

# Saturn Rules!(?)

## Irregular moon populations

**B. Gladman,**



(Univ. of British Columbia)

**E. Ashton,** M. Beaudoin

J-M. Petit (Obs-Besancon, CNRS)

M. Alexandersen (Harvard Smithsonian)

now



# Irregular moon discoveries

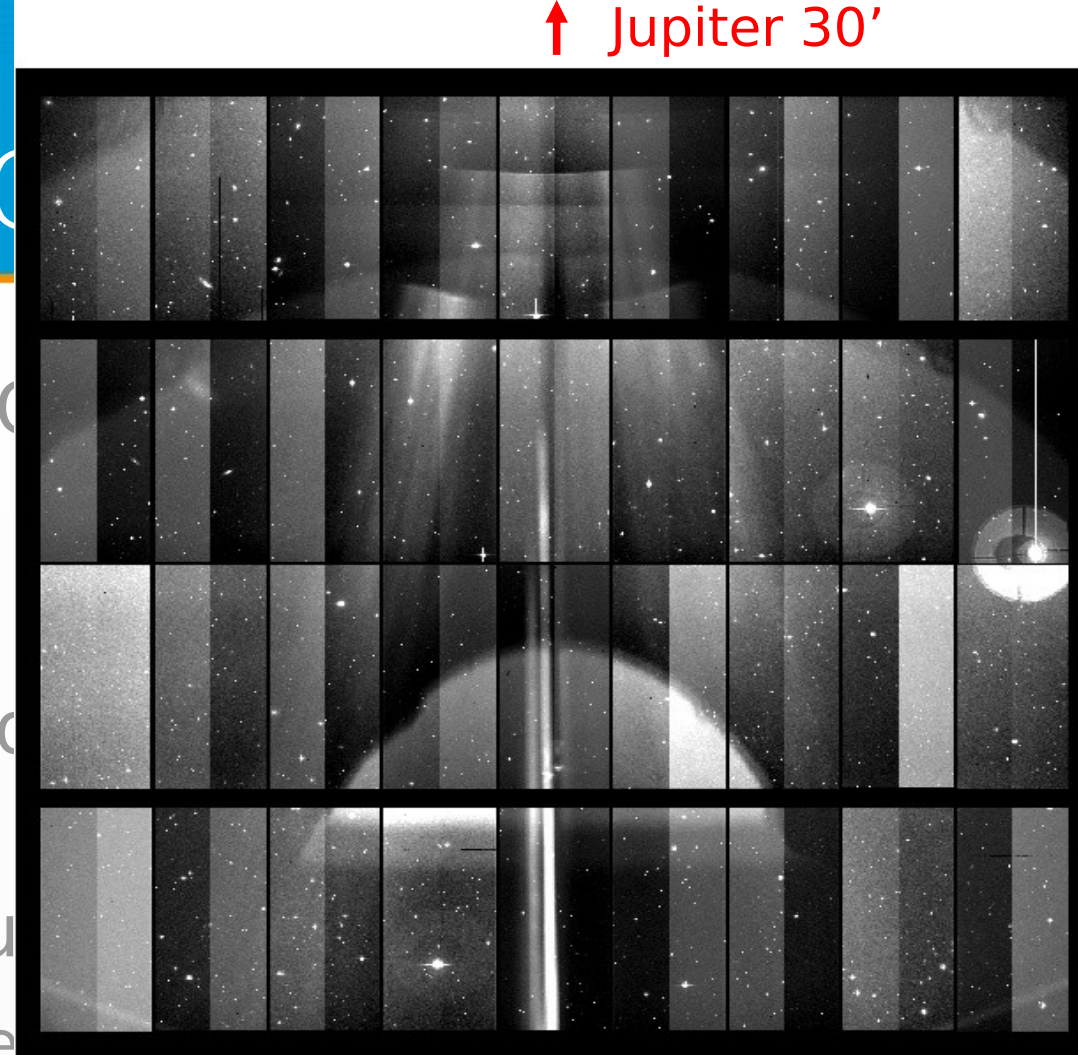
- Nearly all have been found in the CCD era due to:
  - **Depth**
  - **Area**
- Opposition search planet+moons displace nearly `rigidly' in a night

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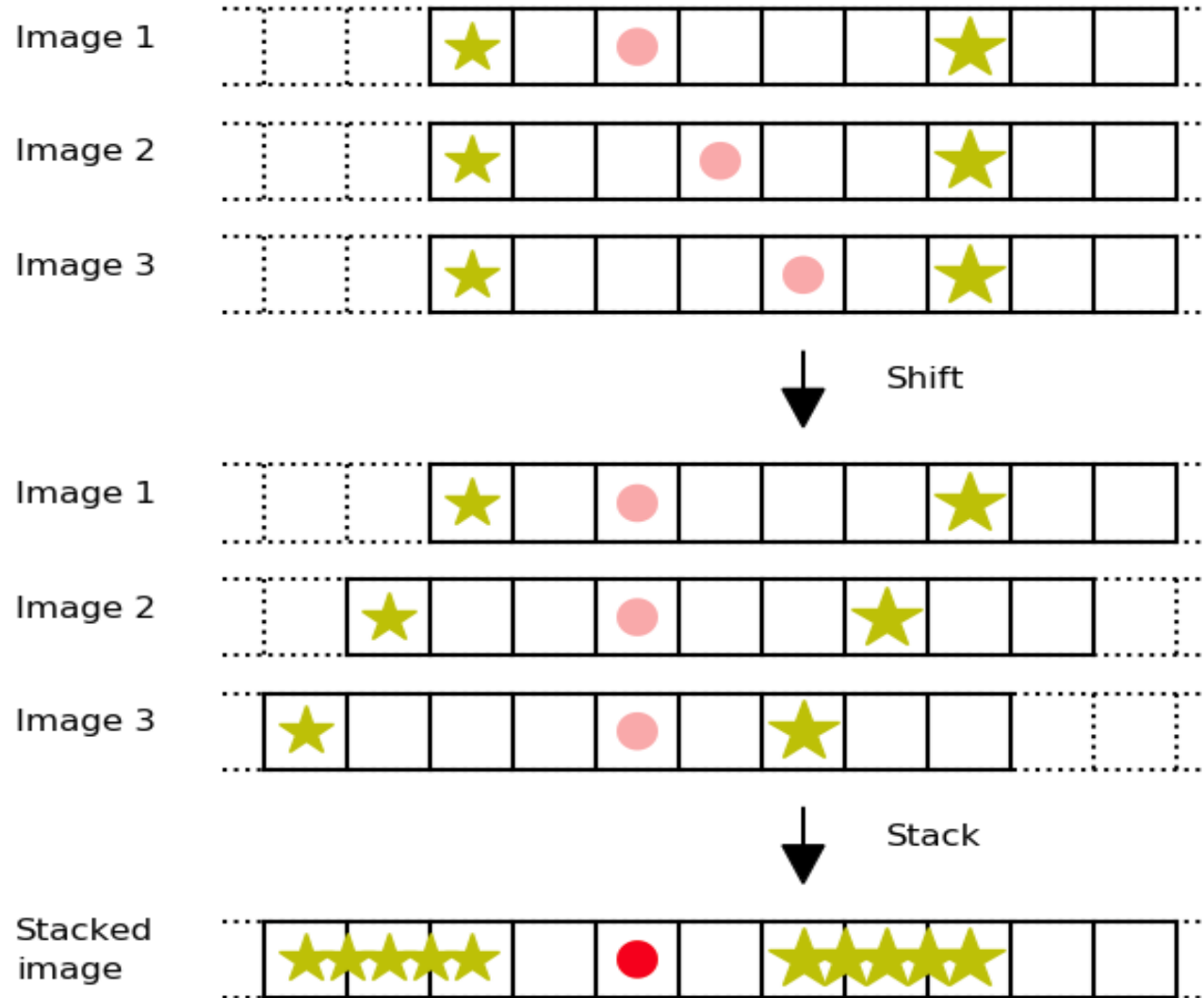


CFHT Megaprime

# Irregular moon discoveries

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- Two main types of search techniques:
  - **A)** 3 image linearly-moving target searches.
    - Shorter exposures limit depth to prevent trailing losses
    - Scattered light can be the limiting factor on depth
  - **B)** 'Shift and stack' or 'pencil-beam' searches
    - Difficult for J&S due to huge range of possible rates and angles

