances raise eccentricities



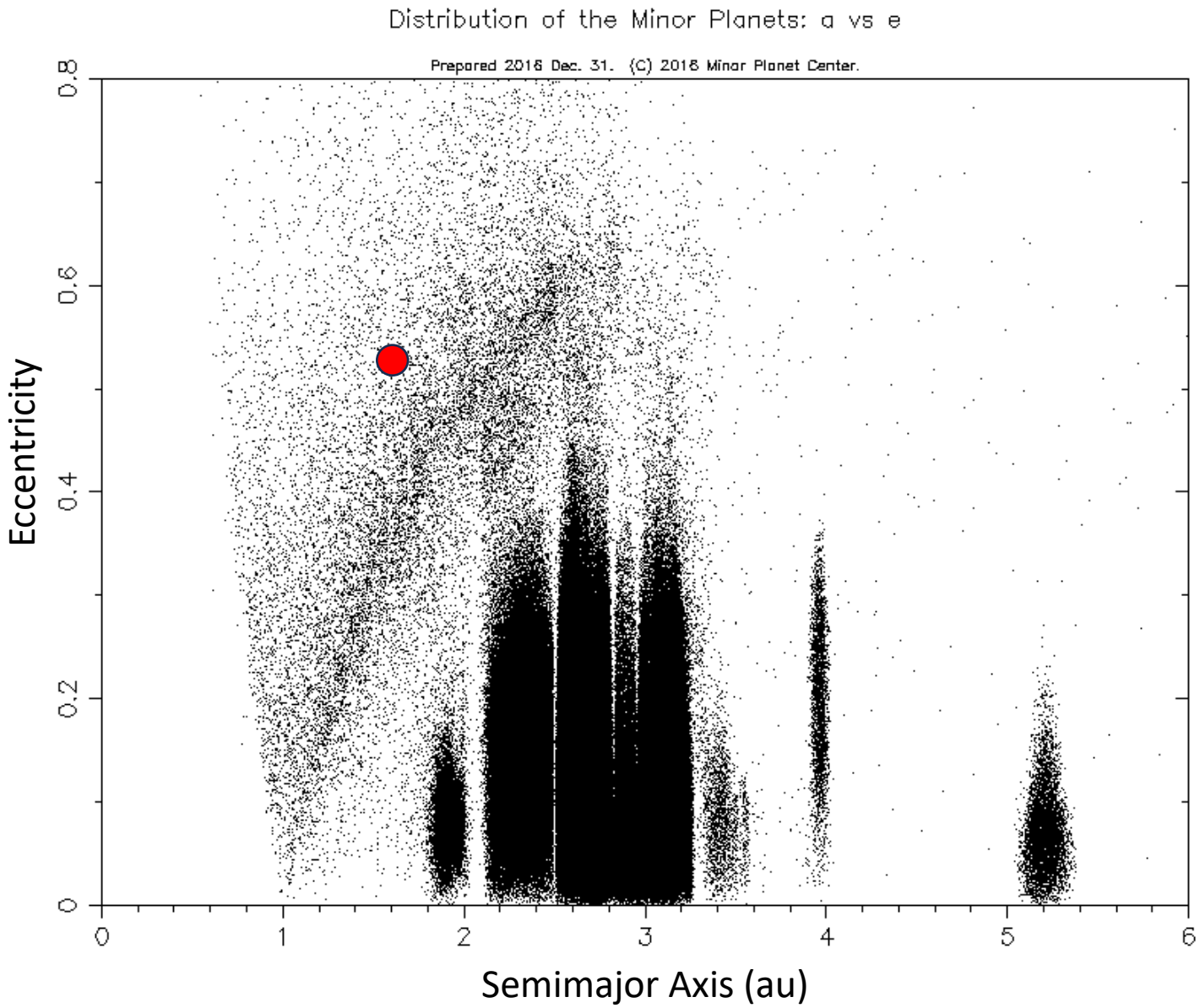
Main-Belt Resonances Feed Near-Earth Objects



