



Planet 9 Hypothesis to be or not to be?

Tianjun Gan (干天君) Haochang Jiang (蒋昊昌)

Supervisor: Wei Zhu

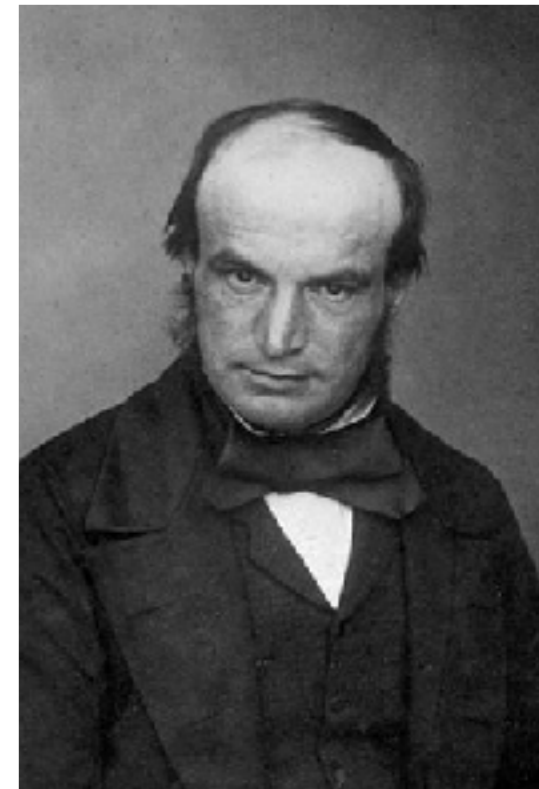
March 11th, 2022, DoA student seminar

Neptune

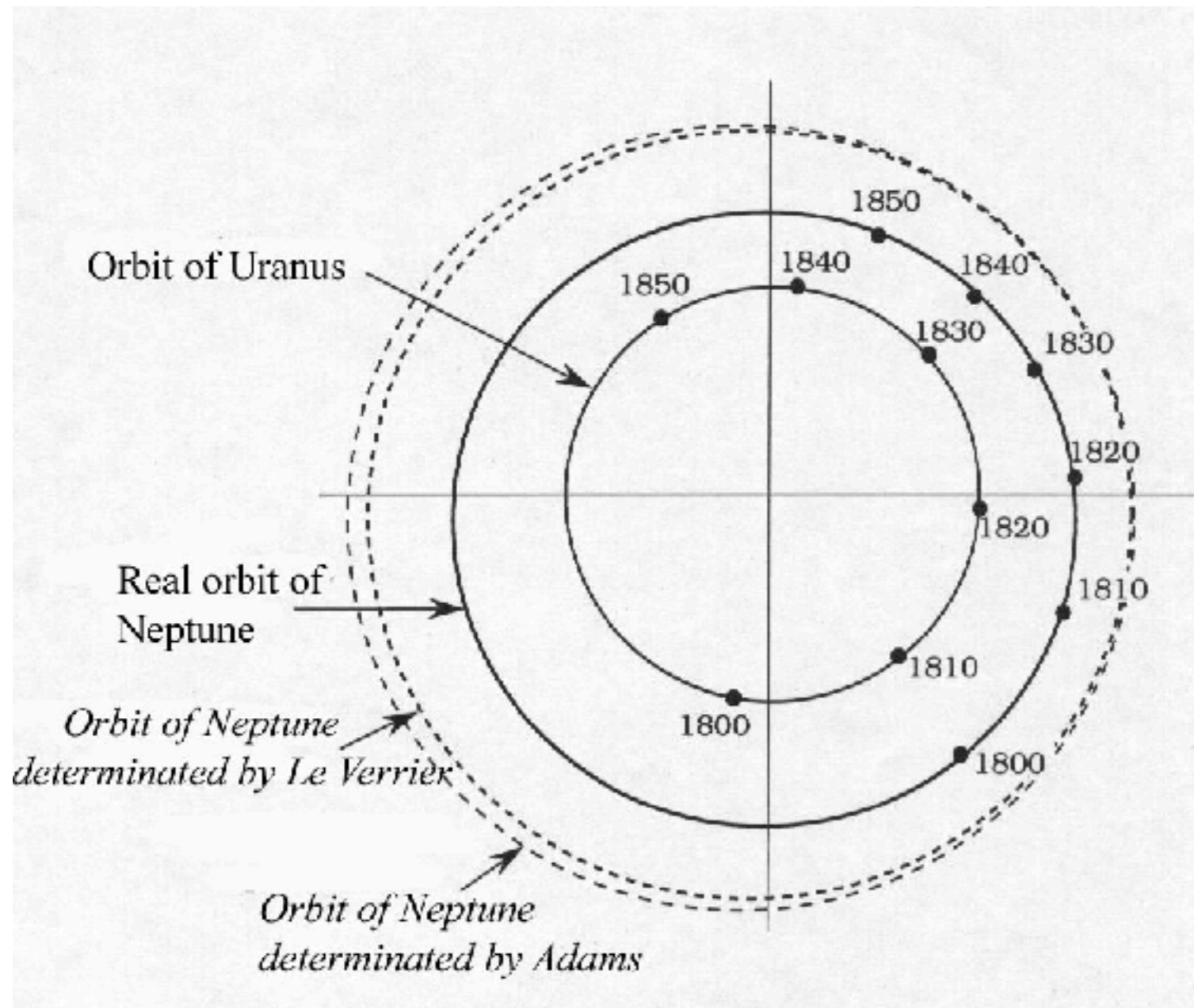
1840s



Urbain Le Verrier



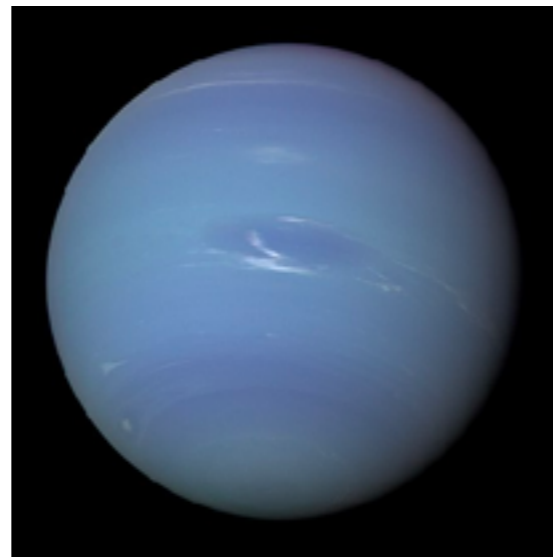
John Couch Adams



Credit : IMCCE-BDL

Neptune

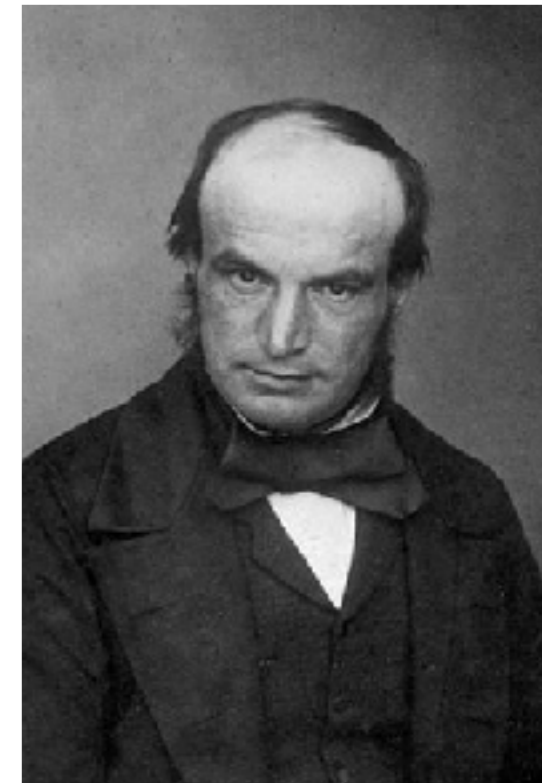
Sep. 23, 1846



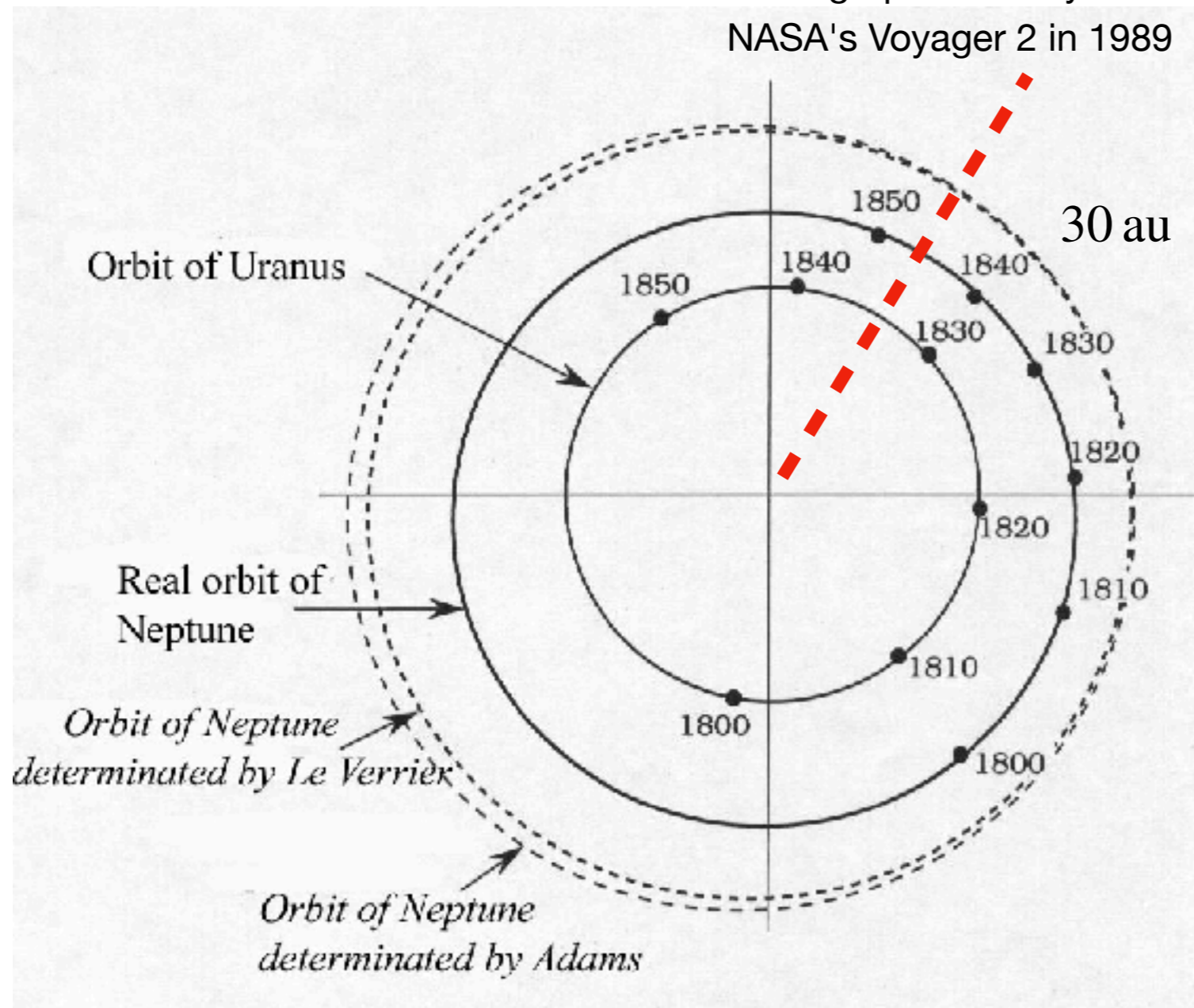
Photograph taken by
NASA's Voyager 2 in 1989



Urbain Le Verrier



John Couch Adams



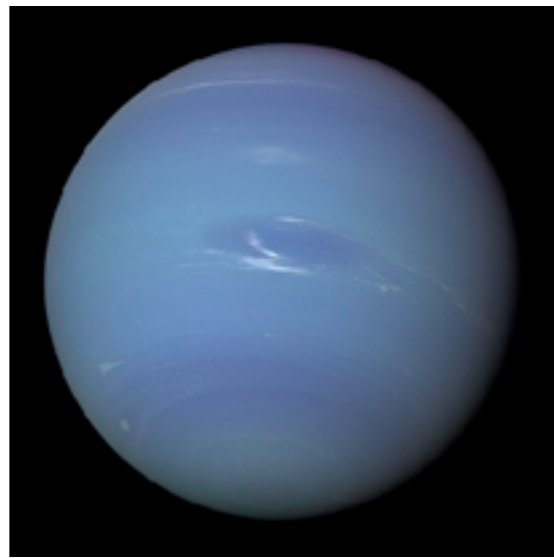
Credit : IMCCE-BDL

Johann Galle



Neptune

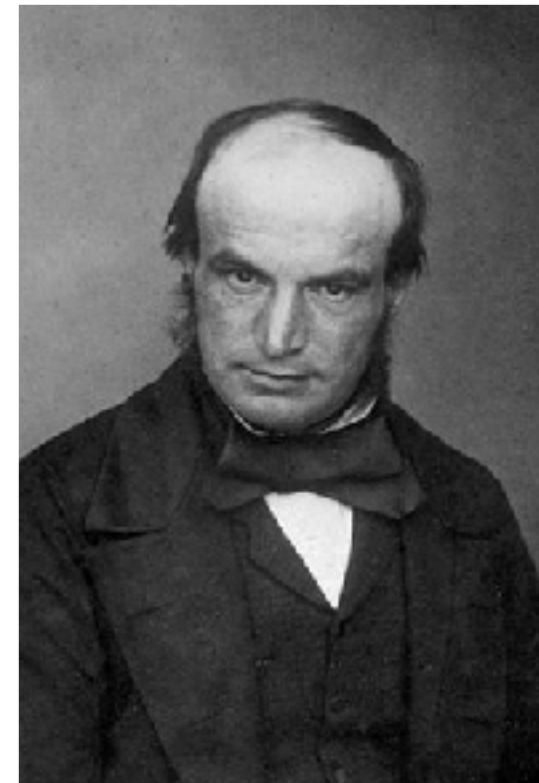
Sep. 23, 1846



Photograph taken by
NASA's Voyager 2 in 1989

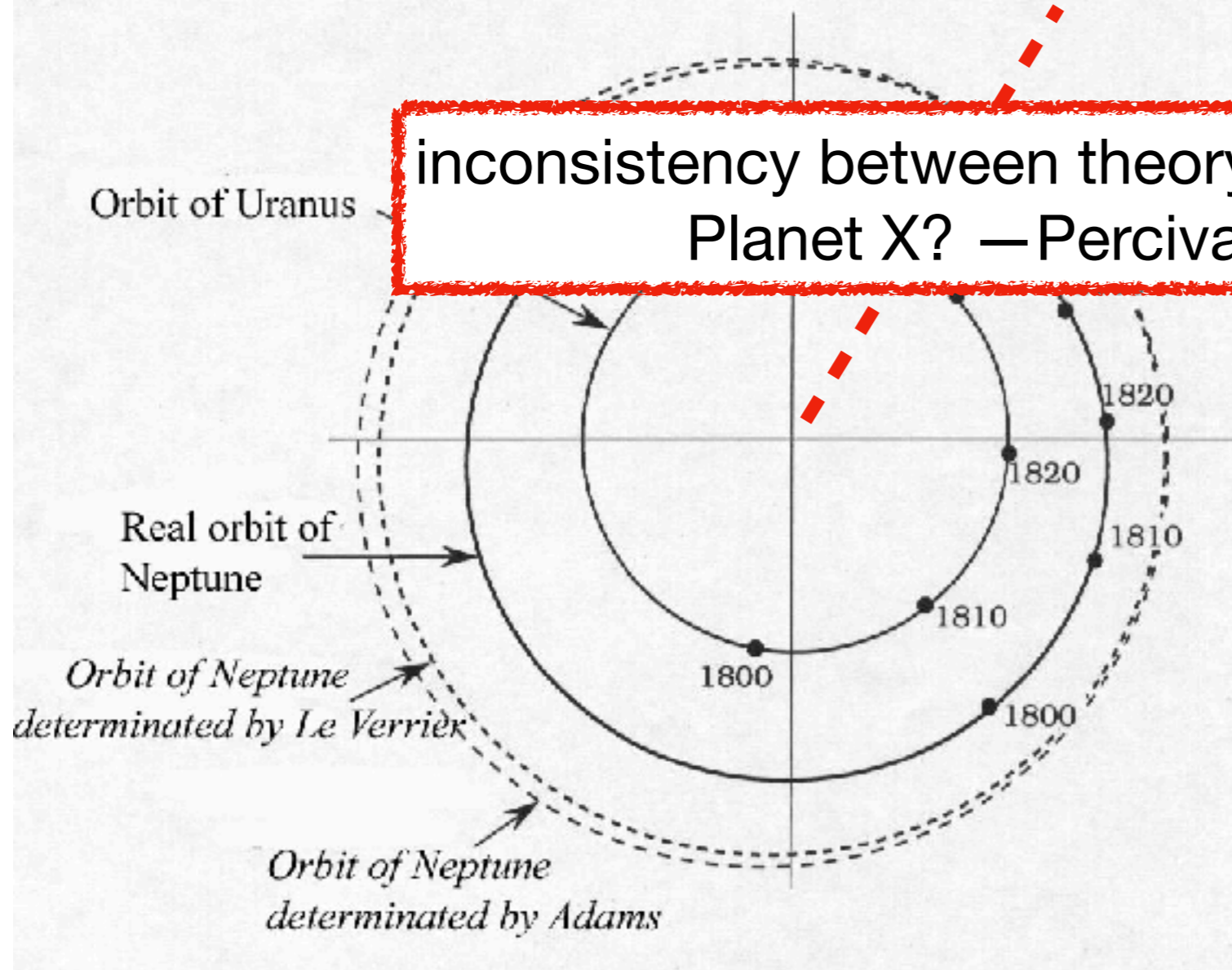


Urbain Le Verrier



John Couch Adams

inconsistency between theory and observation
Planet X? — Percival Lowell

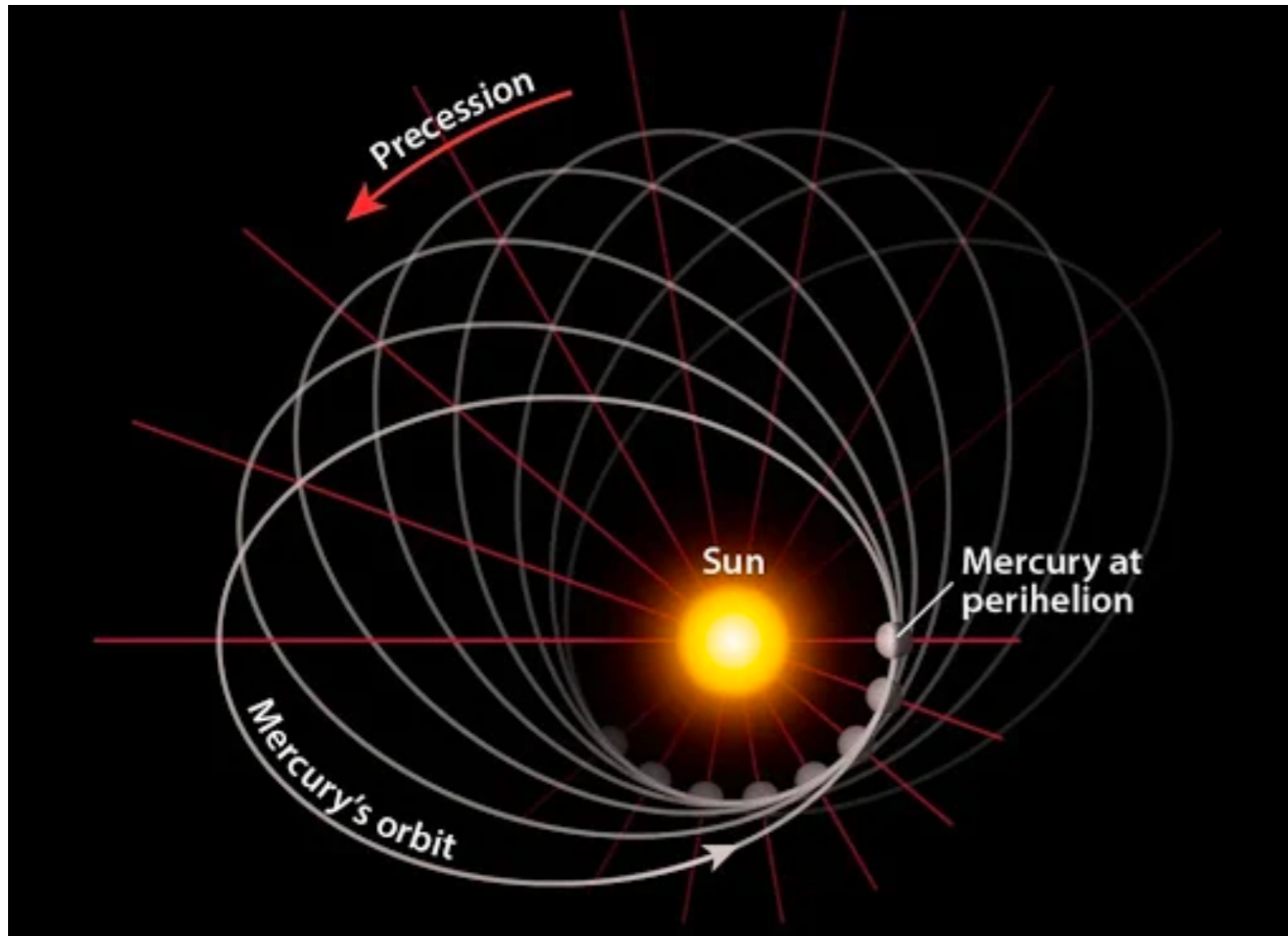


Johann Galle



Vulcan

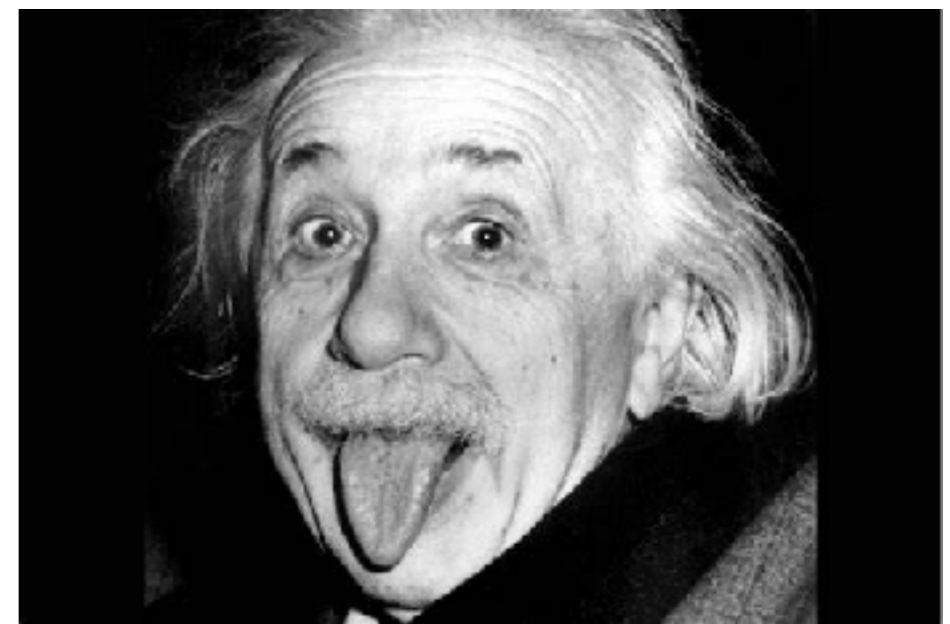
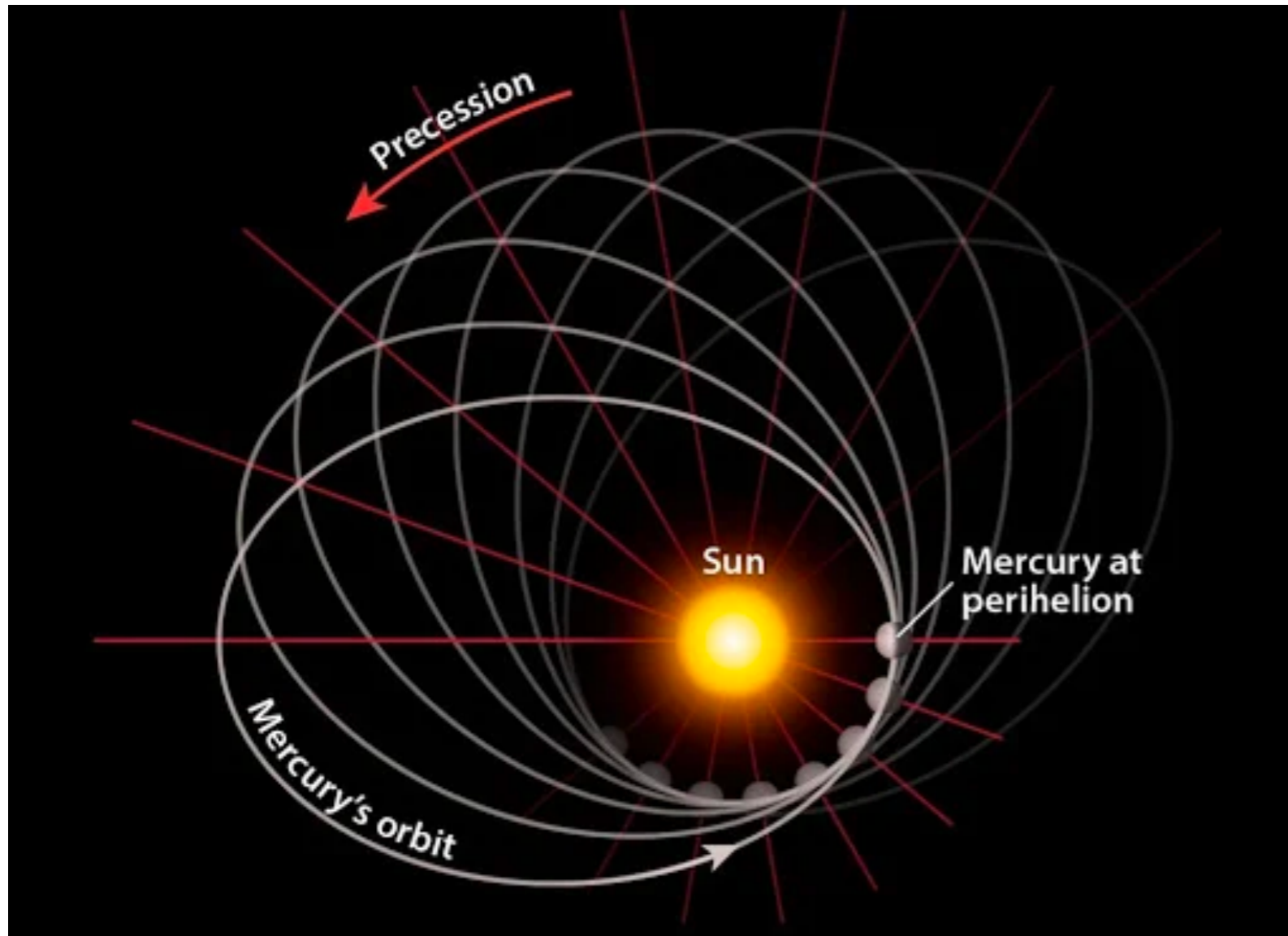
$3 M_{\oplus}$, 3 day period



artist view of Mercury's orbit precession

Vulcan

False alarm



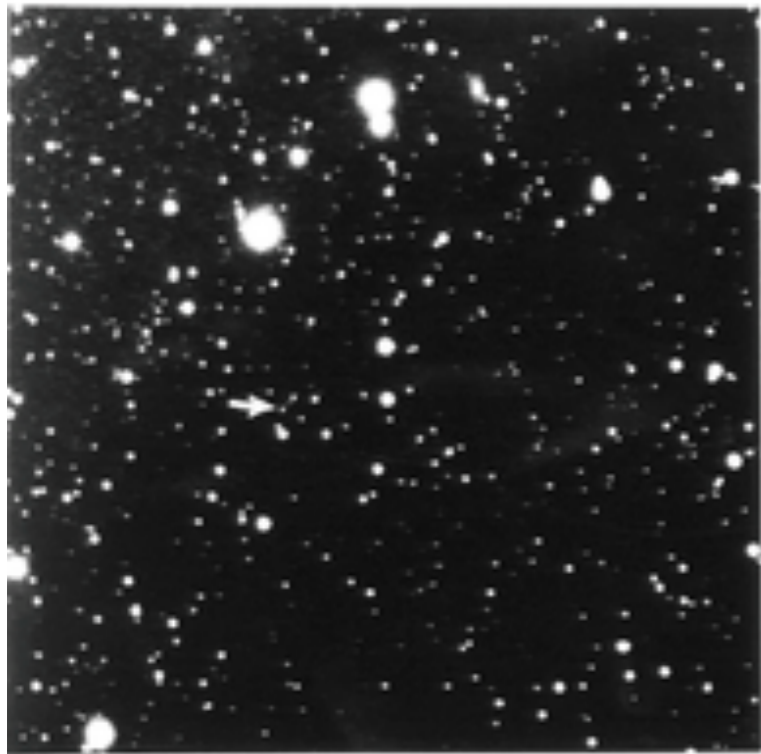
artist view of Mercury's orbit precession