# Shift and stack



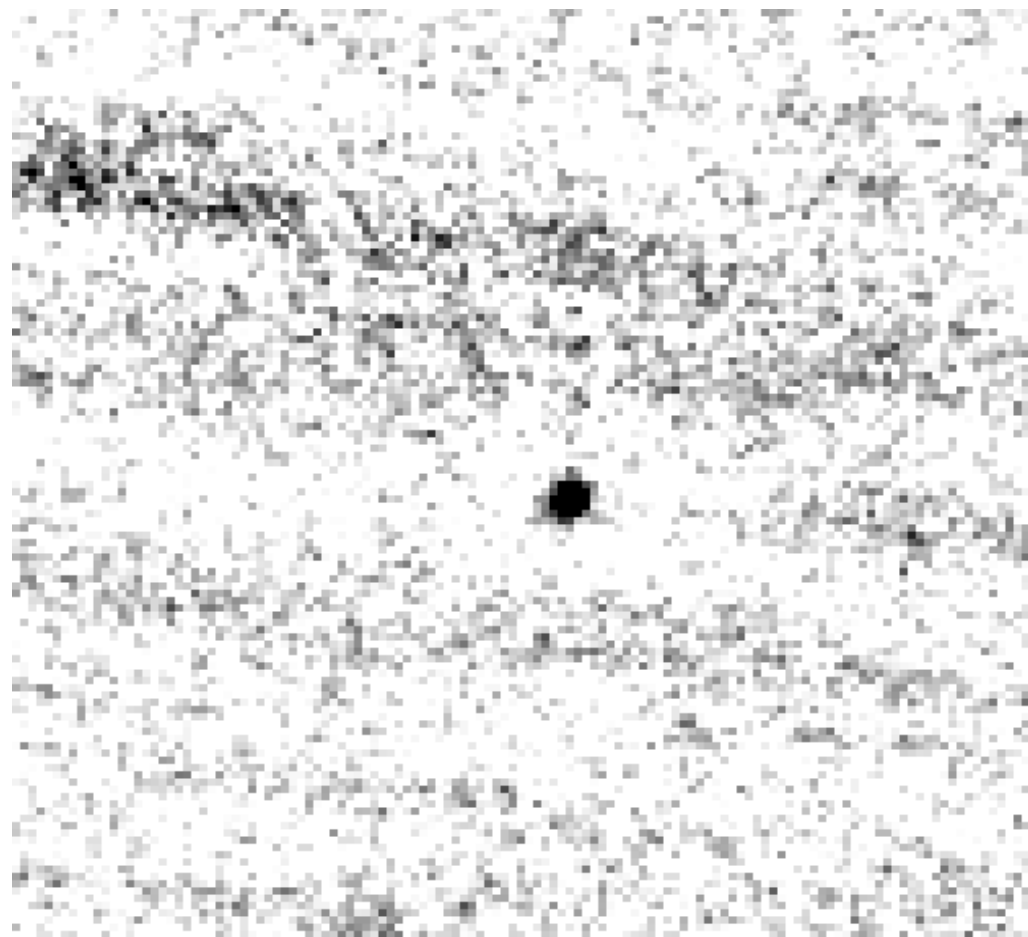
# Shift Rate Too Slow

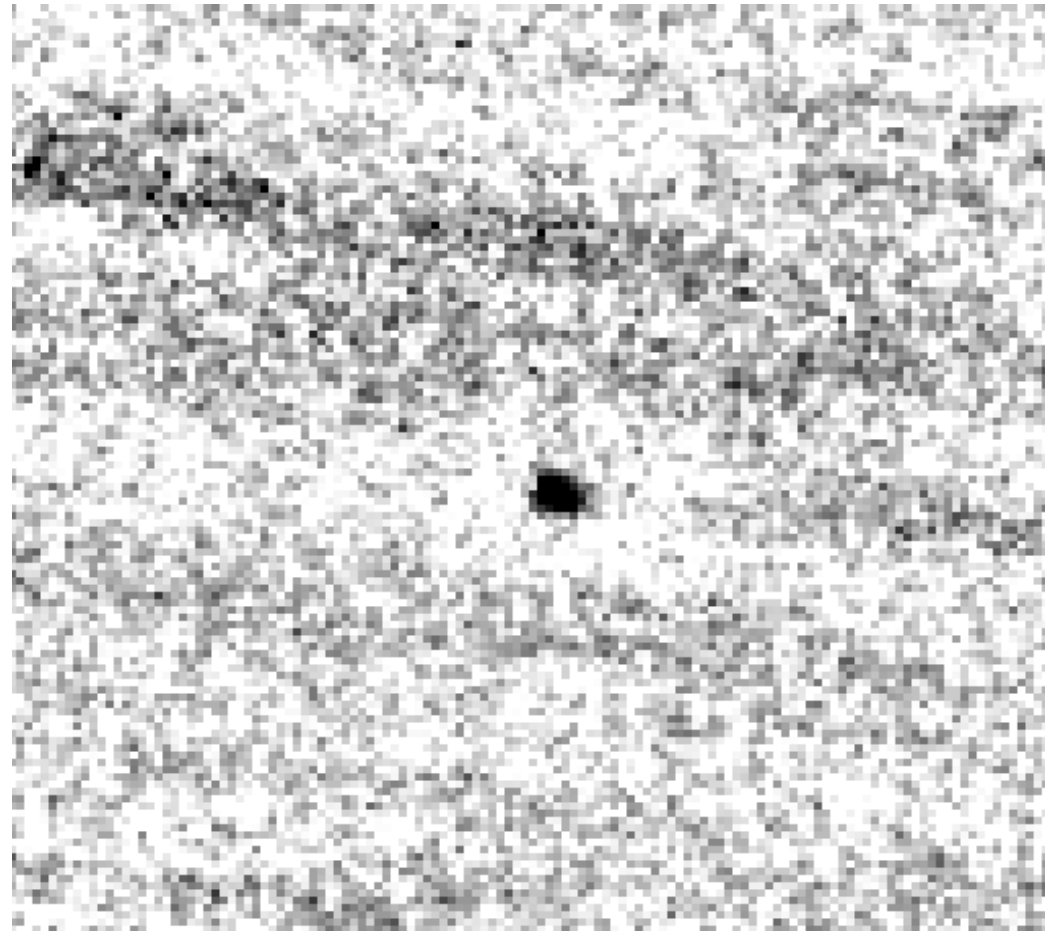






**Juust right**

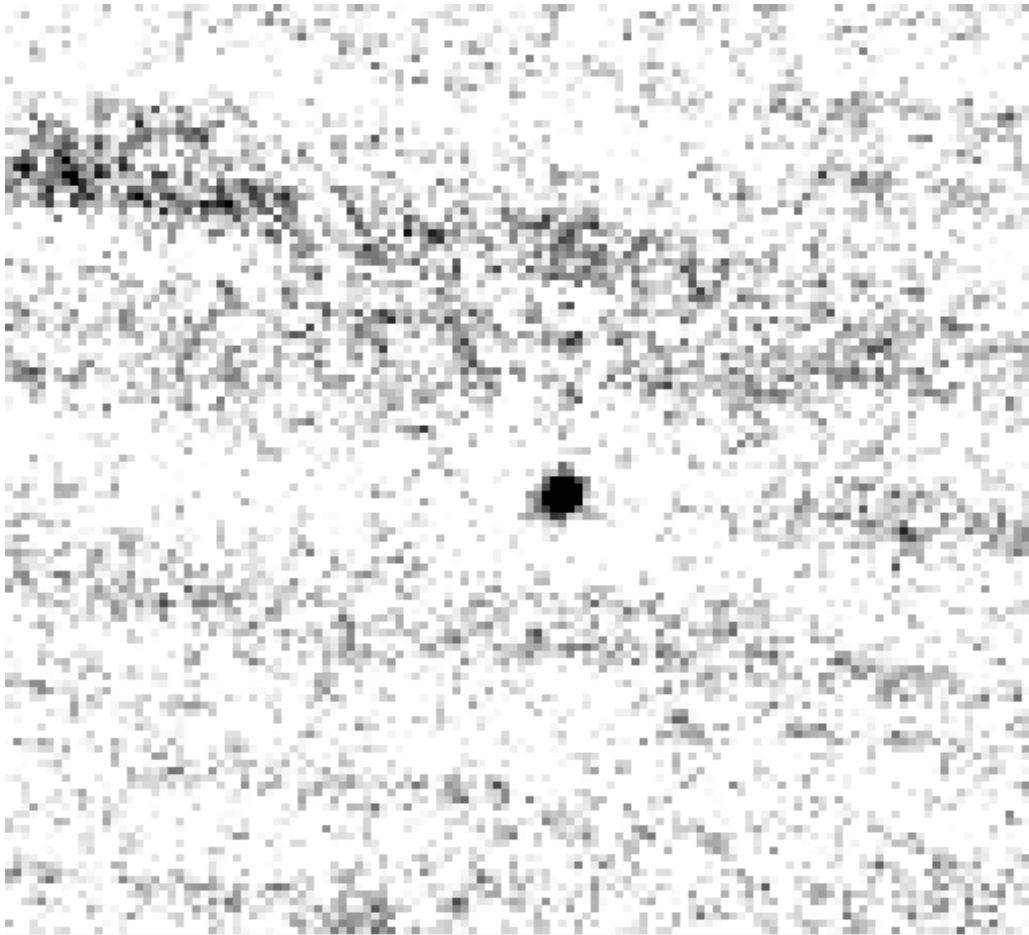




# Shift Rate Too Fast



# At sub-arcsec IQ, there is a large parameter space of recombination rates and angles



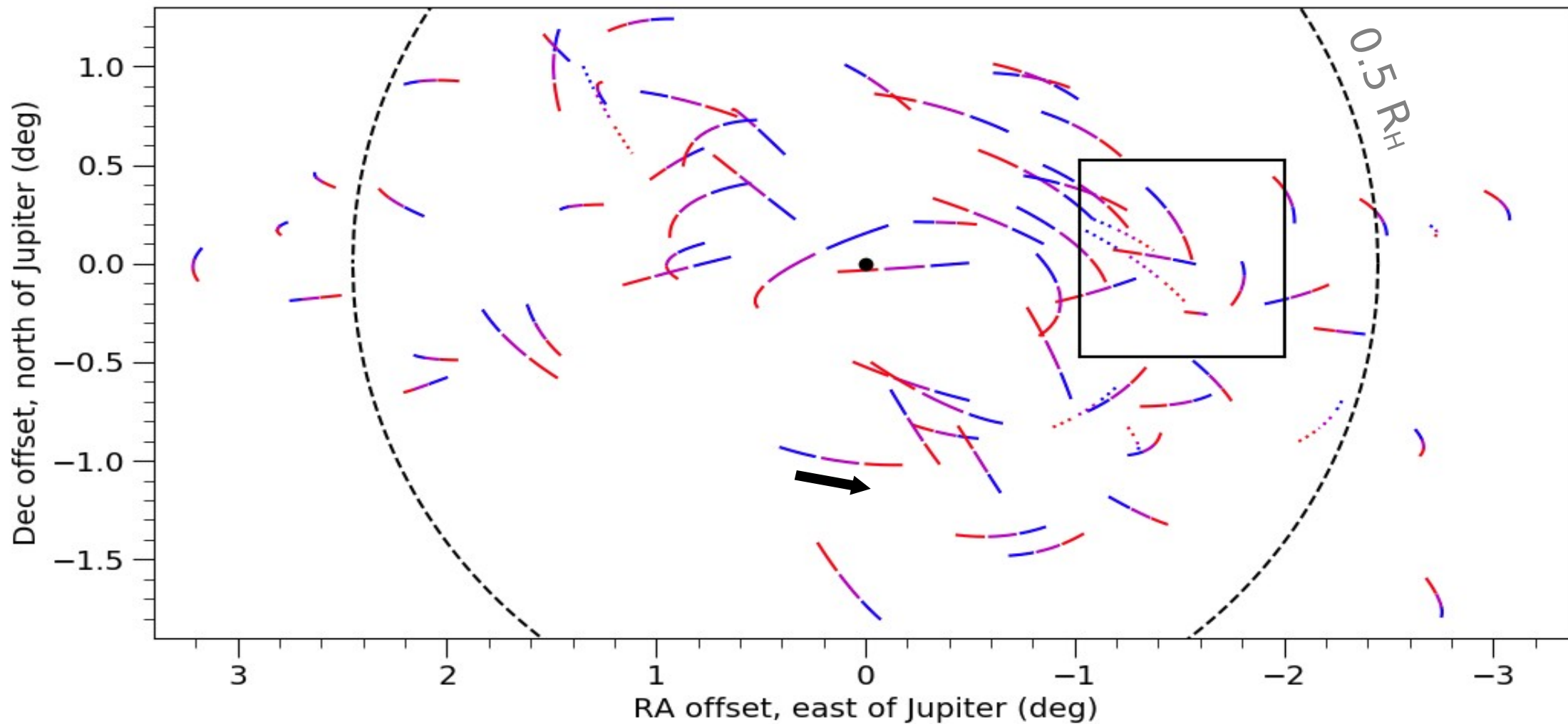
## Uranus + Neptune:

- parameter space moderate
- pencil-beams covered most of Hill spheres ~20 years ago
- mag ~25 ==>  $D > \sim 10$  km

## Jupiter+Saturn:

- huge challenge due to proximity and large Hill Spheres
- 3-image methods done by ~2006