Asteroids move from main-belt to near-Earth space

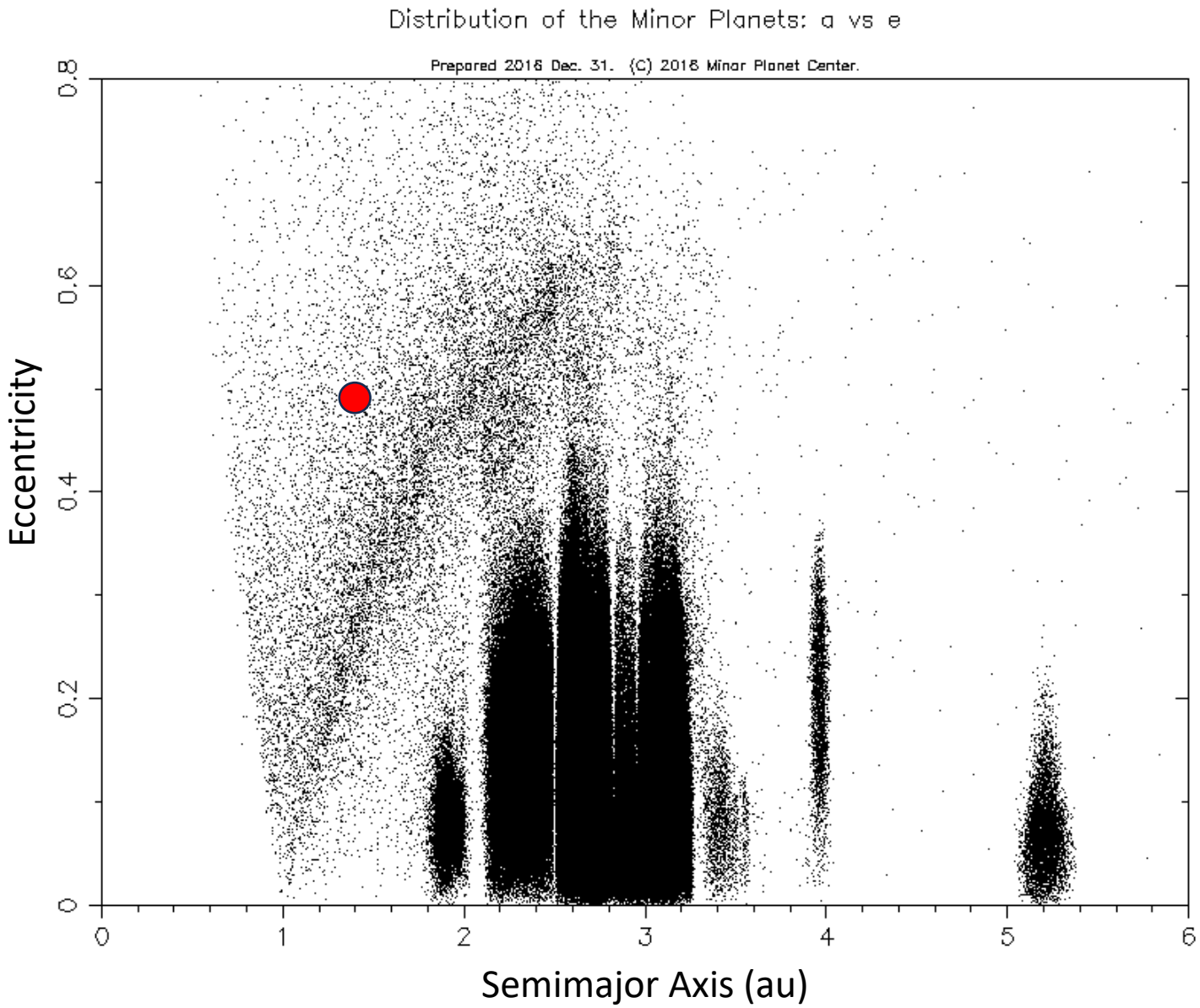


Main-Belt Resonances Feed Near-Earth Objects



Gravitational close encounters with the planets then scatter the asteroid around near-Earth space

Main-Belt Resonances Feed Near-Earth Objects



Gravitational close encounters with the planets then scatter the asteroid around near-Earth space

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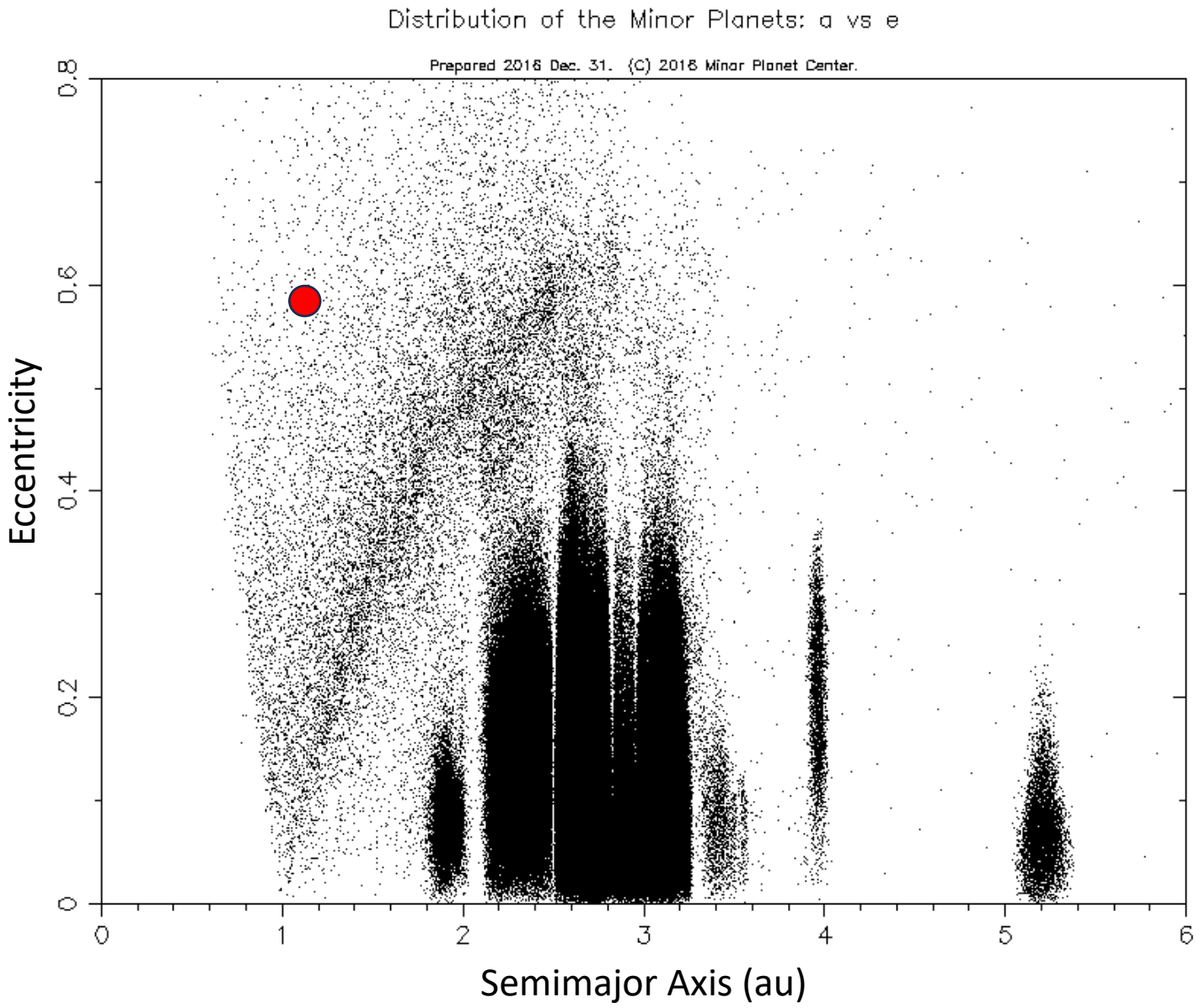

