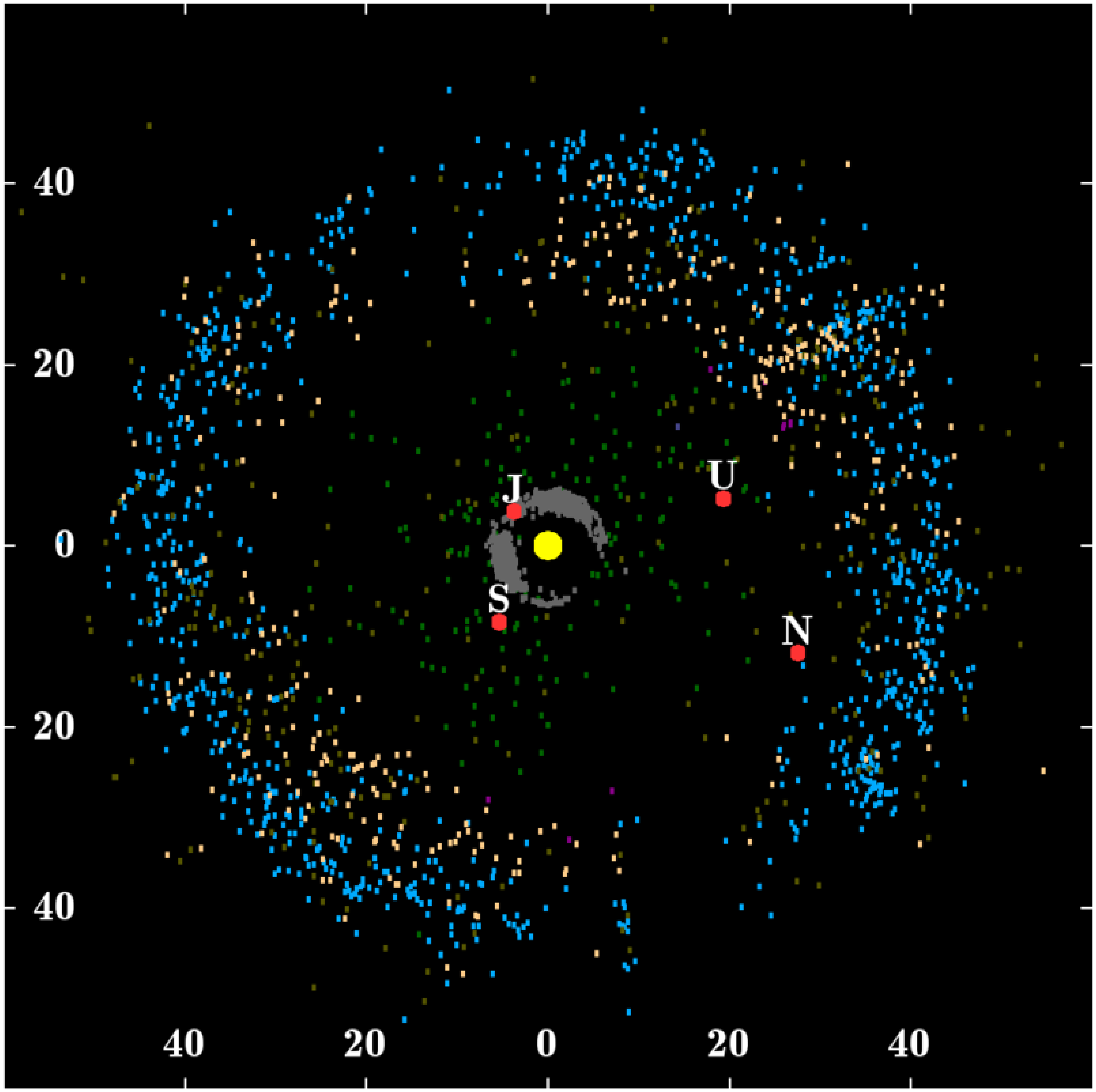
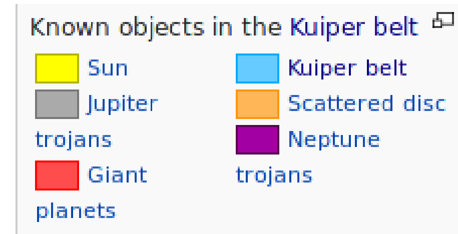
The Solar system