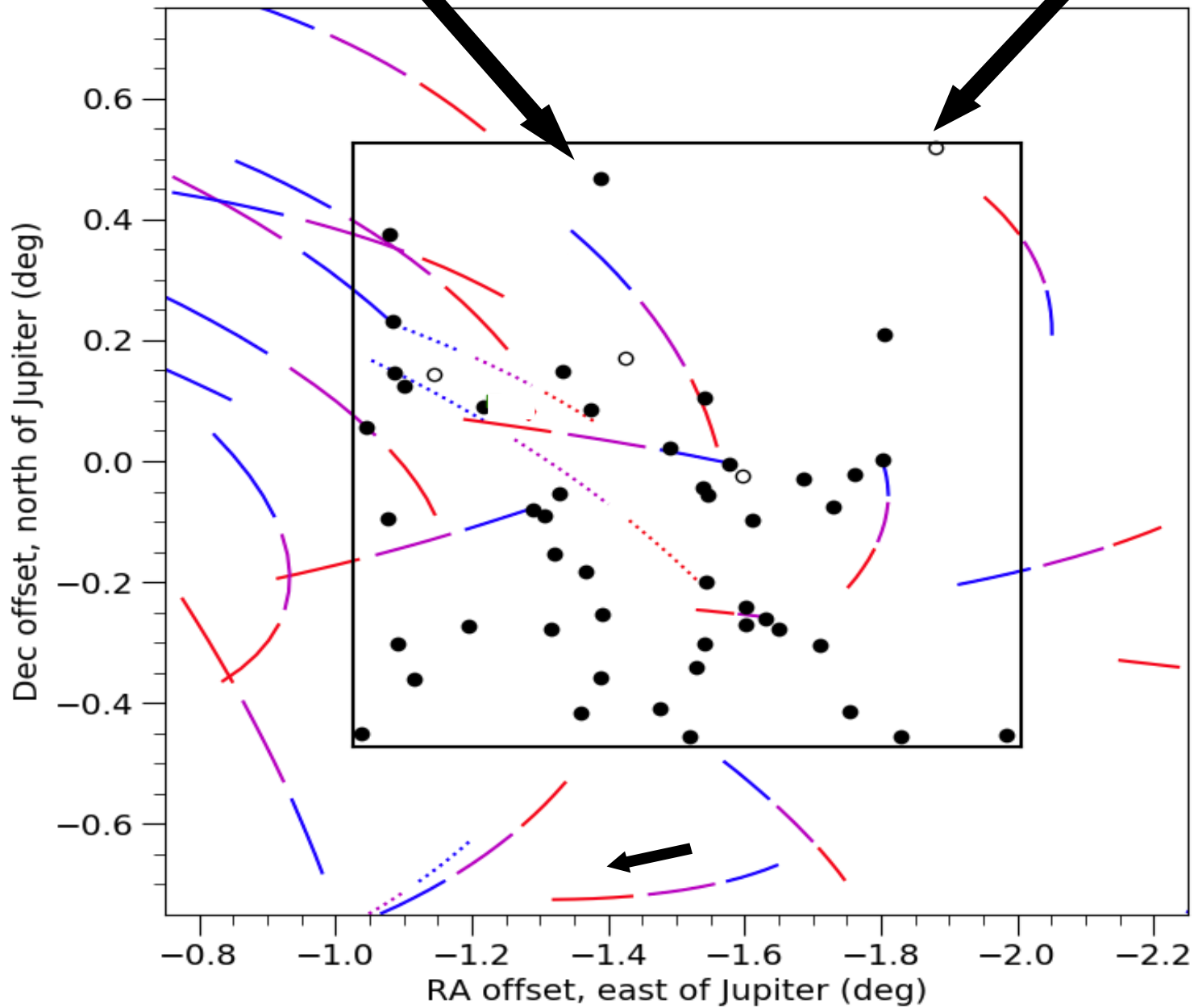
# Jovian System

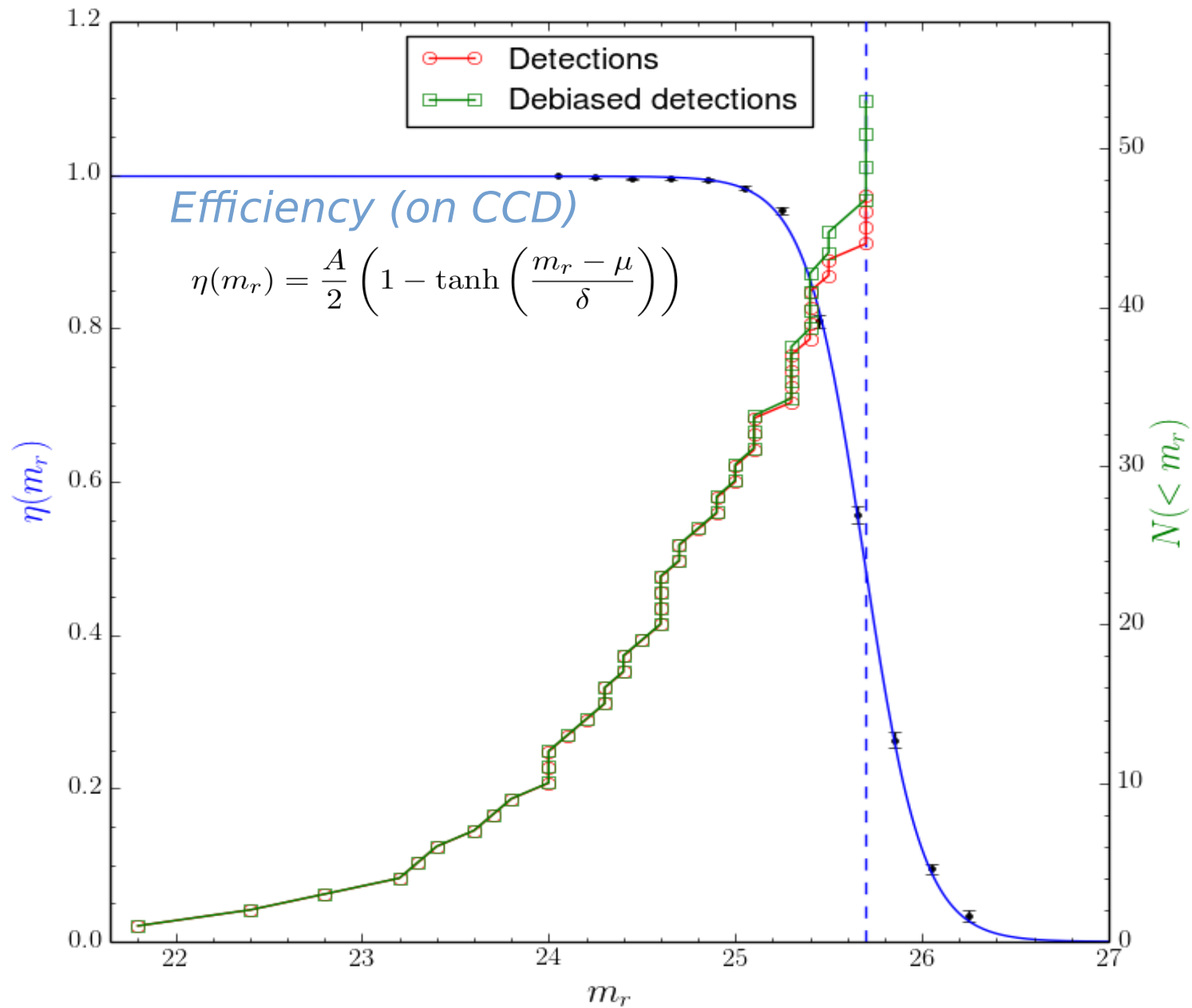


*Ashton (2021) PhD*

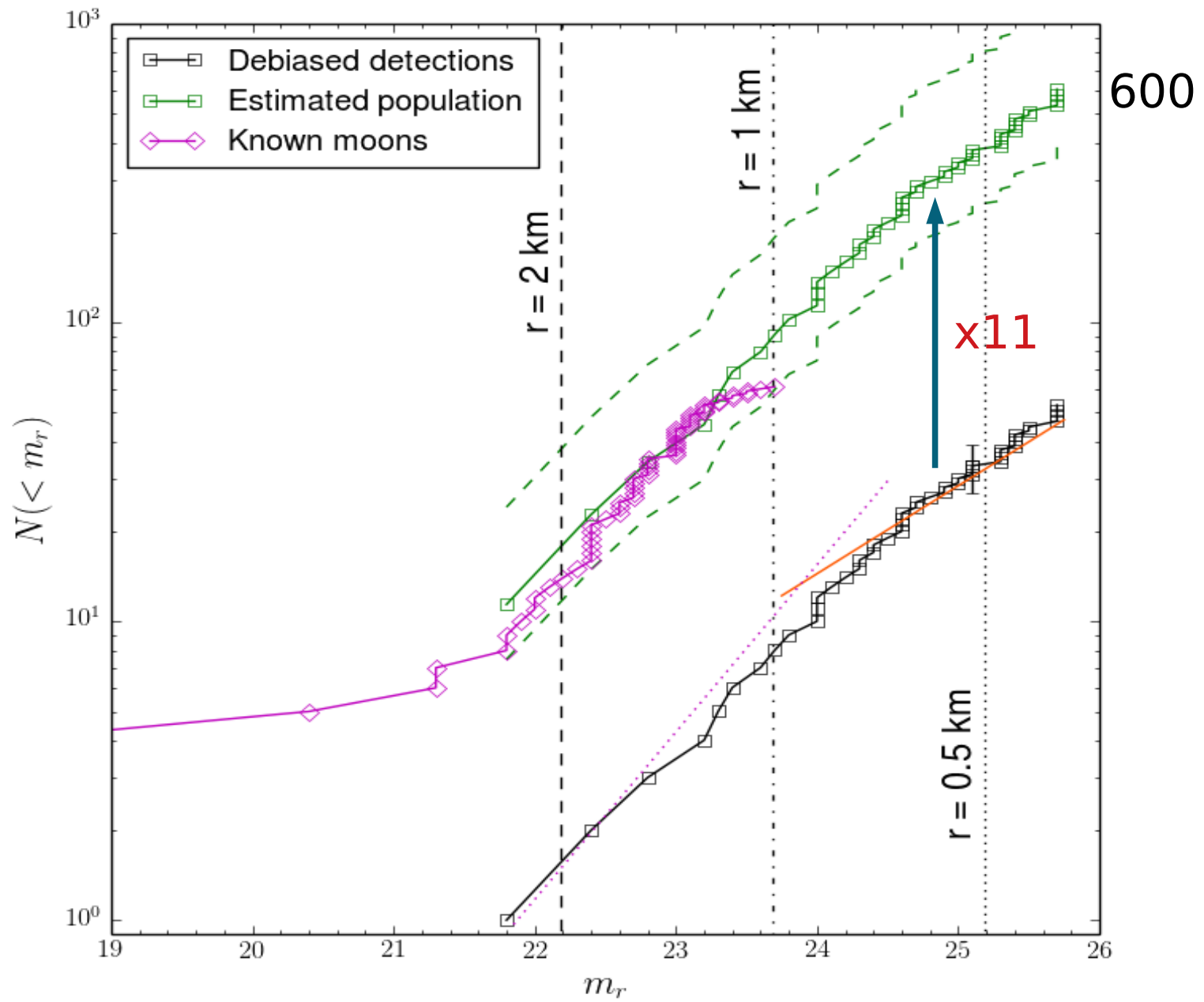
Characterised Detection

Uncharacterised Detection