Gravitational close encounters with the planets then scatter the asteroid around near-Earth space

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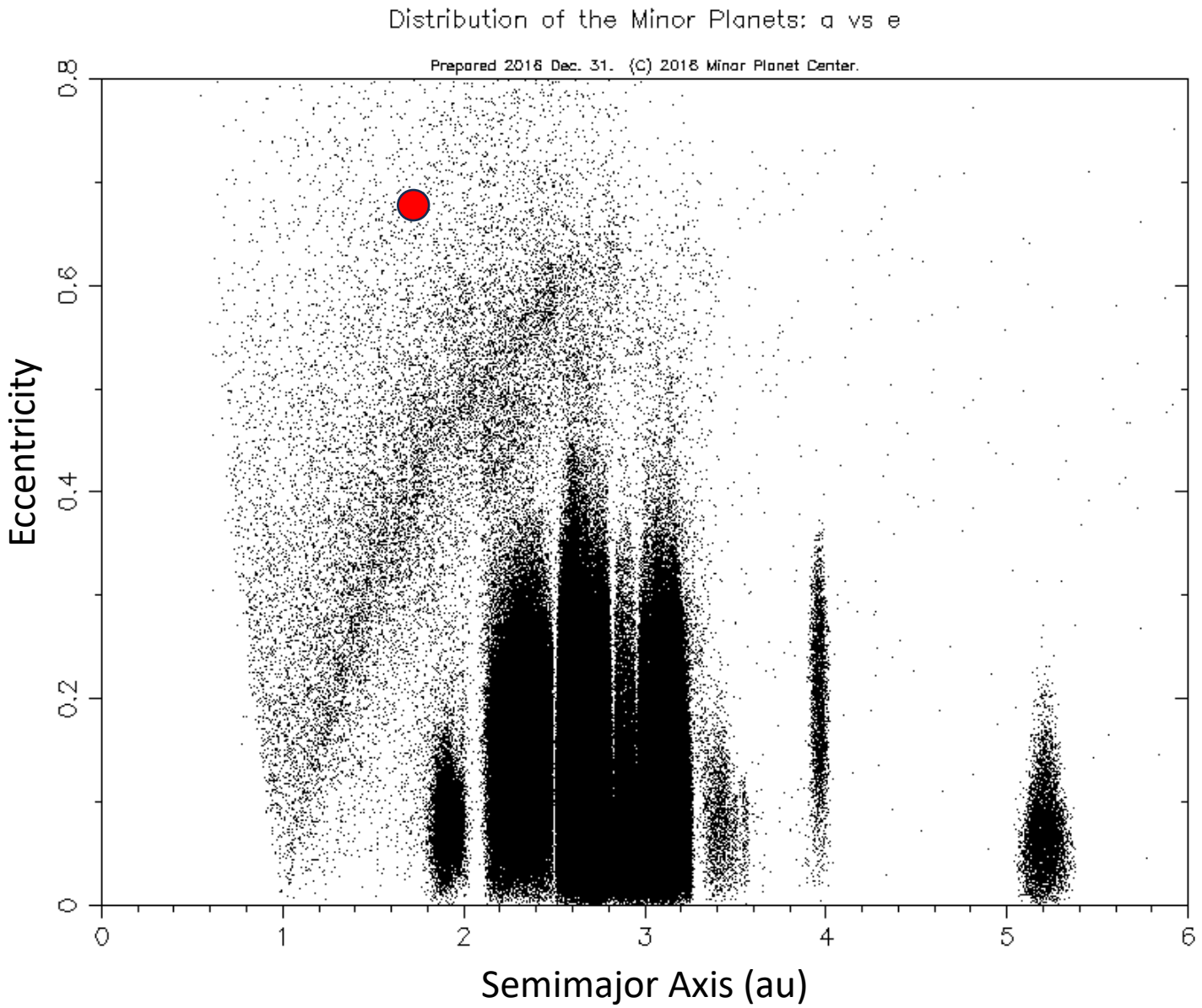
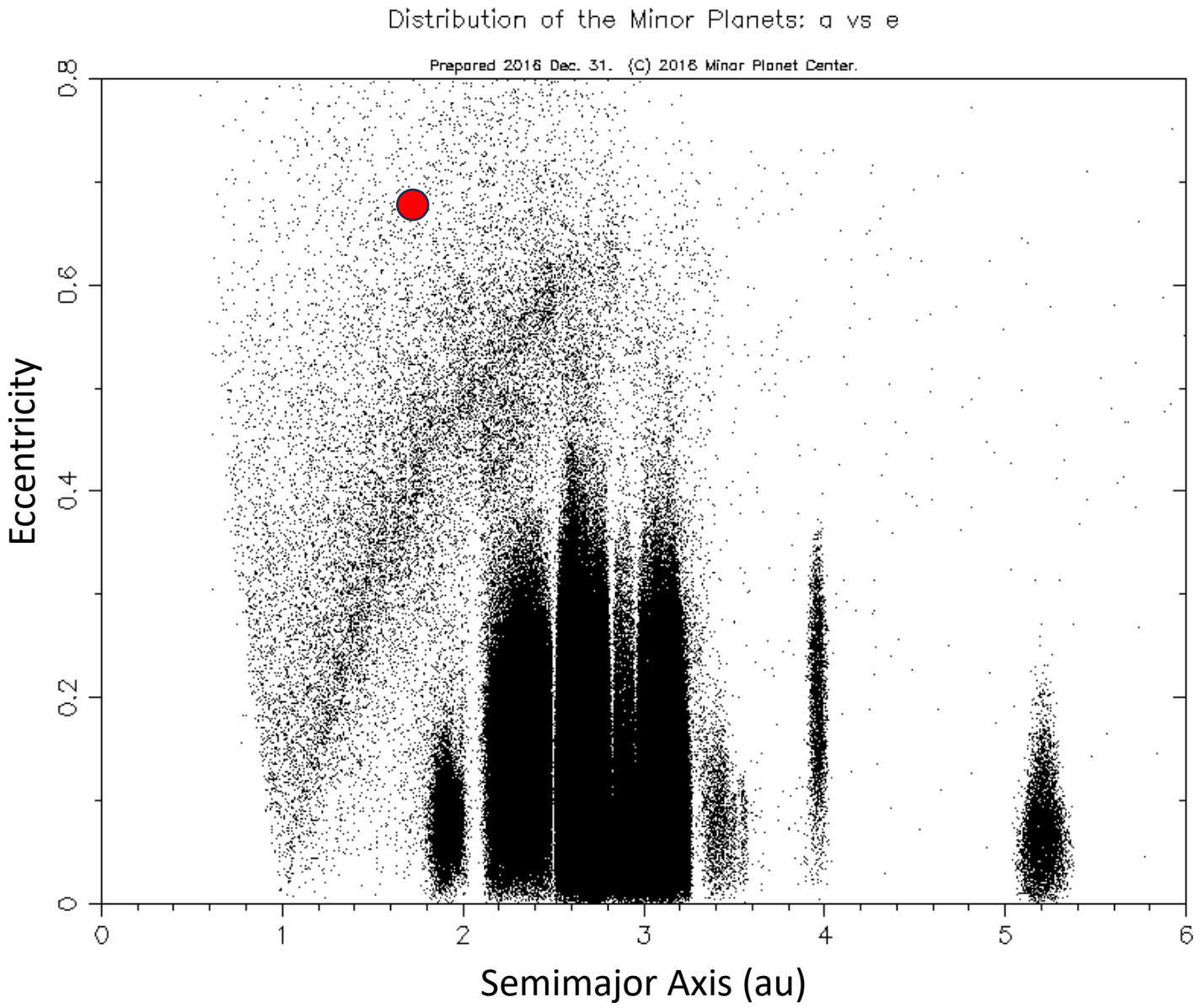