Pluto

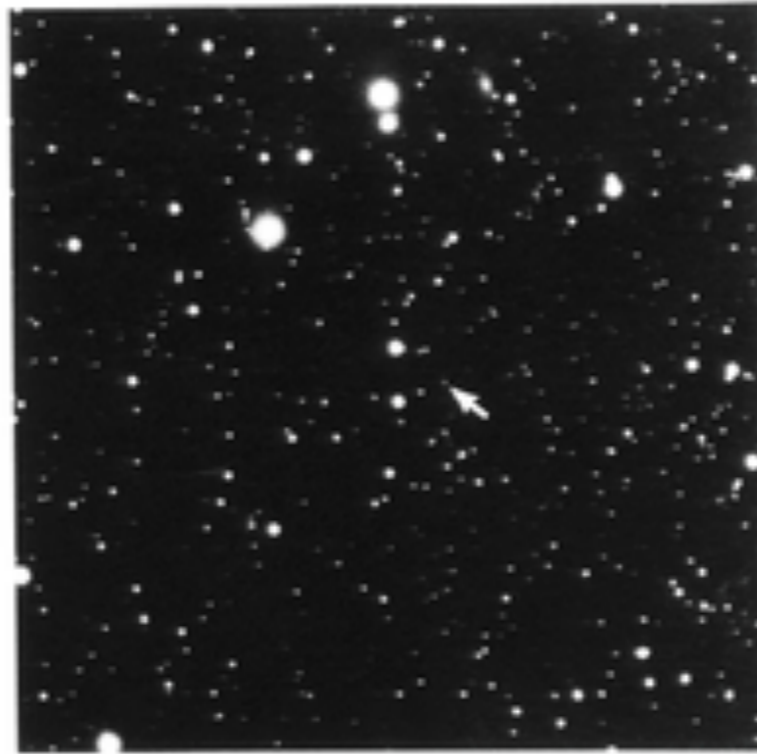
1930s

Clyde William Tombaugh

DISCOVERY OF THE PLANET PLUTO



January 23, 1930

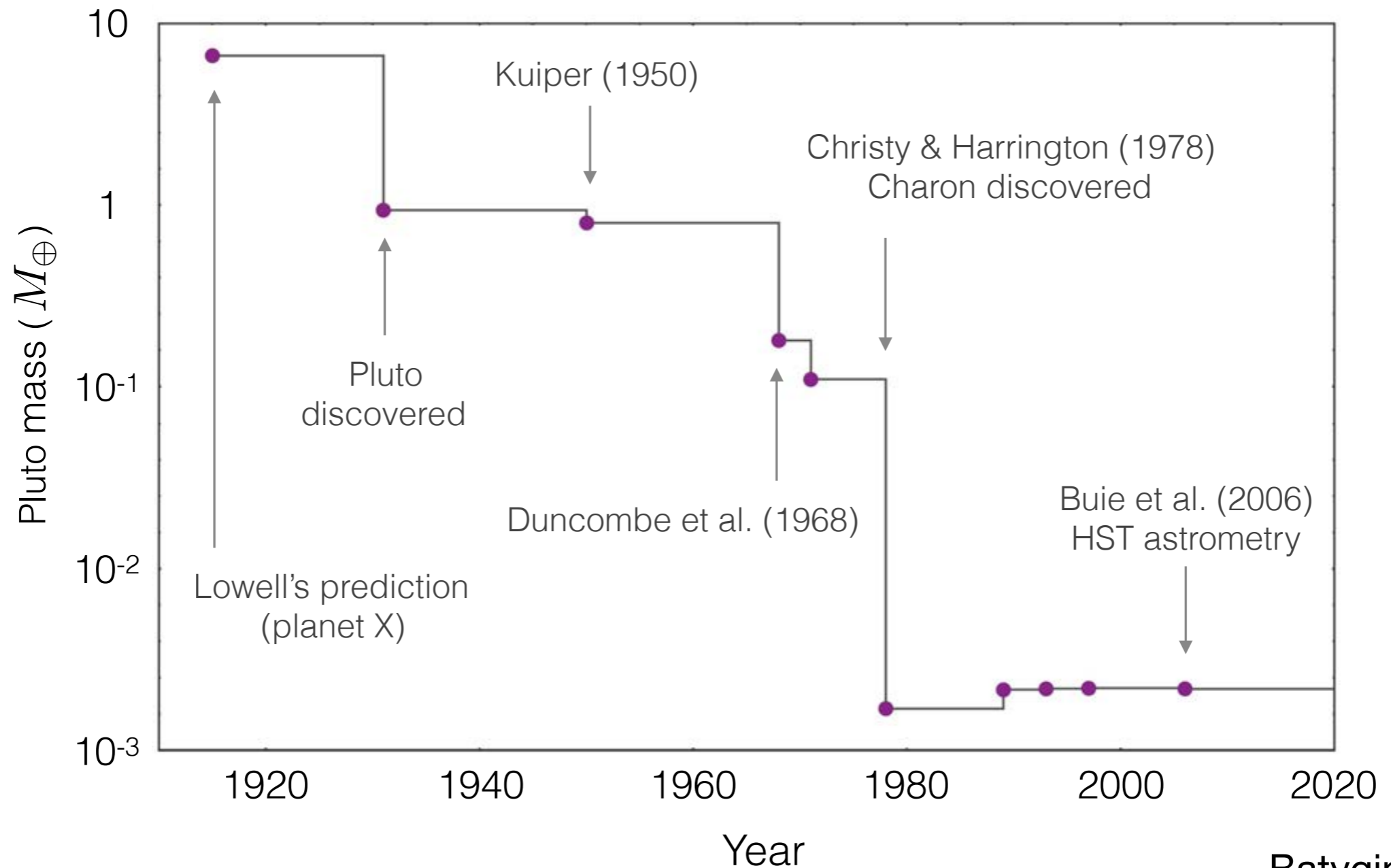


January 29, 1930



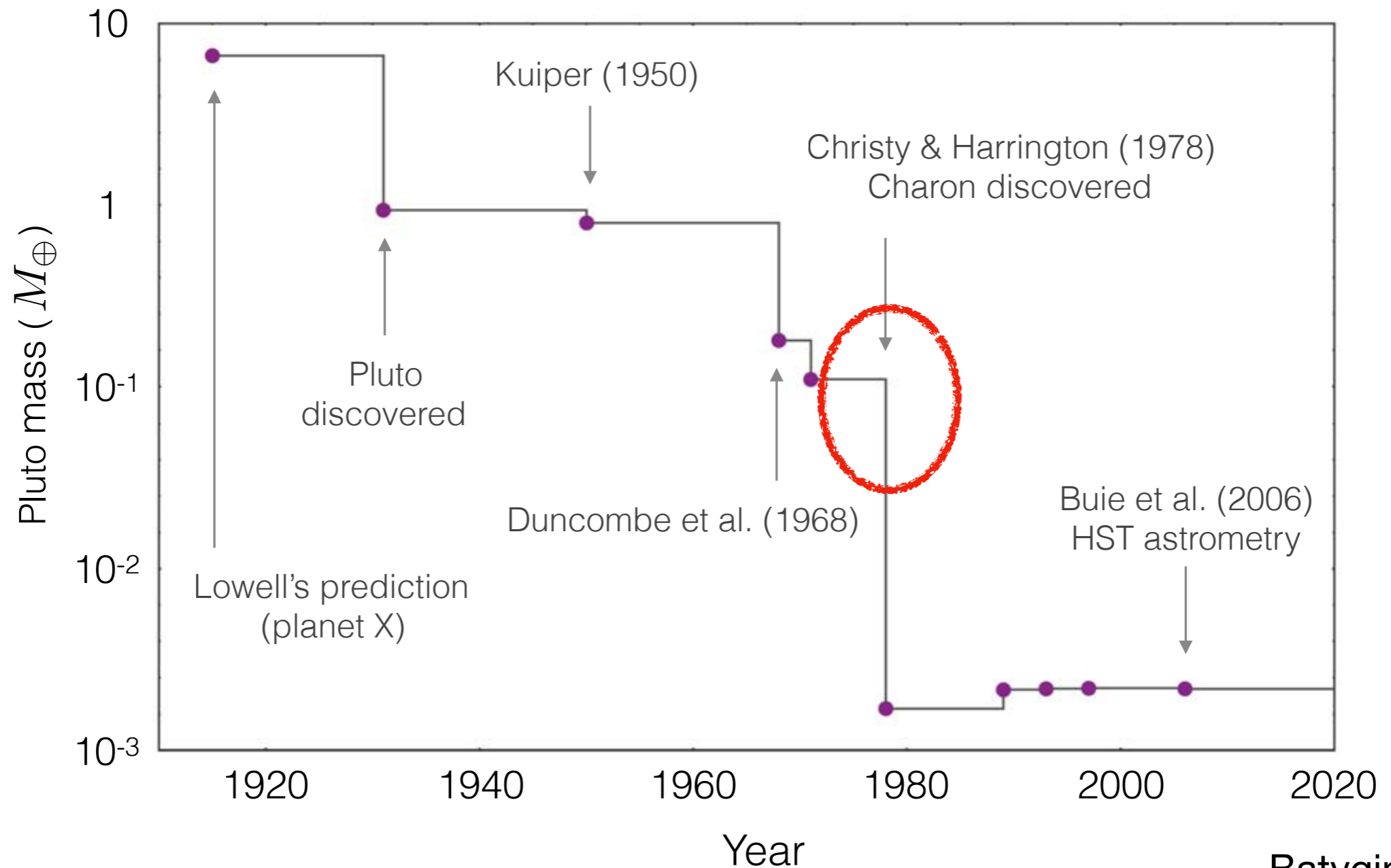
Pluto

Estimated mass of Pluto as a function of time



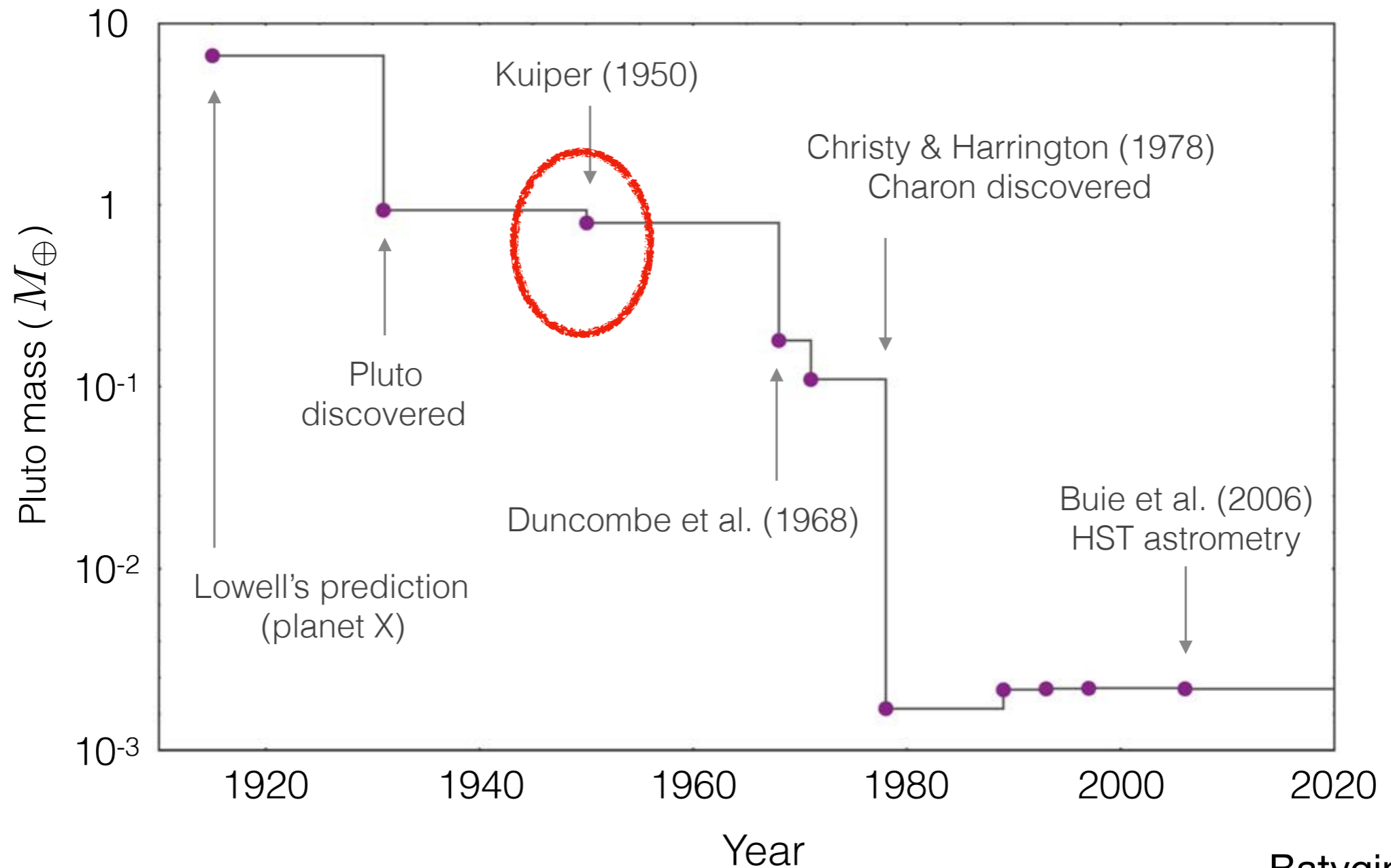
Pluto

Estimated mass of Pluto as a function of time



Pluto

Estimated mass of Pluto as a function of time



Kuiper Belt

1951

Gerard Peter Kuiper

lots of small objects at the baby solar system

Kuiper Belt

1951

Gerard Peter Kuiper

lots of small objects at the baby solar system

left-over of the planet formation

the $1 M_{\oplus}$ Pluto massive enough to cleanup its orbit and explain Uranus orbit

Kuiper Belt

$\sim 0.002 M_{\oplus}$



True color photo of Pluto

Credit: NASA New Horizons Program

1951

Gerard Peter Kuiper

lots of inconsistency between theory and observation
another planet again? em

left-over of the planet formation

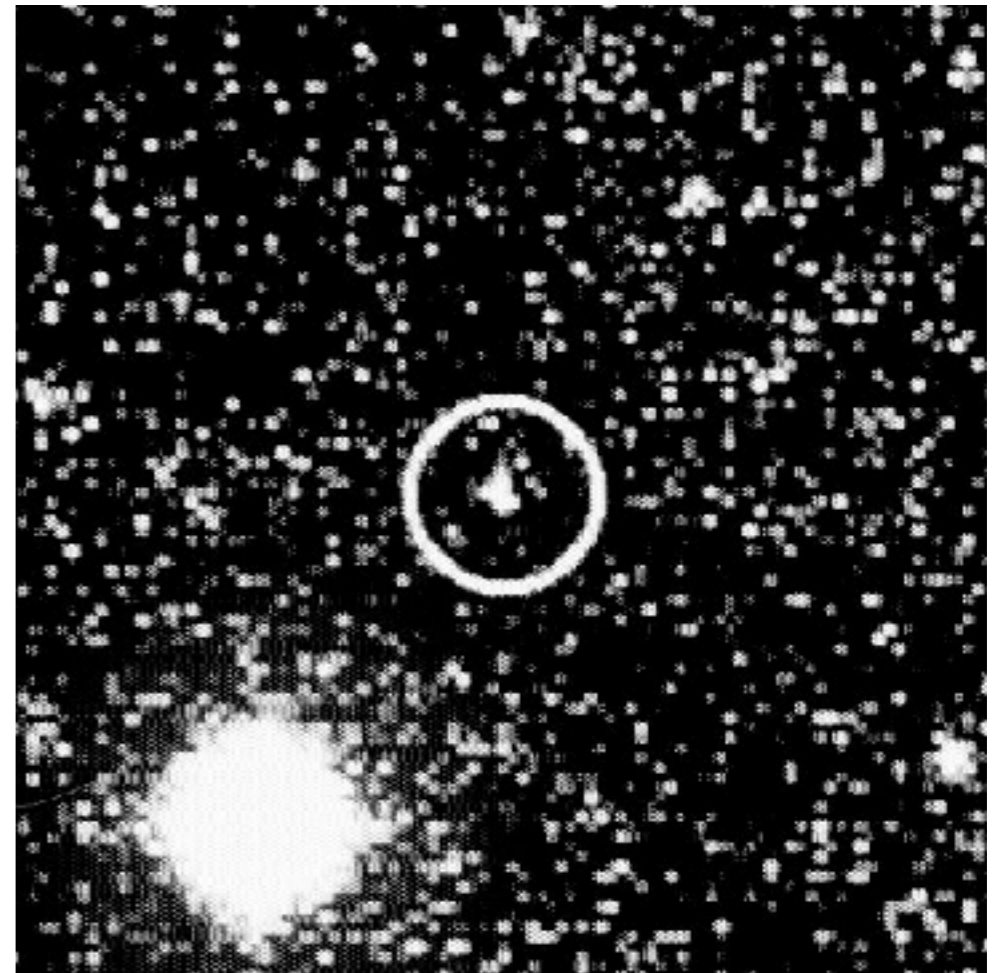
the $1 M_{\oplus}$ Pluto massive enough to cleanup its orbit and explain Uranus orbit

Kuiper Belt - Trans-Neptunian object

1990s

David C. Jewitt, Jane Luu

- Trans Neptune Objects
 - 1992 QB₁ (Cubewanos)
 - 1993 FW



Long-exposure image of Albion (circled) taken by the European Southern Observatory in September 1992

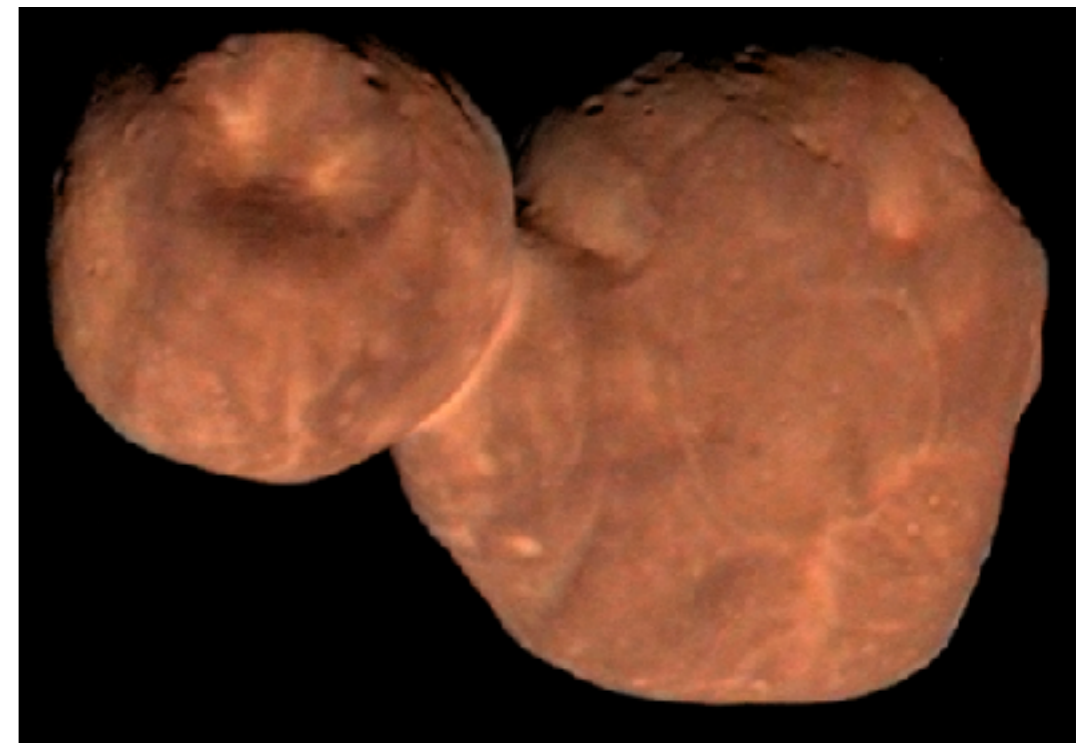
Kuiper Belt - Trans-Neptunian object

1990s

David C. Jewitt, Jane Luu

- Trans Neptune Objects
 - 1992 QB₁ (Cubewanos)
 - 1993 FW

see Yan Liang's talk Fall 2021



486958 Arrokoth, the first cubewano visited by a spacecraft

Kuiper Belt - TNO

David C. Jewitt, Jane Luu

The 2012 Prize in Astronomy

David C Jewitt
Jane Luu

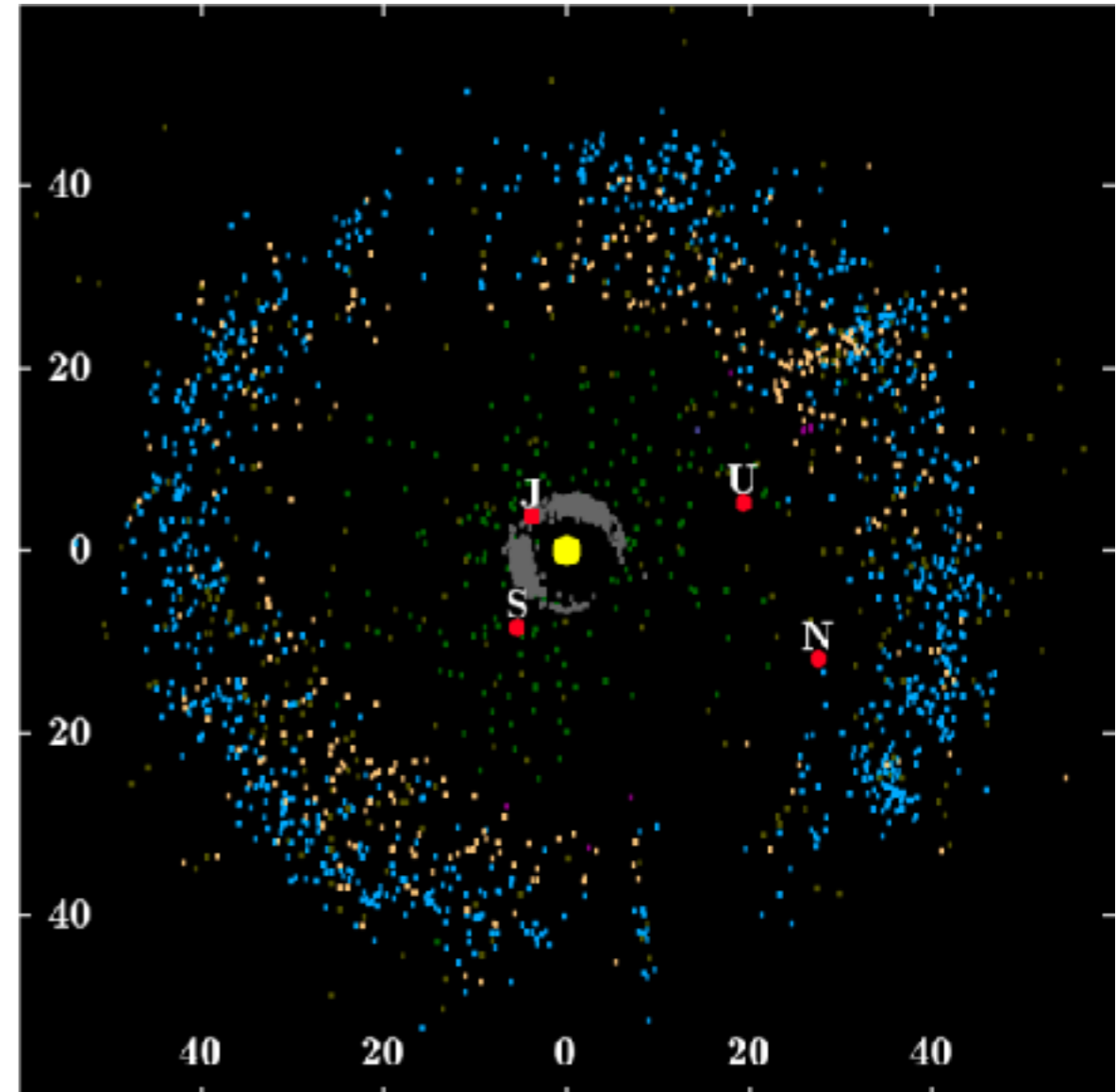
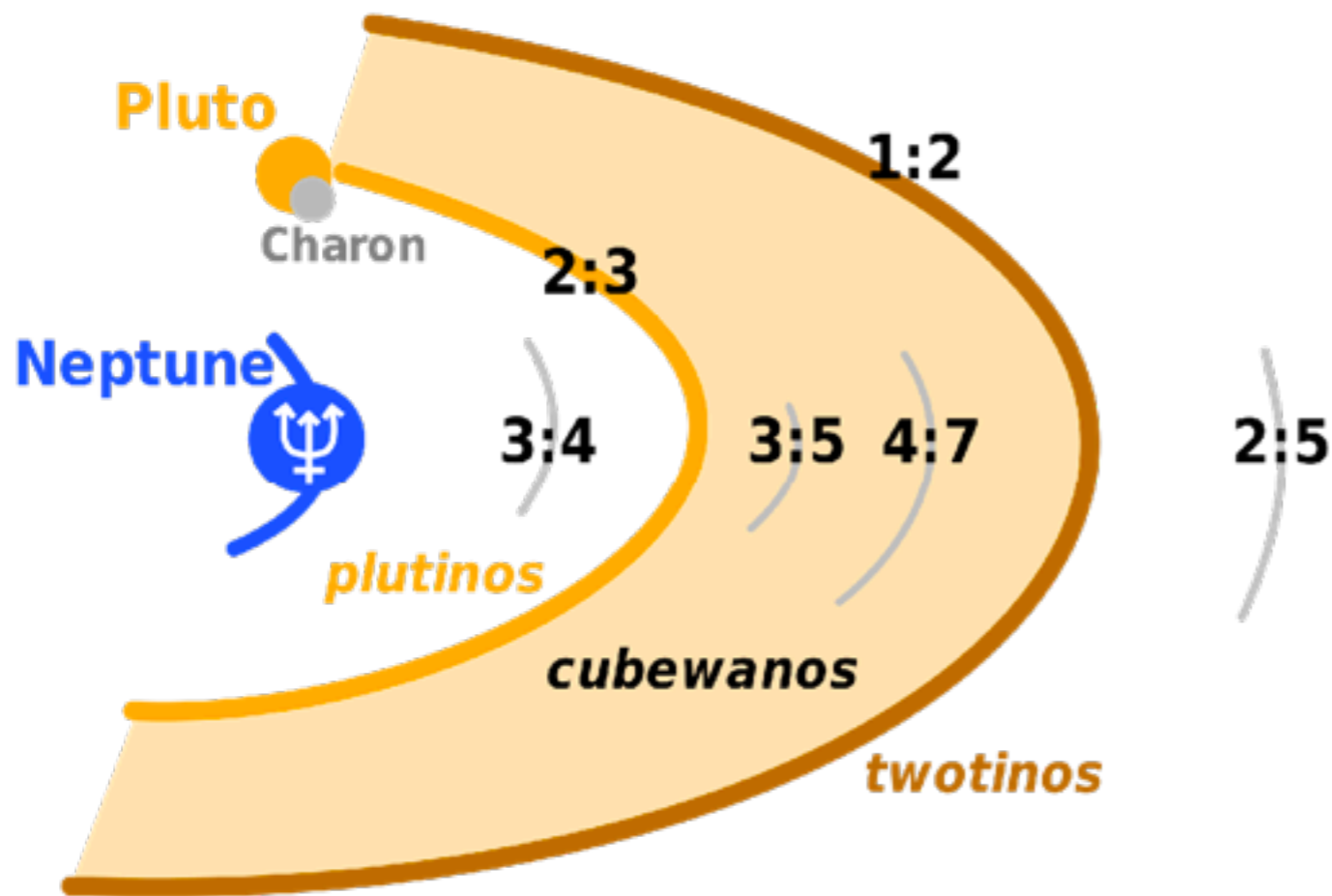
for their discovery and characterization of trans-Neptunian bodies, an archeological treasure dating back to the formation of the solar system and the long-sought source of short period comets.