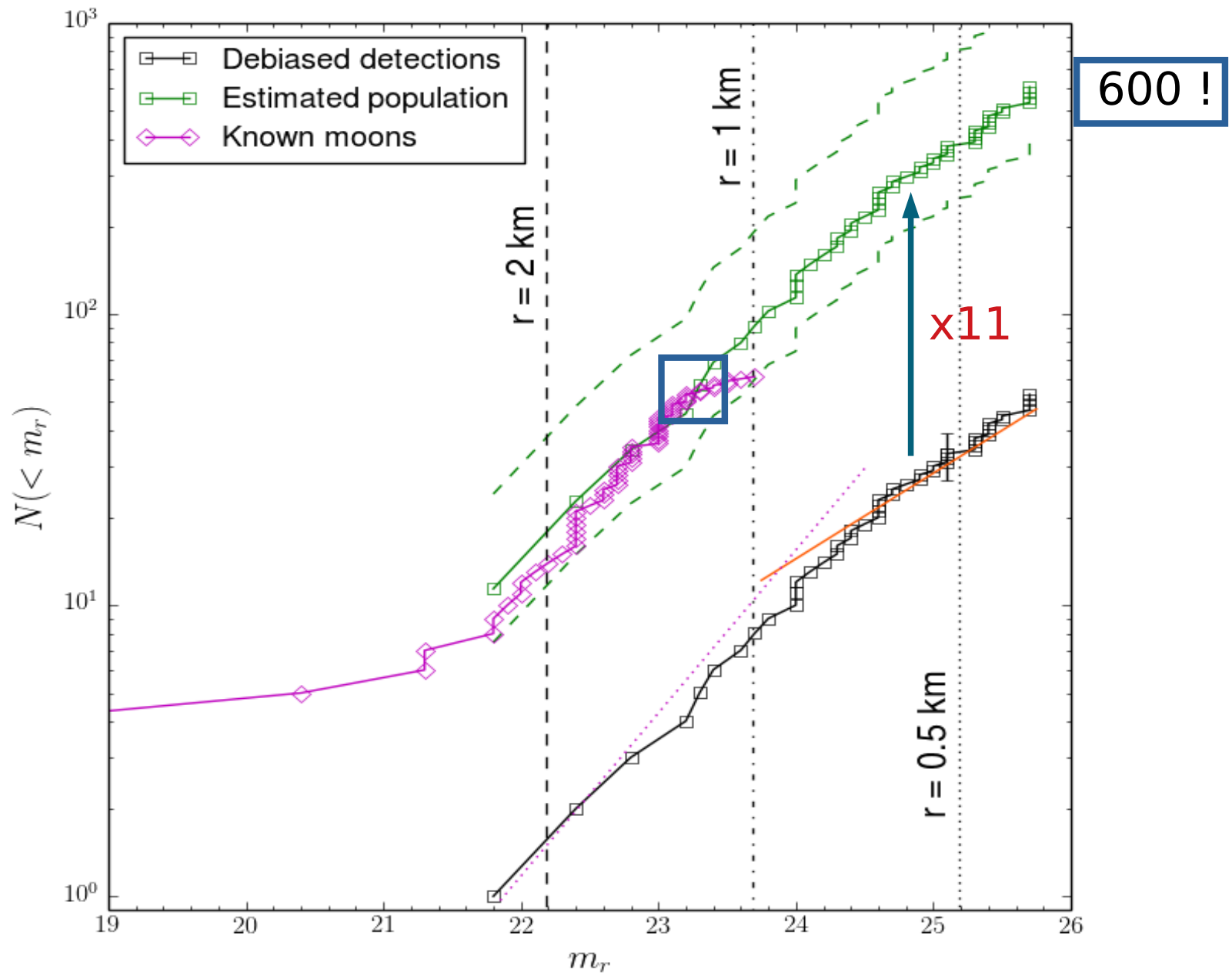


Ashton et al  
(2020) PSJ



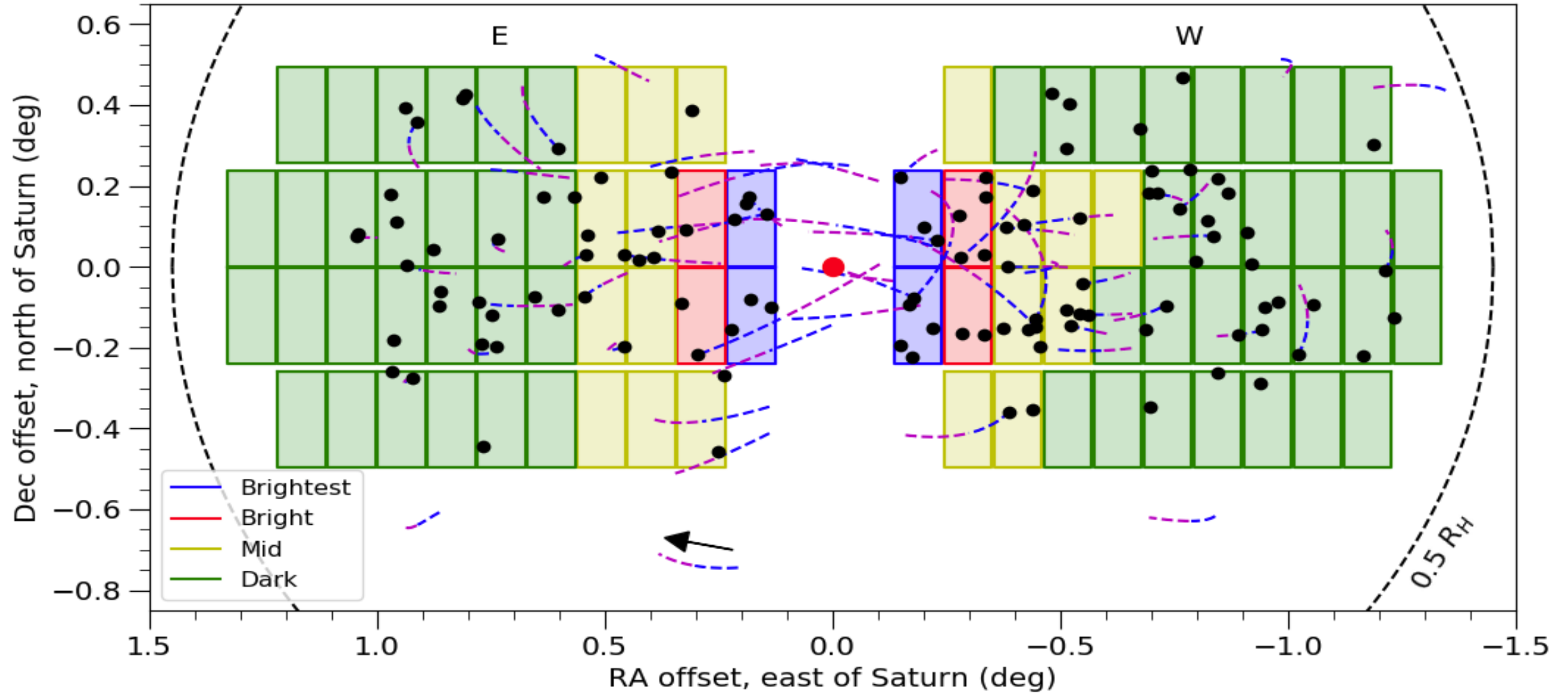
Ashton et al  
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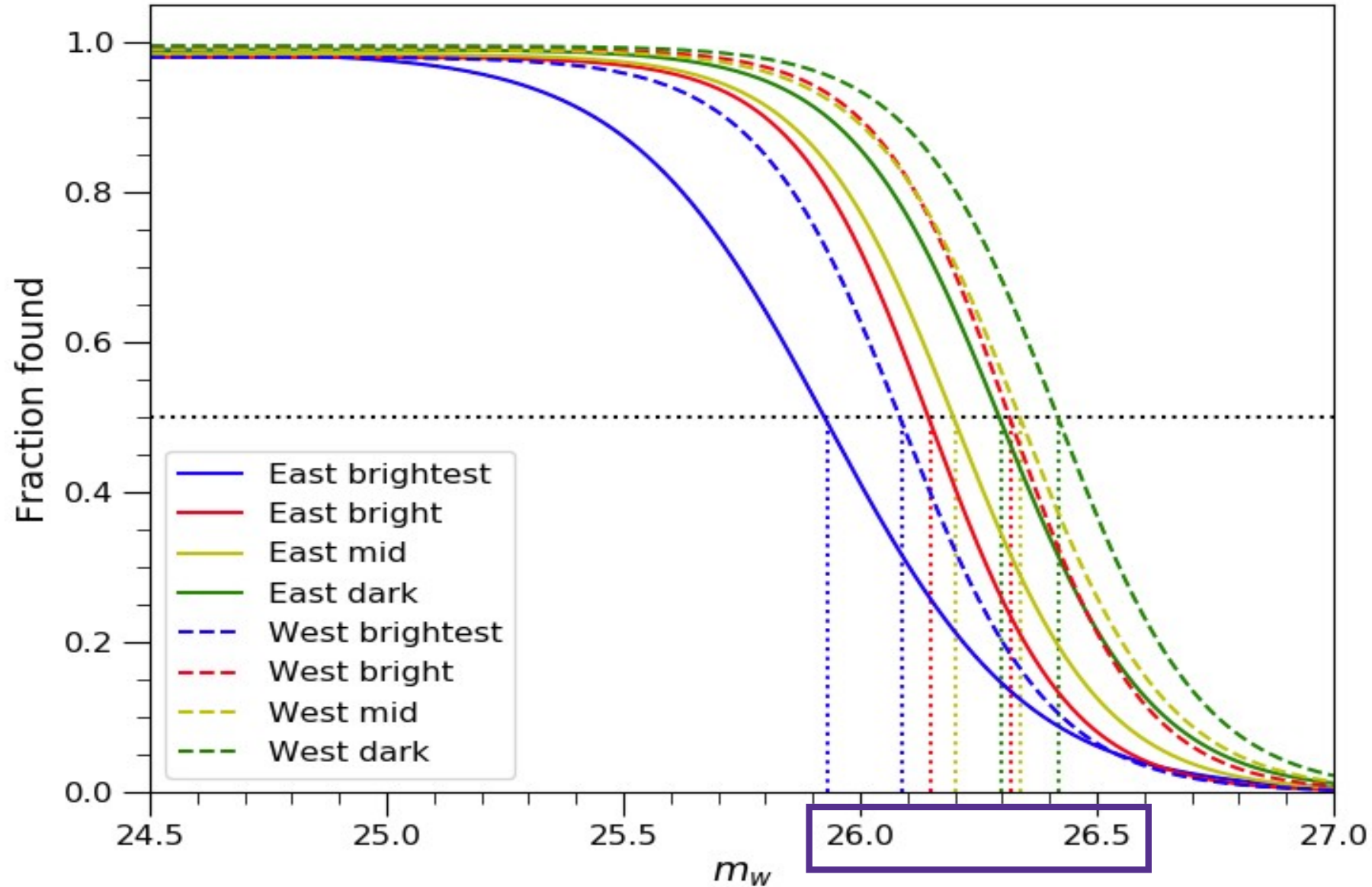