Kuiper belt (30-50 AU)
KBO=Kuiper Belt Object

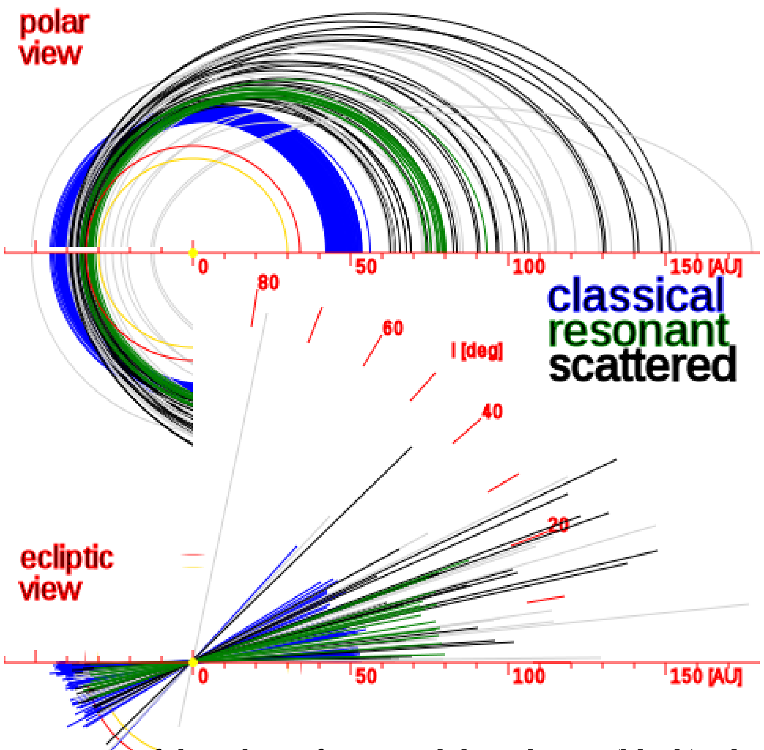


- Can be roughly divided into the **classical** belt and the **resonances**. Resonances are orbits linked to that of Neptune (e.g. twice for every three Neptune orbits, or once for every two).

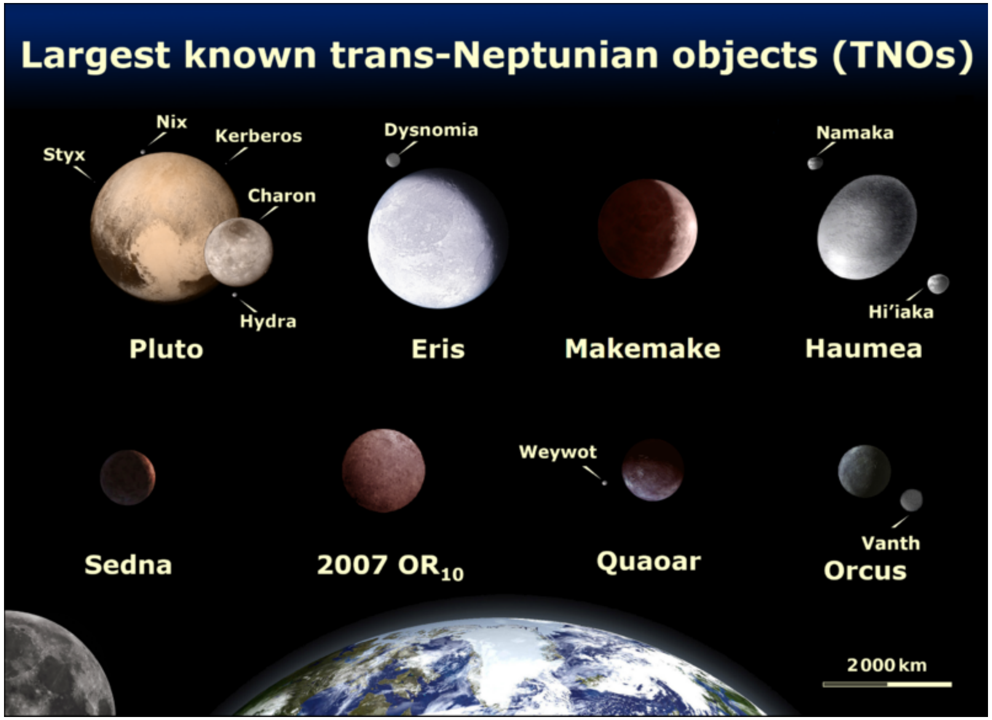
- Makemake (45.79 AU average), although smaller than Pluto, is the largest known object in the **classical** Kuiper belt (KBO not in a confirmed resonance with Neptune).

- The dwarf planet Pluto (39 AU average) is the largest known object in the Kuiper belt. When discovered in 1930, it was considered to be the ninth planet; this changed in 2006 with the adoption of a formal definition of planet (3/2 **resonance** with Neptune)

Typical objects in KBO



Comparison of the orbits of scattered disc objects (black), classical KBOs (blue), and 2:5 resonant objects (green). Orbits of other KBOs are gray. (Orbital axes have been aligned for comparison.)



Trans-neptunian planets

– Similar to Uranus or Neptune, but formed directly at 125-250 AU?
– Formed closer and scattered by the giant planets ealry in SS history?
– Captured from another planetary system?