Kuiper Belt

30 au (Neptune) - 50 au

Kuiper belt and orbital resonance

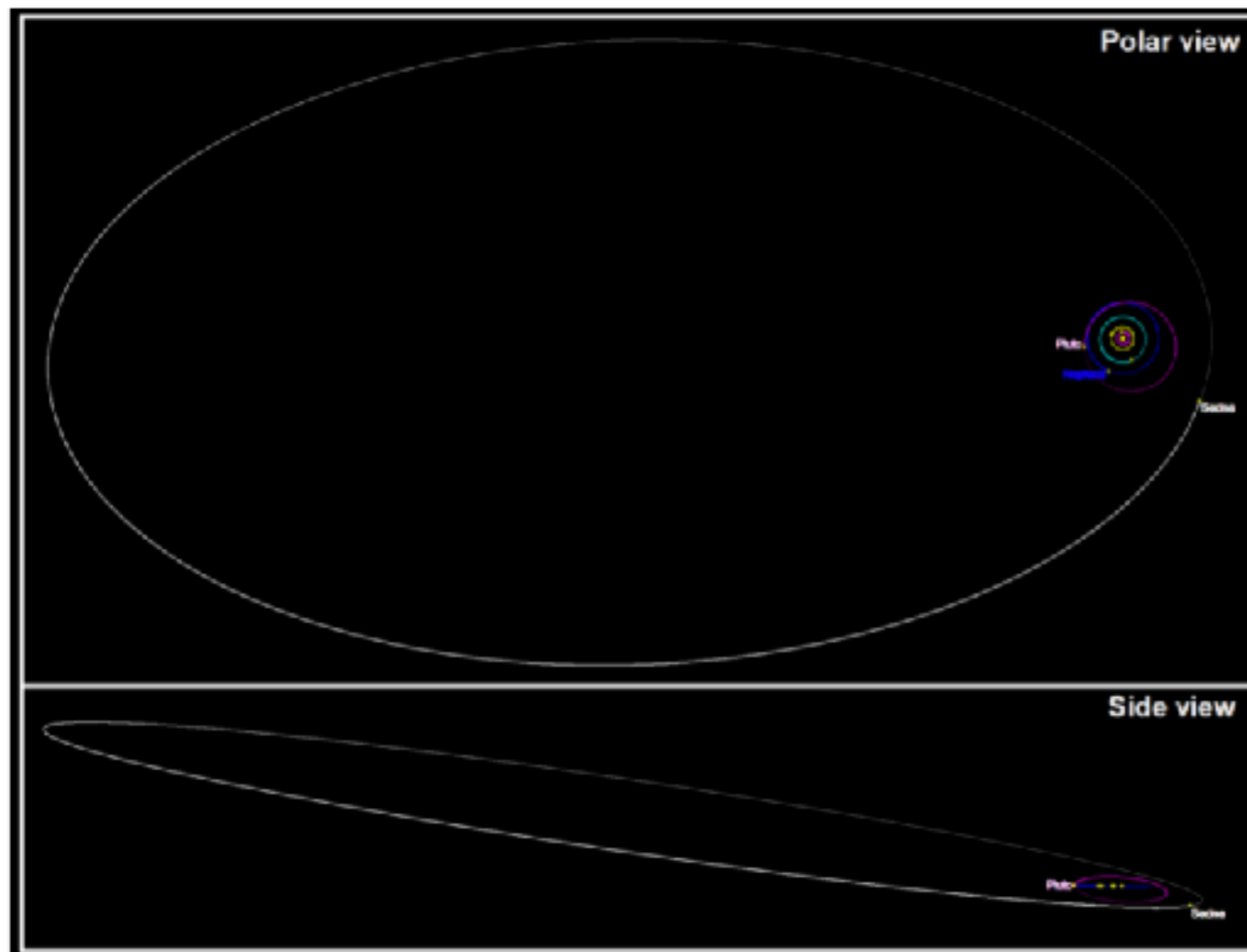


Known objects in the Kuiper belt beyond the orbit of Neptune. epoch as of January 2015.

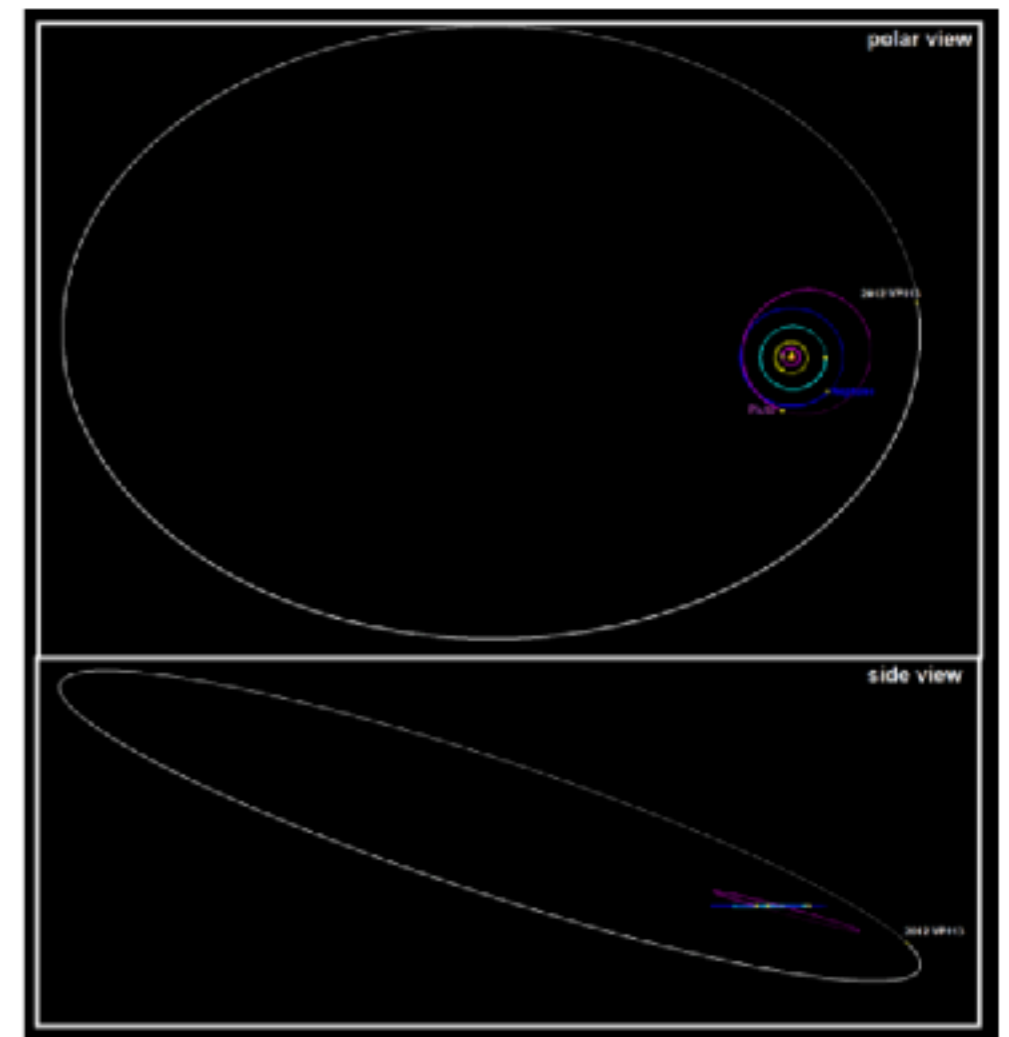
Two outliers

Trujillo & Shepard 2014

2003 VB₁₂: Sedna



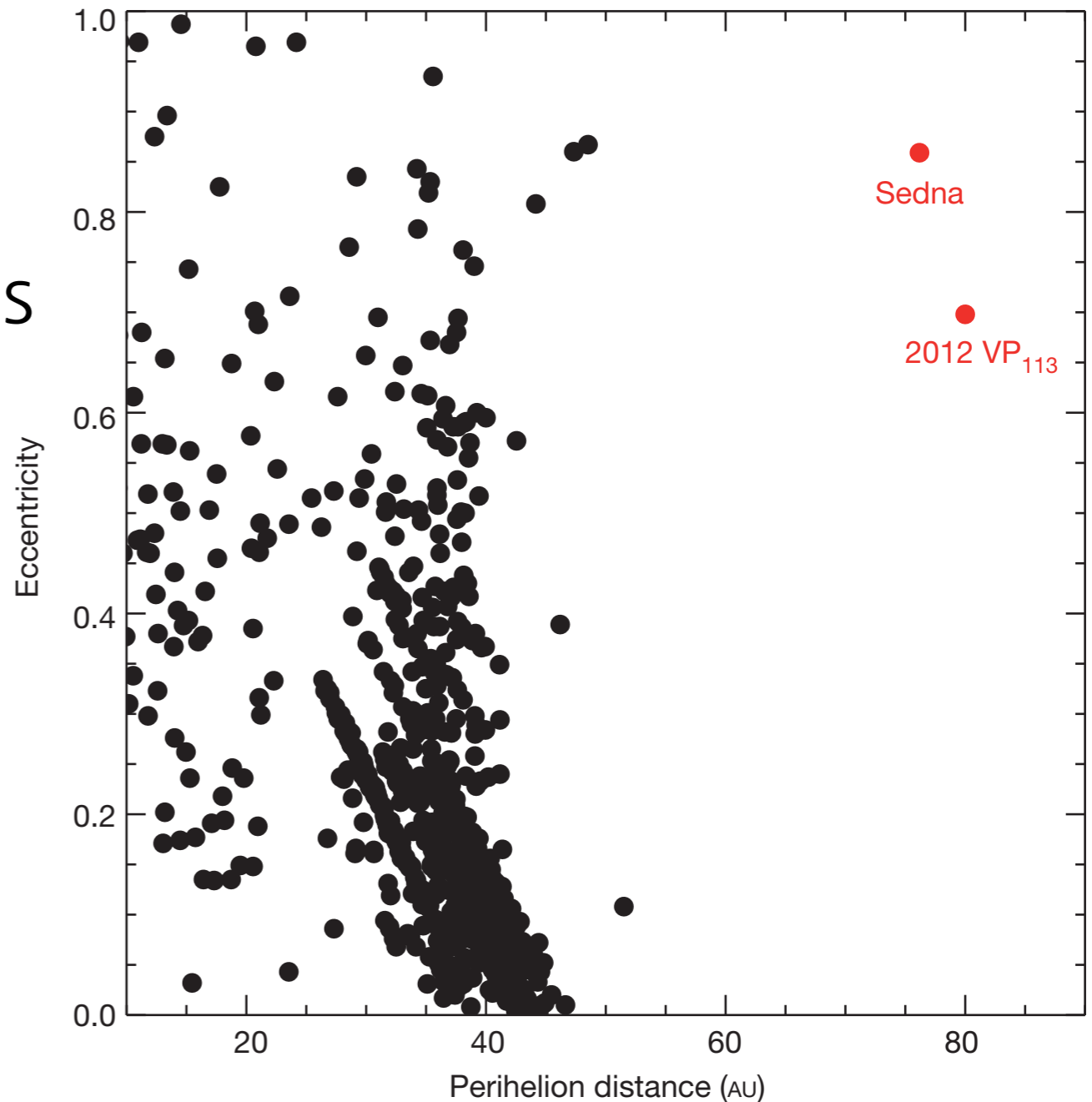
2012 VP₁₁₃: *Biden*



Extreme TNO

Trujillo & Shepard 2014

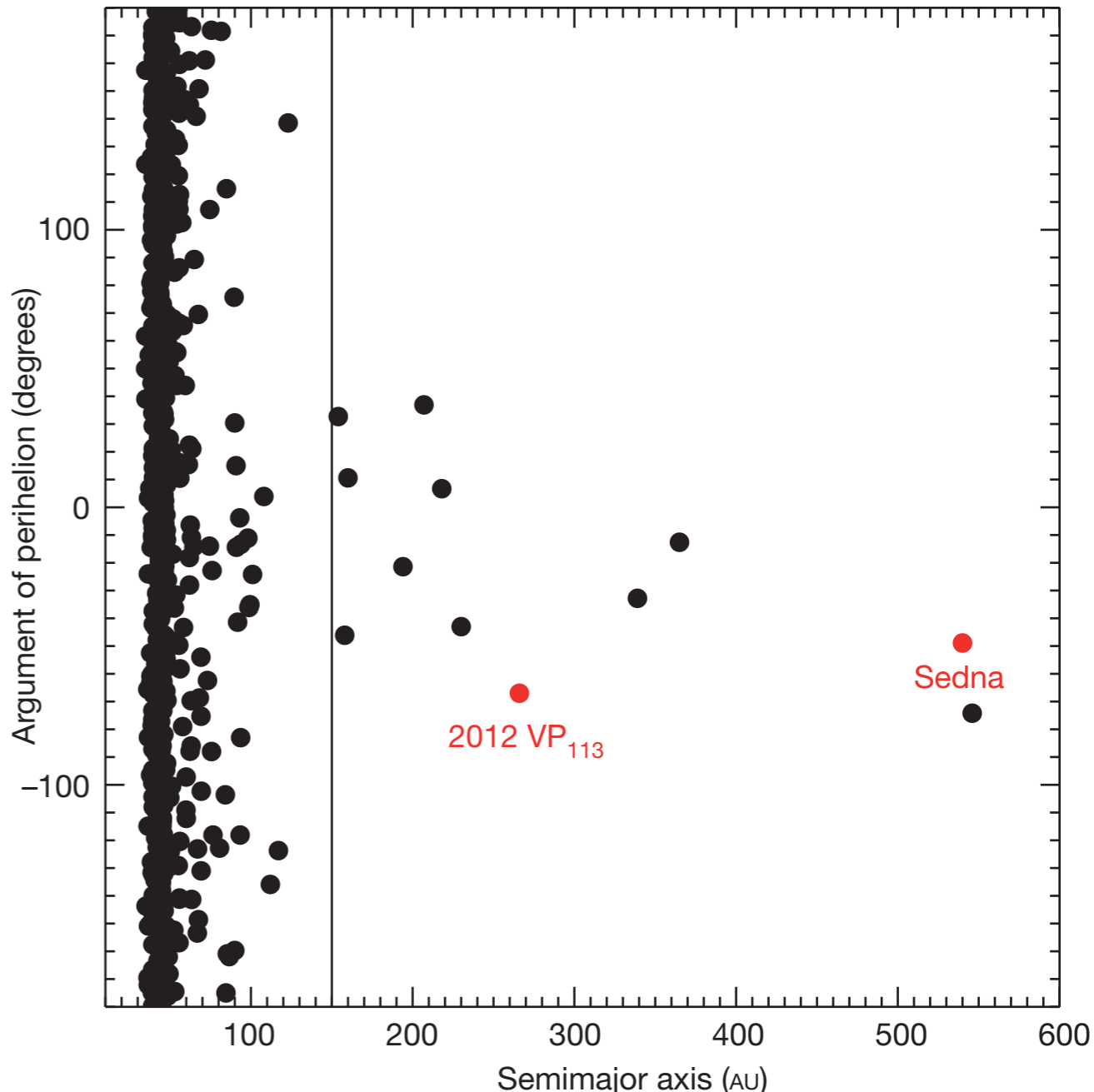
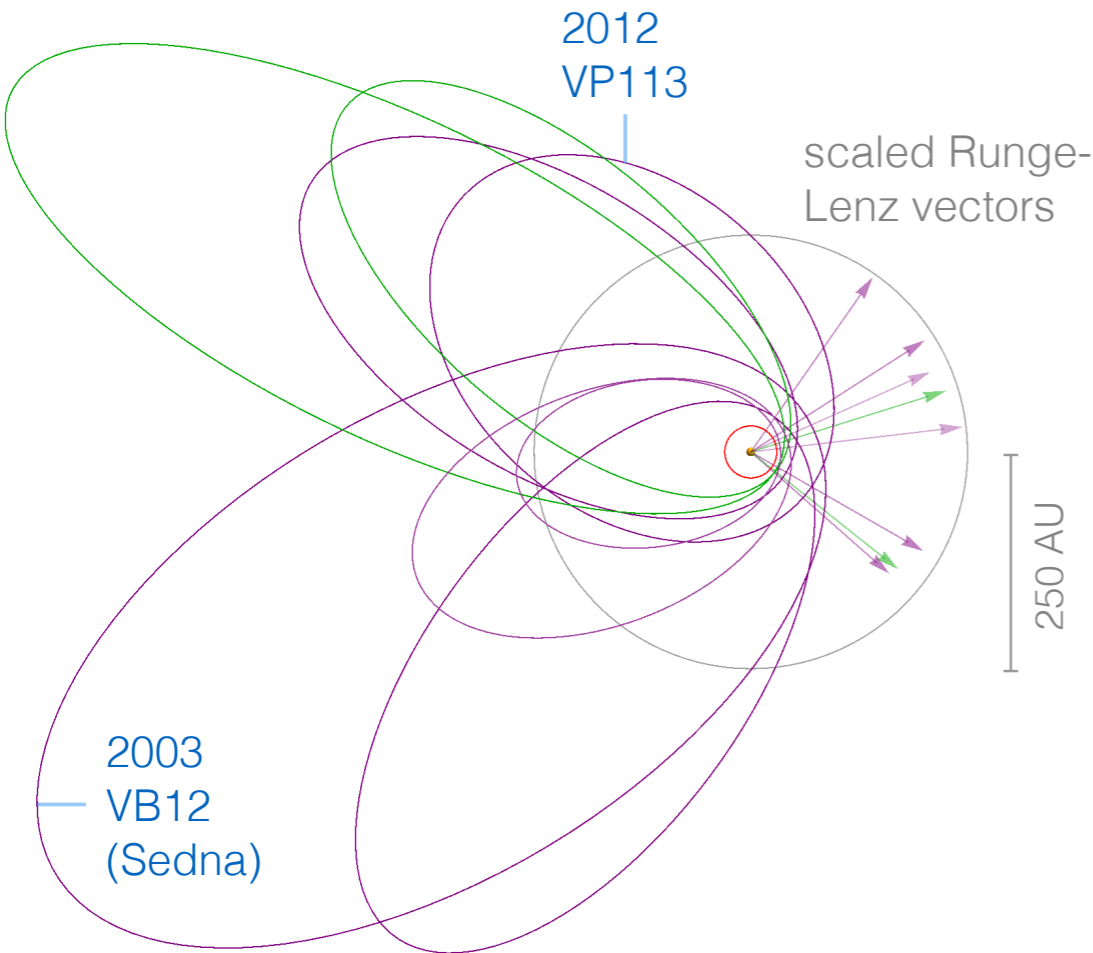
- semi-major axis > 150 au
- perihelium > 30 au
 - Neptune semimajor axis
- dynamical outliers



Extreme TNO

Trujillo & Shepard 2014

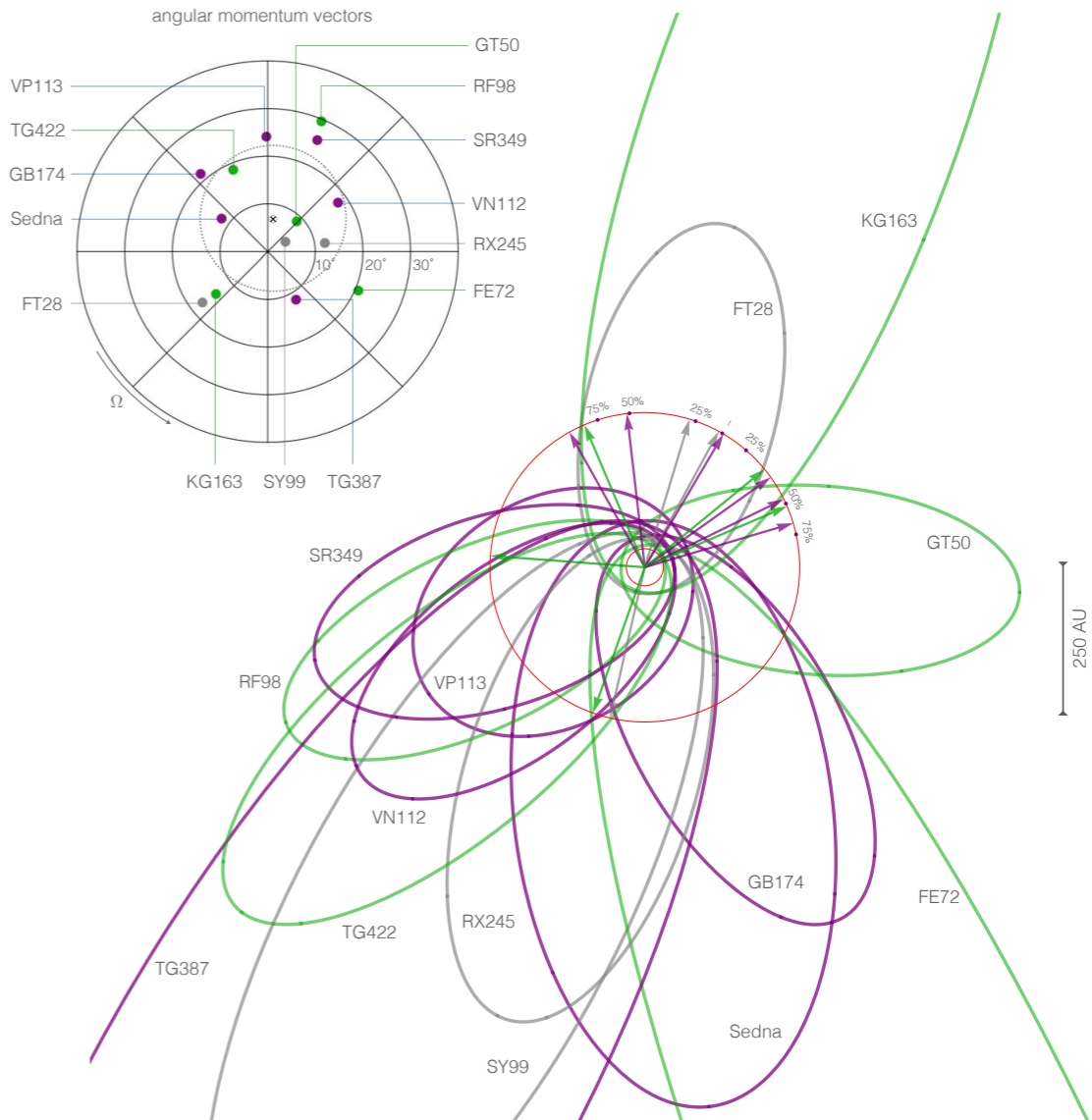
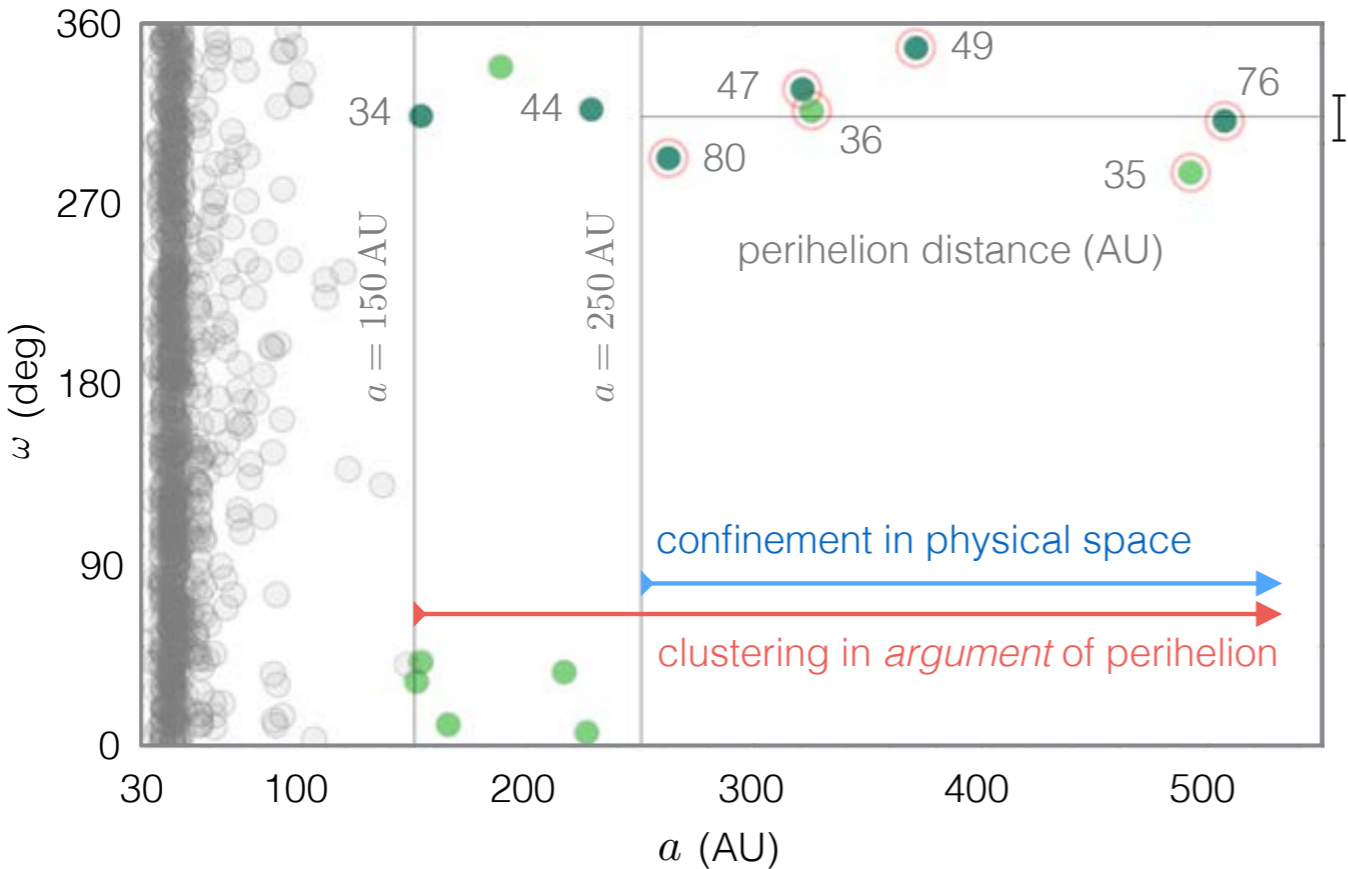
- ETNOs show clustering?