Ashton et al (2020) PSJ

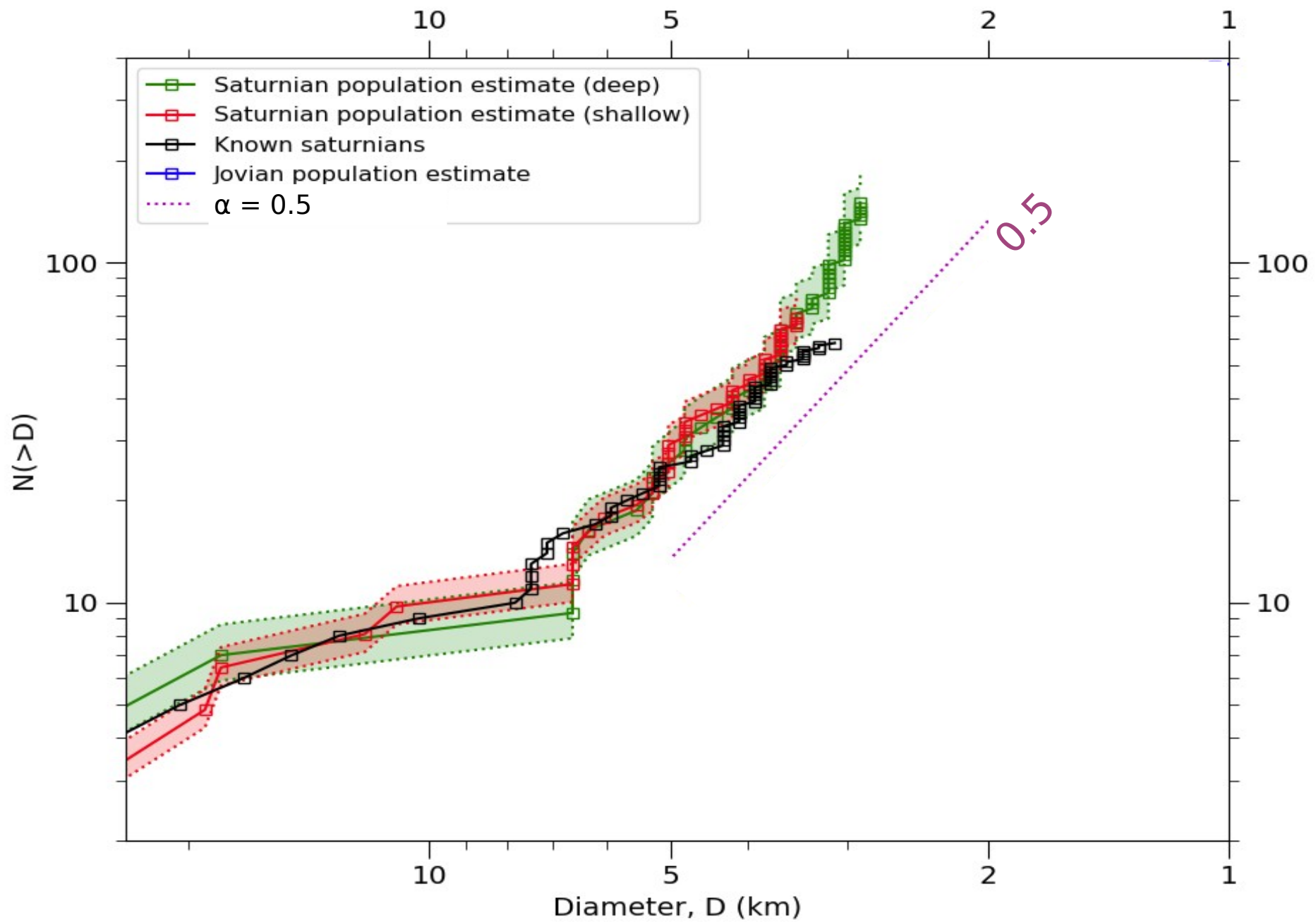
# Saturnian detections

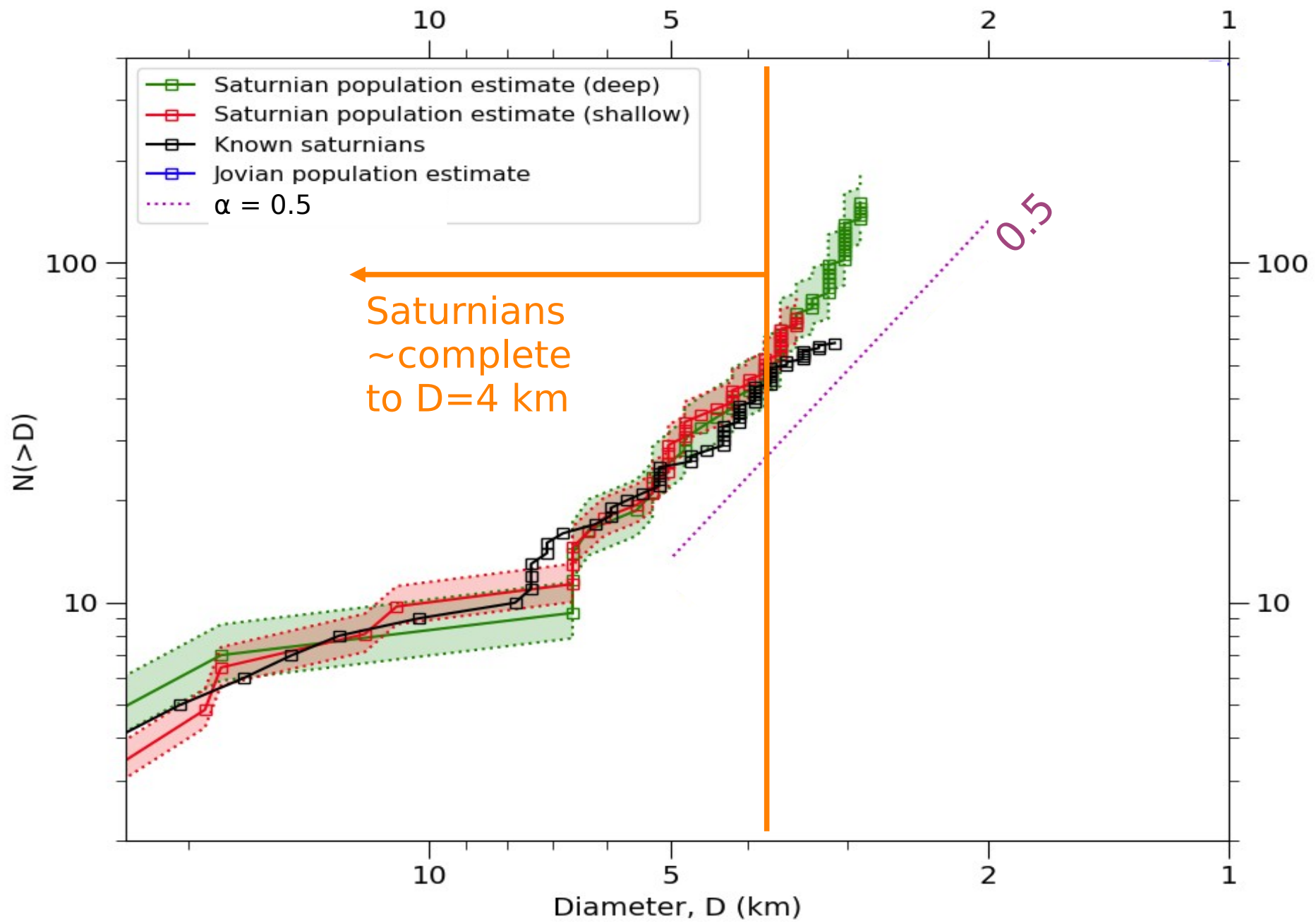


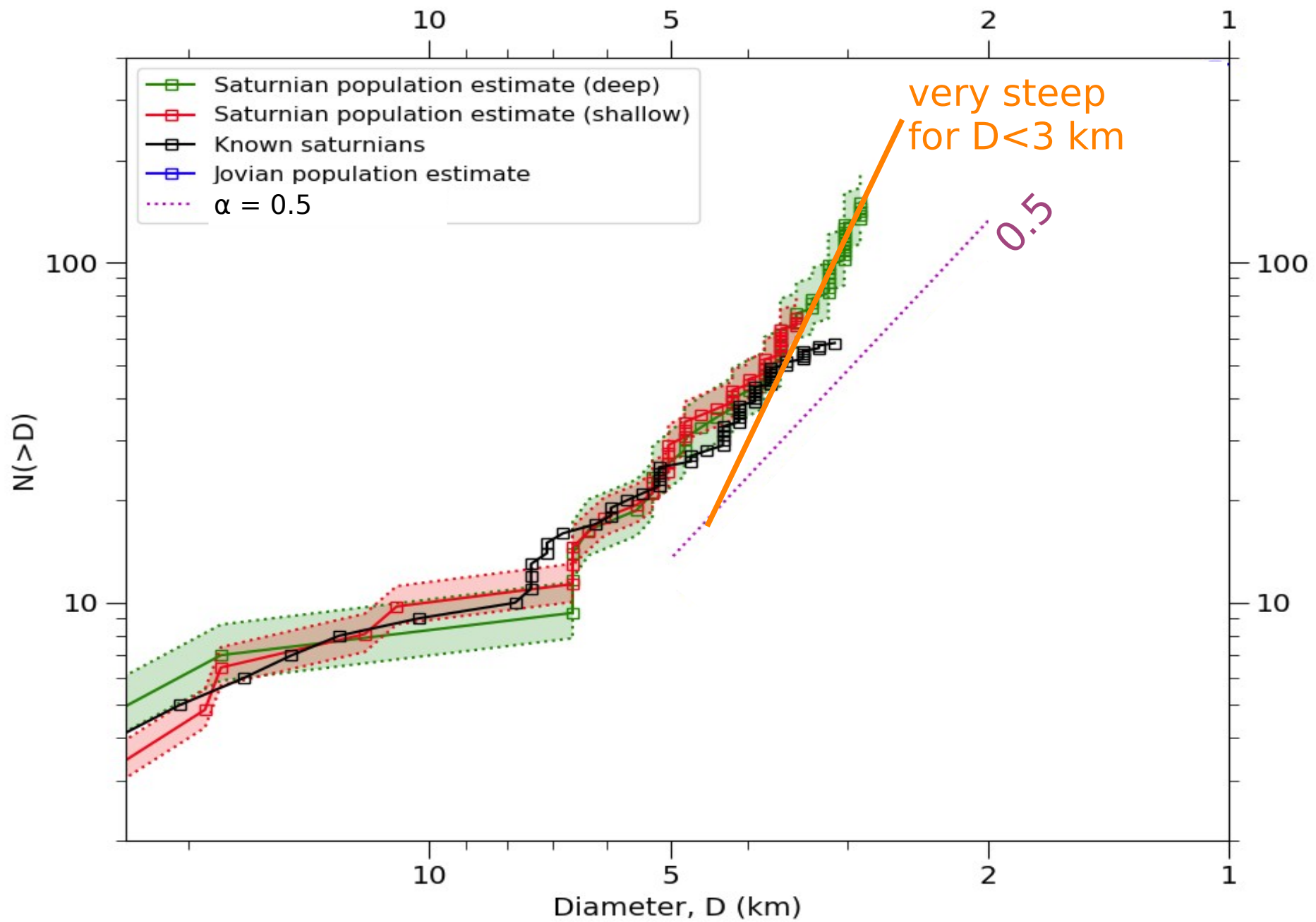
# Efficiency functions



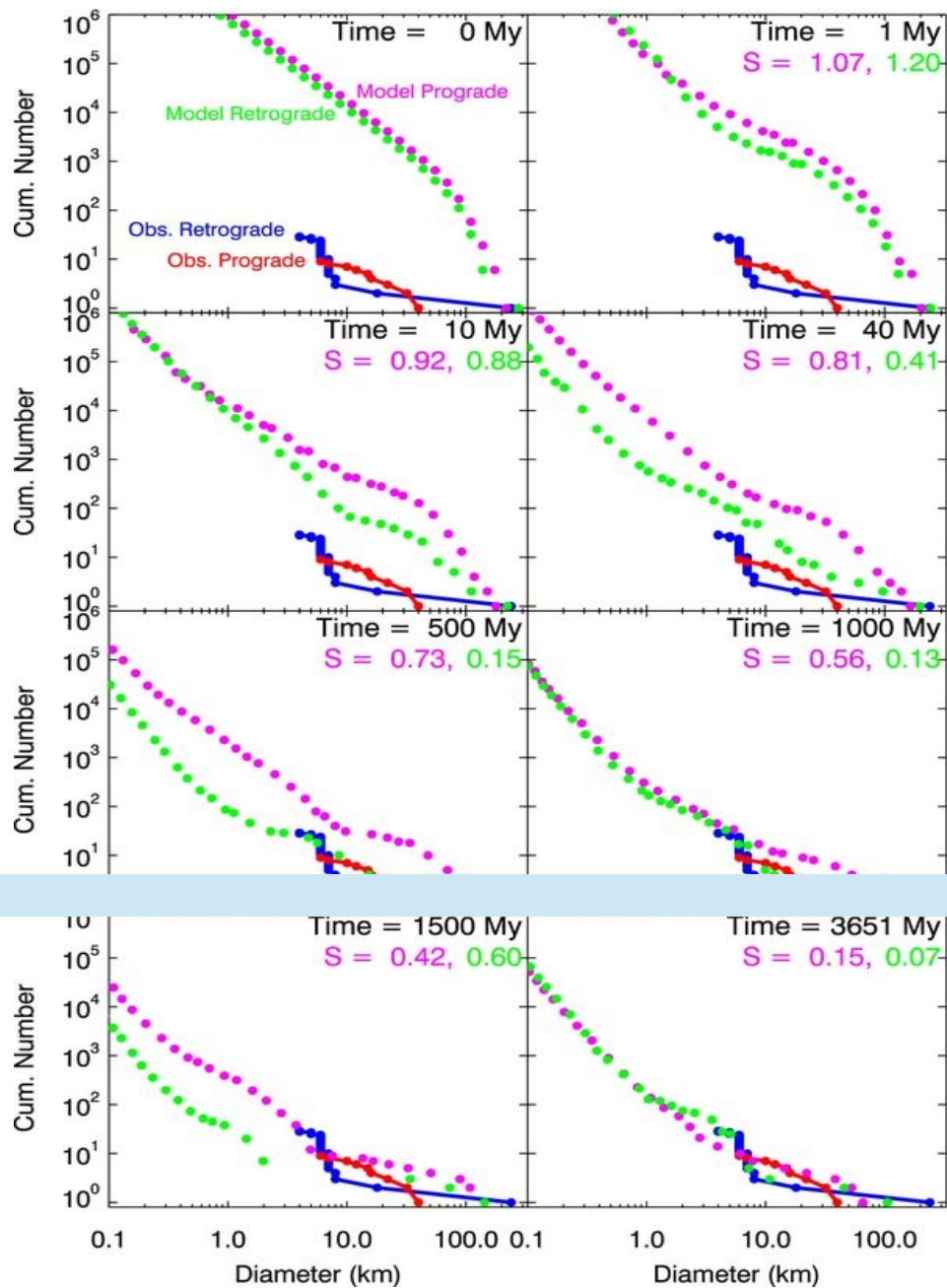
Ashton et al  
(2021) PSJ



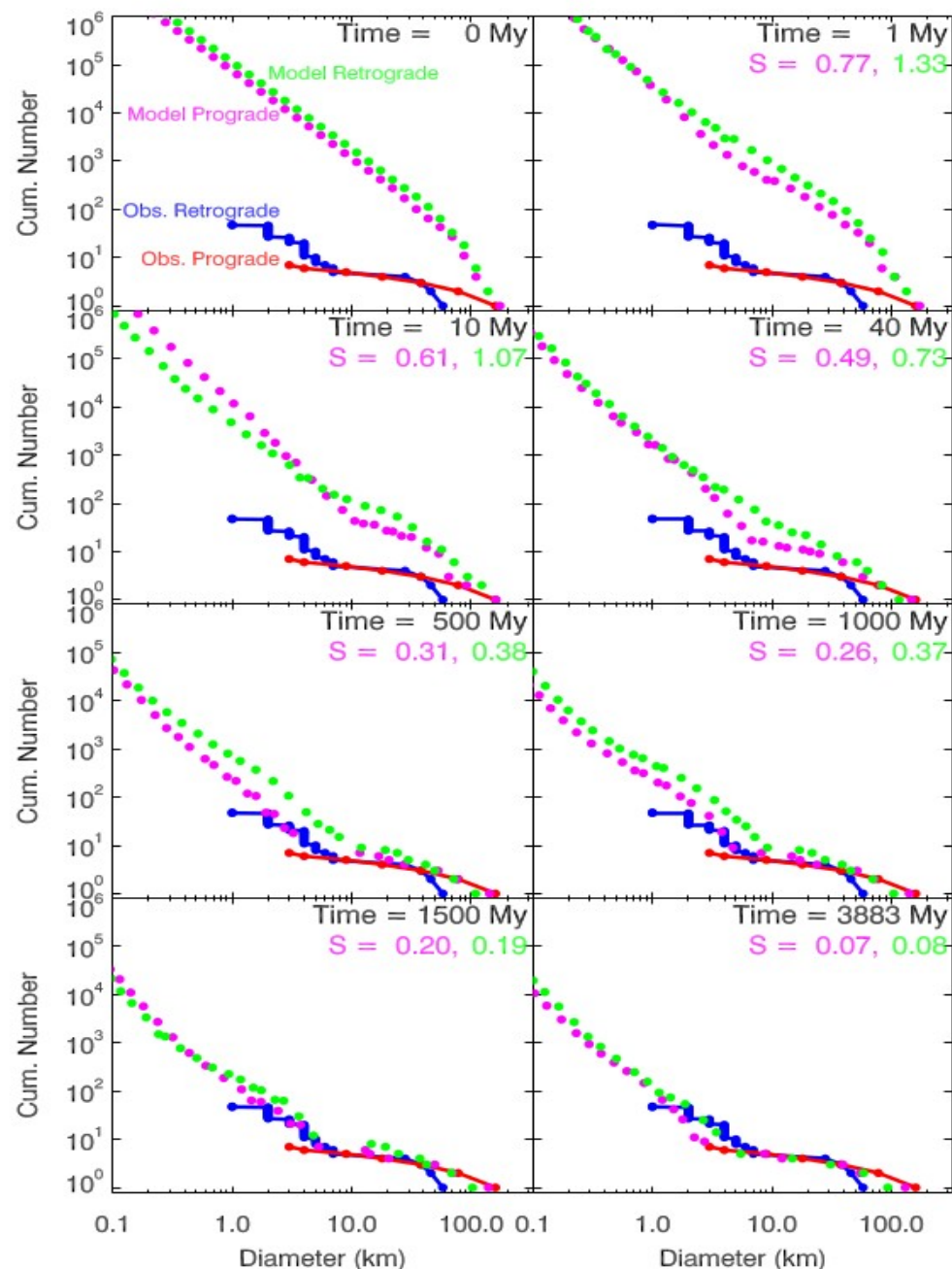


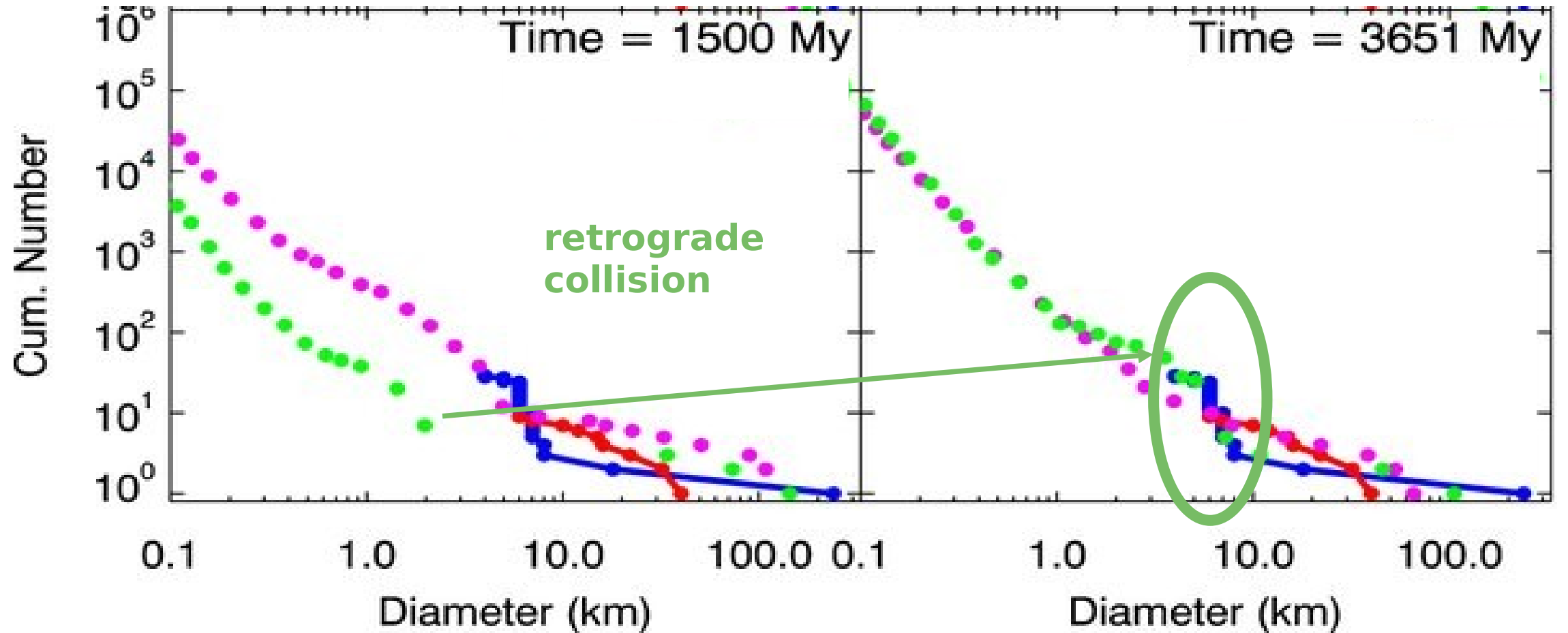