Discovery of Sedna-like body

Trujillo & Sheppard, Nature 507, 471 (2014)

Surveyed 52 deg^2 of sky for new inner Oort cloud objects using the Dark Energy Camera (DECam) at CTIO 4-m telescope: each patch imaged 3 times with 1.5 h to 2 h between images to detect the motion of objects beyond 300 AU when compared to background stars + position and colour of 2012 VP 113 measured using the Magellan 6.5-m telescope

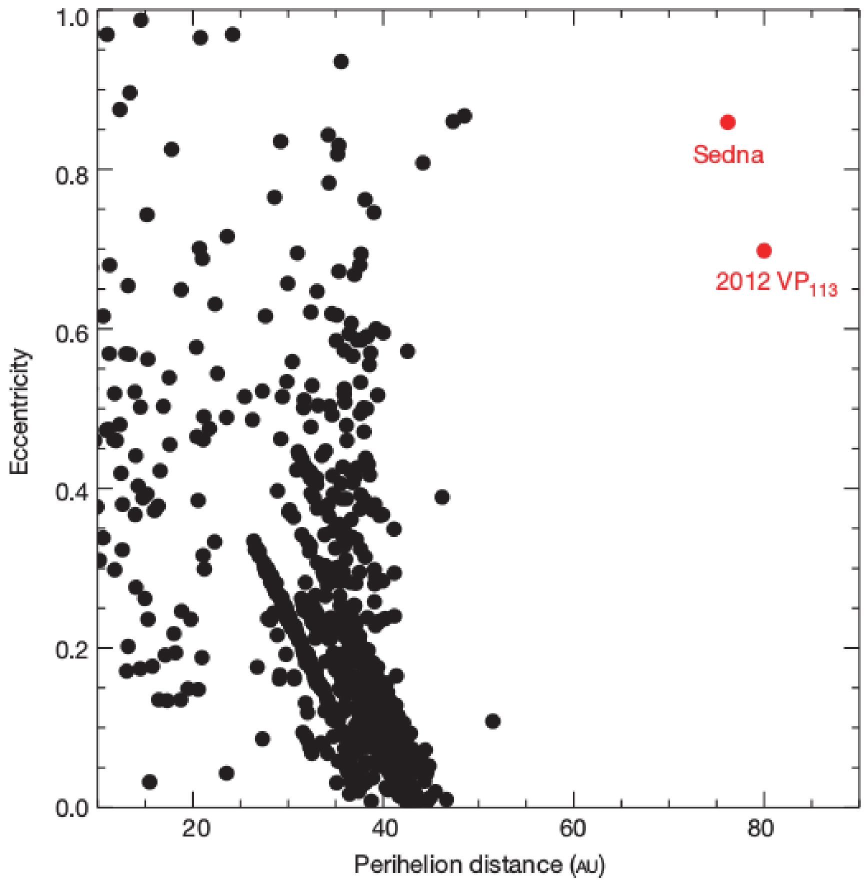


Figure 1 | Sedna and 2012 VP$_{113}$ are clear dynamical outliers in the Solar System. Eccentricity versus perihelion distance for the approximately 1,000 minor planets with well-determined (multi-year) orbits beyond 10 AU are

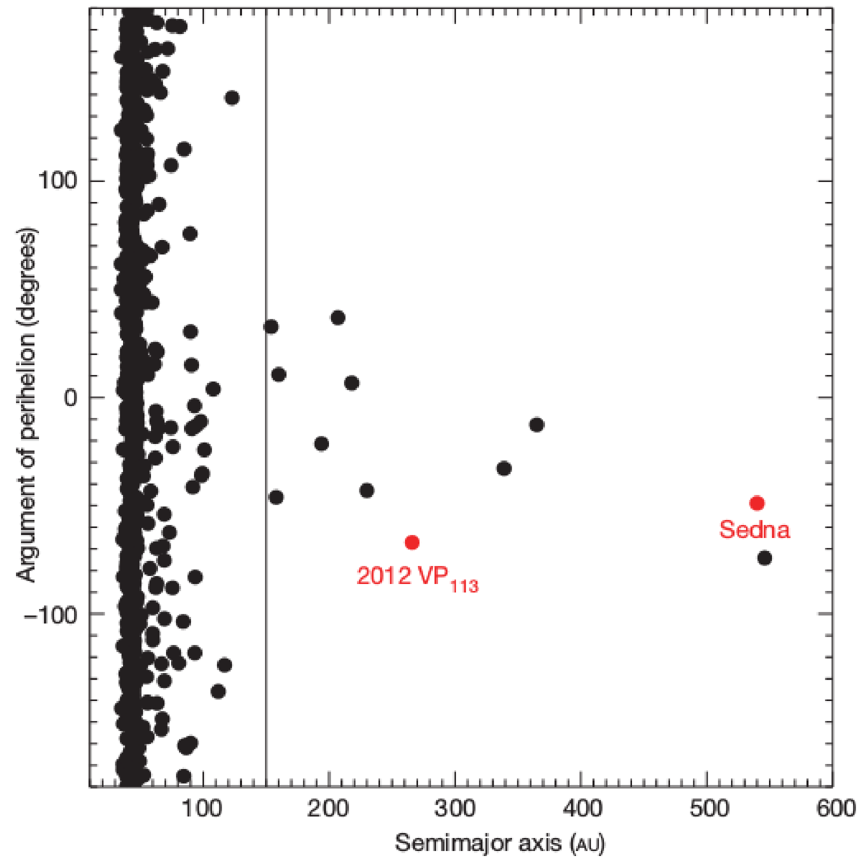
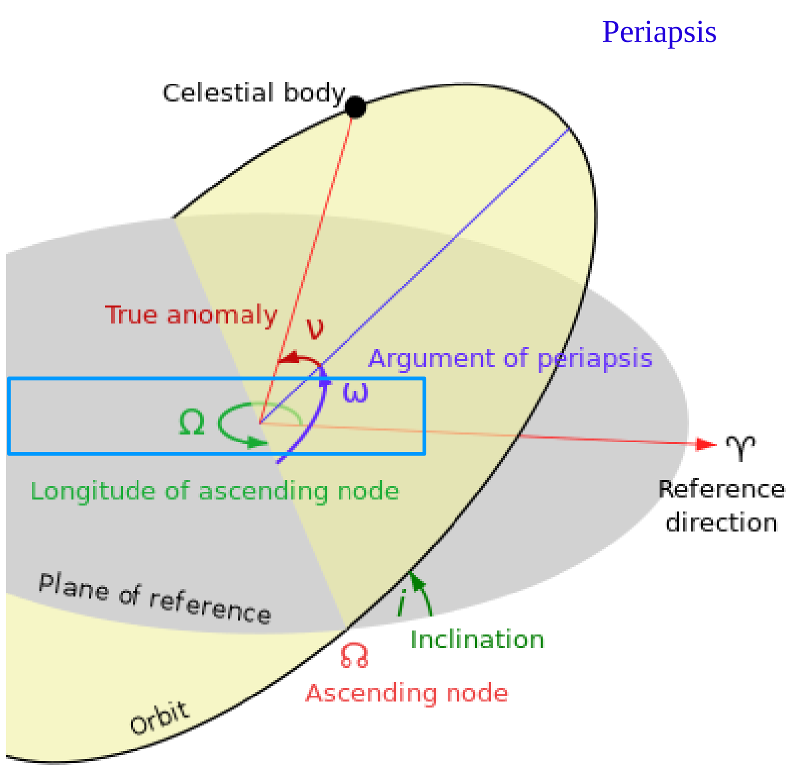