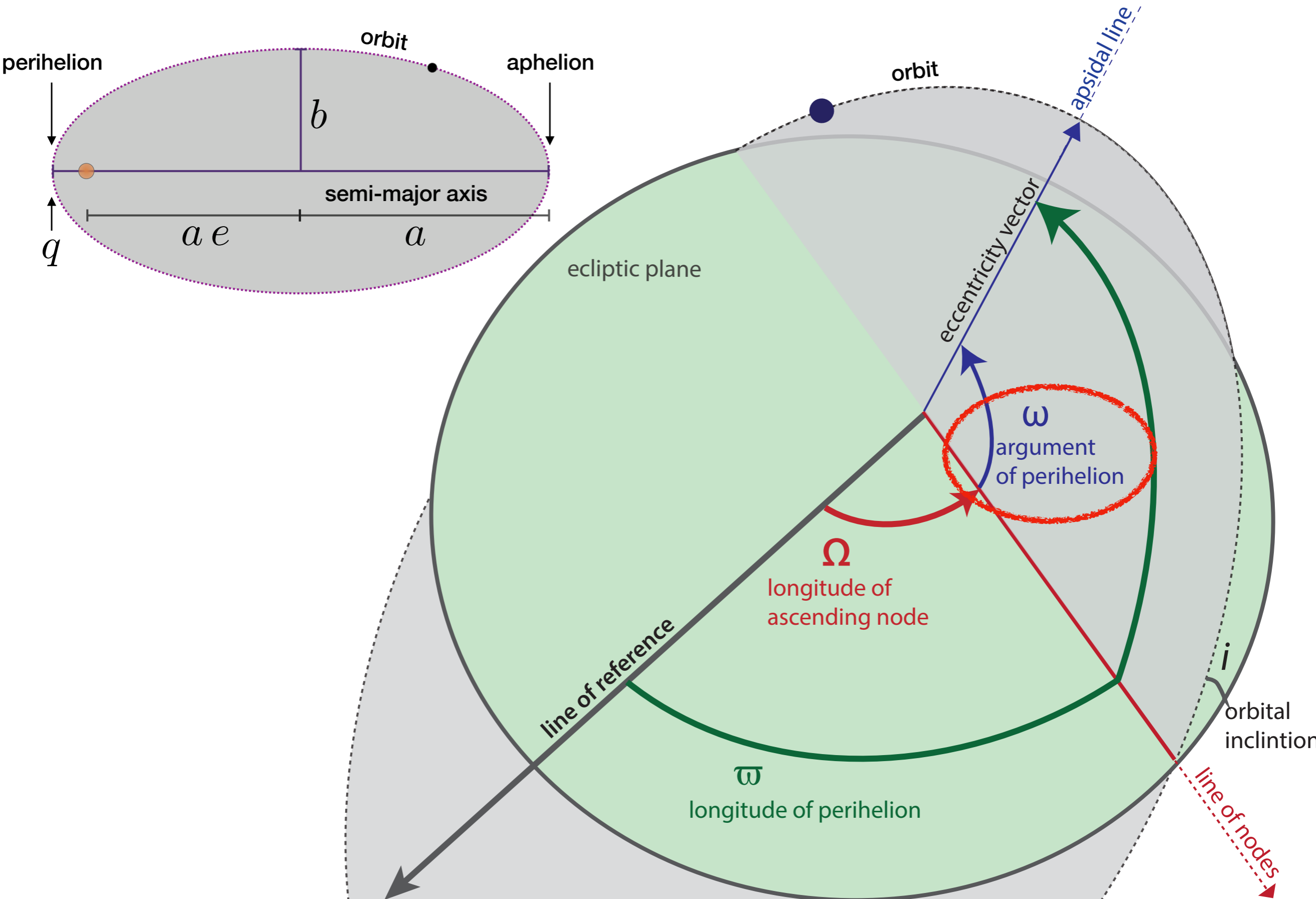


Orbital Clustering

Batygin & Brown 2016

- 8 ETNO, clustering of their perihelion

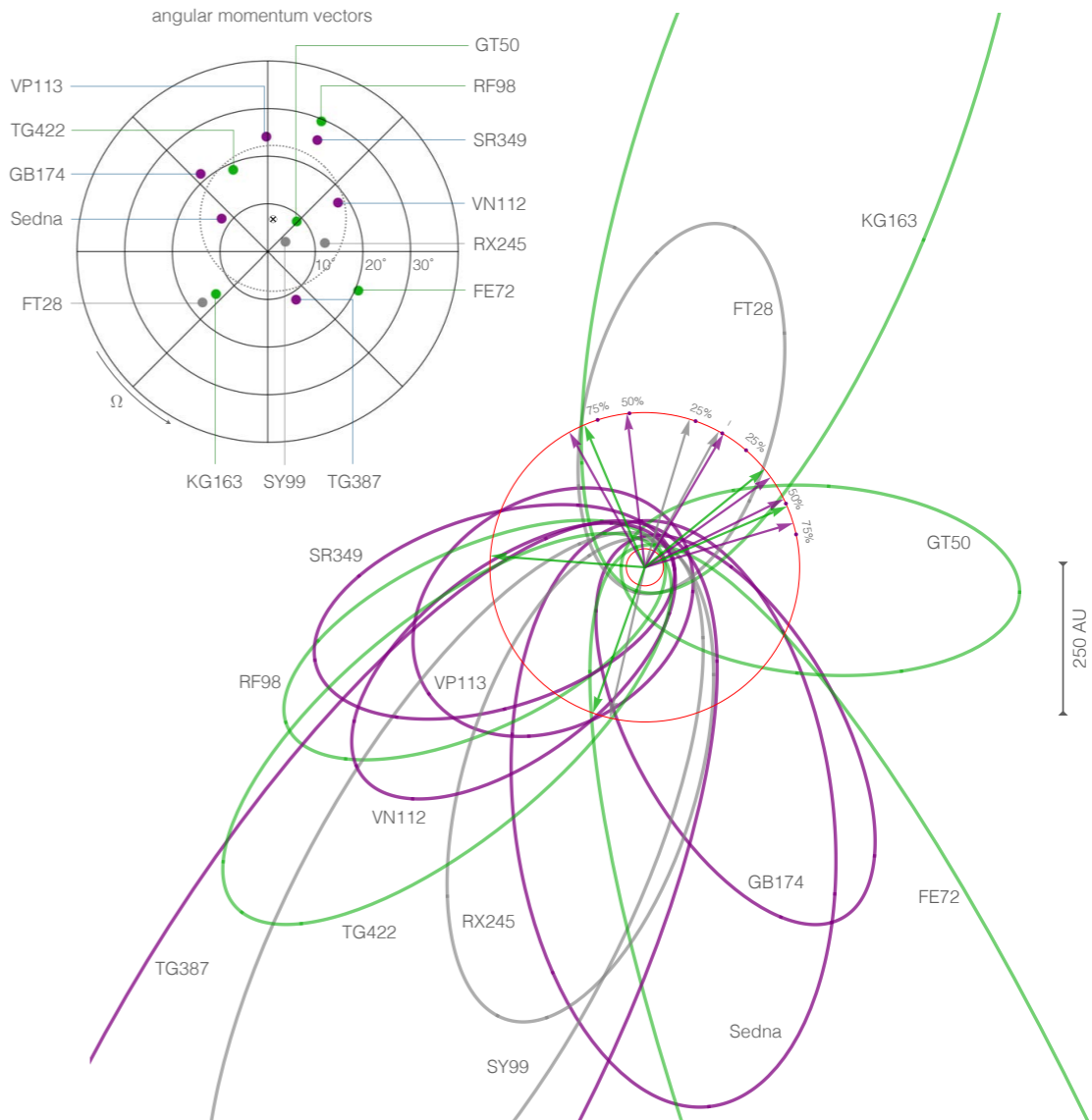
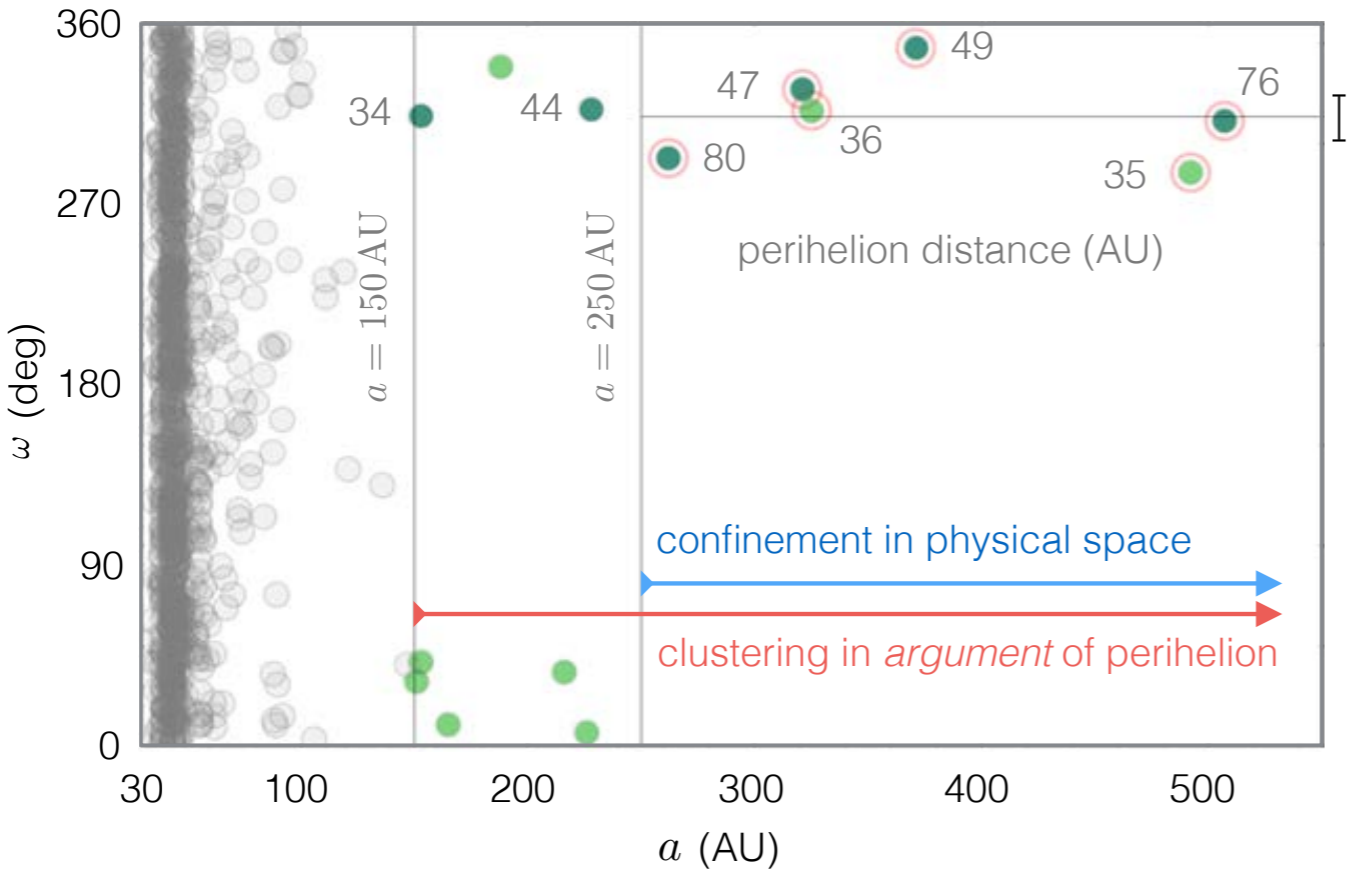




Orbital Clustering

Batygin & Brown 2016

- 8 ETNO, clustering of their perihelion



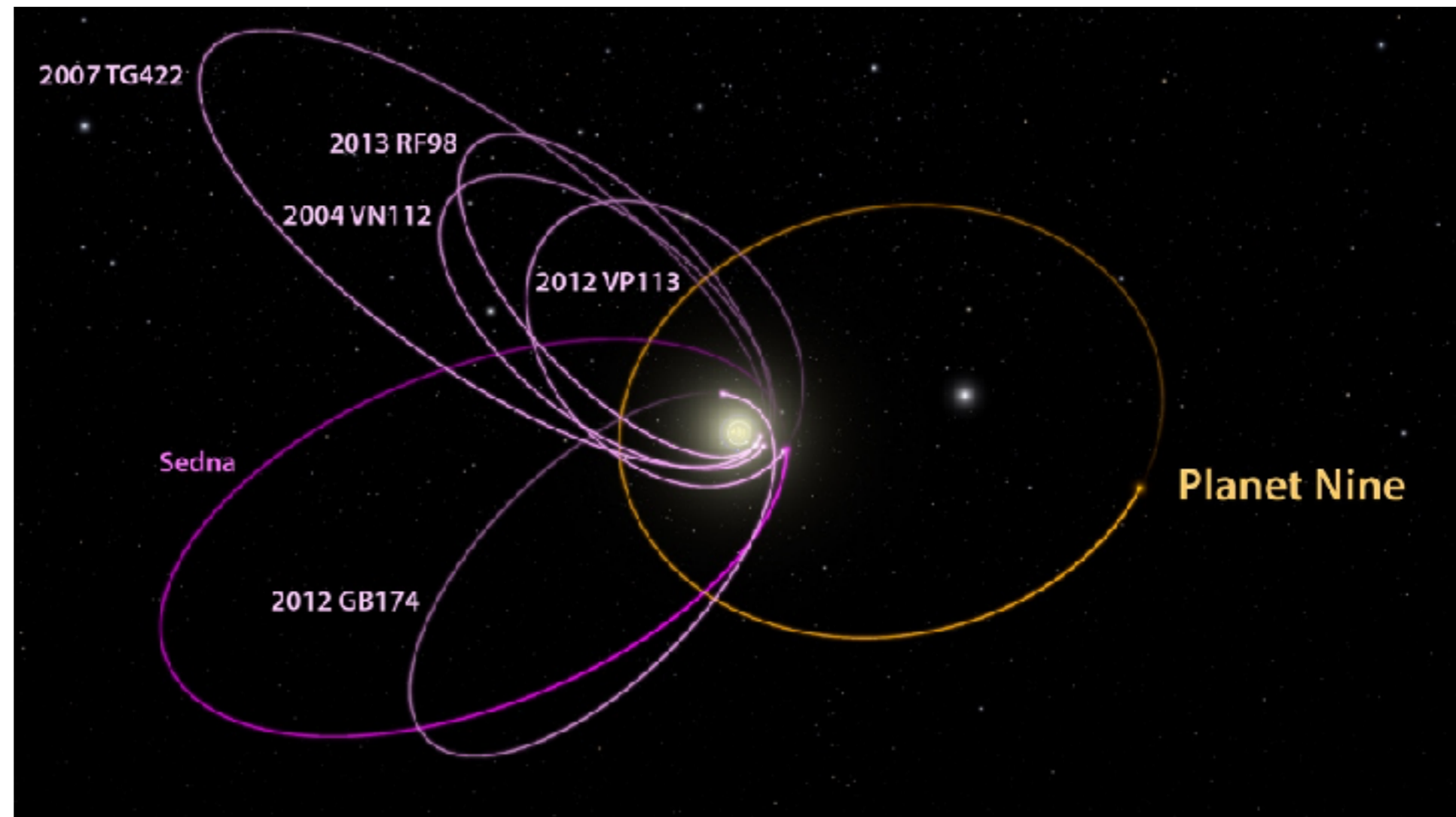
de la Fuente Marcos & de la Fuente Marcos 2014

Batygin & Brown 2016

Brown & Batygin 2016

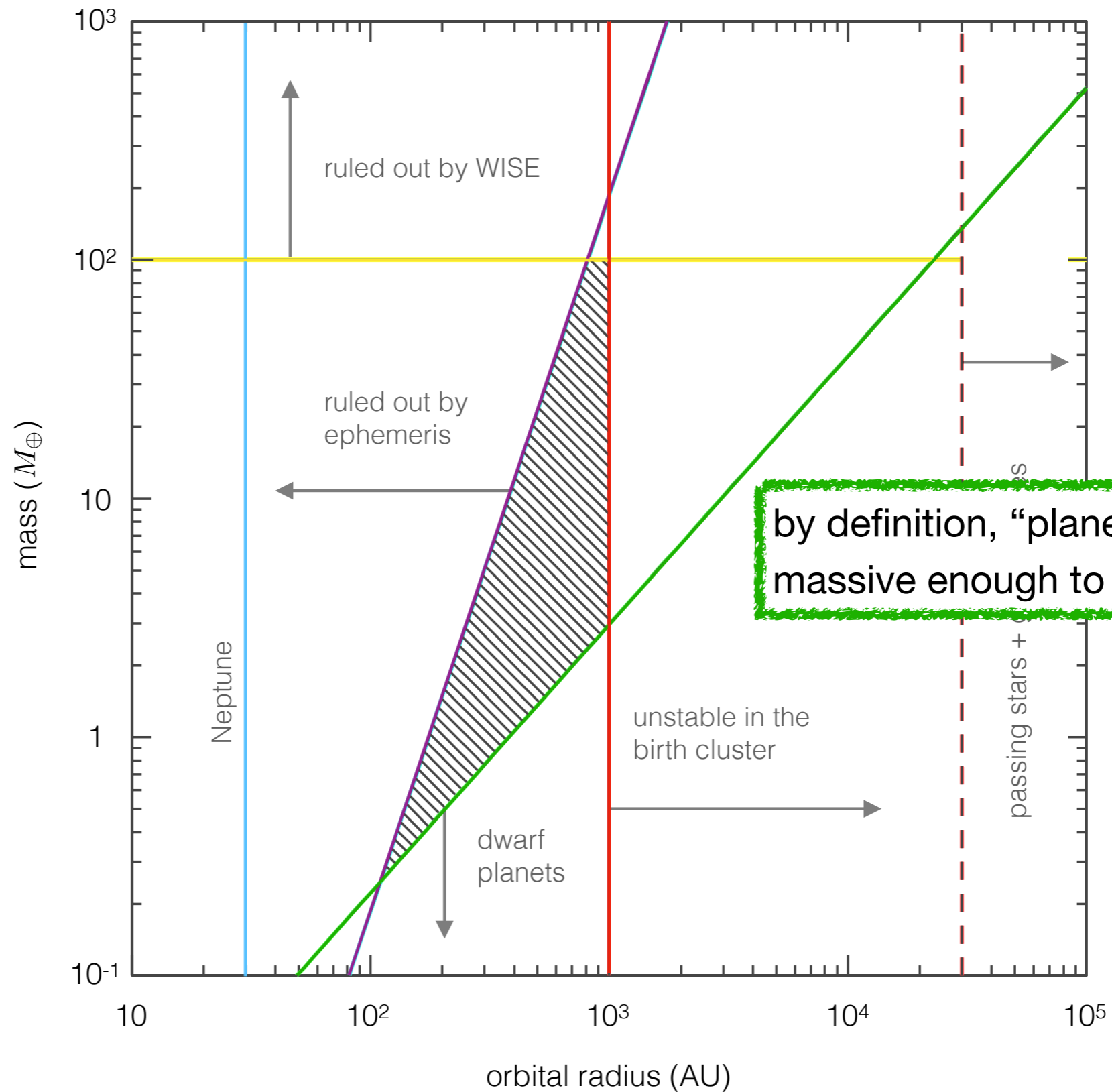
Planet 9?