# Saturn

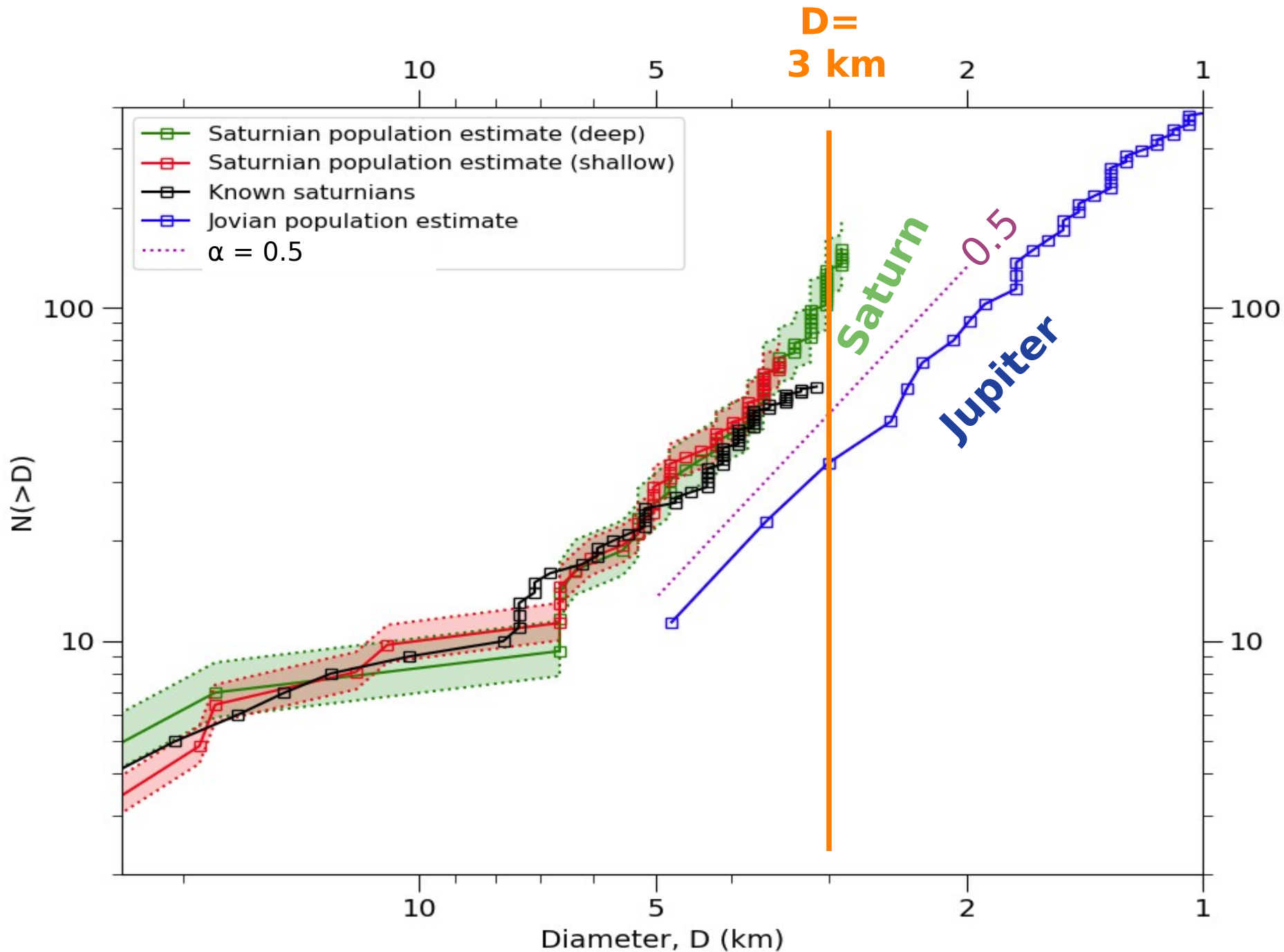


# Jupiter







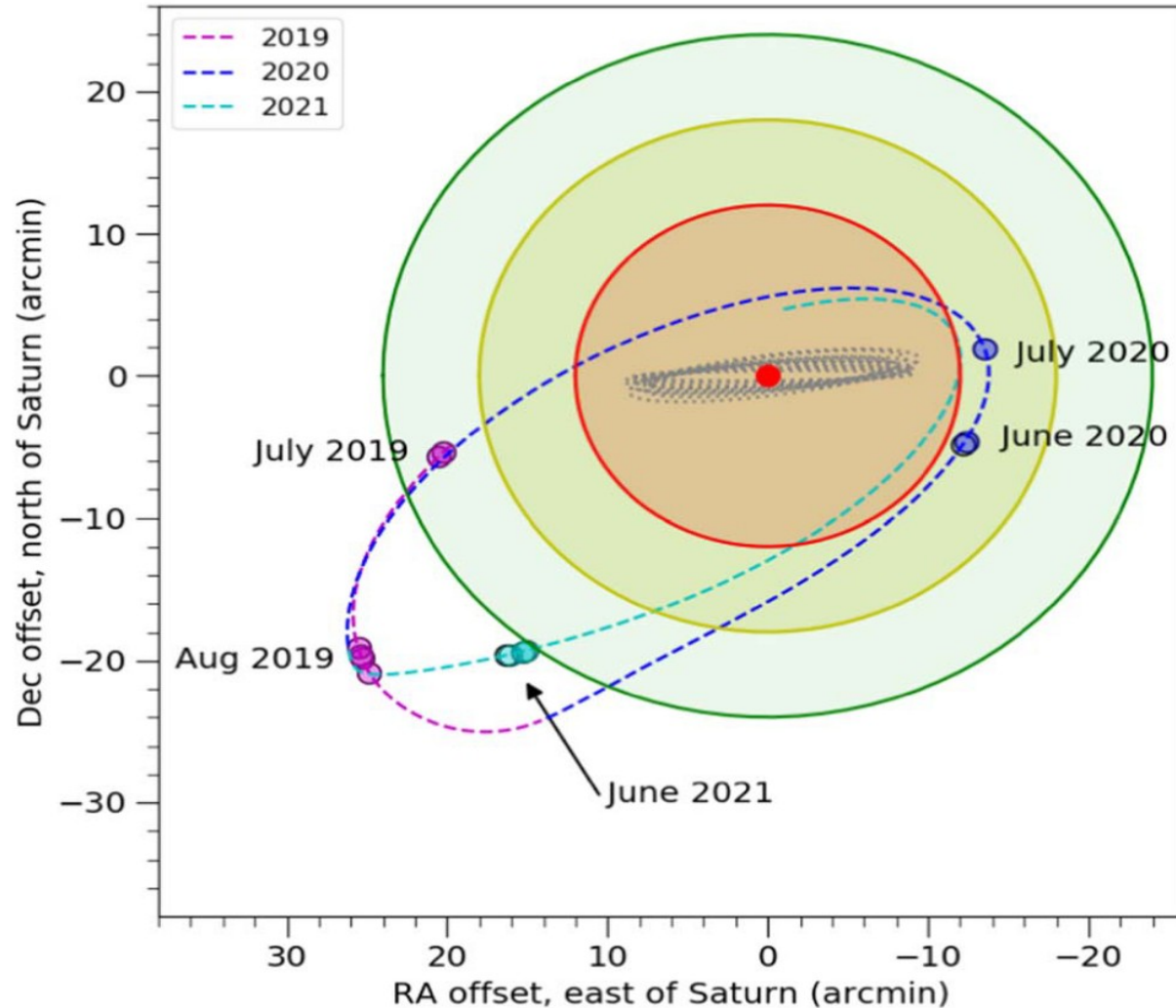


- **Jupiter IS consistent with ~ collisional equilibrium**
- **At  $D \sim 3$  km, Saturn has ~4 times as many irregular as Jupiter (!)**
- **Saturn may have more moons than all other planets combined(!)**