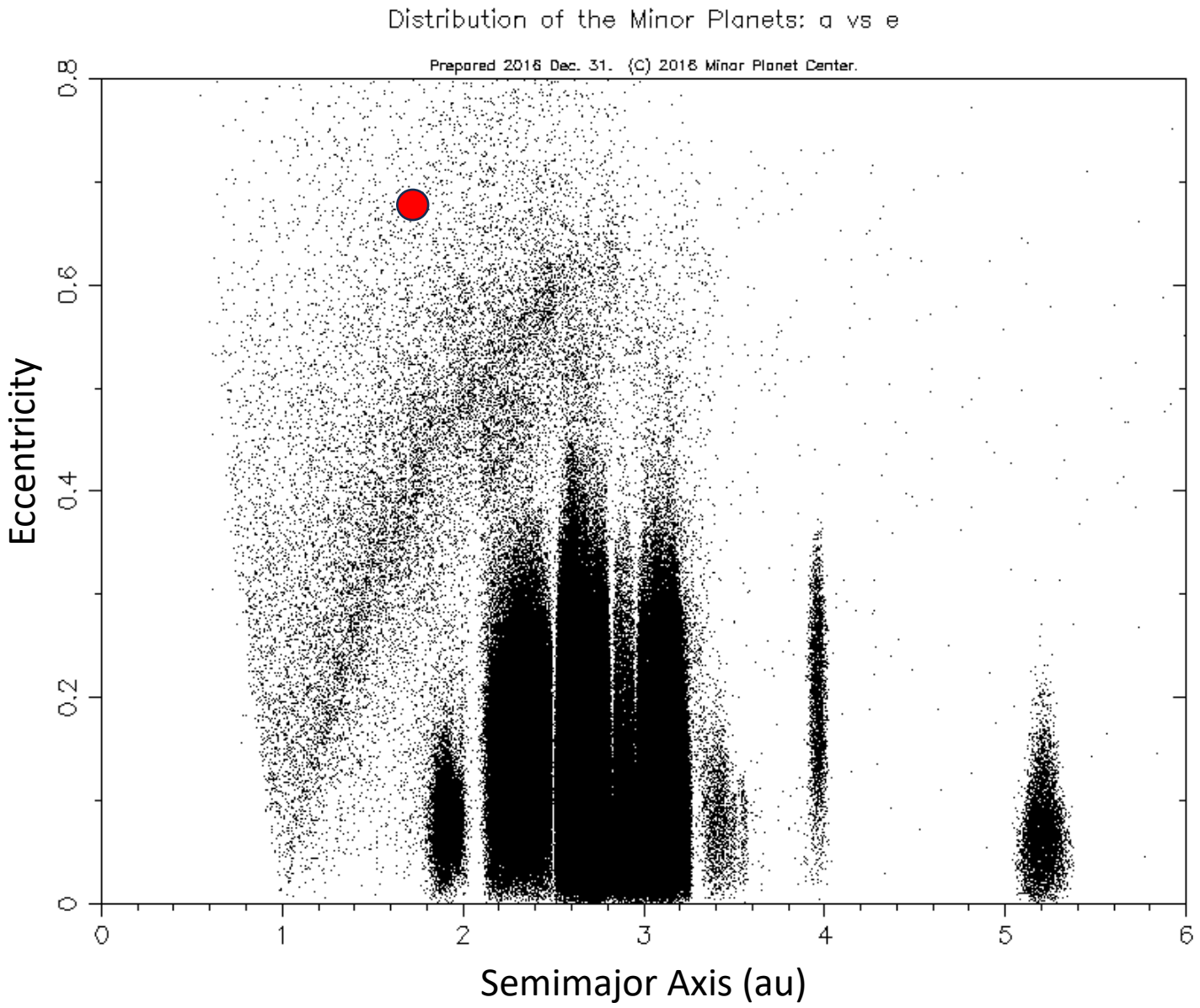
Gravitational close encounters with the planets then scatter the asteroid around near-Earth space