Figure 3 | The argument of perihelion for distant objects clusters about 0°. All minor planets with perihelion greater than 30 AU as a function of semi-major axis are shown. All bodies with semi-major axis greater than the line at 150 AU show a pronounced concentration near $\omega \approx 0°$. Errors on these orbital

→ Consistent with simulated Super Earth-mass body at 250 AU

Celestial mechanics: orbital elements (wikipedia)



- Argument of periapsis ω: angle from the body's ascending node to its periapsis, measured in the direction of motion

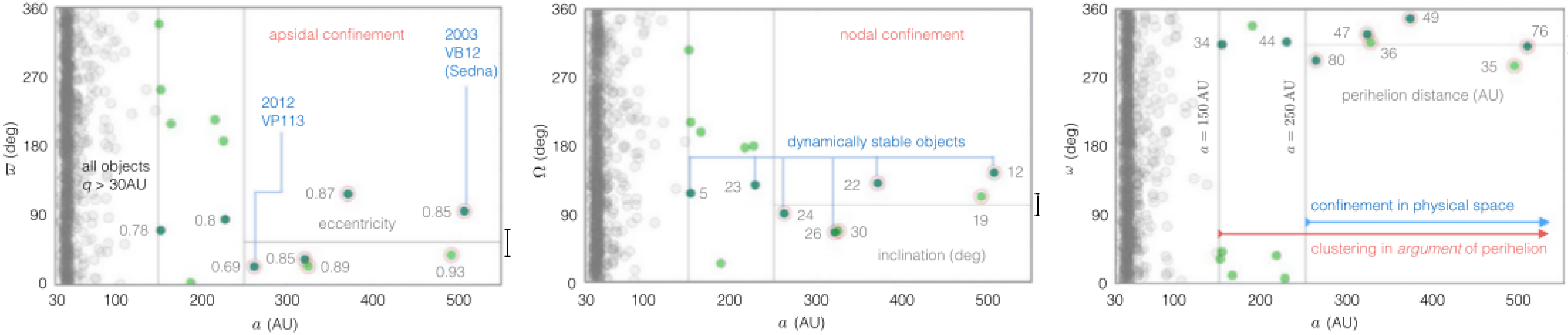
  [Perihelion (or apsidal or orbital) precession ω = rotation of the orbit of a celestial body]

  $$\omega_{\text{total}} = \omega_{\text{General Relativity}} + \omega_{\text{quadrupole}} + \omega_{\text{tide}} + \omega_{\text{perturbations}}$$

- Longitude of ascending node Ω

- Longitude of perihelion (or periapsis) $\varpi = \omega + \Omega$

Batygin & Brown, ApJ 151, 22 (2016)



Observations

- Confinement in ω space
- Confinement in physical space

N.B.: strong observational bias towards w =0, but accounted for in analysis

- Argument of periapsis ω: angle from the body's ascending node to its periapsis, measured in the direction of motion