- $m_9 \sim 5 - 10 M_{\oplus}$
- $a \sim 400 - 800$ au



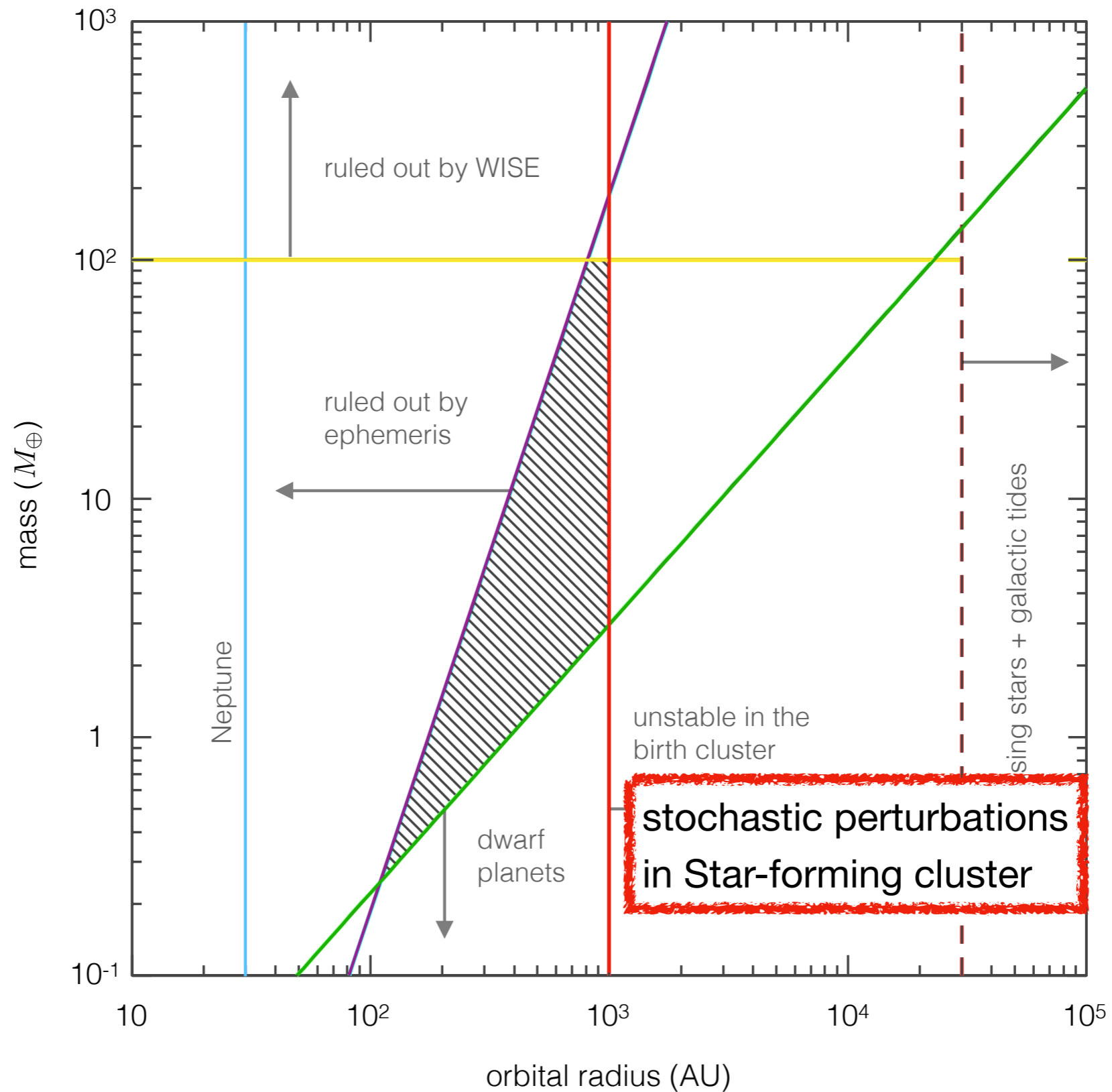
Available Window

Batygin et al. 2019



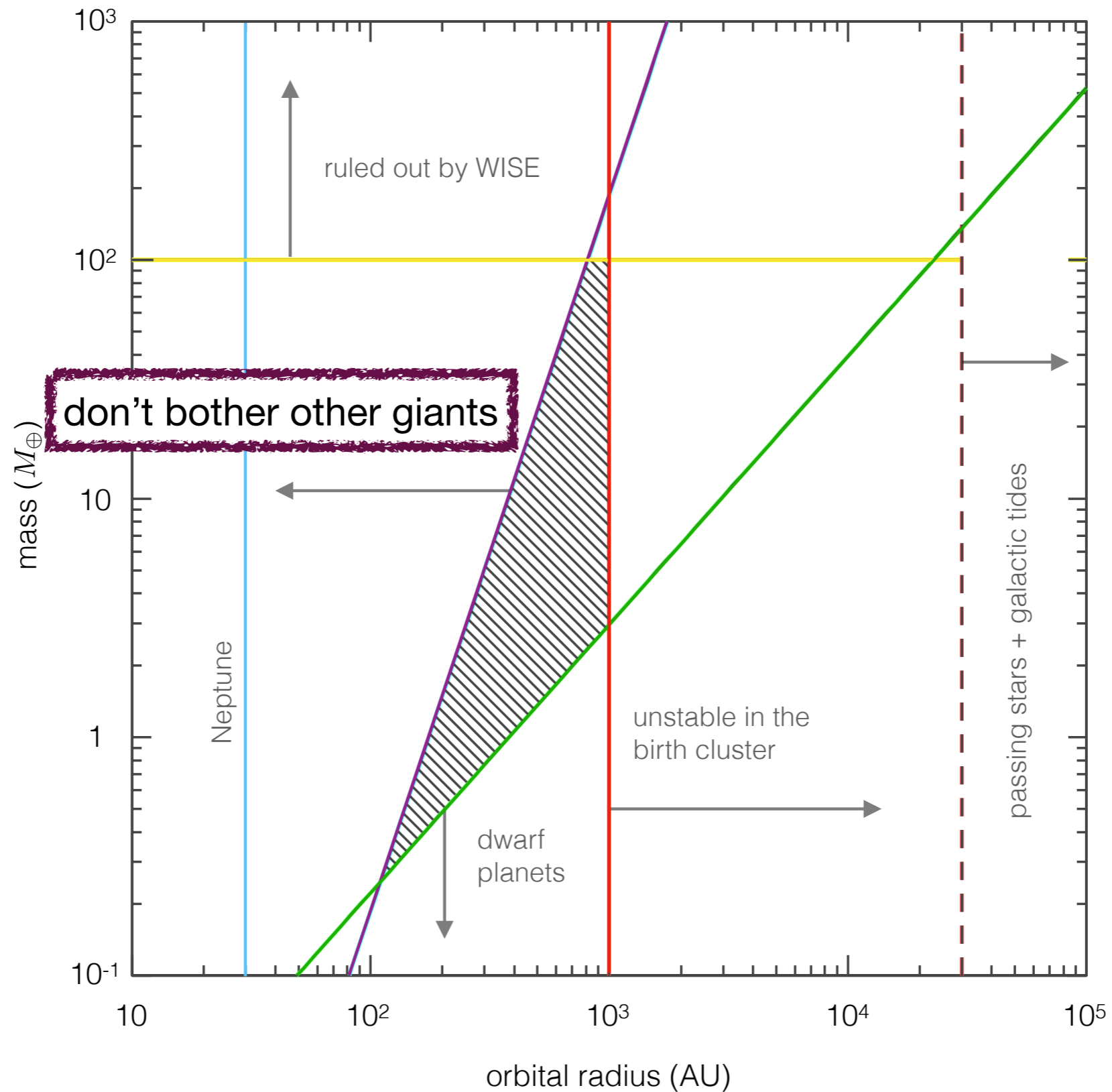
Available Window

Batygin et al. 2019



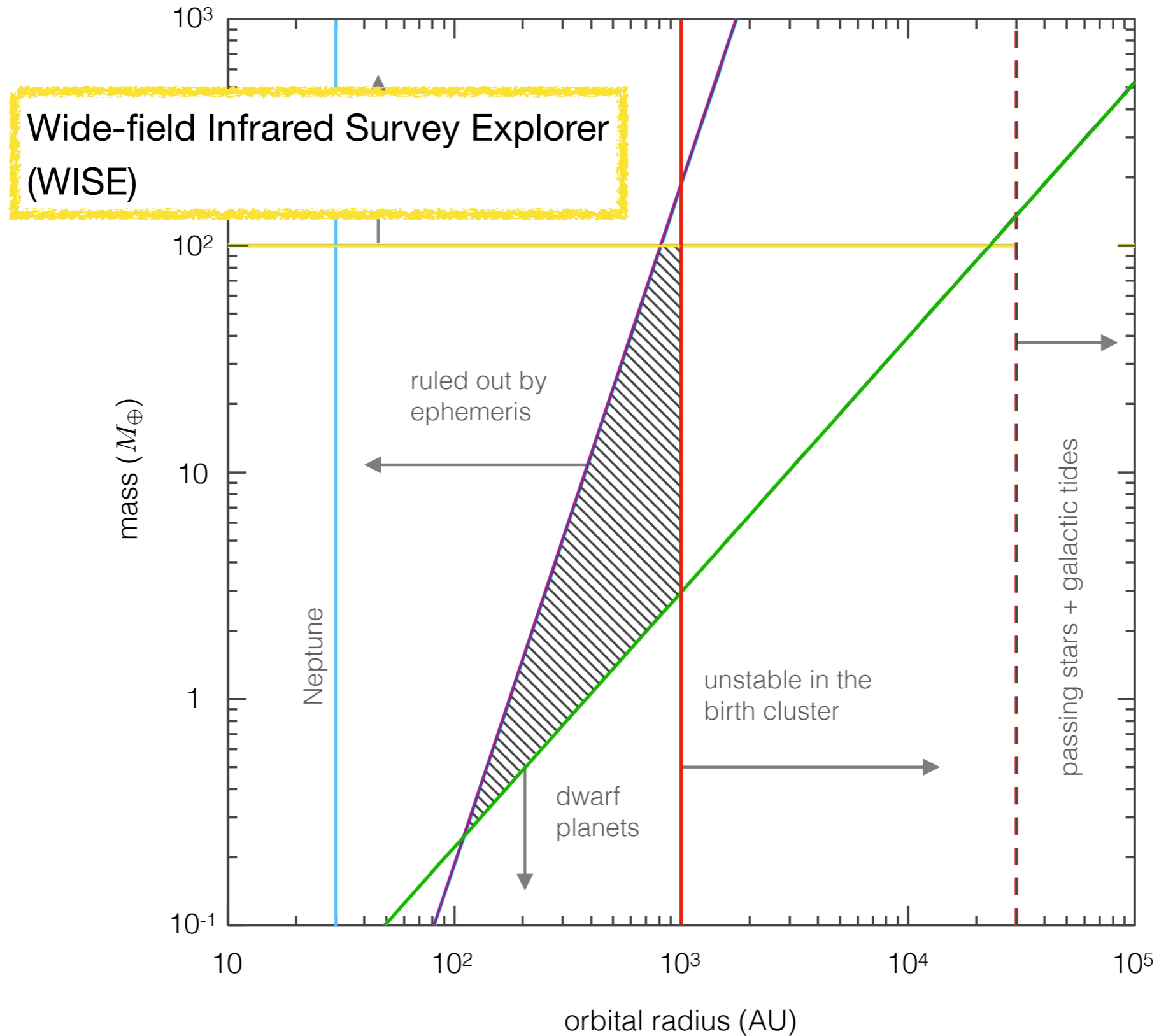
Available Window

Batygin et al. 2019



Available Window

Batygin et al. 2019





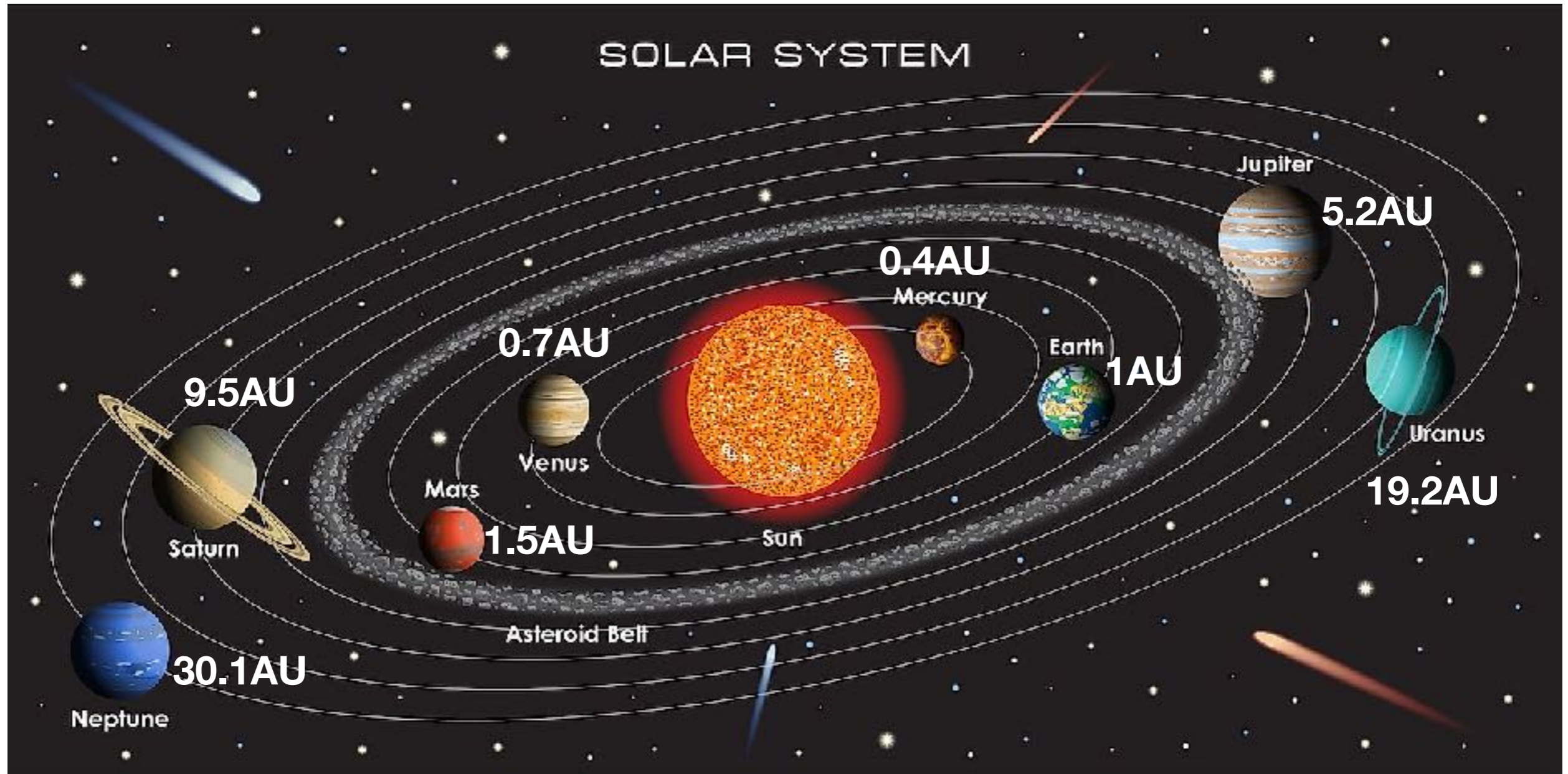
Planet 9

physical effect or observational bias?

Outline

- A short summary of the history about Planet Nine hypothesis
- Evidence of observational bias - OSSOS survey results
- Formation channels of Planet Nine (if real)?
- Summary

Emptiness of the outer Solar System?

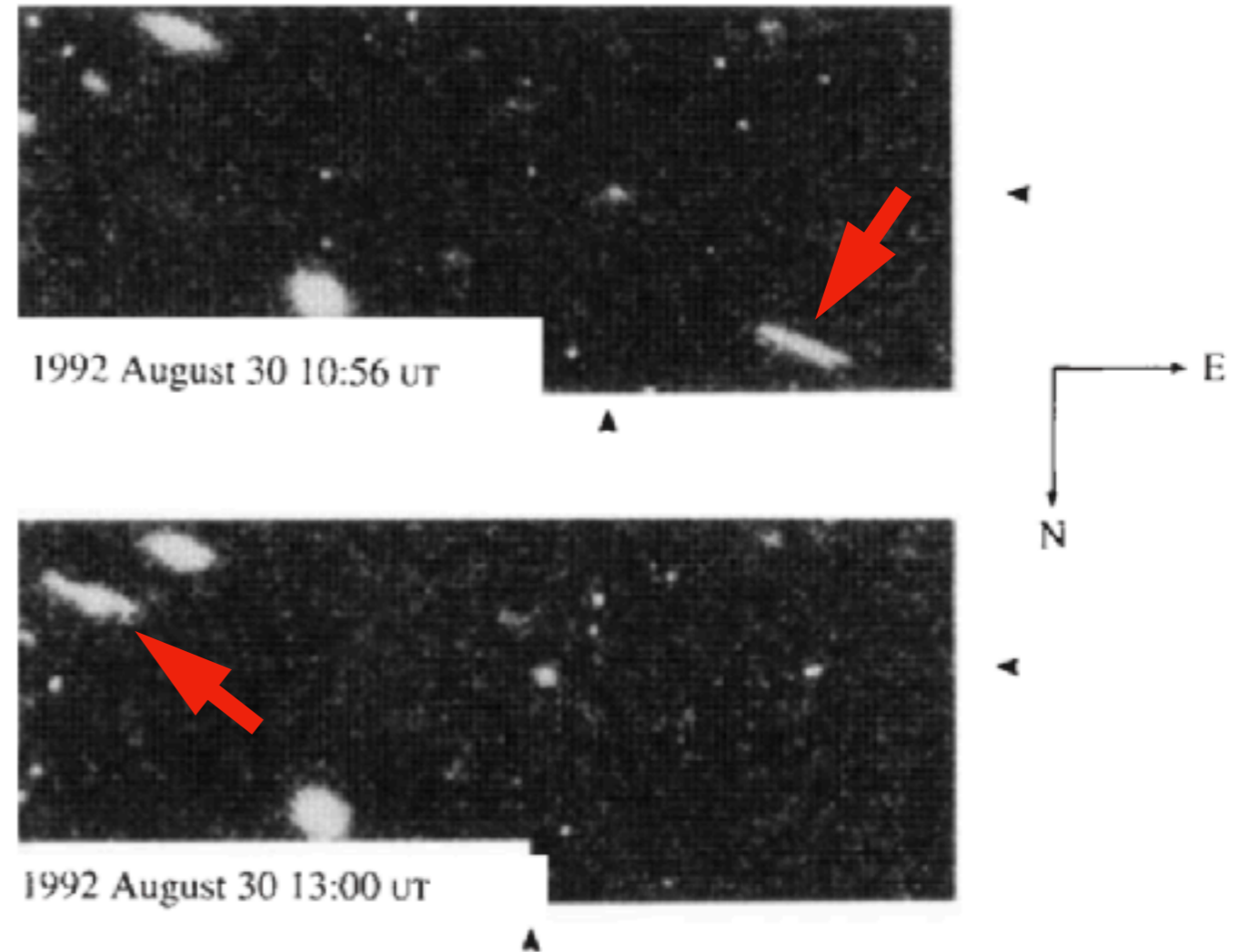


Objects beyond Neptune are too faint to be detected?

First detection of an object in the Kuiper Belt (trans-Neptunian)

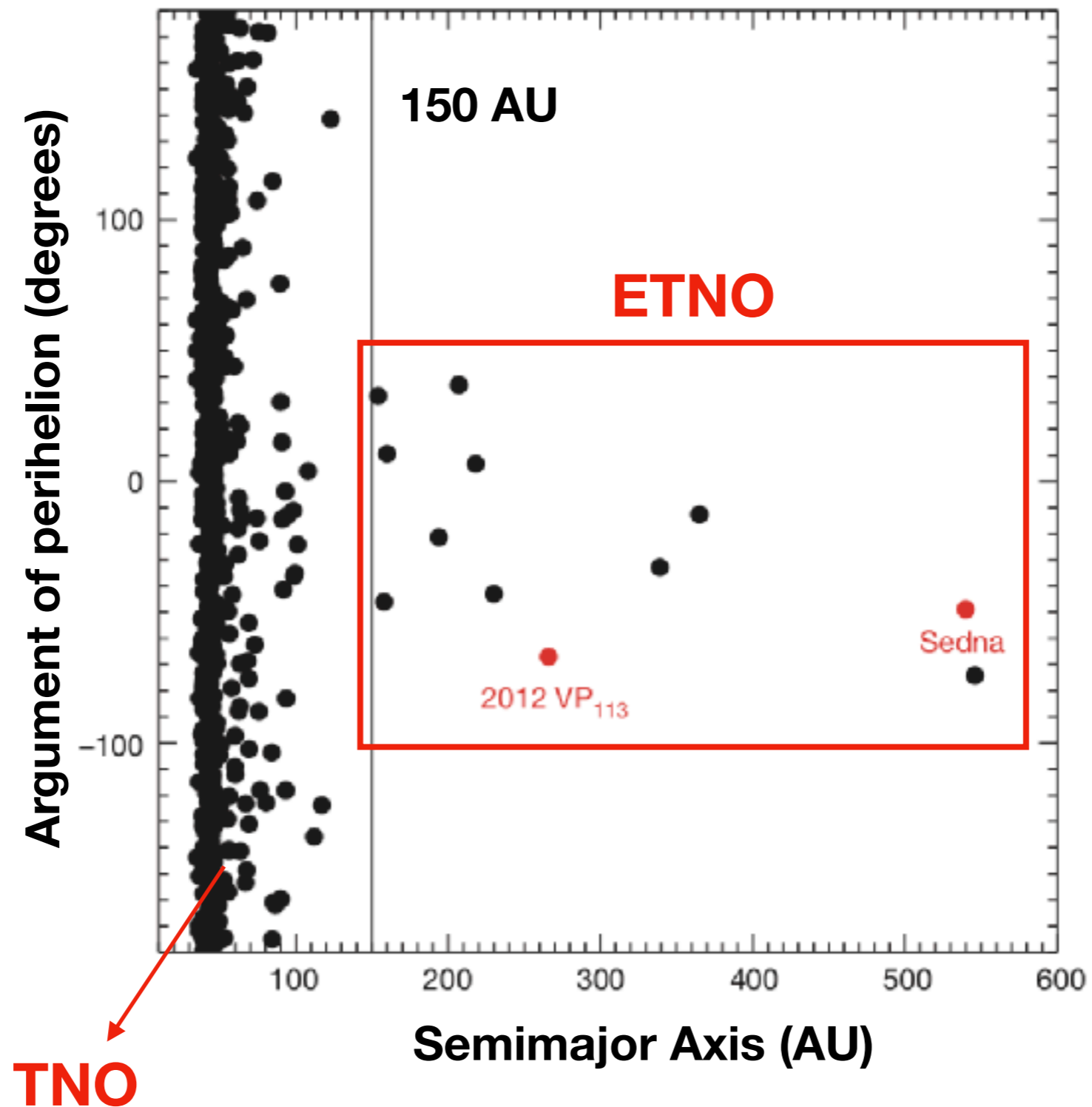


2.2m telescope at MK

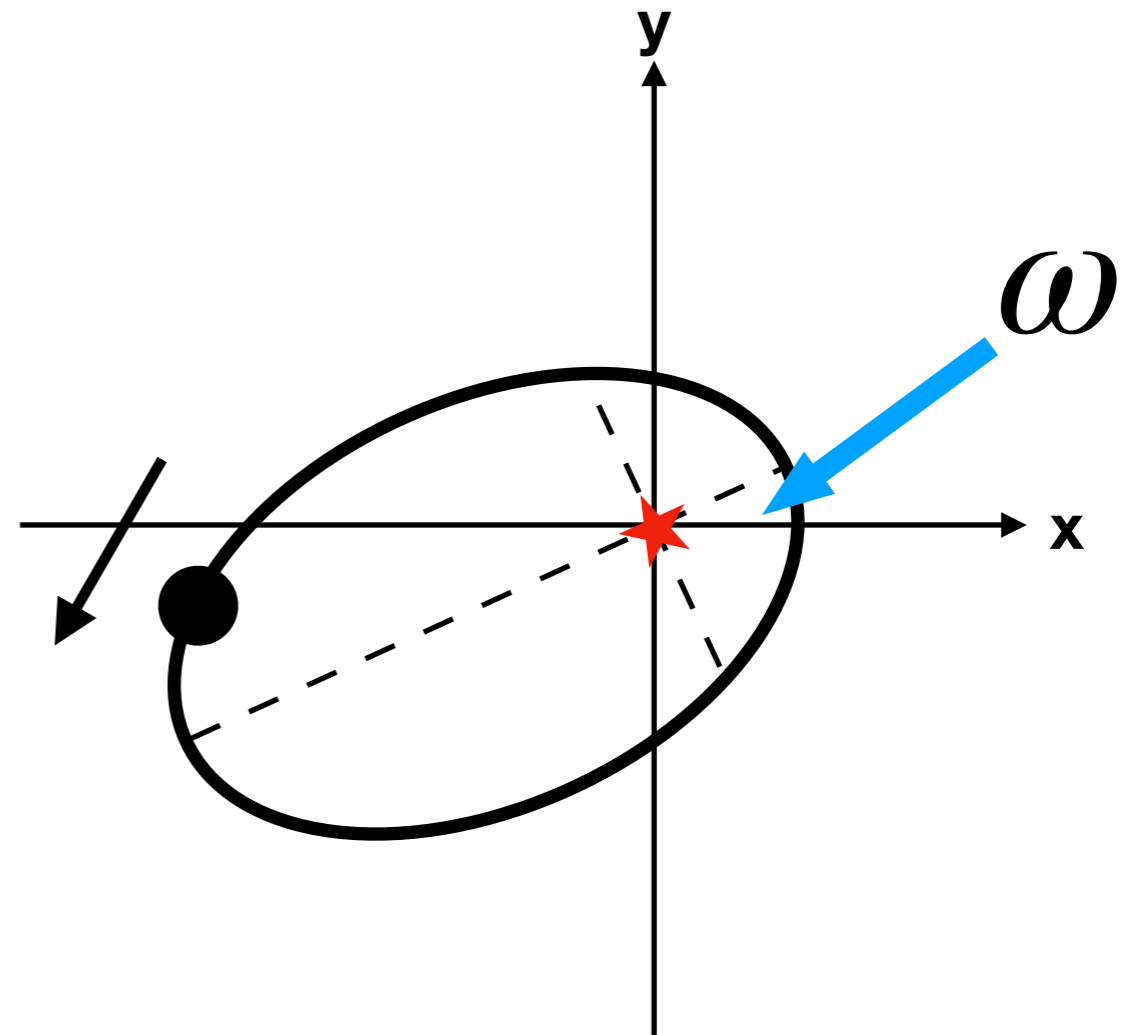
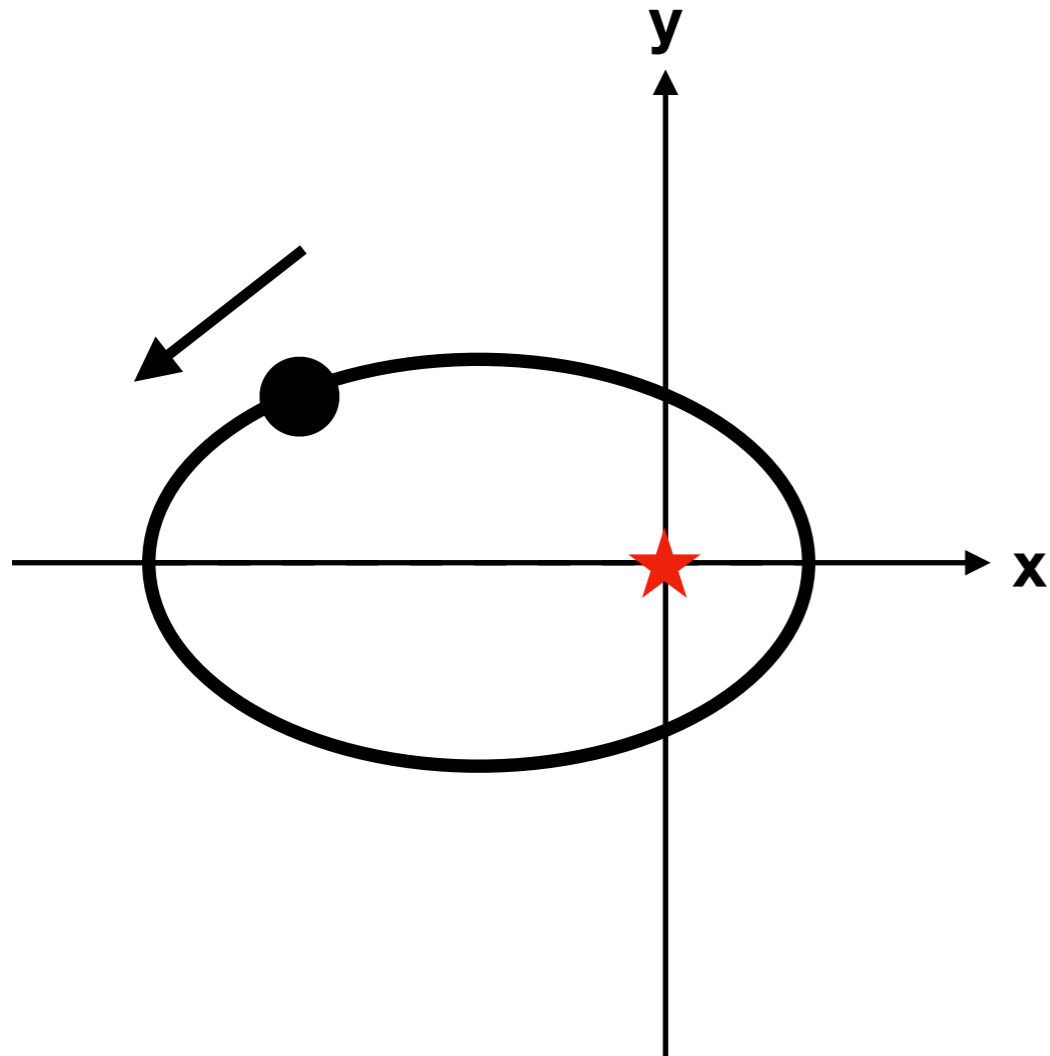


A deep image survey to find slowly moving objects beyond Neptune

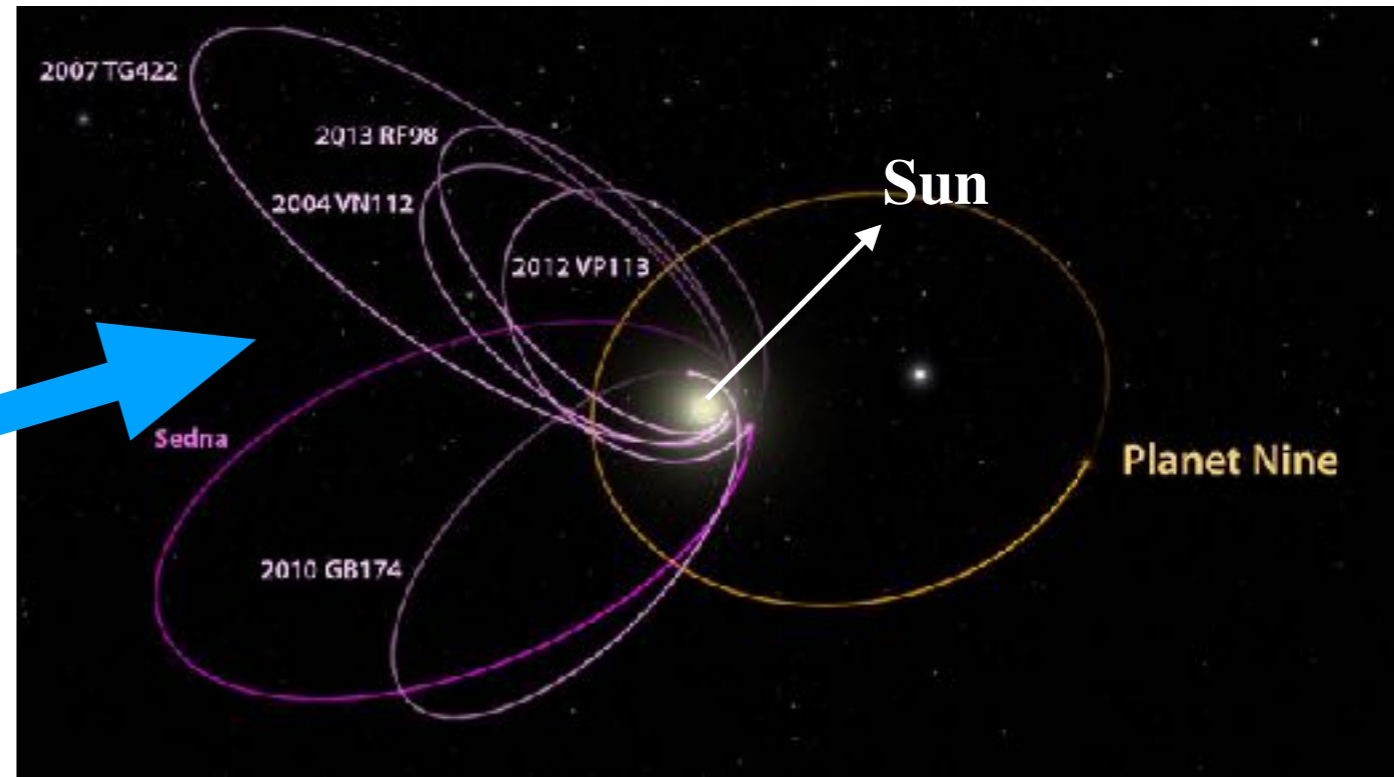
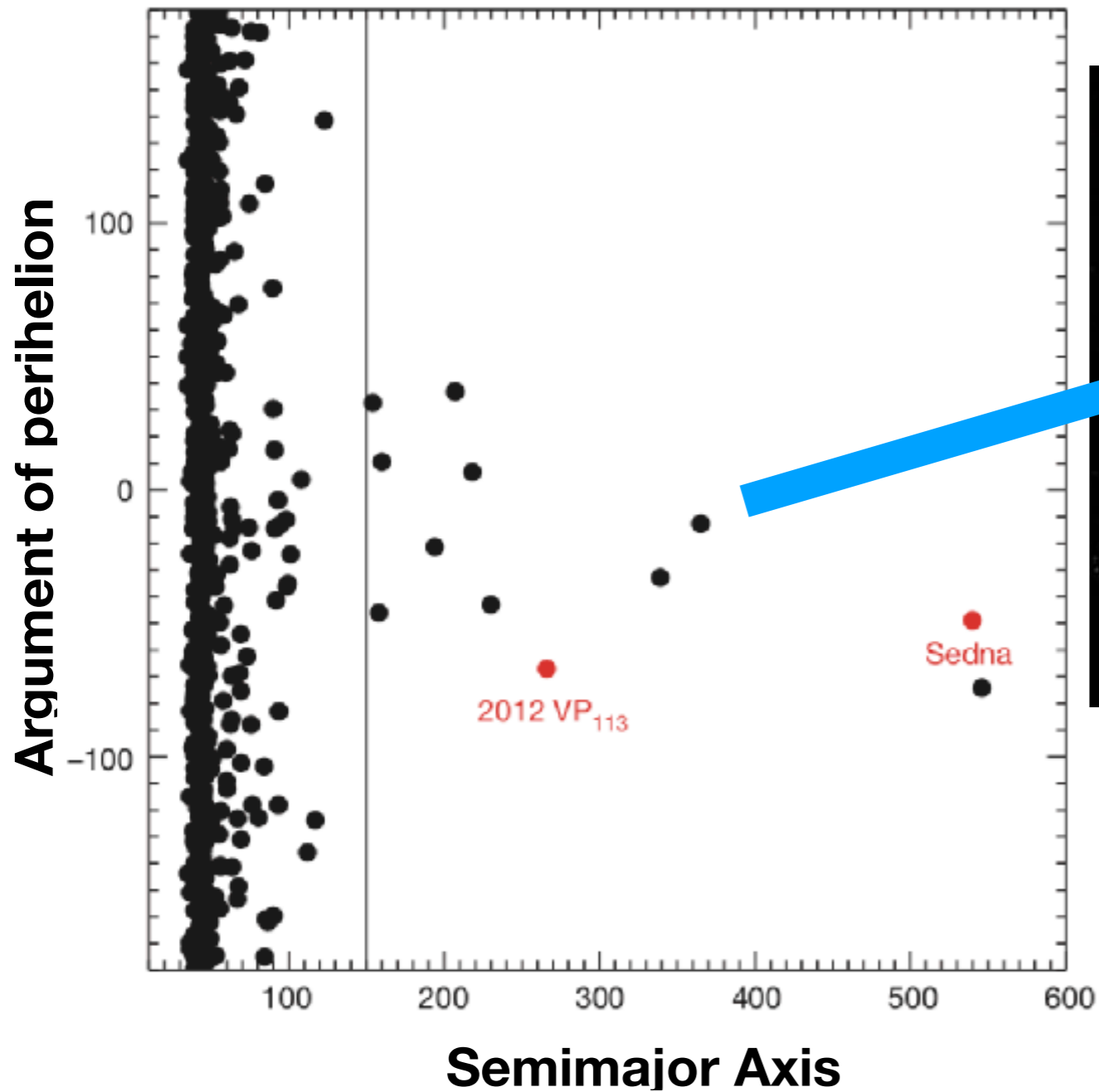
Clustering of extreme trans-Neptunian objects (ETNO)