Main-Belt Resonances Feed Near-Earth Objects



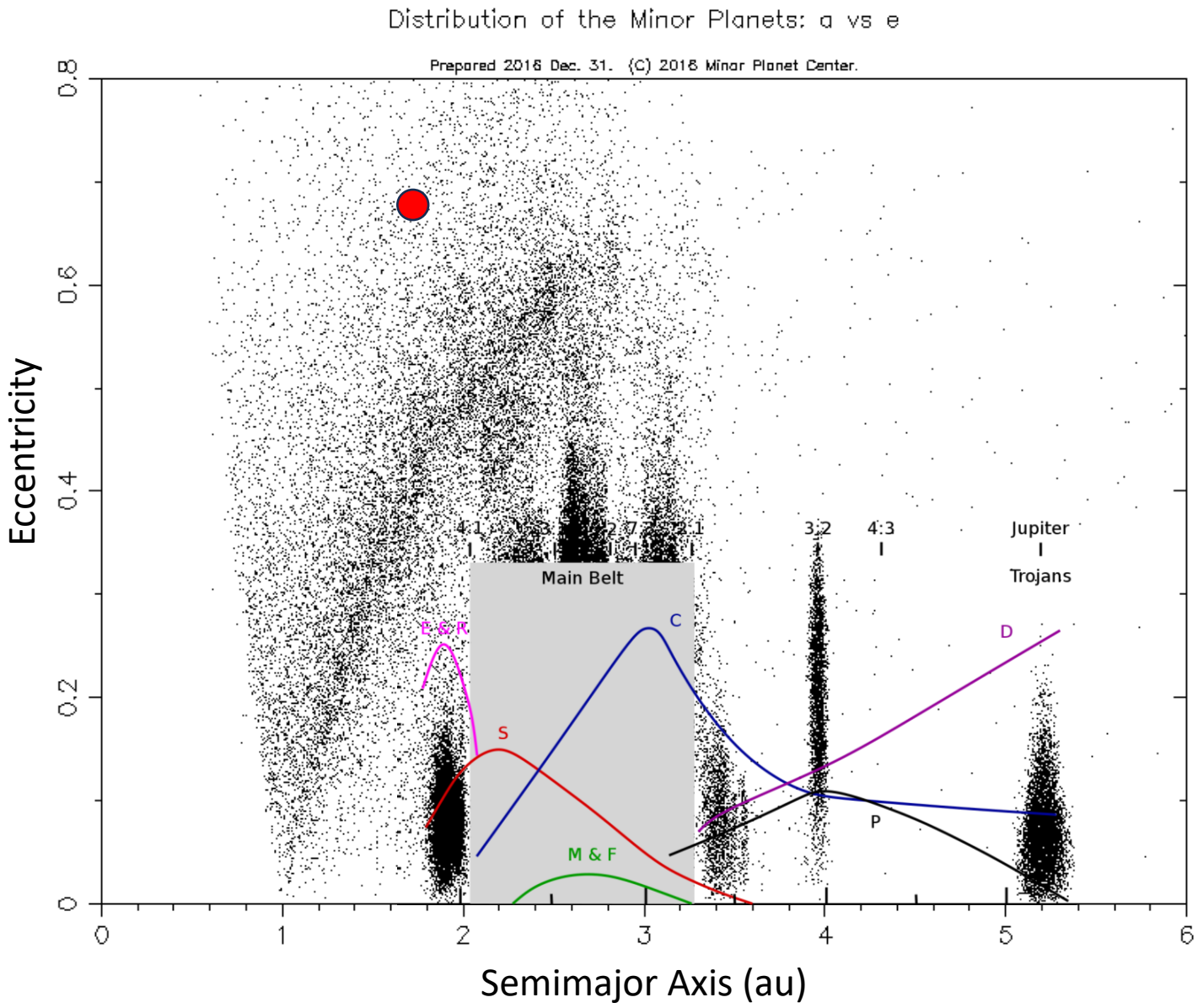
Near-Earth asteroids then typically live for ~10 Myr before being pushed into the Sun or hitting a planet