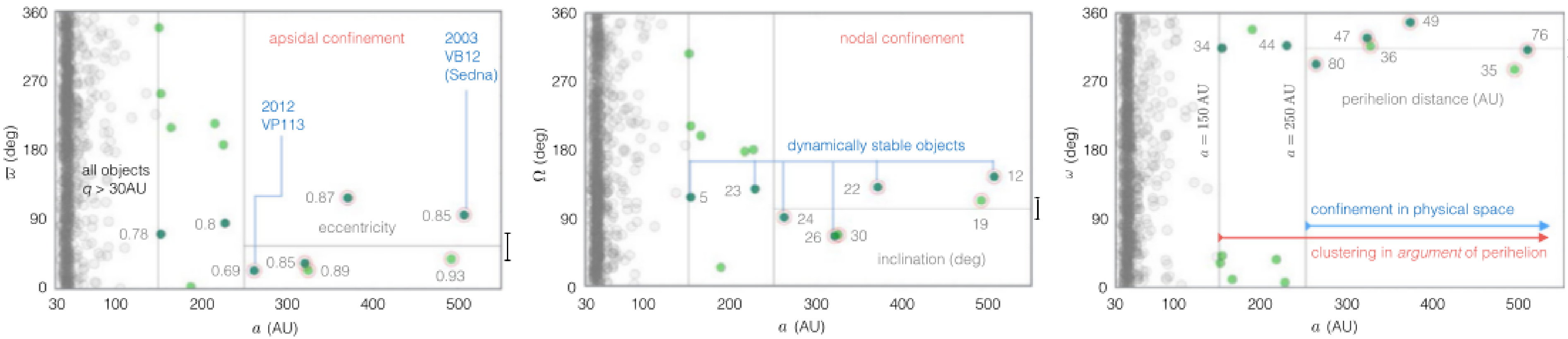
  [Perihelion (or apsidal or orbital) precession ω = rotation of the orbit of a celestial body]

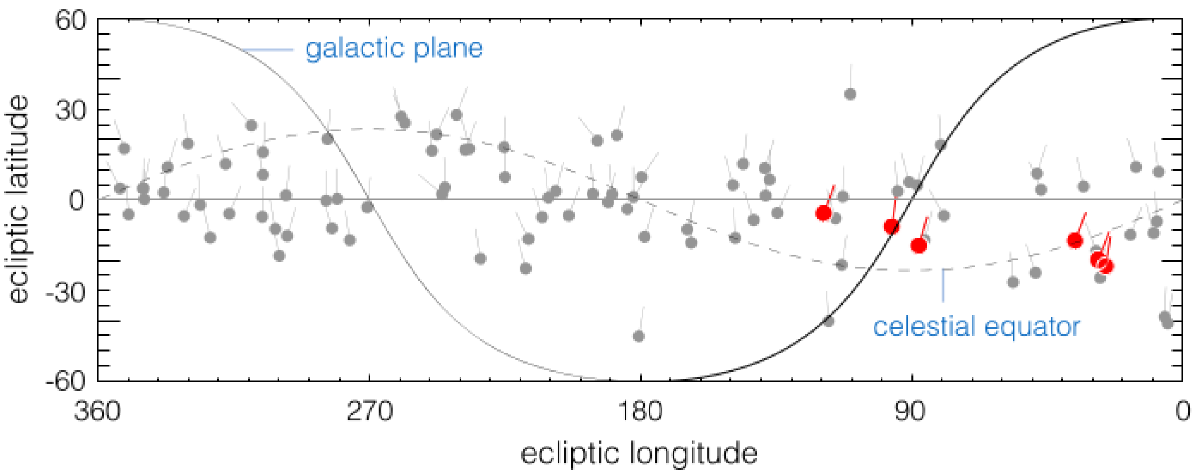
  $$\omega_{\text{total}} = \omega_{\text{General Relativity}} + \omega_{\text{quadrupole}} + \omega_{\text{tide}} + \omega_{\text{perturbations}}$$

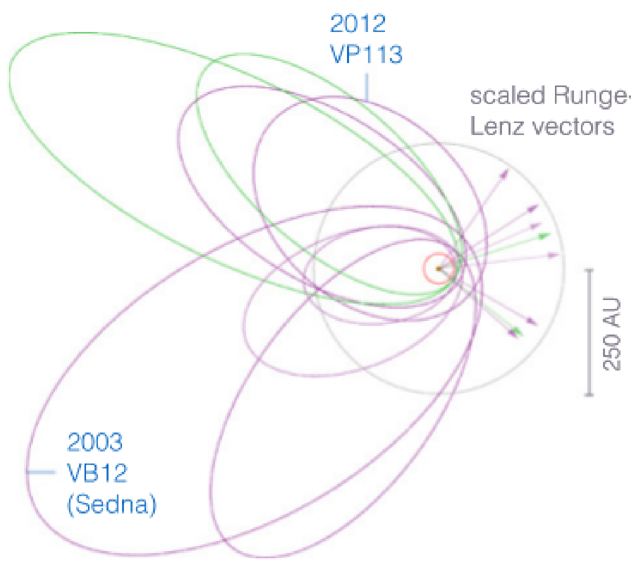
- Longitude of ascending node Ω

- Longitude of perihelion (or periapsis) $\varpi = \omega + \Omega$

Batygin & Brown, ApJ 151, 22 (2016)