# S/2019 S 1 : Exceptionally close

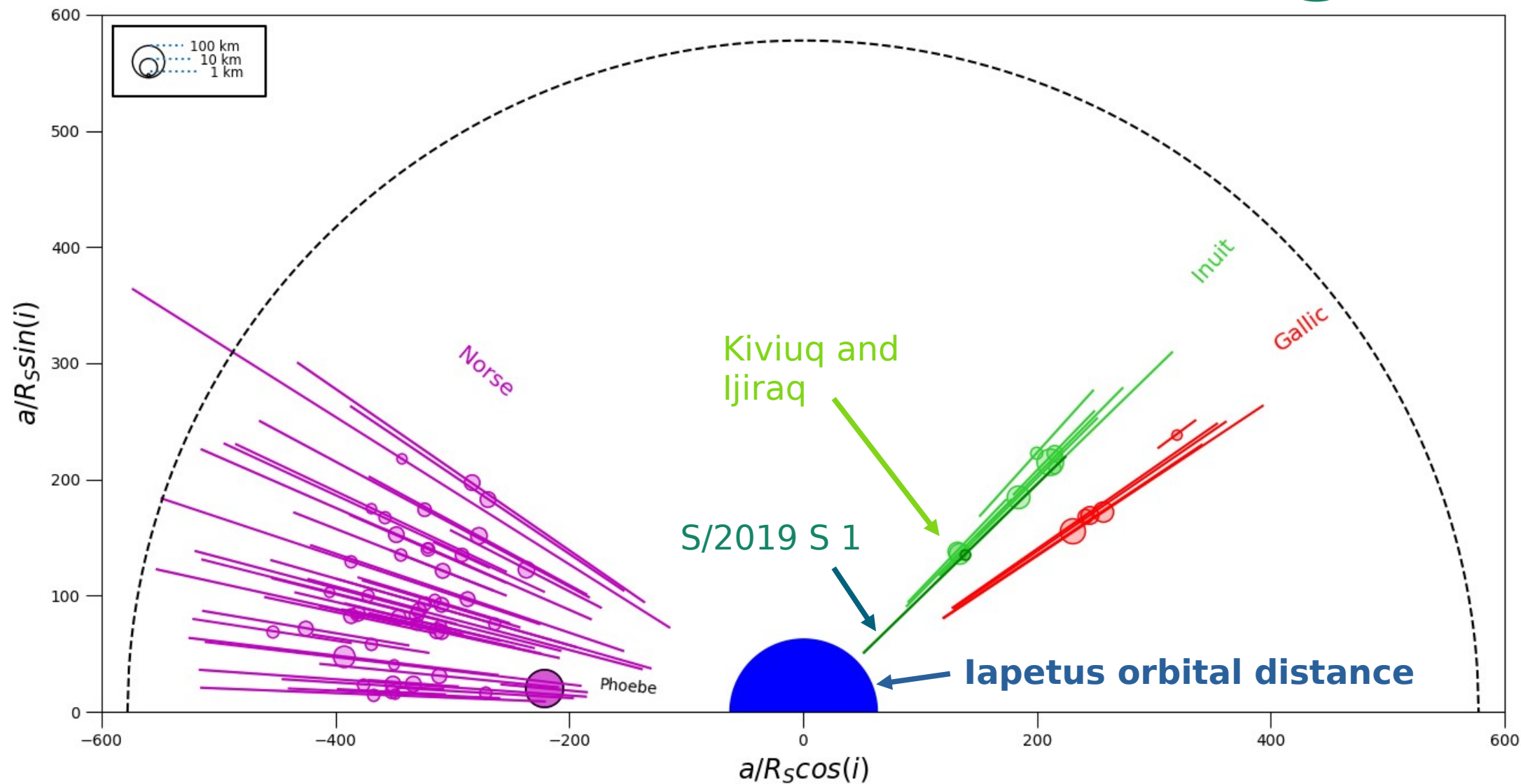
THE PLANETARY SCIENCE JOURNAL, 3:107 (5pp), 2022 May

Ashton et al



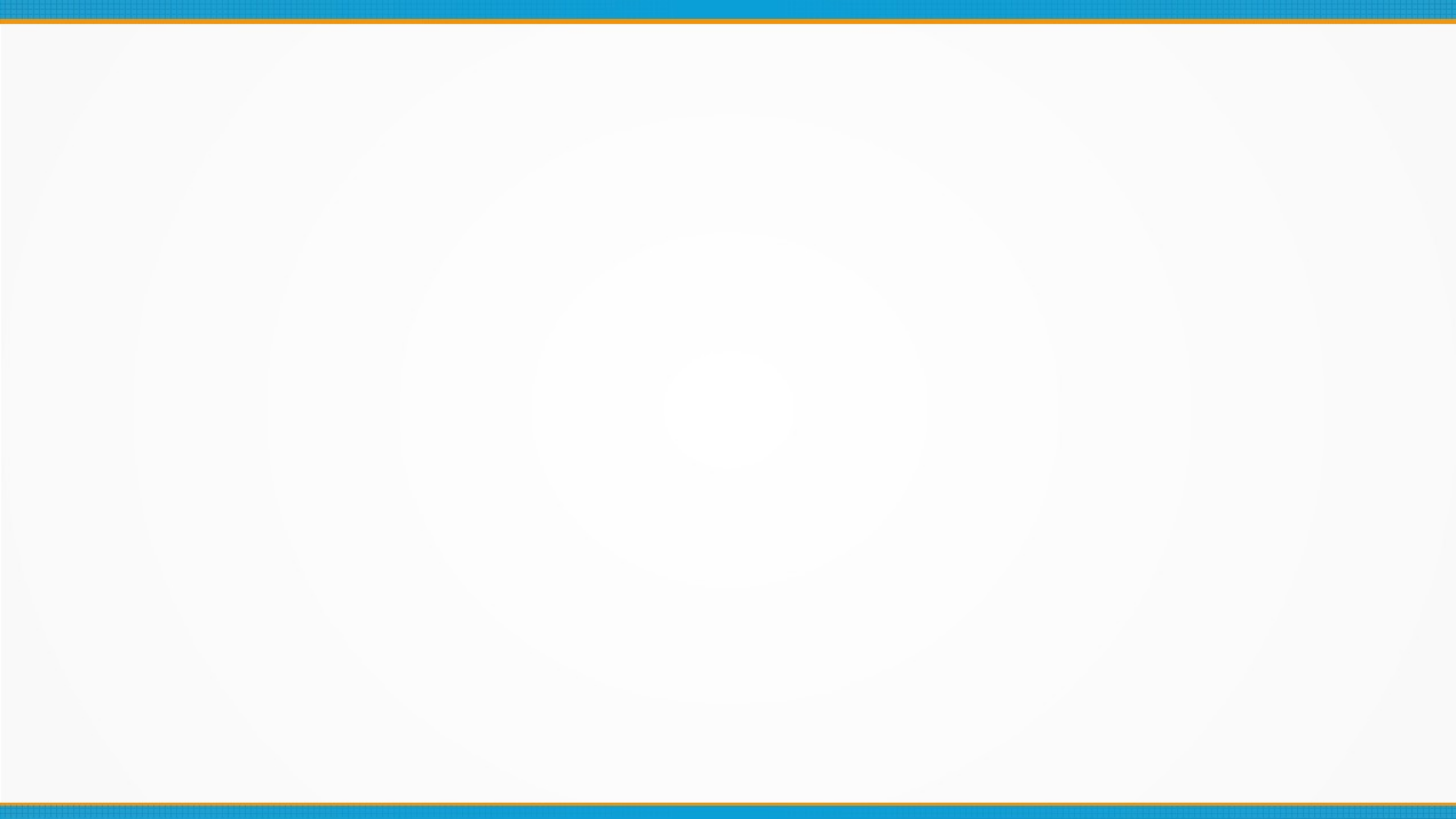
- **Often deep in Saturn's scattered light.**
- **Direct orbits harder to find?**
- **Gets very close to Iapetus (1.15x)**

# S/2019 S 1 is in the Inuit group

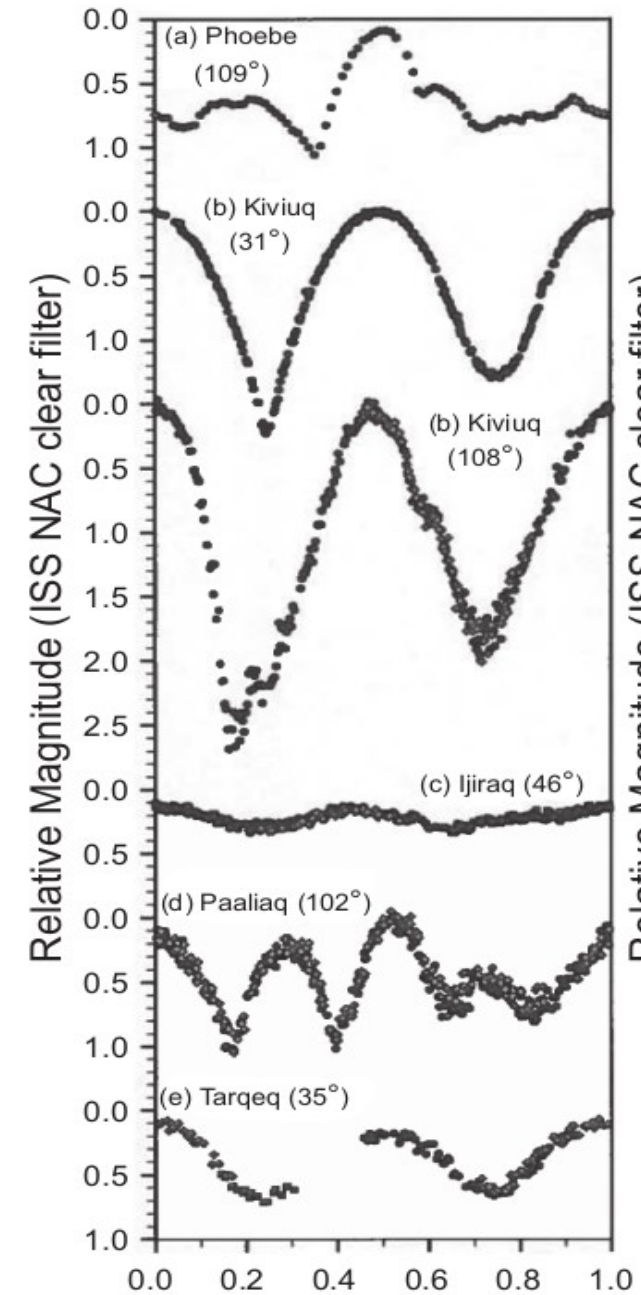
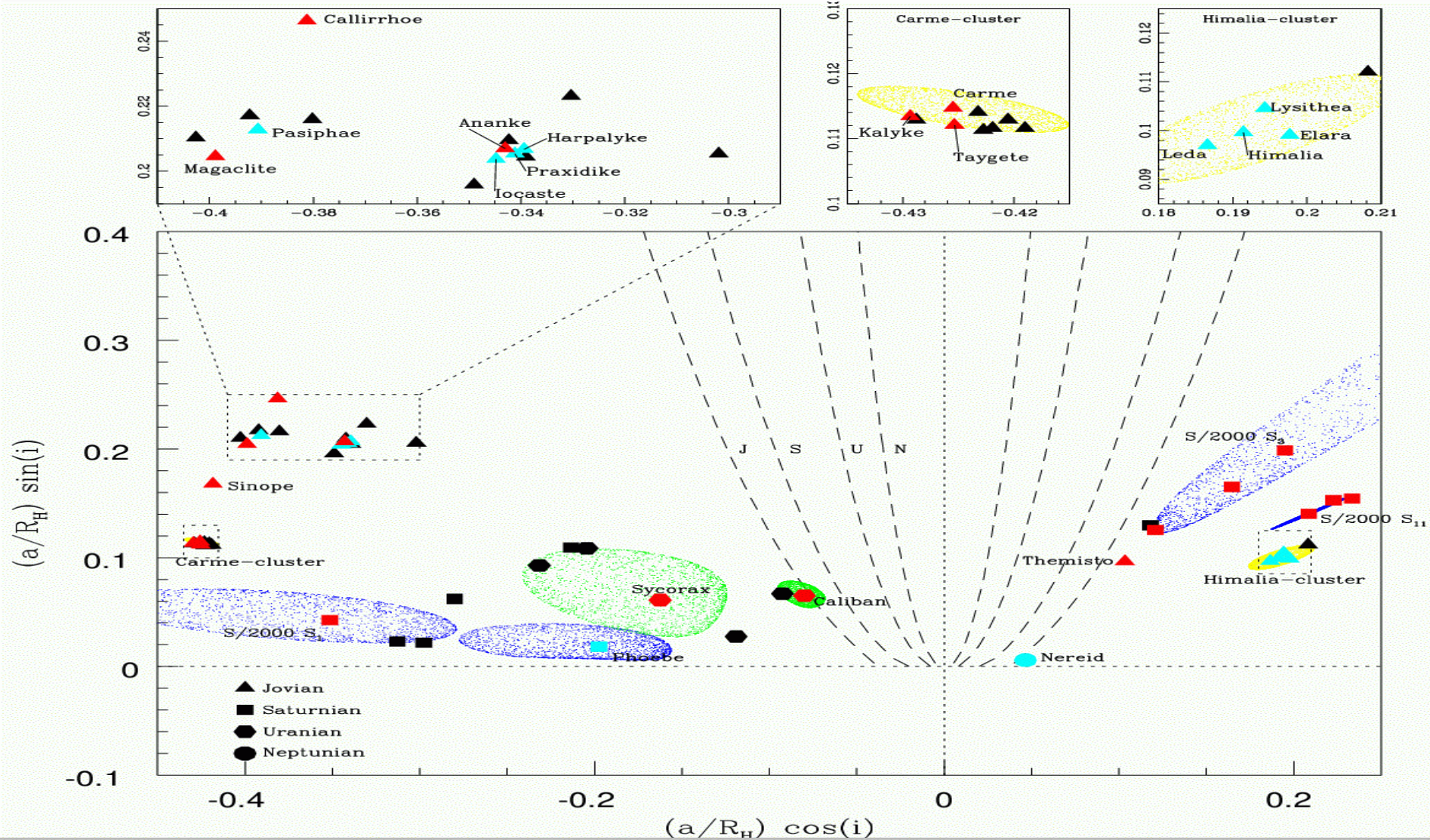