Main-Belt Resonances Feed Near-Earth Objects



This dynamical process has been ongoing for the age of the Solar System

Near-Earth Objects Inform Planet Formation



This dynamical process can help us to map near-Earth asteroids back to their birthplace in main belt through their compositions

Small Body Dynamics Tool

SBDynT

A user-friendly python tool to characterize solar system small bodies

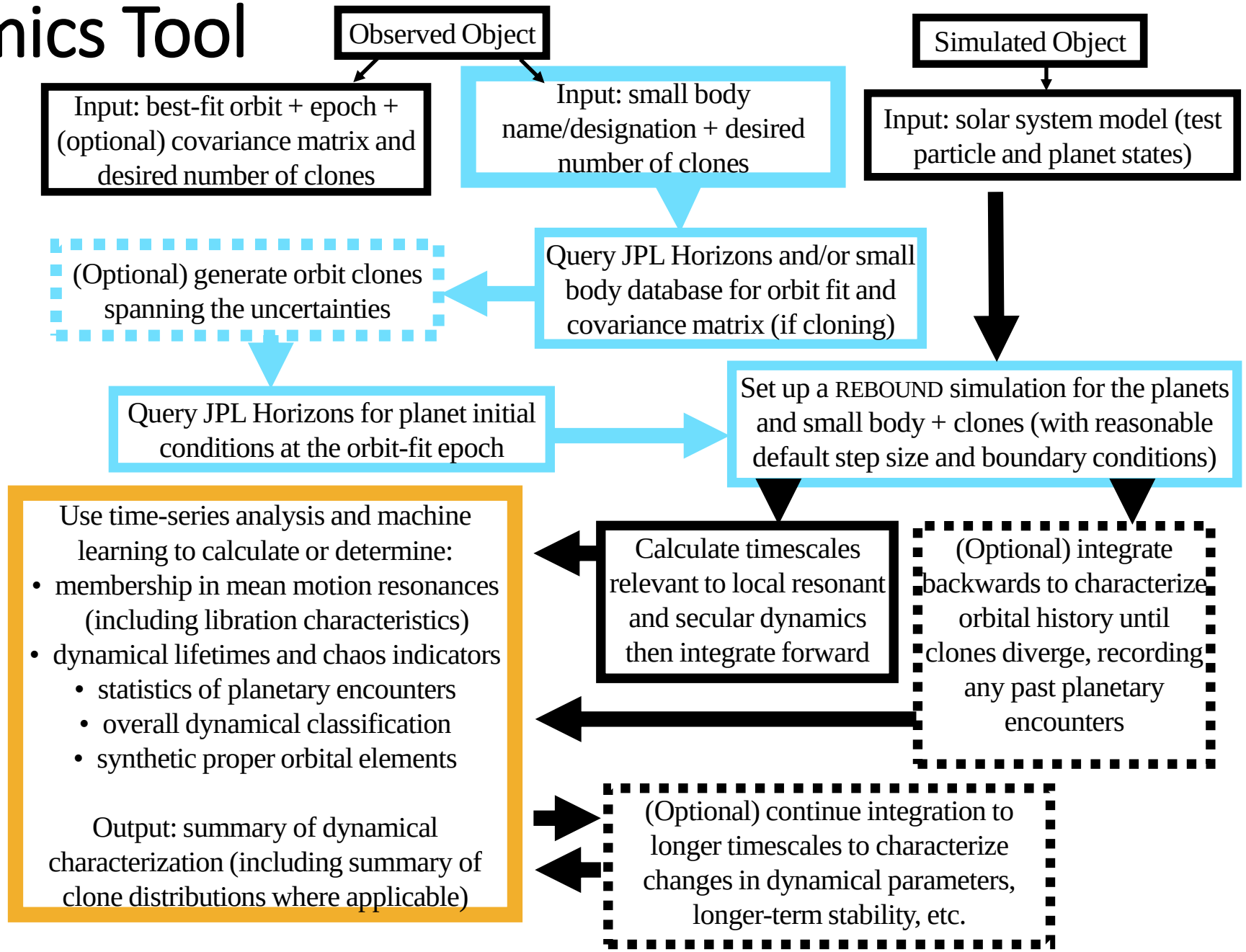
Our goal: make integrating and analyzing an object's basic orbital evolution easy, with just a few lines of python code!

We are on GitHub: https://github.com/small-body-dynamics/SBDynT

Tool coming to the main repository:

- A machine learning classifier for outer solar system objects (TNOs)

Developed by Kat Volk (PSI) & Dalin Spencer (BYU).