- Argument of periapsis ω: angle from the body's ascending node to its periapsis, measured in the direction of motion

  [Perihelion (or apsidal or orbital) precession ω = rotation of the orbit of a celestial body]

$$\omega_{\text{total}} = \omega_{\text{General Relativity}} + \omega_{\text{quadrupole}} + \omega_{\text{tide}} + \omega_{\text{perturbations}}$$

- Longitude of ascending node Ω

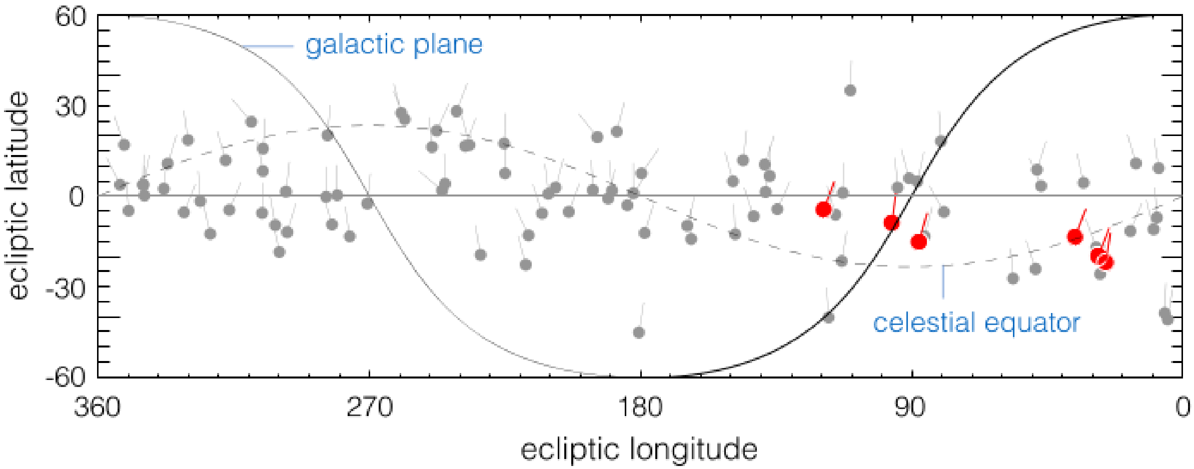
- Longitude of perihelion (or periapsis) $\varpi = \omega + \Omega$

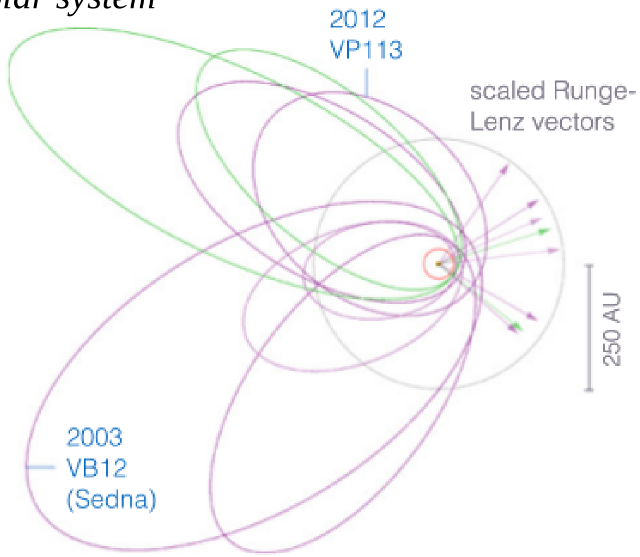
Batygin & Brown, ApJ 151, 22 (2016)

1) Coherent dynamical structures in particle disks can be sustained by
- self-gravity (Tremaine 1998)
- gravitational shepherding by an extrinsic perturber (Goldreich & Tremaine 1982)

2) Mass of Kuiper Belt insufficient for self-gravity to play a role in its dynamical evolution

→ hypothesized that observed structure of the Kuiper Belt is maintained by a gravitationally bound perturber in the solar system





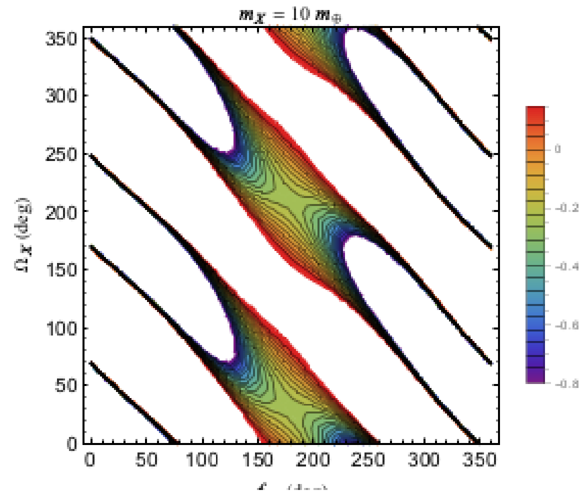
Numerical simulations of this perturber

→ Although the model parameters are inherently degenerated, calculation suggests d∼700 AU, e∼0.6 (280-1120 AU), inclination=30 deg, M=10 $m_\oplus$