Definition of argument of perihelion



Planet Nine Hypothesis



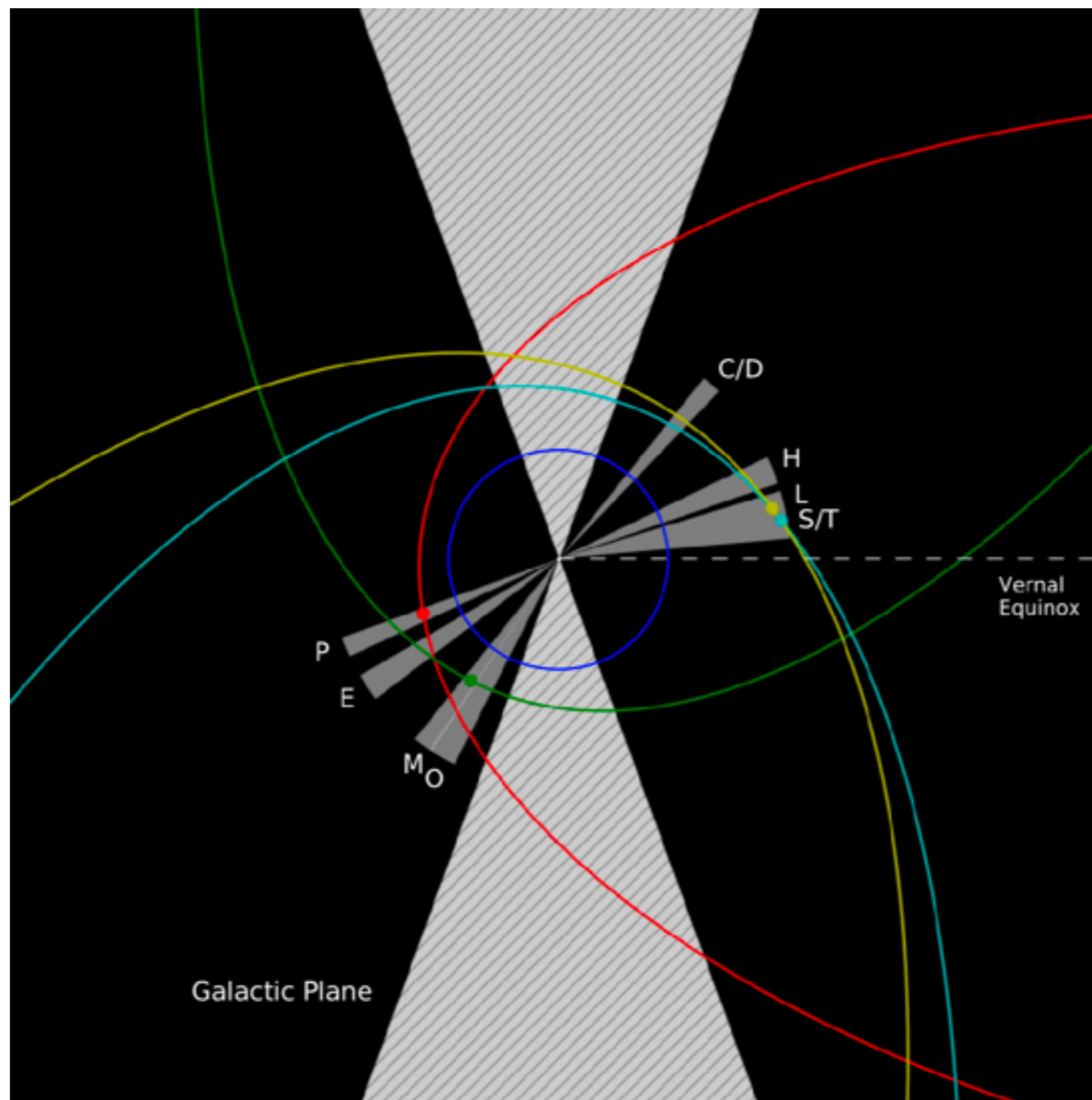
$$m_9 \sim 5 - 10 M_{\oplus} \quad a_9 \sim 400 - 800 \text{ AU}$$

$$i_9 \sim 15 - 25^\circ \quad e_9 \sim 0.2 - 0.5$$

Take home message

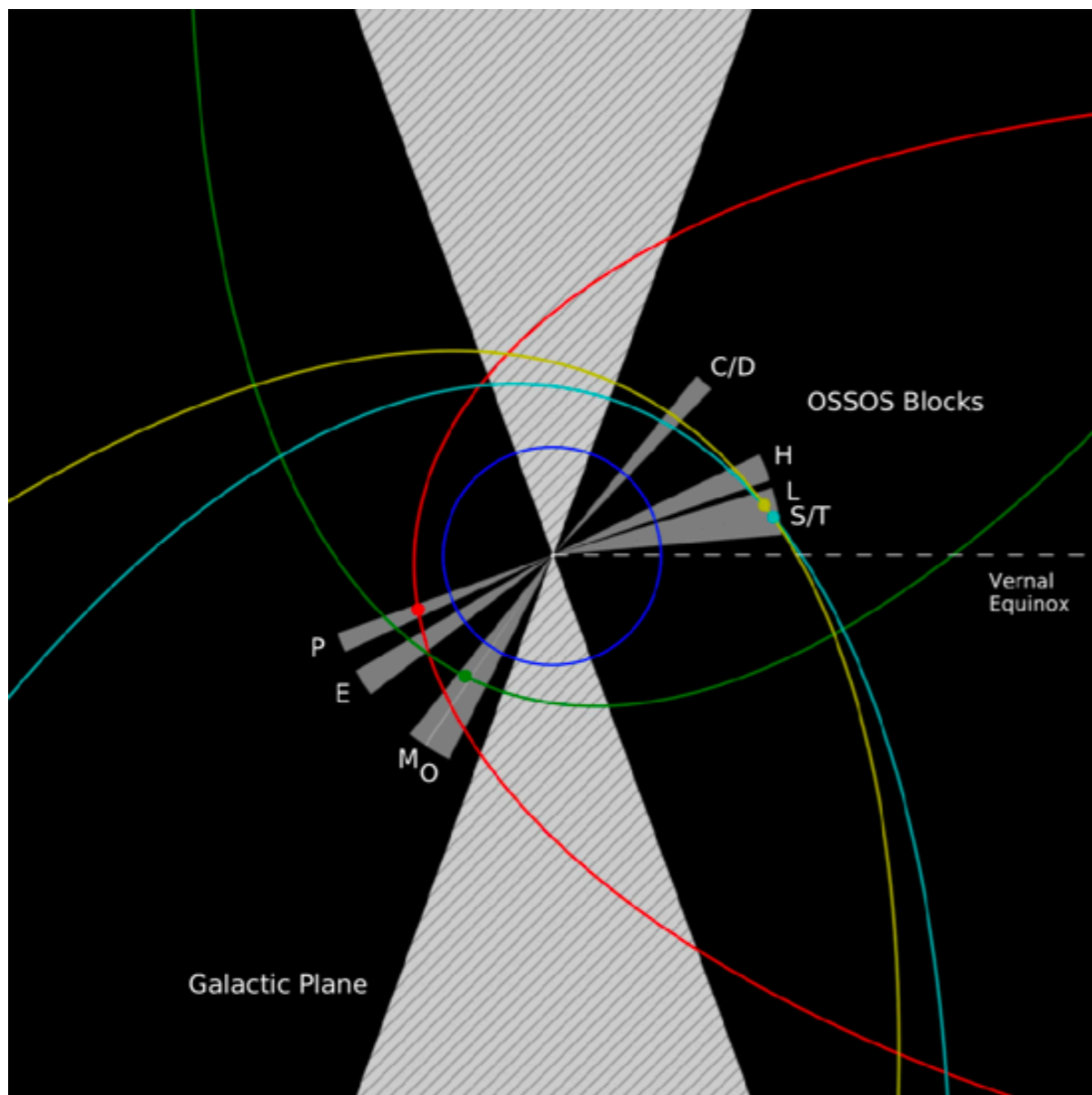
- The clustering of extreme trans-Neptunian objects indicates the existence of Planet Nine.
- The clustering feature may be caused by observational bias.
- The formation of Planet Nine (if indeed exists) remains a mystery.

Observational Bias I: geometry



Most ETNOs were detected around the perihelion (近日点)

Observational Bias II: Seasonal changes



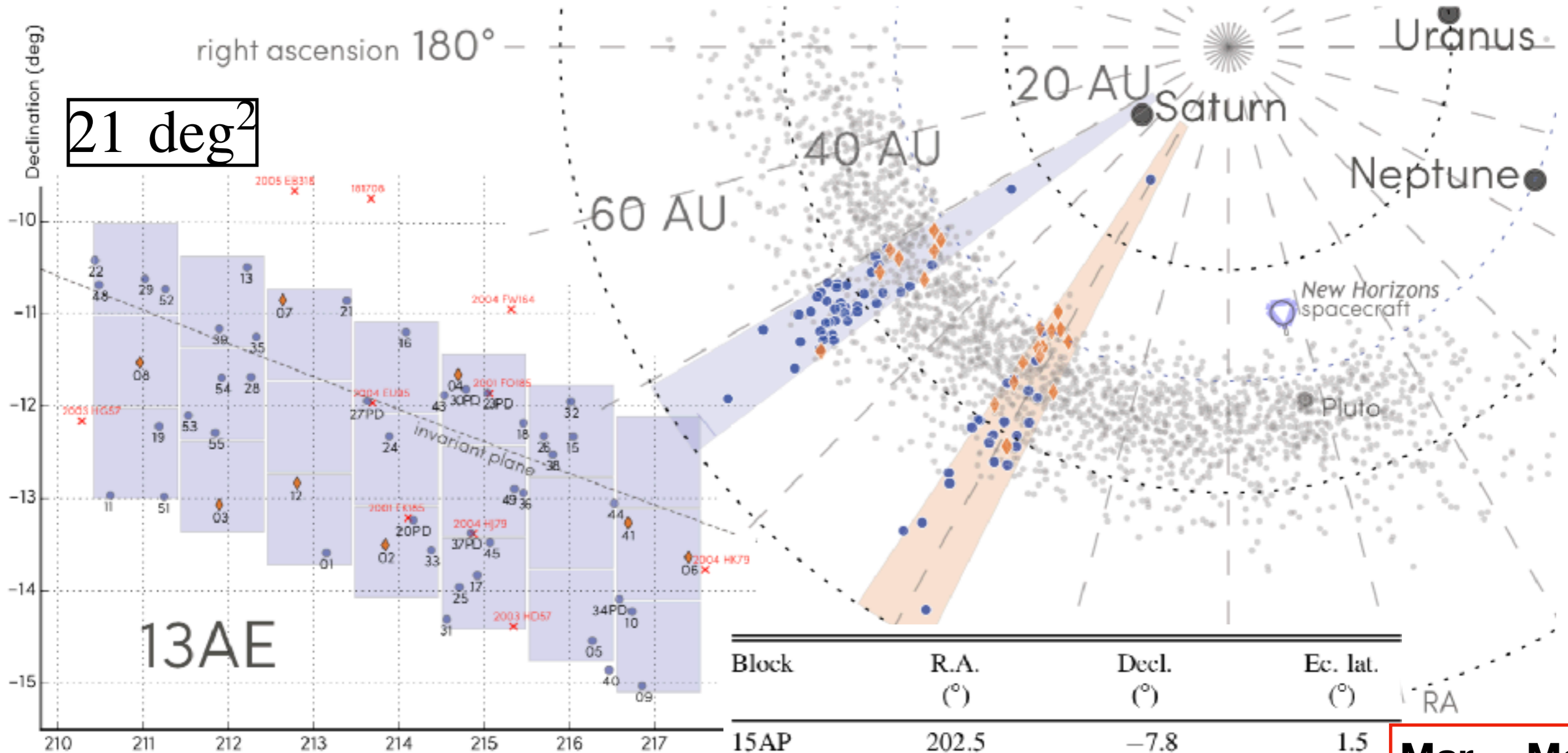
Lijiang Observatory

一月	二月	三月	四月	五月	六月
七月	八月	九月	十月	十一月	十二月

RA~12h

Are people looking at the same quadrant of the solar system?

Outer Solar System Origins Survey (OSSOS)



Block	R.A. ($^\circ$)	Decl. ($^\circ$)	Ec. lat. ($^\circ$)
15AP	202.5	-7.8	1.5
13AE	213.9	-12.5	1.0
15AM	233.8	-12.2	6.9
13AO	239.5	-12.3	8.0
15BS	7.5	5.0	1.6
13BL	13.5	3.8	-1.8
14BH	22.5	13.0	3.3
15BD	48.8	16.5	-1.5

Mar. ~ May

Sep. ~ Nov.

OSSOS survey simulation

Initial settings

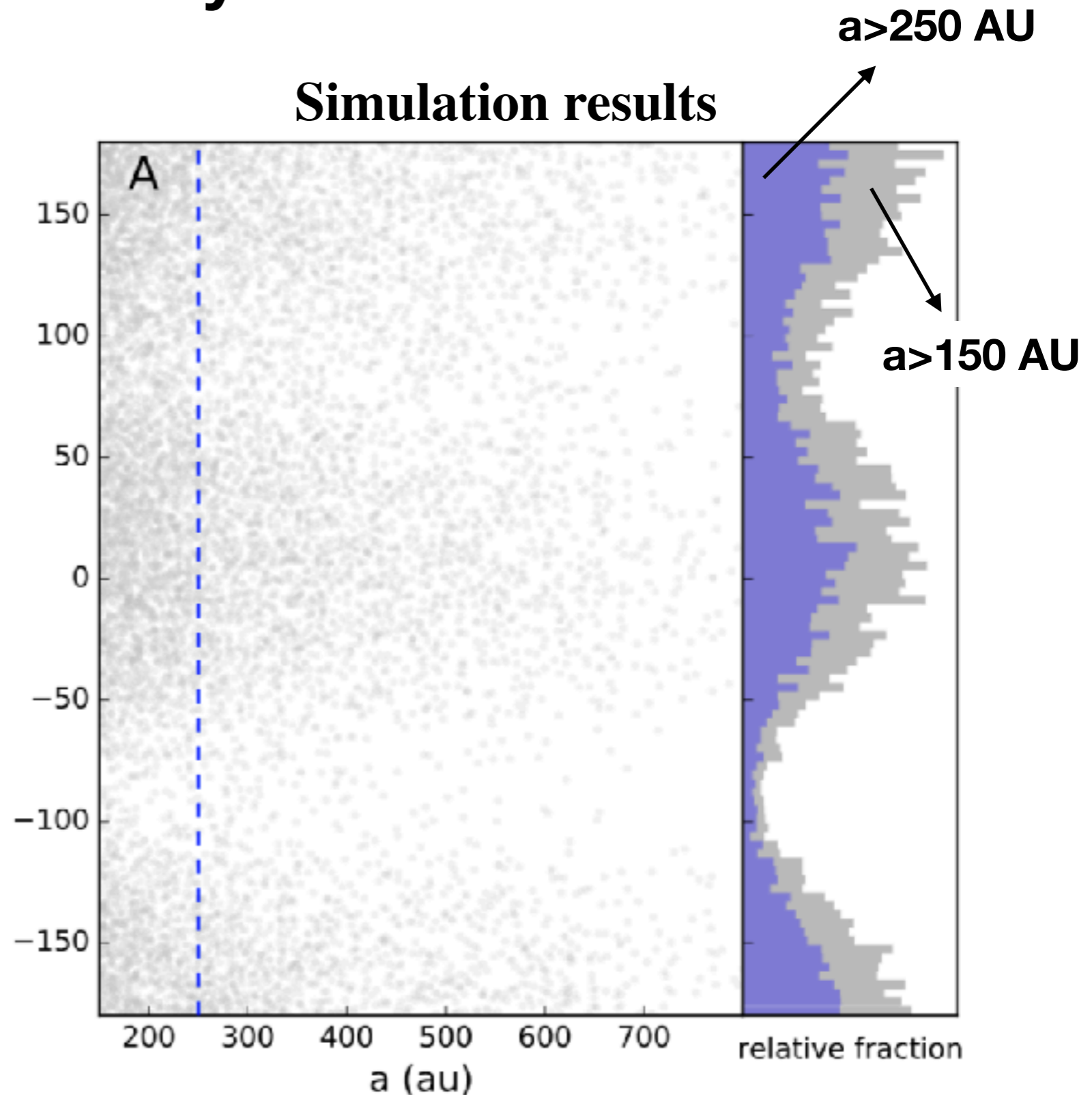
$a : U(150, 1000)$ AU

$\omega : U(-180, 180)$ degrees

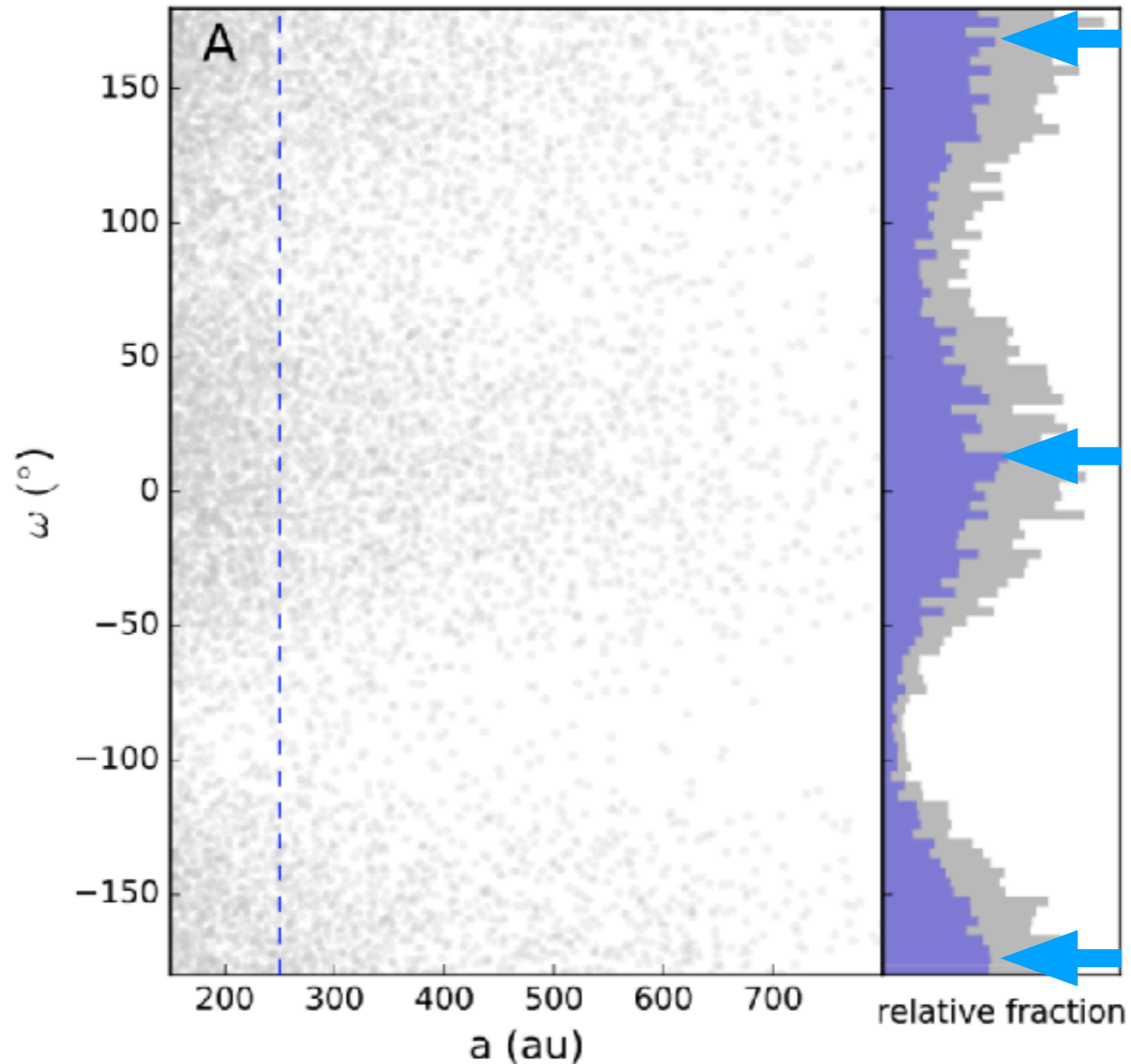
$e : U(0.7, 0.95)$

$i : U(0, 55)$ degrees

Simulation results

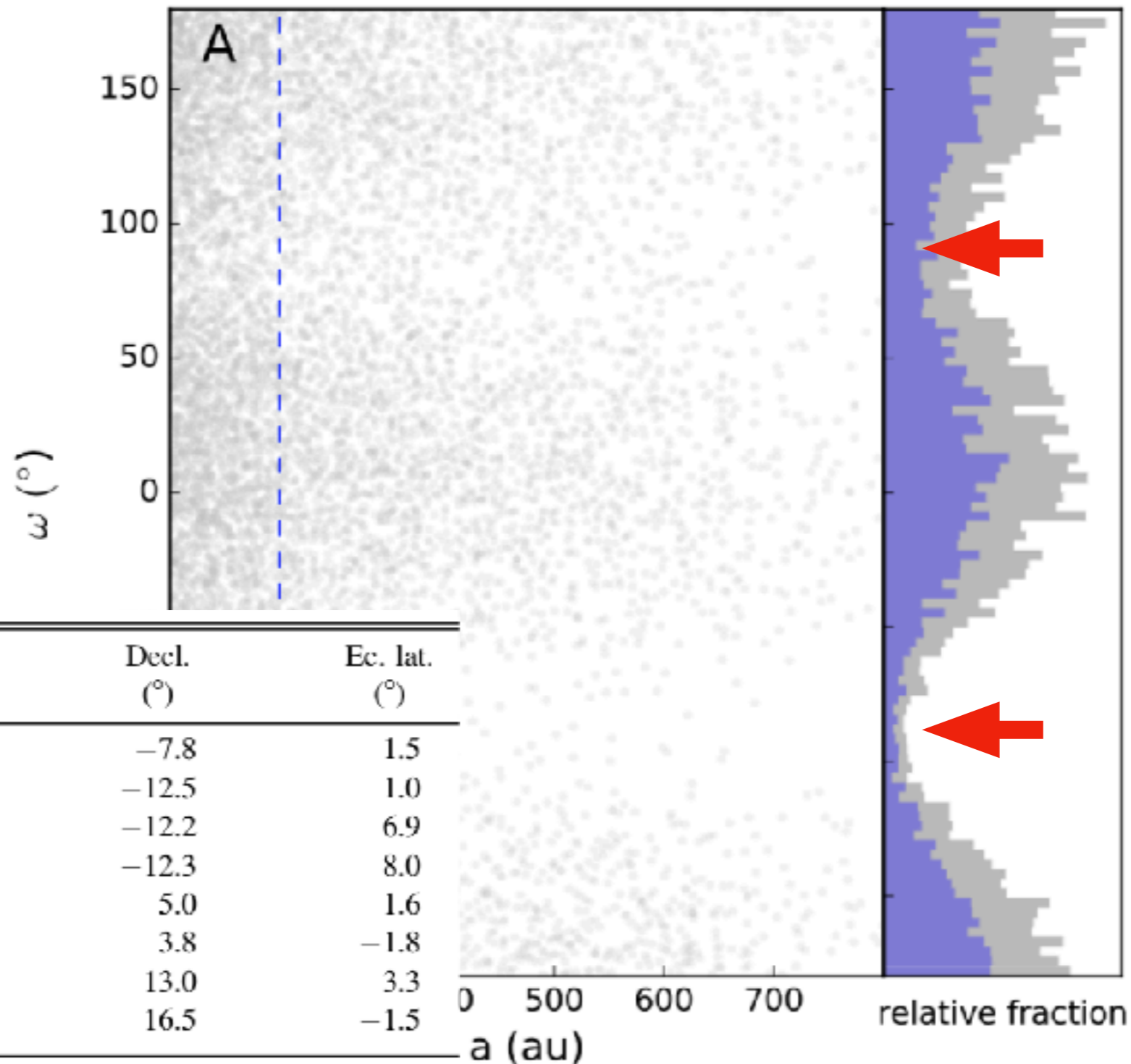


OSSOS survey simulation



Bias from near-ecliptic surveys

OSSOS survey simulation



Block	R.A. (°)	Decl. (°)	Ec. lat. (°)
15AP	202.5	-7.8	1.5
13AE	213.9	-12.5	1.0
15AM	233.8	-12.2	6.9
13AO	239.5	-12.3	8.0
15BS	7.5	5.0	1.6
13BL	13.5	3.8	-1.8
14BH	22.5	13.0	3.3
15BD	48.8	16.5	-1.5

Bias from off-ecliptic pointing

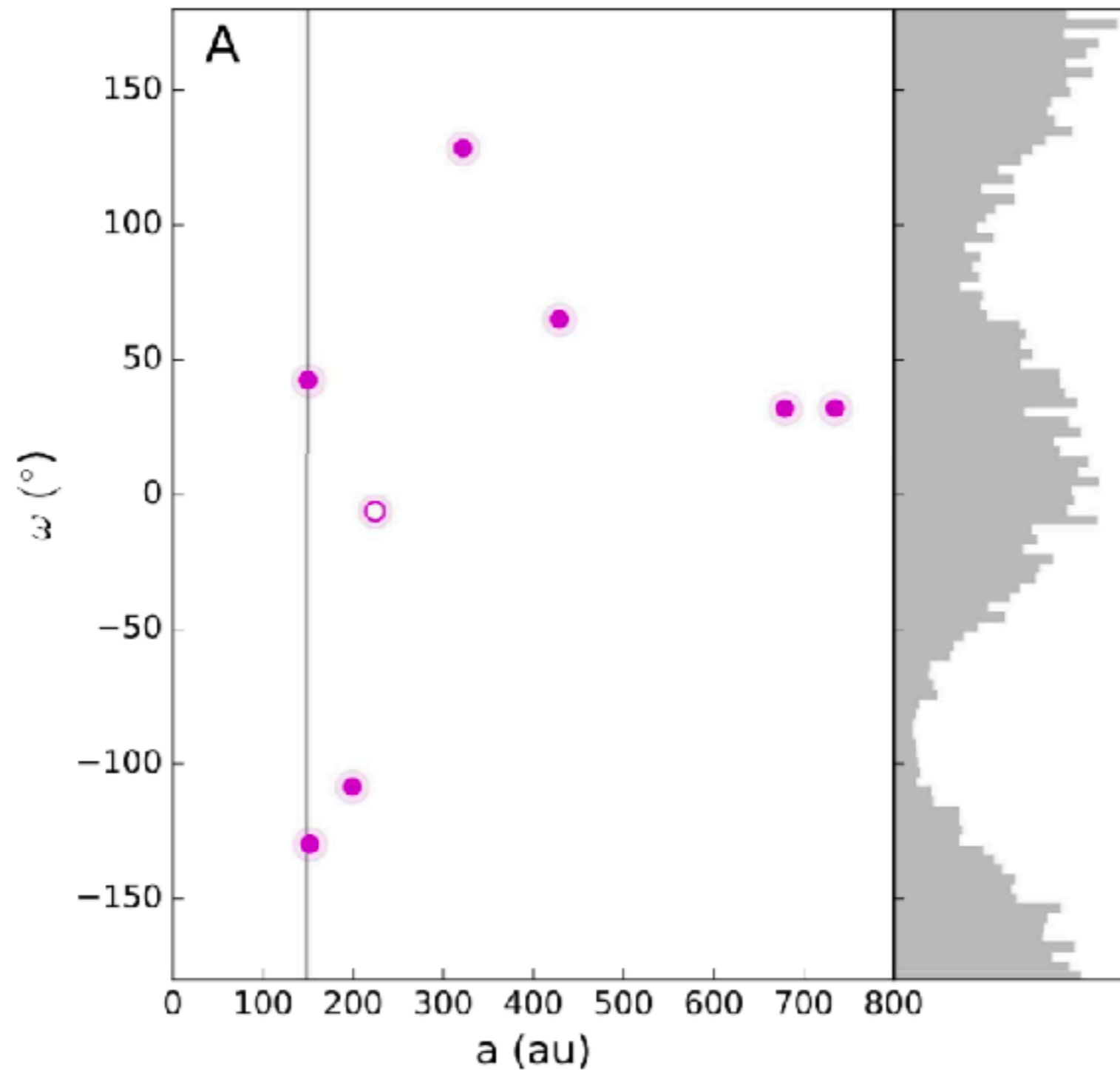
OSSOS Discoveries

~800 new TNOs, 8 new ETNOs

OSSOS Desig.	a (au)	e	q (au)	i ($^{\circ}$)	Ω ($^{\circ}$)	ω ($^{\circ}$)	ϖ ($^{\circ}$)	r (au)	m_r (discovery)	H_r
o3e39	150.2 ± 0.1	0.727	41.0	33.5	-149.3	45.4	-106.8	45.5	23.1	6.4
o5m85	153.0 ± 0.3	0.739	39.9	27.1	67.6	-129.2	-61.6	51.7	24.7	7.6
o3l83	200 ± 1	0.780	43.9	10.7	-168.0	-107.9	84.1	61.2	24.1	6.2
o5s13	226 ± 3	0.861	31.4	6.0	-18.5	-5.5	-24.0	34.3	24.6	9.1
o5p060	312 ± 2	0.877	38.4	8.8	46.1	129.0	175.1	41.0	24.5	8.3
o5t52	430 ± 20	0.894	45.5	12.1	8.6	65.2	73.8	62.4	24.1	6.1
o5m52	680 ± 2	0.940	40.5	14.0	-140.9	32.1	-108.8	41.1	24.3	8.1
uo3l91	735 ± 15	0.932	50.0	4.2	29.5	32.2	61.7	60.9	24.8	6.8

Clustering feature in this independent sample?