Lucy Mission Targets

- Carefully integrated five Jupiter Trojan Lucy targets for 50 Myr to study stability in jovian 1:1 resonance
- Find all 1000 clones for each of five mission targets remain stable in resonance over this timescale
- Thus all almost certainly primordial objects

More Metastable Jupiter Companions Will Be Found

- More metastable jovian co-orbitals will certainly be detected
  - Capture is rare, so discoveries will likely be small, reason not found to date
- Upcoming (2025) Rubin Observatory's Legacy Survey of Space & Time (LSST) expected to increase Jupiter Trojan population by ~15x
  - Fainter detections will provide more objects in current metastable traps with Jupiter
  - Identification as metastable will require more than simple osculating element cuts in a and e near Jupiter's values, as we've demonstrated
- Building pipeline to automatically classify resonant nature of detections from current & upcoming surveys, such as Rubin
  - Construct public database of resonant classifications for all objects with $a \approx a_J$

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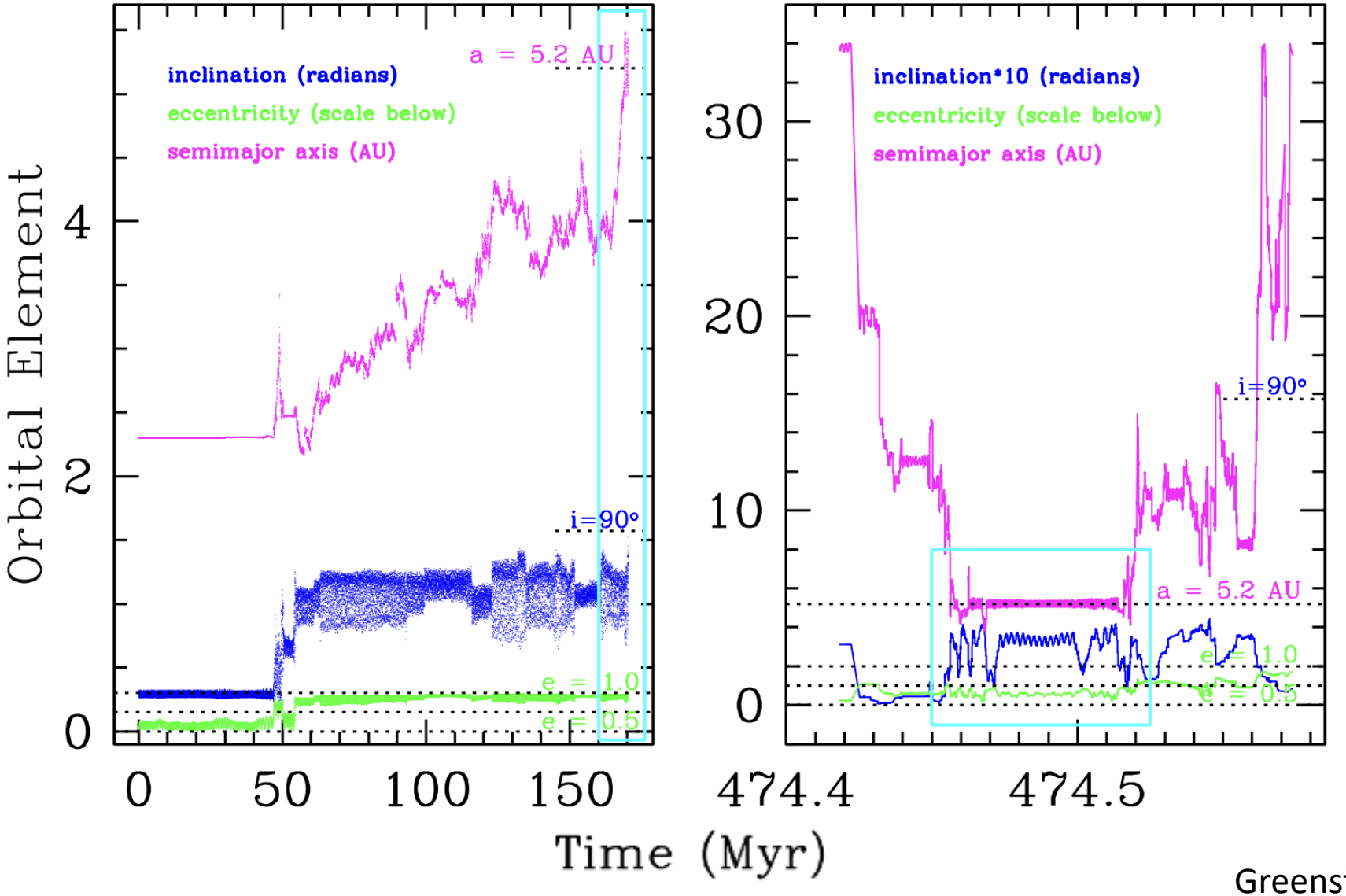
Jovian Co-orbitals From NEA & Centaur Sources (Greenstreet et al. 2020)

NEA source (3 Myr trap)