N.B.: long-term modulation of scattered KBO eccentricities provides a natural explanation for the existence of the so-called distant detached objects such as Sedna and 2012VP113

Discussions related to planet 9

- **Where is Telisto/Planet Nine?** (Iorio, arXiv:1512.05288)
  - Use of Saturn ephemerides: modifications in secular precession of ϖ
    [N.B.: formalism used ~ to what MOND theory would give]
    f ∈ [150-200] deg ⟶ a ∈ [930-1027] AU
  - New Horizons mission (~35 AU): Δx~100 m by Telisto expected)
    [or dedicated mission to test gravitational laws?]



- **Constraints from the Cassini data** (Fienga et al., A&A 587, L8 (2016))
  - Also use all planets + Pluto + Moon ephemerides
  - Cross-check deviations with Cassini data
  - Global fit (150 params, 150000 observations)
    Contradict Iori's conclusion: 'a' can be smaller than 1000
    Motivation to extend Cassini up to 2020

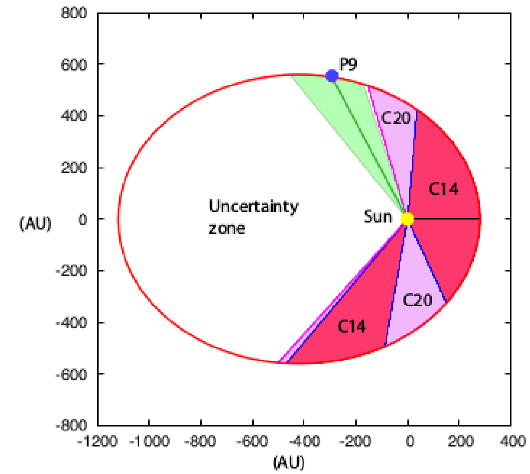
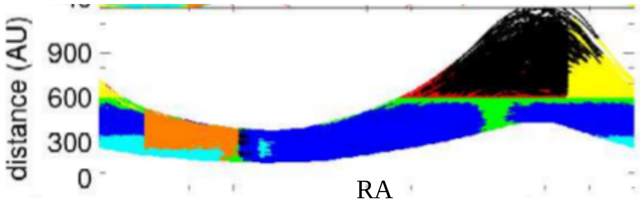


Fig. 6. Allowed zone for P9. The red zone (C14) is excluded by the analysis of the *Cassini* data up to 2014 (Sect. 4). The pink zone (C20) is how much this zone can be enlarged by extending the *Cassini* data to 2020 (Sect. 4). The green zone is the most probable zone for P9 ($v \in [108°:129°]$), with maximum reduction of the residuals at $v = 117.8°$

- **Observational constraints on the orbit** (Brown & Batygin, arXiv:1603:05712)
  - WISE (μm), CRTS (Catalina Real-Time Transient Survey), **DES (photometry)**, Pan-STARRS (PST: survey for transients), Pan-STARRS (moving object analysis), Pan-STARRS (expected limits), Ephemerides Saturne
  - Not excluded in previous or currently planned surveys

Distance, magnitude, speed, declination



Discussions related to planet 9

- **Evolution and magnitude** (Linder & Mordasini, arXiv:1602:07465)
  - Internal luminosity released may allow detection (isolated from Sun)
  - 50 $M_\oplus$: would have been seen
  - 10 $M_\oplus$ (23.7 mag@1120 AU): OK with null detection

LSST (down to R=26 mag) or dedicated surveys should be able to find/exclude planet 9

- **Blackbody rad. from isolated Neptunes** (Ginzburg et al., arXiv:1603:02876)
  - Cooling study to relate surface T/luminosity to mass/composition
  - Use a two-layer Neptune model (rocky/icy core + H/He envelope)

$$T_{\rm eff} \approx 50\ {\rm K} \left(\frac{R}{R_{\rm N}}\right)^{1/2} \left(\frac{M_{\rm atm}}{M_\oplus}\right)^{1/12} \left(\frac{t}{4.5\ {\rm Gyr}}\right)^{-1/3} \qquad T_c \approx 2700\ {\rm K} \left(\frac{M_{\rm atm}}{M_\oplus}\right)^{1/3}$$

Null detection can constrain the size and composition

- **Cosmologist in search of planet 9** (Cowan et al.,arXiv:1602.05963)
  - Scaling Neptune: $F_{\rm 1mm} = 30\ {\rm mJy} \left(\frac{T_{\rm eff}}{40\ {\rm K}}\right)\left(\frac{R_p}{R_{\rm N}}\right)^2\left(\frac{d}{700\ {\rm AU}}\right)^{-2},$

$$F_{\rm 2mm} = 8\ {\rm mJy} \left(\frac{T_{\rm eff}}{40\ {\rm K}}\right)\left(\frac{R_p}{R_{\rm N}}\right)^2\left(\frac{d}{700\ {\rm AU}}\right)^{-2}$$