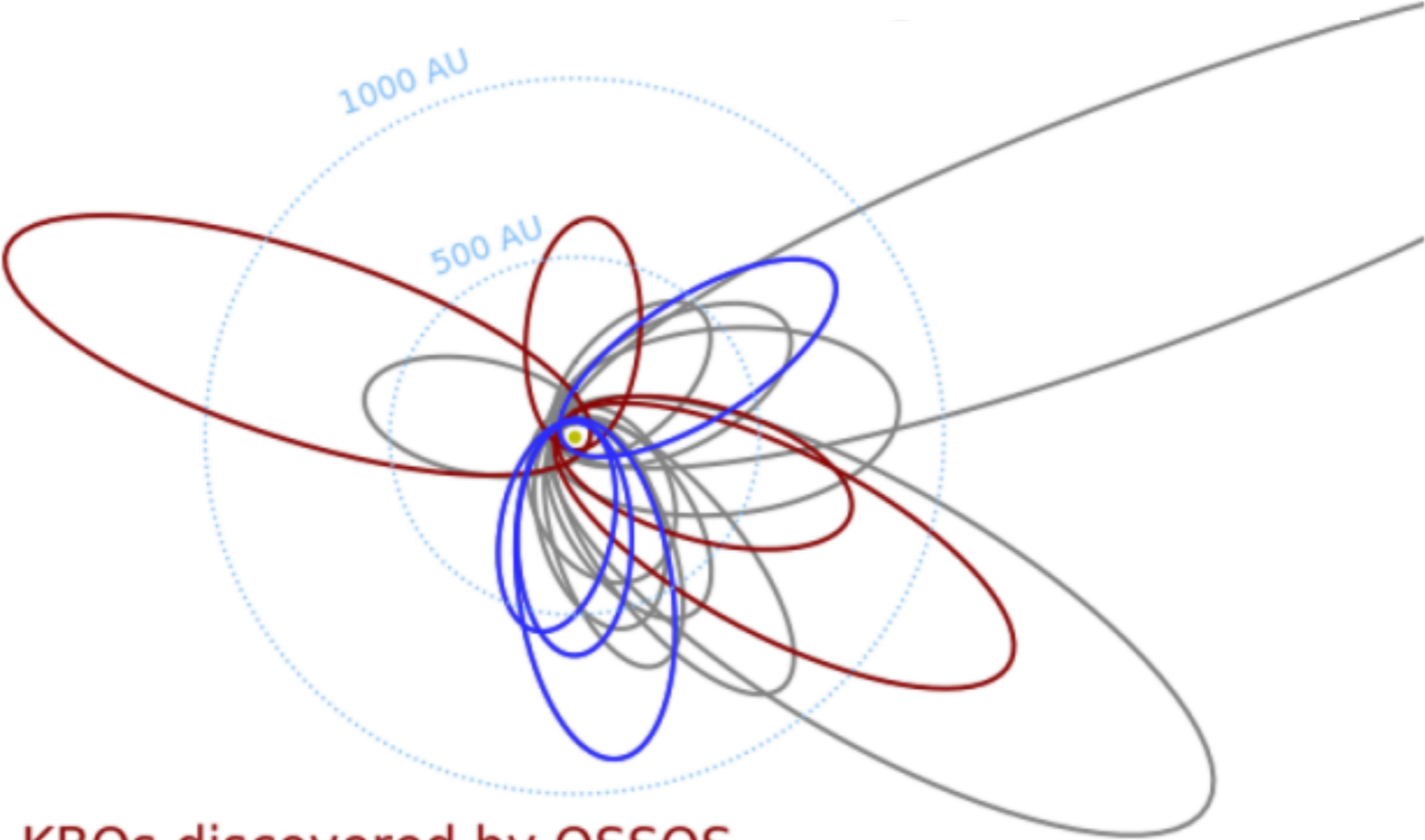
8 New ETNOs from OSSOS: little evidence of clustering



A uniform intrinsic distribution?

rejectable at **47%**

Recent picture of all ETNOs with $a > 250$ AU



KBOs discovered by OSSOS

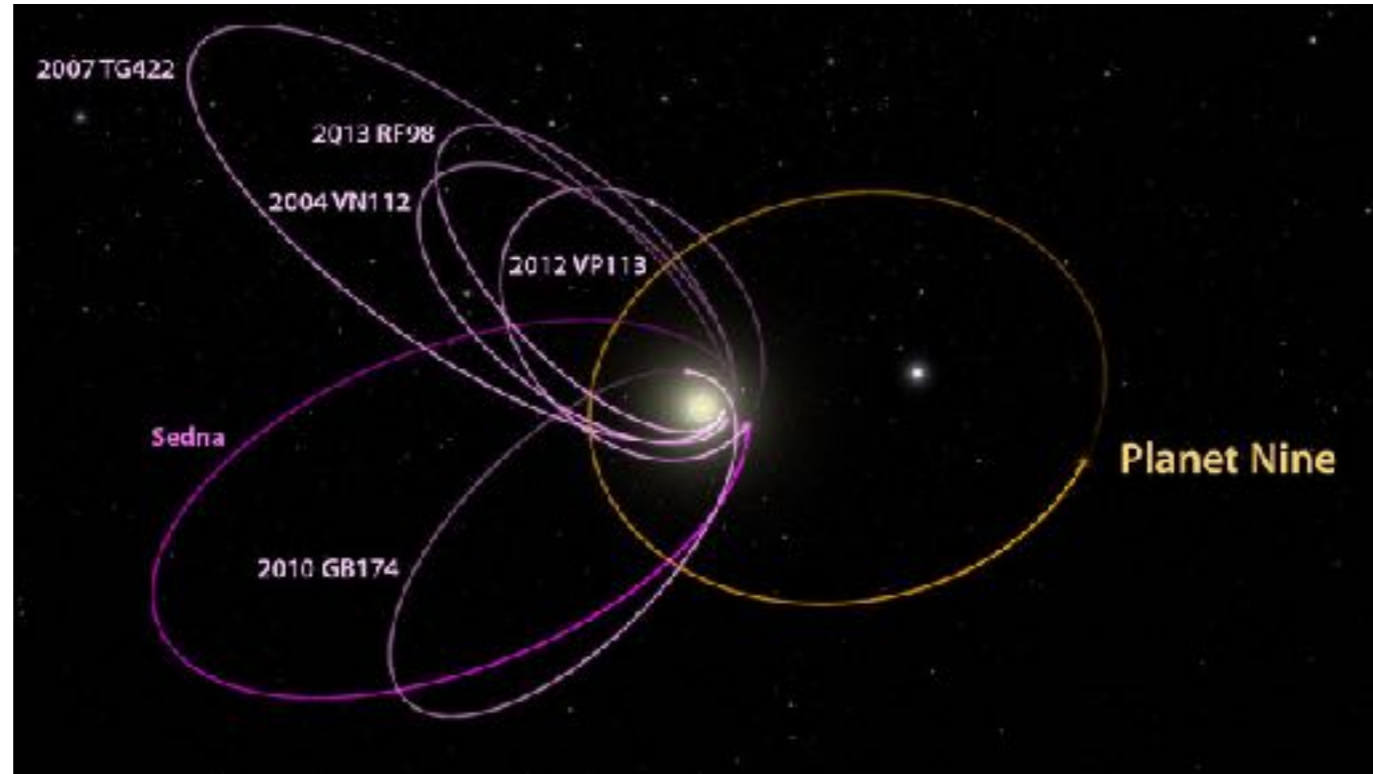
KBOs discovered by DES



Dark Energy Survey

KBOs discovered in other surveys

How was “Planet Nine” formed?



$$a_9 \sim 400 - 800 \text{ AU}$$

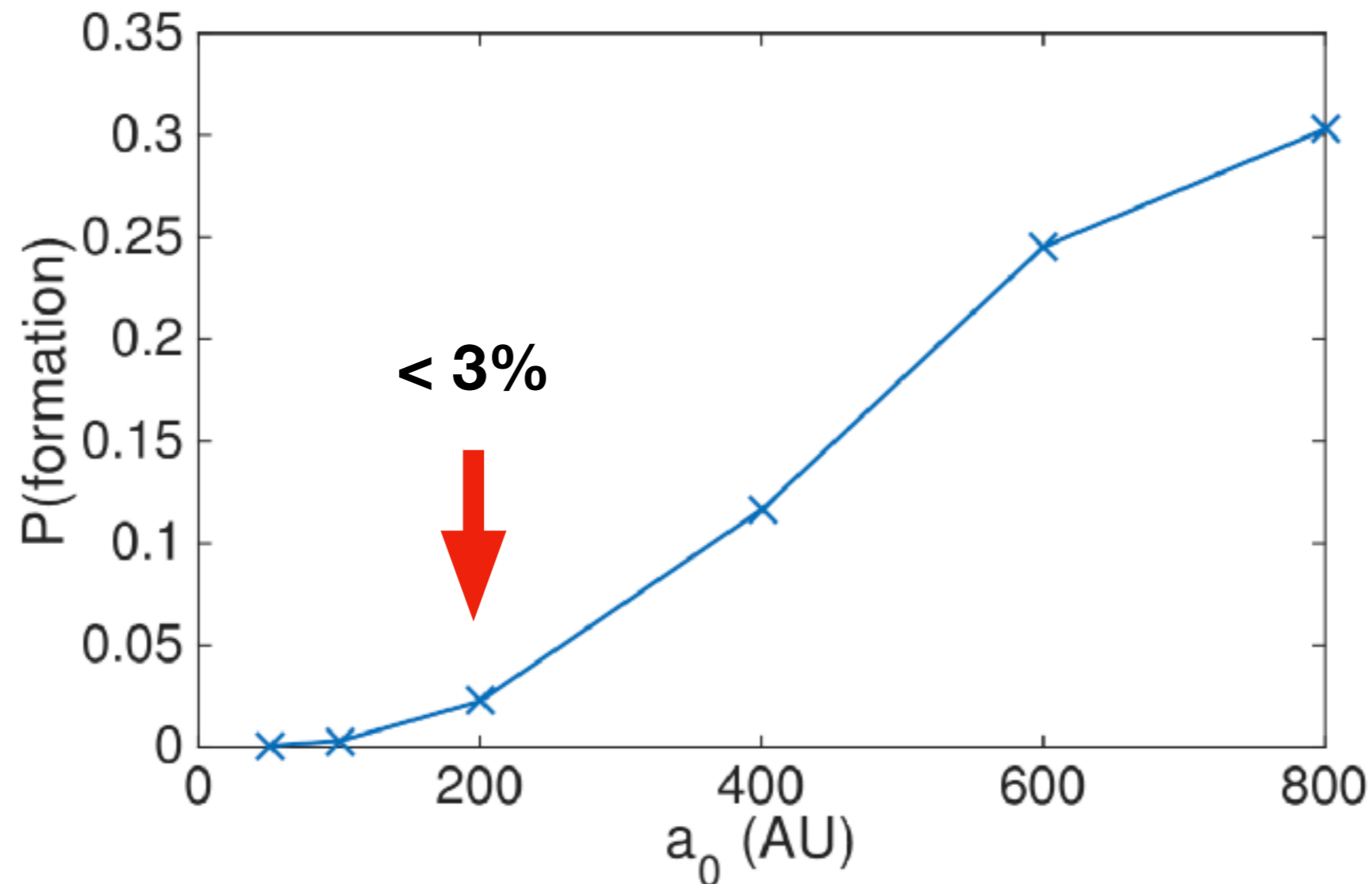
$$m_9 \sim 5 - 10 M_{\oplus}$$

Core accretion?

Disk instability?

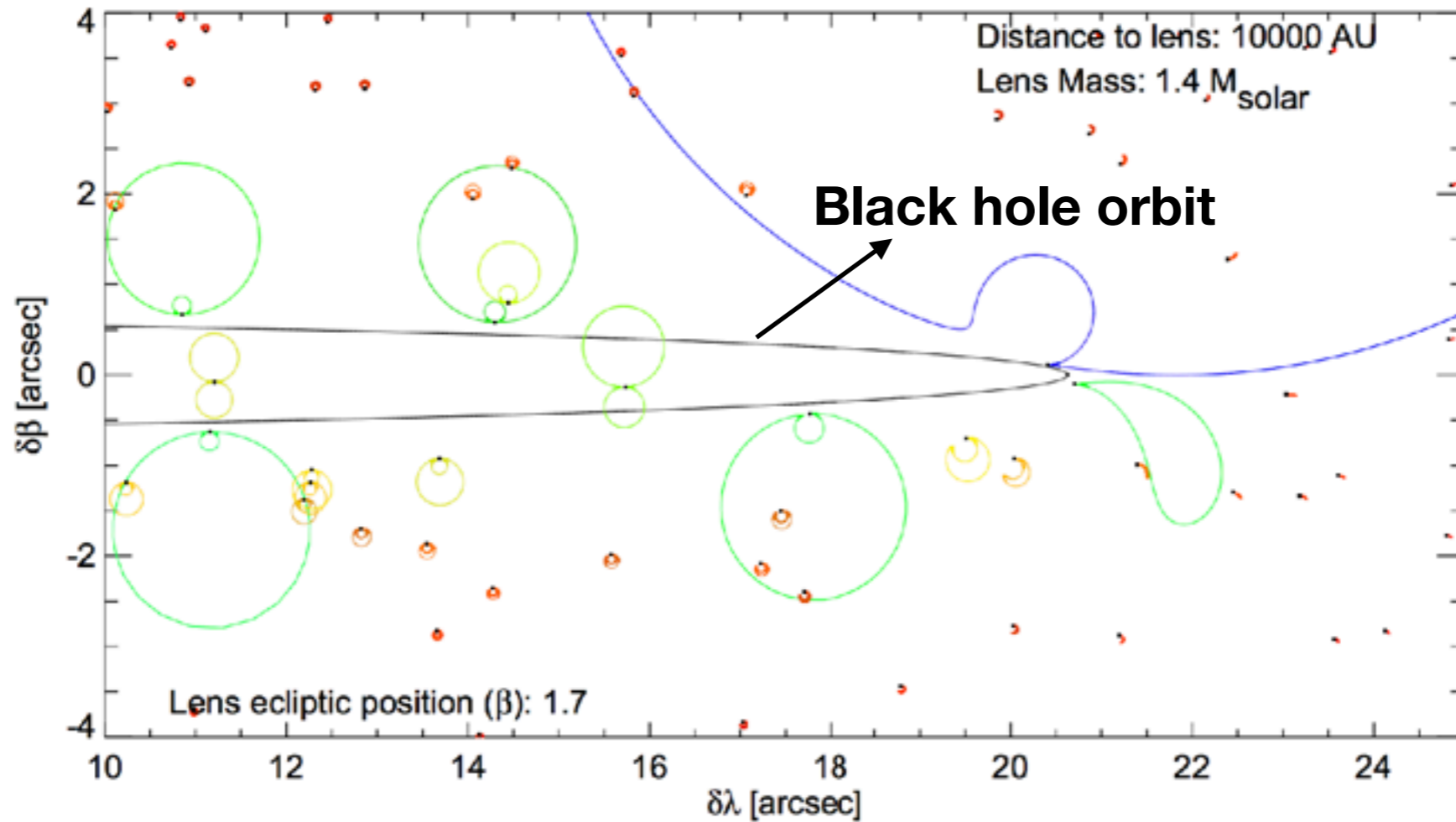
How was “Planet Nine” formed?

1. Scattering outwards $a_9 \sim 400 - 800$ AU



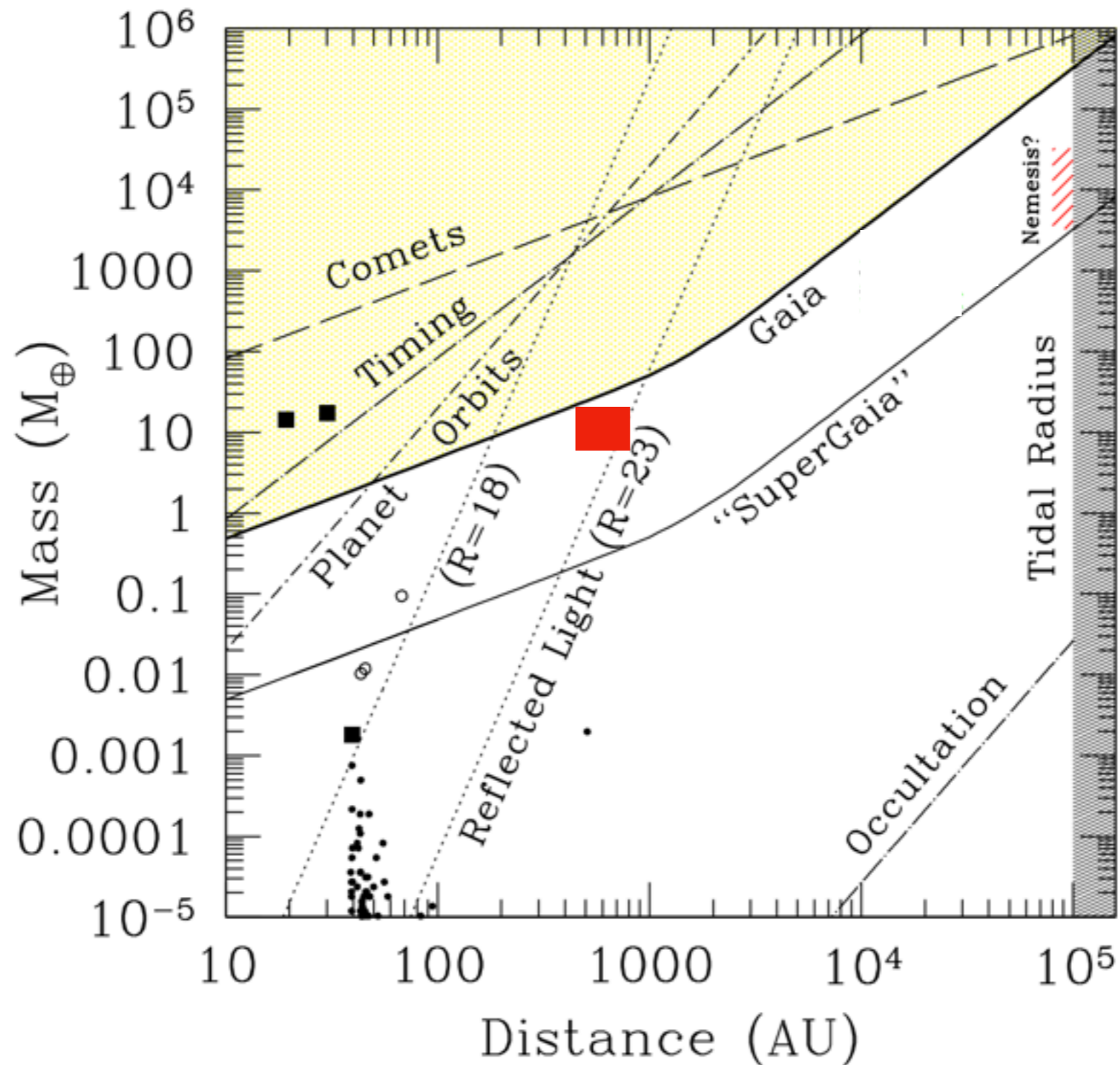
2. Capture from another system or free floating planet: $< 1\%$

A planet mass primordial black hole?



Astrometric microlensing constraints from Gaia

A planet mass primordial black hole?



異議あり!



New evidence

de la Fuente Marcos & de la Fuente Marcos 2022

MNRAS **000**, 1–5 (2022)

Preprint 21 February 2022

Compiled using MNRAS L^AT_EX style file v3.0

Twisted extreme trans-Neptunian orbital parameter space: statistically significant asymmetries confirmed

C. de la Fuente Marcos¹★ and R. de la Fuente Marcos²

¹*Universidad Complutense de Madrid, Ciudad Universitaria, E-28040 Madrid, Spain*

²*AEGORA Research Group, Facultad de Ciencias Matemáticas, Universidad Complutense de Madrid, Ciudad Universitaria, E-28040 Madrid, Spain*

Accepted 2022 February 3. Received 2022 February 1; in original form 2021 December 15

ABSTRACT

Asymmetric debris discs have been found around stars other than the Sun; asymmetries are sometimes attributed to perturbations induced by unseen planets. The presence or absence of asymmetries in our own trans-Neptunian belt remains controversial. The study of sensitive tracers in a sample of objects relatively free from the perturbations exerted by the four known giant planets and most stellar flybys may put an end to this debate. The analysis of the distribution of the mutual nodal distances of the known extreme trans-Neptunian objects (ETNOs) that measure how close two orbits may get to each other could be such a game changer. Here, we use a sample of 51 ETNOs together with random shufflings of this sample and two unbiased scattered-disc orbital models to confirm a **statistically significant (62σ) asymmetry** between the shortest mutual ascending and descending nodal distances as well as the existence of multiple highly improbably ($p < 0.0002$) correlated pairs of orbits with mutual nodal distances as low as **0.2 au at 152 au** from the Solar system's barycentre or **1.3 au at 339 au**. We conclude that these findings fit best with the notion that trans-Plutonian planets exist.

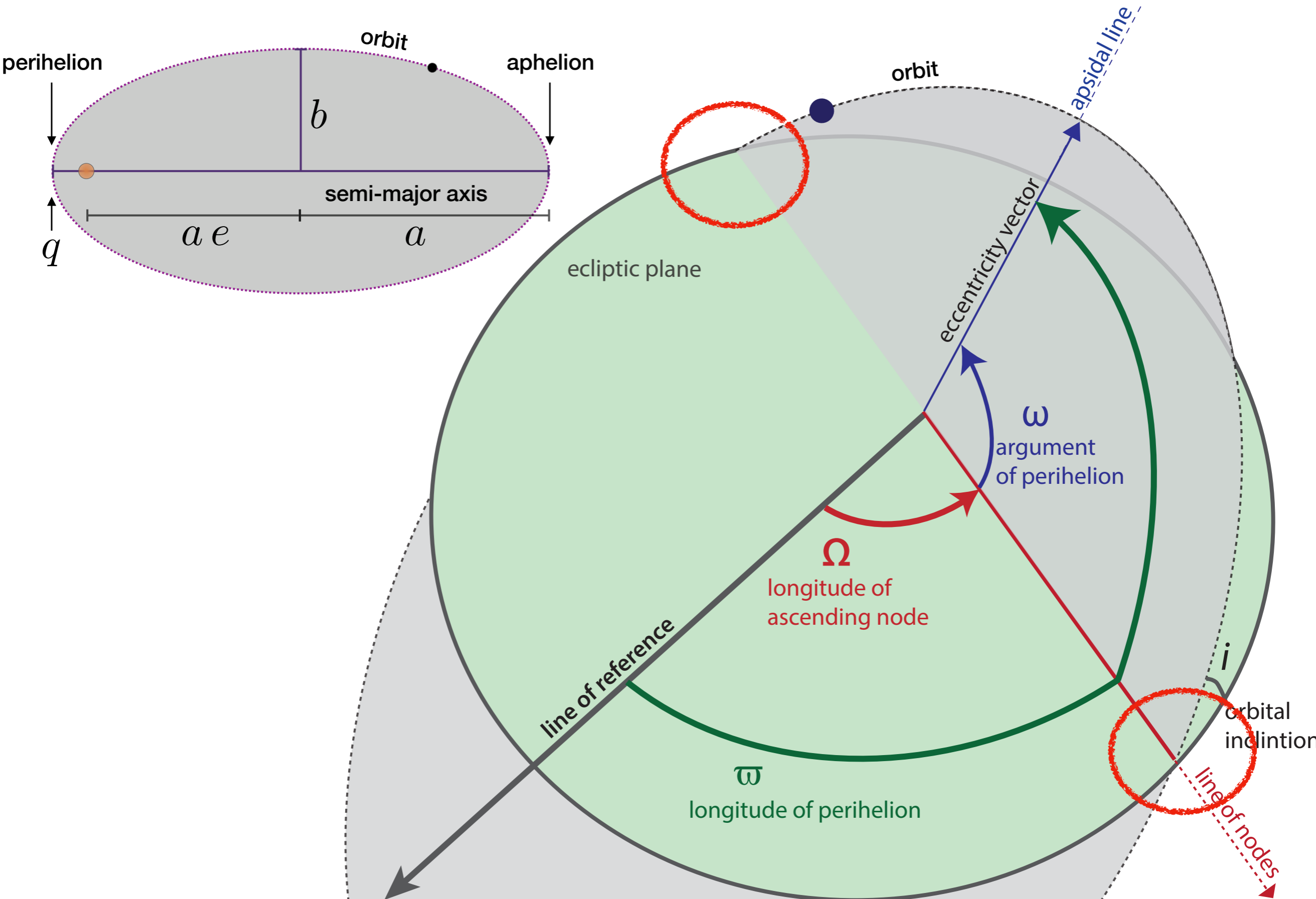
New evidence

- Nodal distance between a(de)scending points
- 51 ETNOs in DES, Bernardinelli et al. 2022
 - 1275 pair nodal distances

pairs whose nodal distance

- 0.2 au at 152 au
- 1.26 au at 339 au

are very rare! They should scatter each other. **viscous stirring**



New evidence

How close between two different orbit

Two object share similar orbits

- the two objects split from the same one
- mechanism(s) exist to keep them close

New evidence

How close between two different orbit

Two object share similar orbits

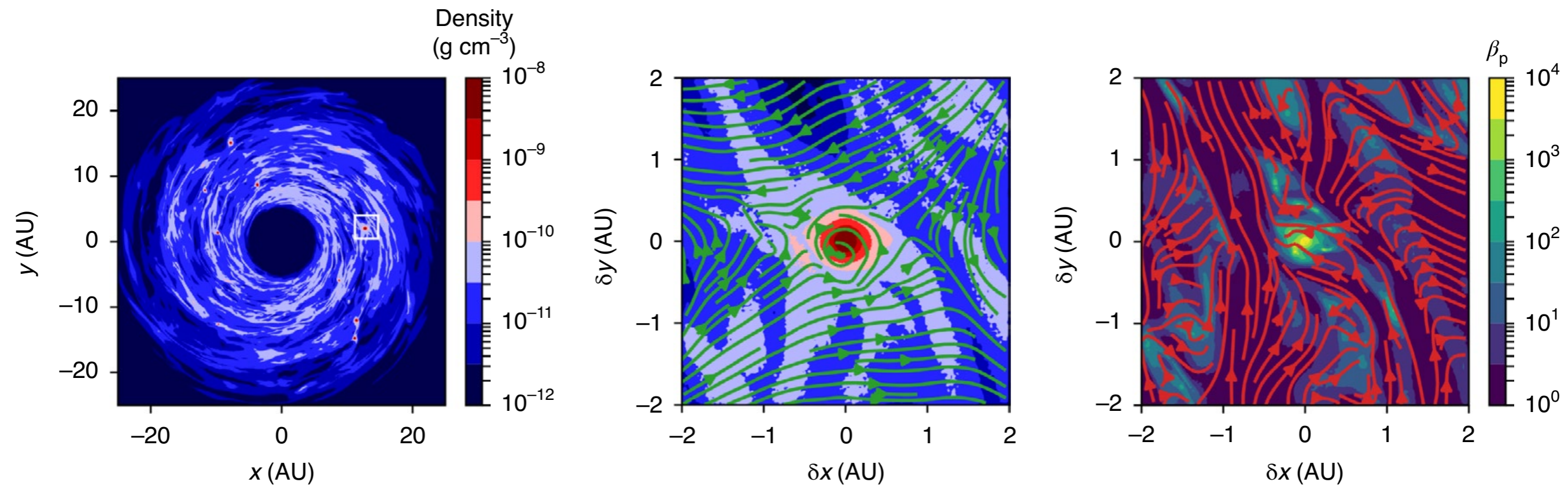
- the two objects split from the same one
- mechanism(s) exist to keep them close