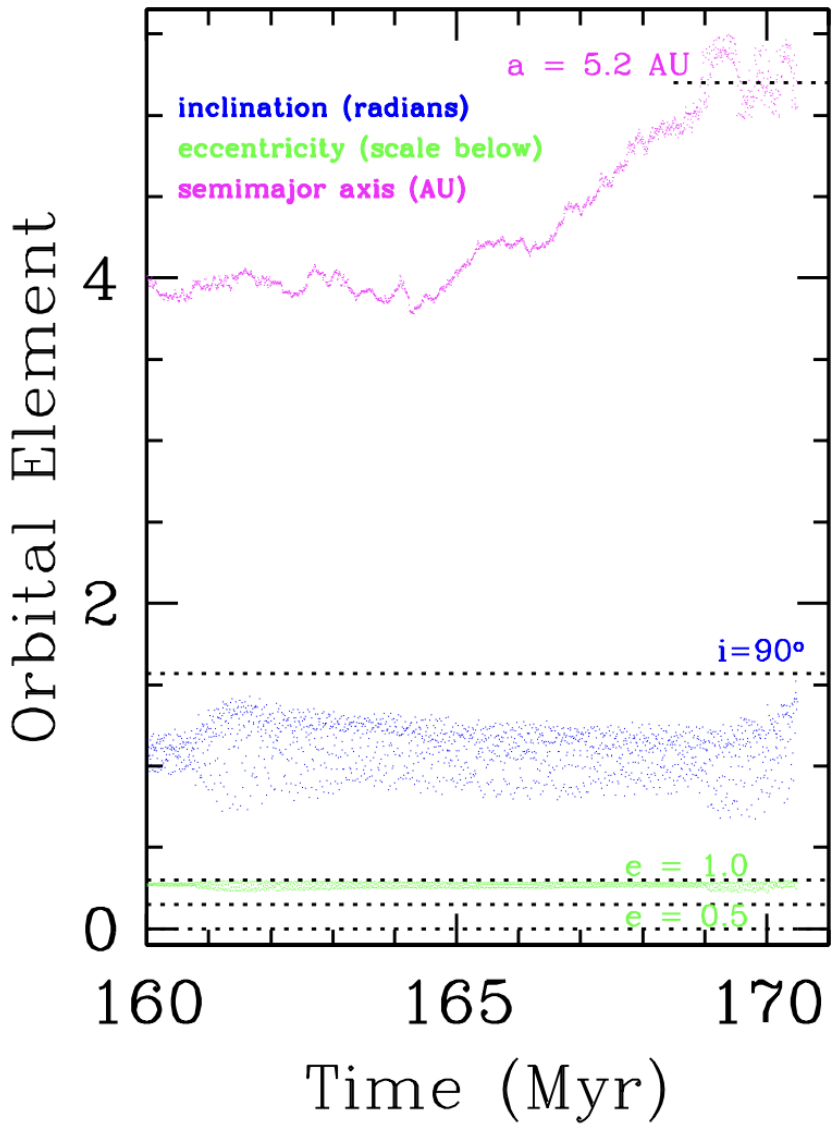


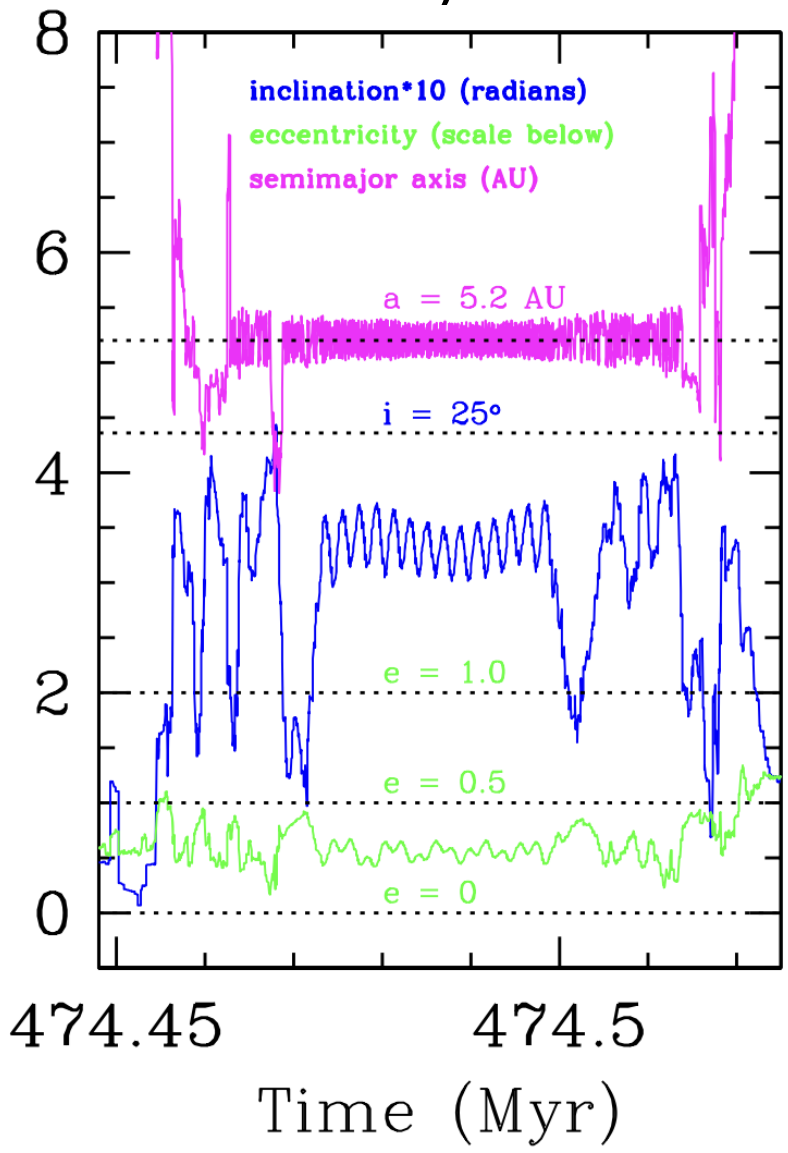
Centaur source (45 kyr trap)

Greenstreet et al. (2020)

Jovian Co-orbitals From NEA & Centaur Sources (Greenstreet et al. 2020)

NEA source (3 Myr trap)





Centaur source (45 kyr trap)

treet et al. (2020)