  - Beware of false positives (stars, asteroids, Trans-Neptunians)

Detection should be achieved with mm skymap every few months (30mJy, ~5 arcmn)

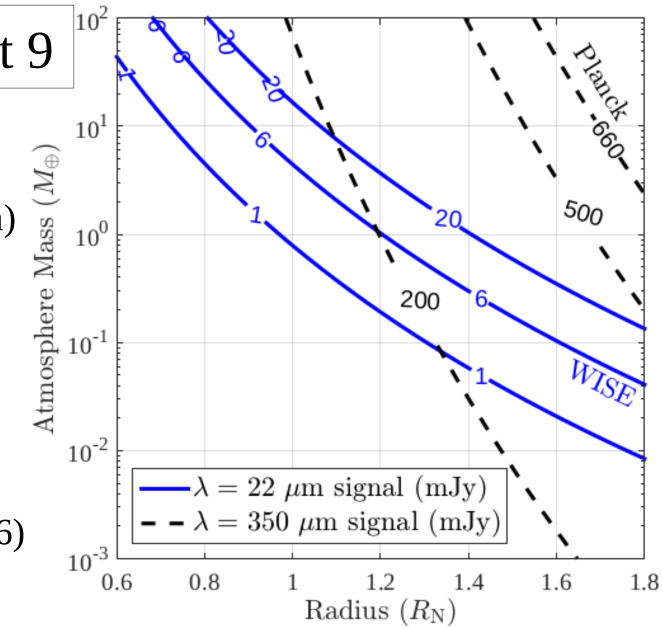
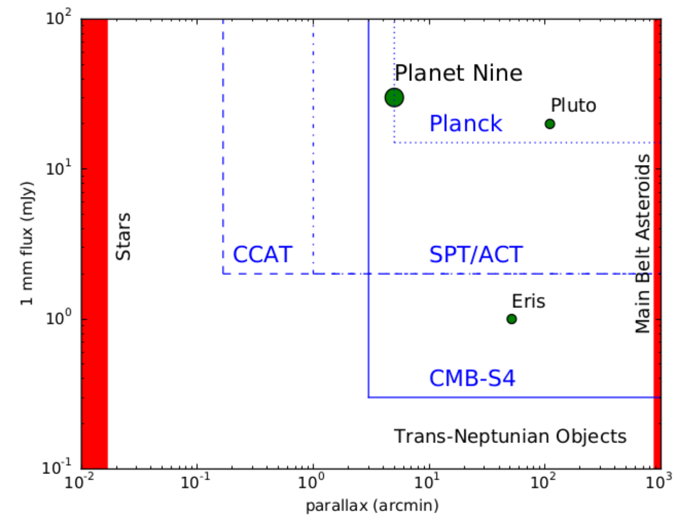


FIG. 4.— Contours of the observable flux density at wavelengths of 22 μm (solid blue lines) and 350 μm (dashed black lines) of 4.5 Gyr old planets at a distance of 700 AU, as a function of their radius and atmosphere mass. The 22 μm sensitivity of WISE is 6 mJy (Wright et al. 2010), corresponding to the middle solid blue line, while the 350 μm sensitivity of Planck is 660 mJy (Planck Collaboration et al. 2014, 2015), corresponding to the top dashed black line.



Discussions related to planet 9

- **Interaction Cross Sections and Survival Rates** (Li & Adams, arXiv:1602:08496)

Astronomy has a long history of considering gravitational perturbations to uncover new Solar system bodies

- Neptune (LeVerrier 1846; Galle 1846; Adams 1846)
- Large Planet X beyond Neptune: never found, but searches led to Pluto (see Tombaugh 1996)
- Nemesis (red dwarf companion to the Sun) to explain periodic extinctions in fossil record...

This paper: possible formation scenarios and dynamical histories for Planet Nine (wide orbit, so highly susceptible to gravitational perturbations from passing stars and binaries).

Formation scenario:

- formed in a nearly circular orbit with a much smaller semimajor axis (a a 9 $\sim$ 400 − 1500 AU)
- scattered by the giant planets into an orbit with perihelion p $\sim$ 30 − 40 AU
- captured from another solar system, and/or as a freely-floating planet within the Solar birth cluster
- can be removed from the Solar System by passing stars

Sun Environment:

- Sun formed in cluster with 10^3−10^4 stars + stay for $\sim$ 100 Myr in $\langle n_* \rangle \sim 100\ pc^{-3}$ *and* $v_b \sim 1\ km/s$
- After leaving cluster, SS $\sim$4.5 Gyr in Solar neighborhood with $\langle n_* \rangle \sim 1\ pc^{-3}$, $v_b \sim 40\ km/s$

Simulations result:

Scattering simulations indicate that survival of Planet Nine is possible but not guaranteed
Formation scenario for Planet Nine represents an important challenge for future investigation