Planet 9 can help

Outreach in theory

Deng et al. 2021

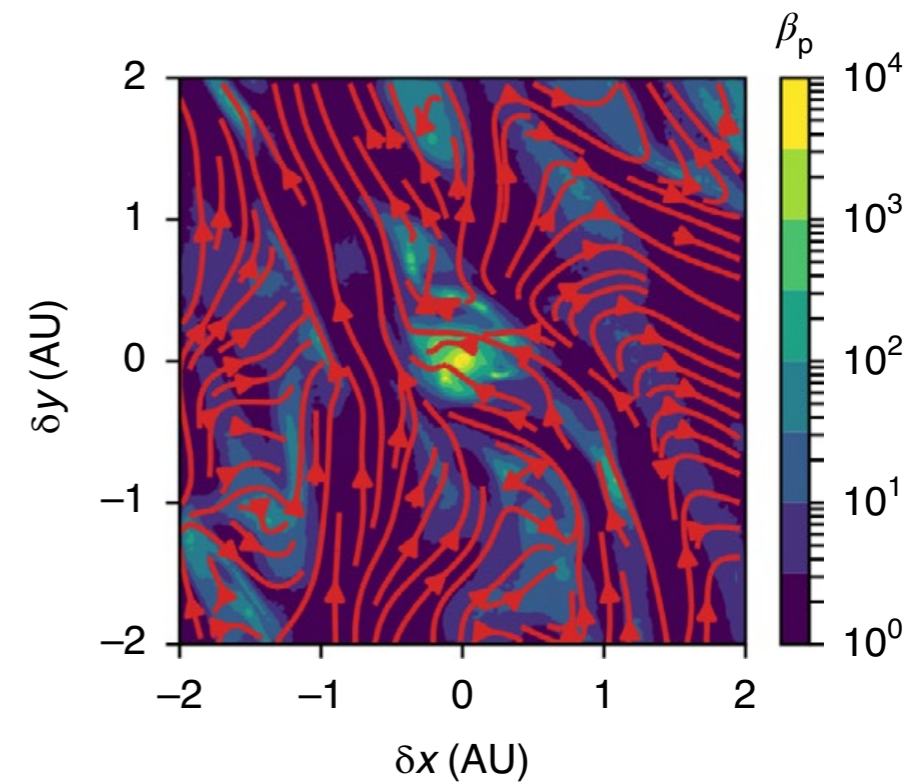
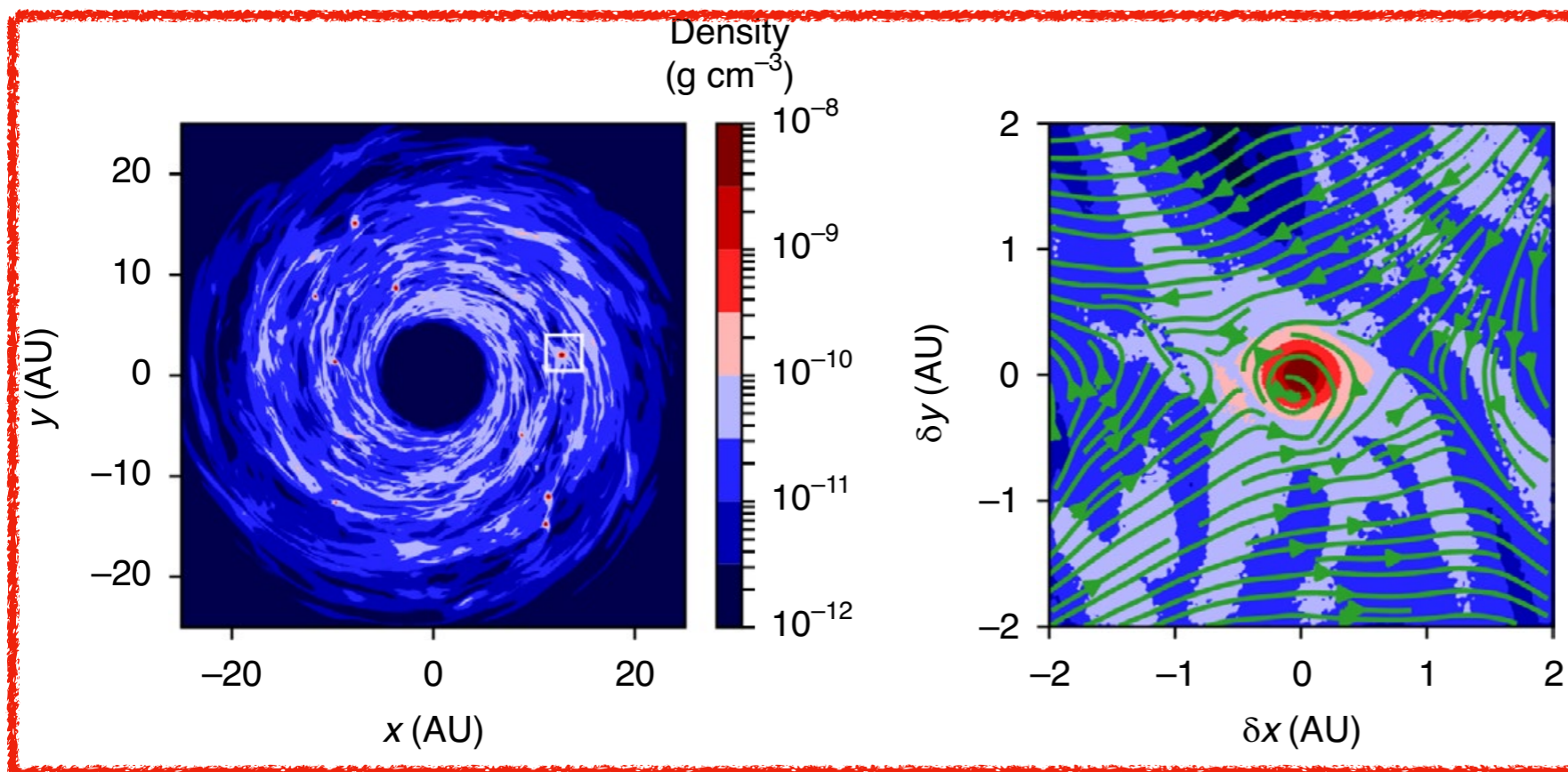
- Magnetic field can help!



Outreach in theory

Deng et al. 2021

- Magnetic field can help!



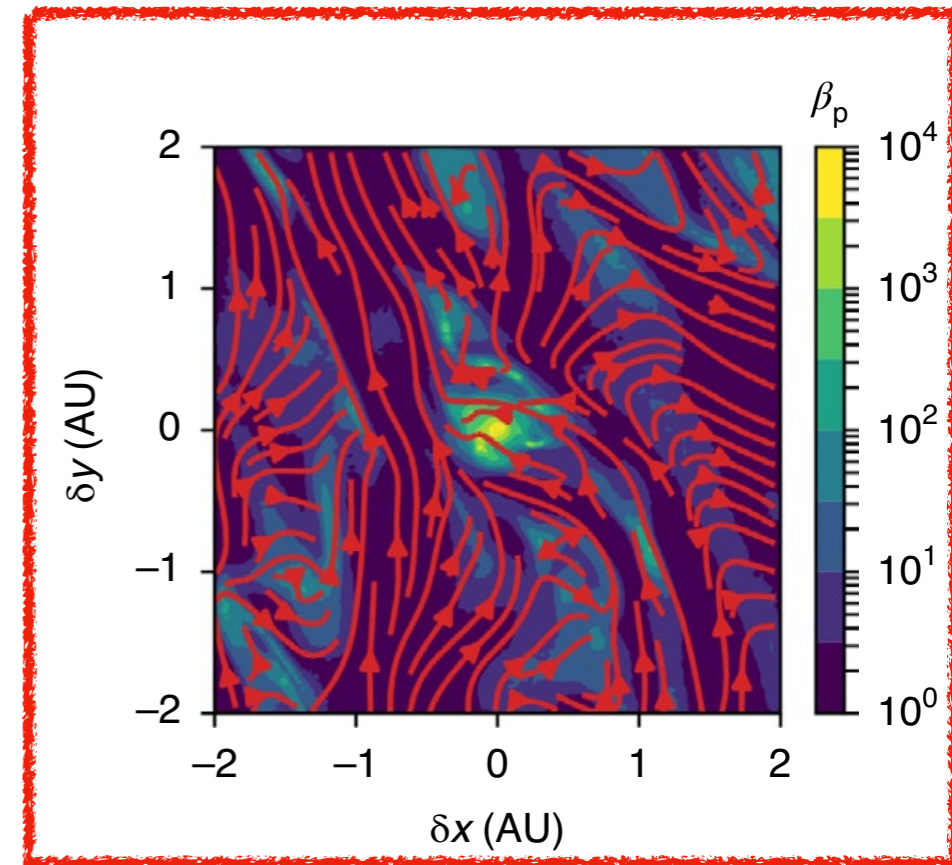
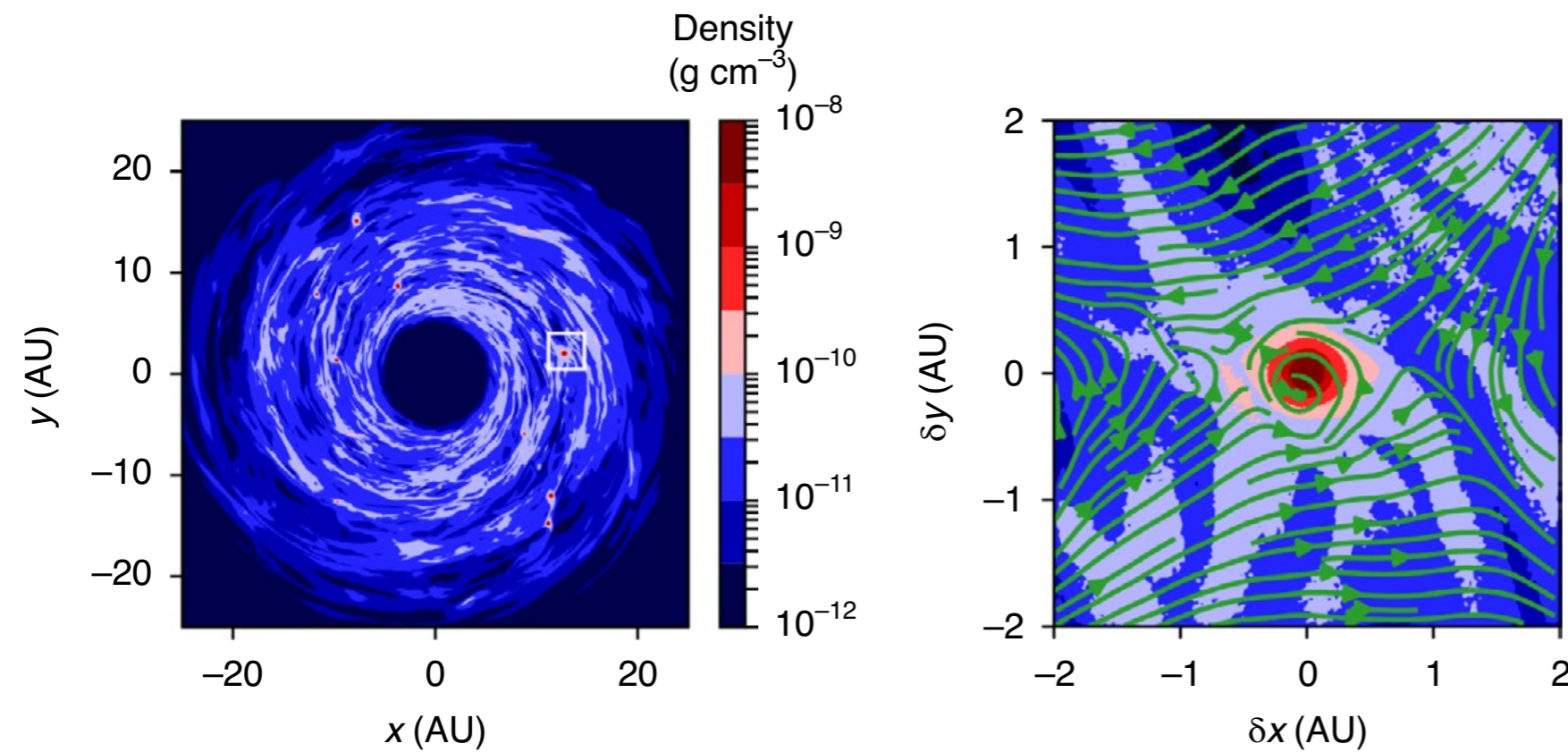
disk fragmentation into “lighter” clump

$$\sim 10 M_{\oplus}$$

Outreach in theory

Deng et al. 2021

- Magnetic field can help!



magnetic field strongly twisted
“shield” the seed from the disk

Future

- More ETNOs detection
 - DES & OSSOS, ~ 23.5 mag

Future

- More ETNOs detection
 - DES & OSSOS, ~ 23.5 mag

LSST

Large Synoptic Survey Telescope

Effective aperture: 6.68 m

Field of view: 9.6 deg²

Pixel scale: 0.2 arcsec/pixel

5 sigma limit r magnitudes ~ 27



Future

- More ETNOs detection
 - DES & OSSOS, ~ 23.5 mag

Discover more TNOs, and refine theoretical models

Rule out a big chunk of Planet Nine's orbit

Find Planet Nine directly!



Summary

- Result from OSSOS survey is consistent with a uniform underlying angular distribution (no clustering).
- New argument based on mutual nodal distance still stands.
- The formation of Planet Nine (if indeed exists) remains a mystery.
- Planet formation theory is still updating. Magnetic field may help with traditional disk instability.
- LSST will help identify more ETNOs and further constrain the Planet Nine hypothesis.

总结

新行星
新物理
观测误差

新行星
新物理
观测误差

新行星
新物理
观测误差

新行星?
新物理?
观测误差?

~1600: 开普勒三定律

1686: 牛顿万有引力定律

1781: Herchel 发现天王星

1846: 海王星的发现

<1919: 水星进动和GR

1930: 冥王星的发现

2006: Eris的发现和冥王星的降级

第九大行星理论



Johannes Kepler



William Herchel



Clyde Tombaugh



Mike Brown

- Detached KBOs
- Orbital clusterings
- 观测认证 (光学, 引力扰动)

反对观点

- 观测样本偏差
- 形成模型
- 另类解释

滚滚长江东逝水，浪花淘尽英雄。

Questions and Comments

- Questions:
- The paucity of TNOs with $\omega \sim 180$ degrees?
- Extraordinary inclination of some ETNOs?
- Comment:
- If you believe something is true, you will find the evidence that it is true.

Dependence on q

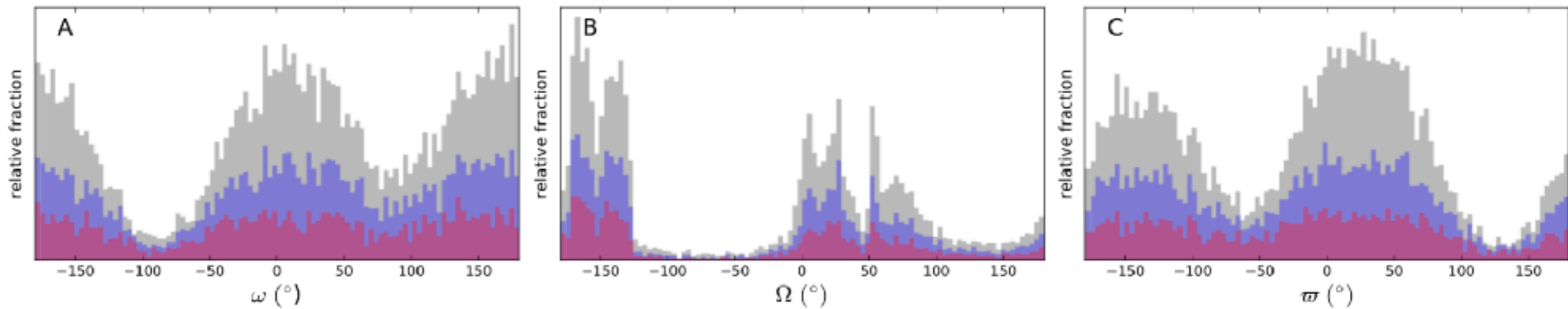
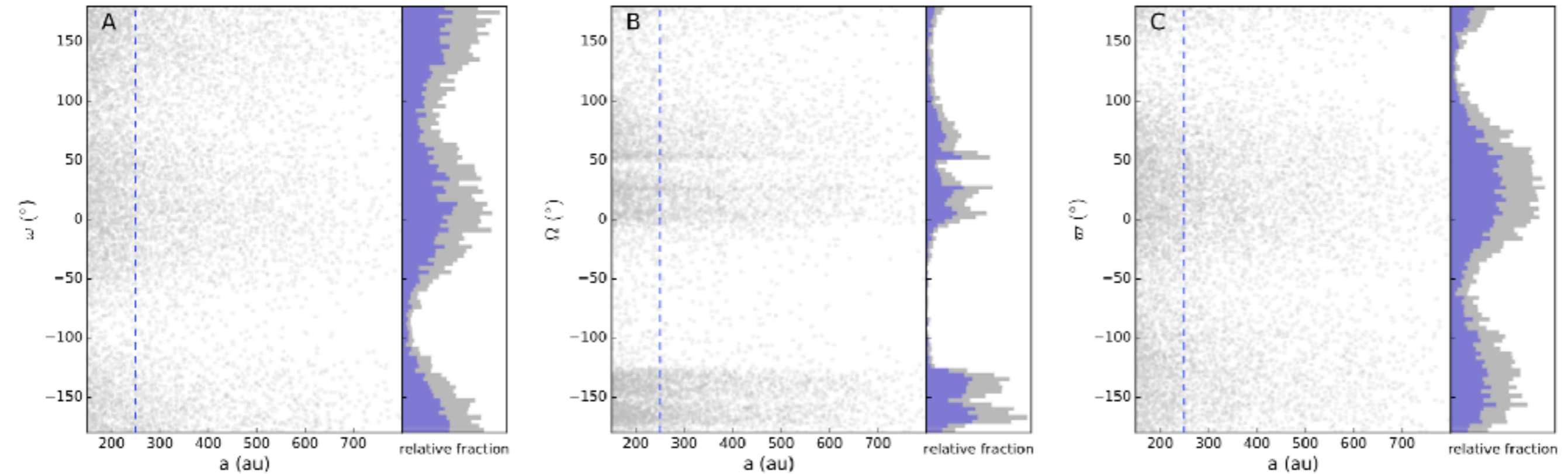
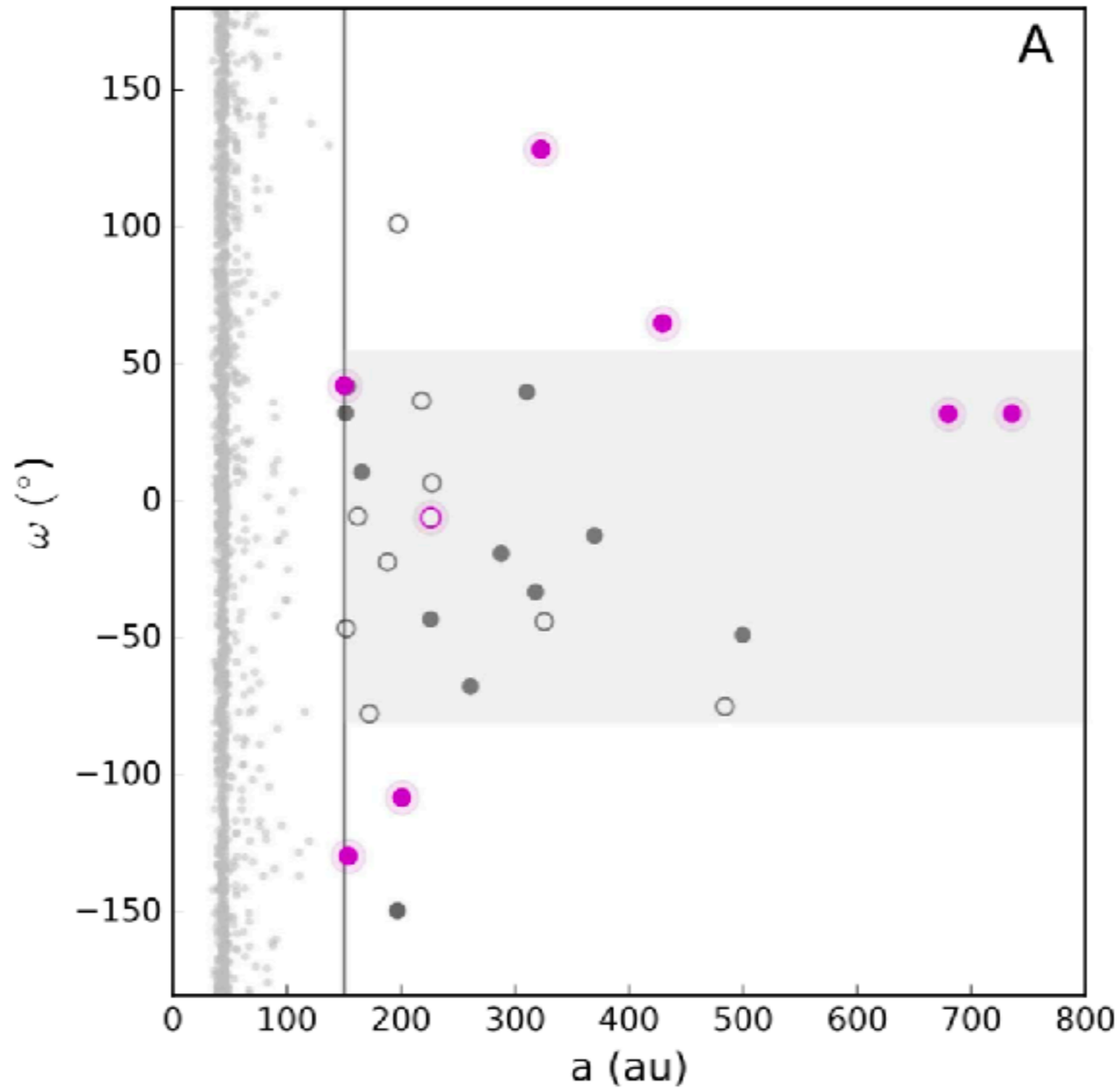


Figure 7. Histograms of the sensitivity of OSSOS as in Figure 1. The gray histogram shows all simulated detections, the blue histogram shows those with $q < 37$ au, and the magenta histogram shows TNOs with an even lower cutoff of $q < 34$ au. The form of the bias is the same for all q cuts, but the bias is more pronounced for the largest q TNOs.

Biases of other orbital parameters



All ETNOs before 2017



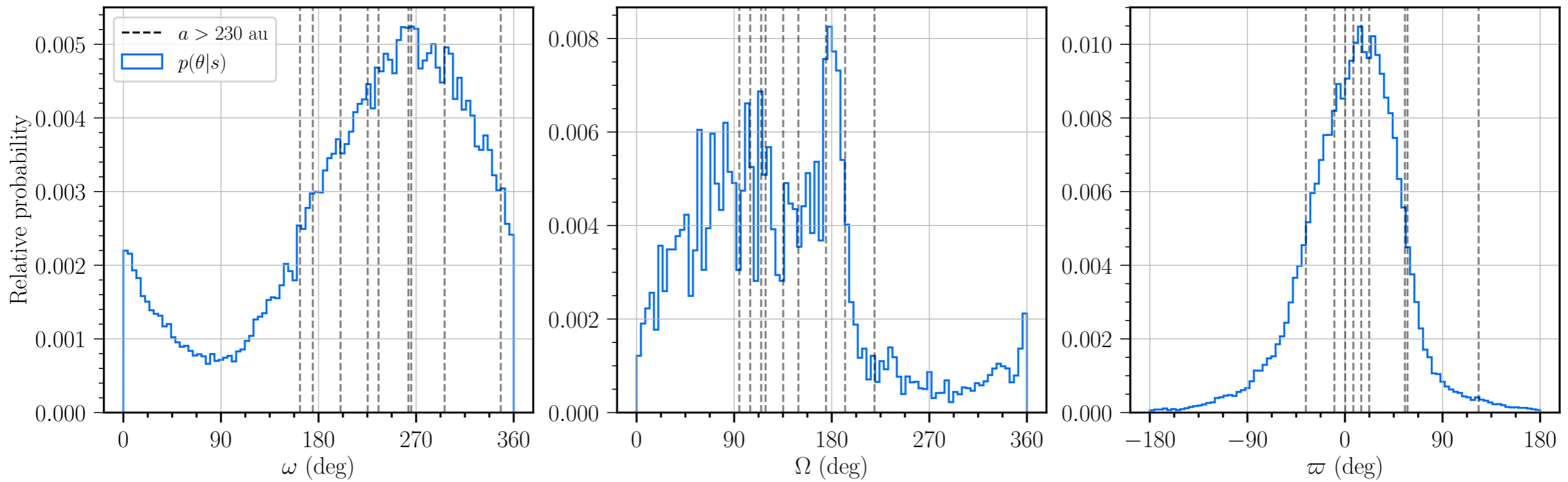


Figure 11. Histograms of the relative detection probabilities for the $a > 230$ au eTNOs (in blue) for ω , Ω and ϖ constructed as in Equation 1 of [Bernardinelli et al. \(2020b\)](#). The black vertical dashed lines represent the detected objects.

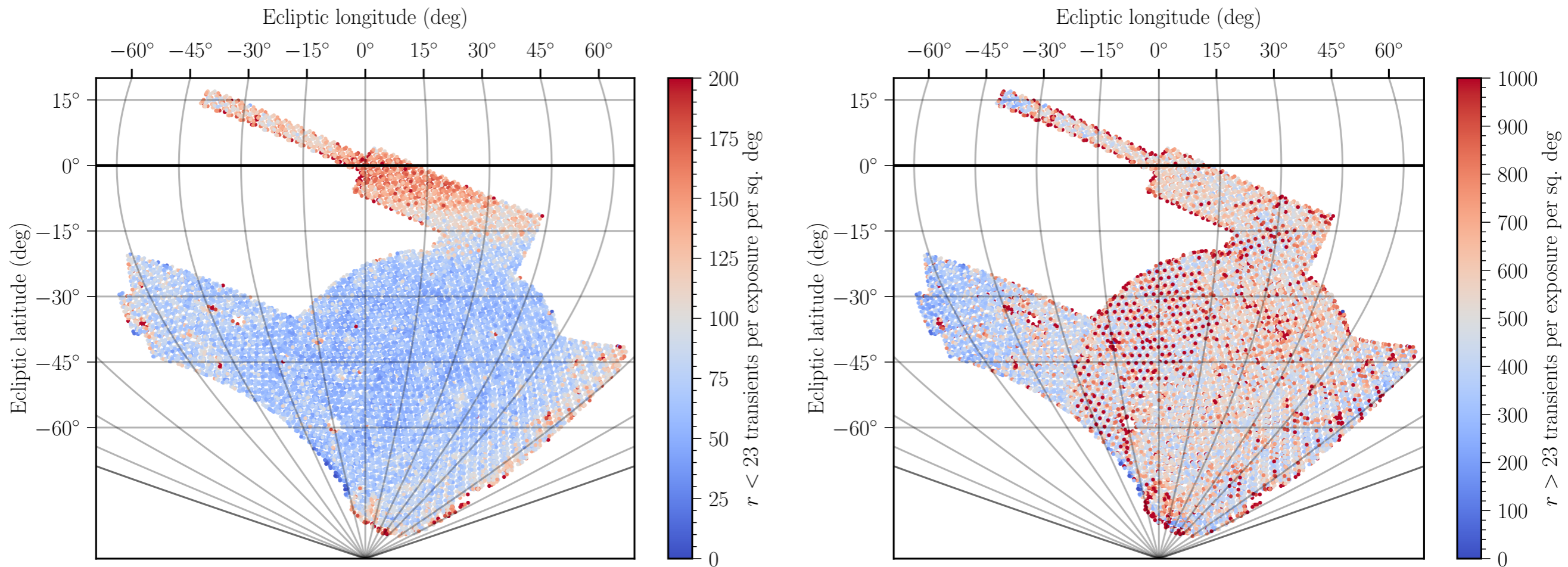


Figure 5. Sinusoidal projection of the *DES* footprint in ecliptic coordinates, each dot corresponding to one r band exposure with its color representing transient counts per exposure and per square degree. The left panel counts transients with $r < 23$ mag. In this regime, most exposures are complete, and the transient density increases strongly toward the ecliptic plane (black line) reflecting density variations in the number of astrophysical transients (asteroids). The right panel corresponds to transients with $r > 23$. The faint end has $3 - 5\times$ more detections than the bright end. The lack of spatial dependence (except for a small decrease in transient counts for longitudes less than -30°) suggests that these are due primarily to noise detections, image artifacts, and/or other non-Solar System transients.