# Summary

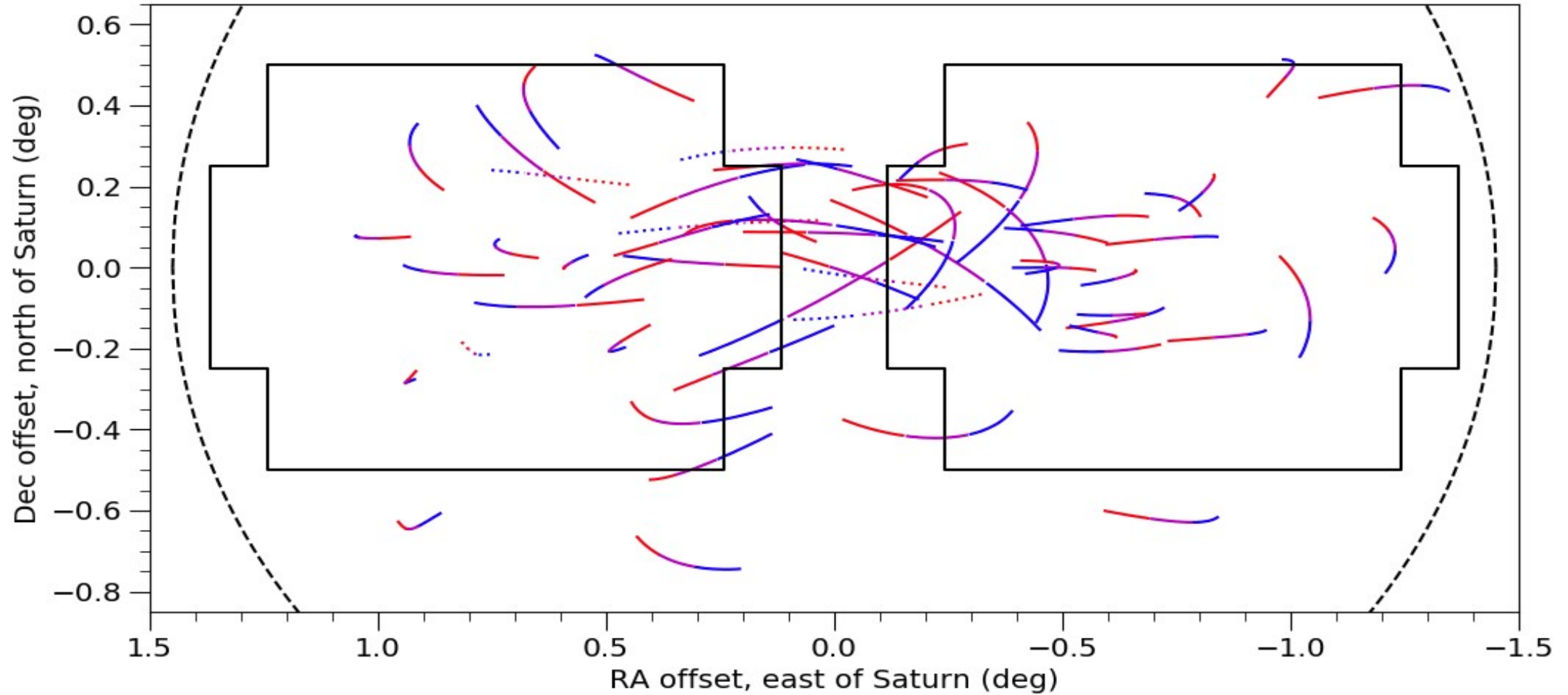
- Jupiter's moons in ~collisional equilibrium down to  $<1$  km
- Saturnian system had a collision generating many few-km moons  $\sim < 100$  Myr ago
  - This results in it having  $>100$  moons with  $D > 3$  km
- The preponderance of retrograde irregulars is enhanced by selection effects, as the direct moons suffer from scattered light due to their closer orbits.



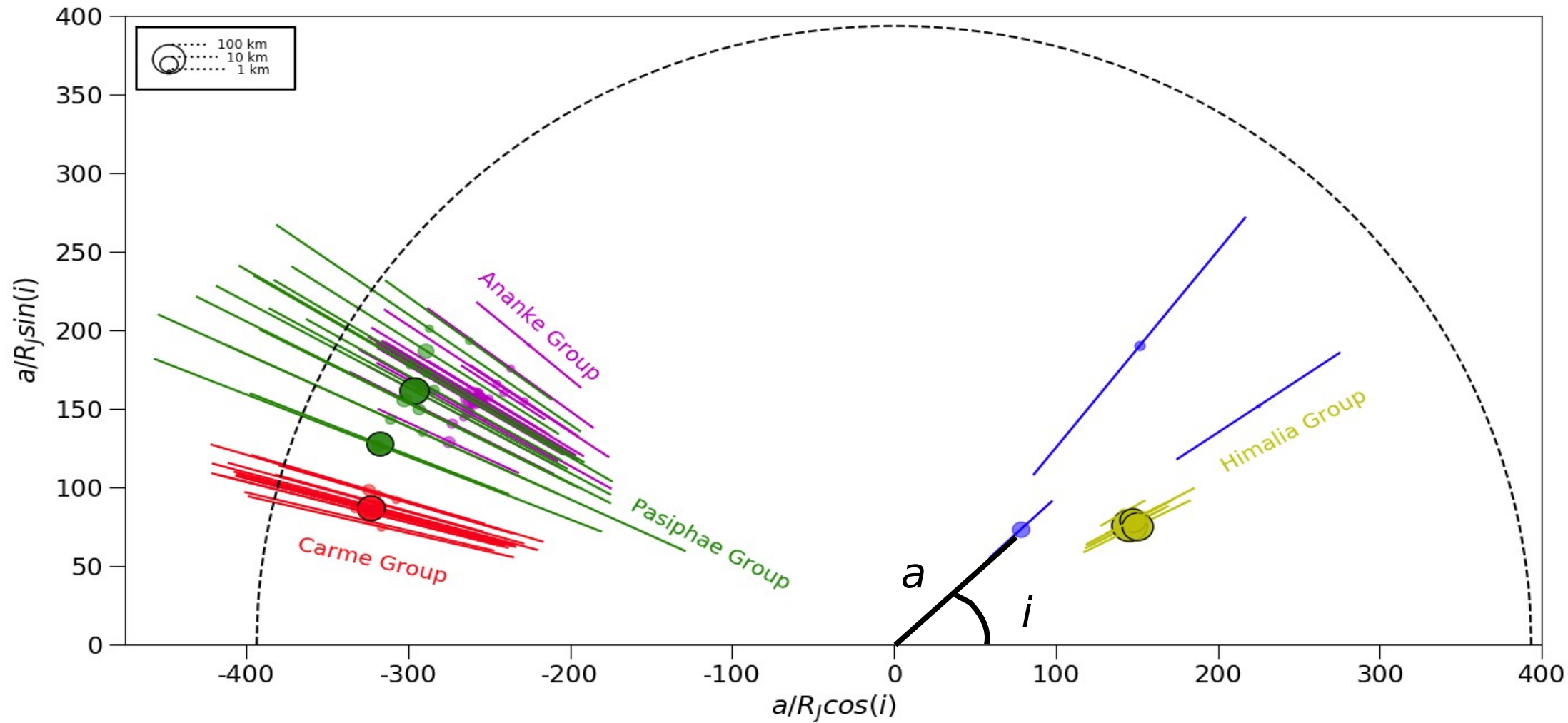
# Clues from physical studies



# Saturnian system

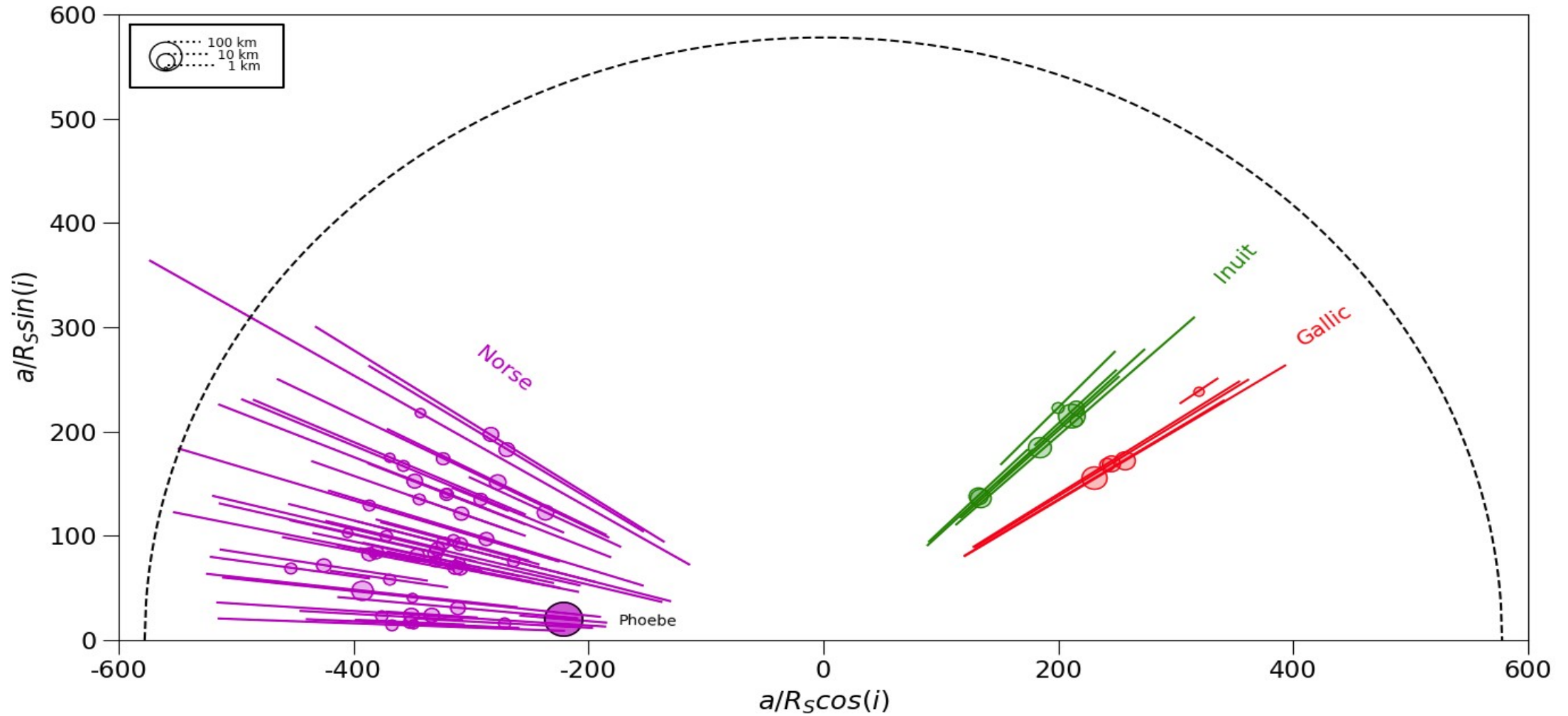


# Jovian irregular system



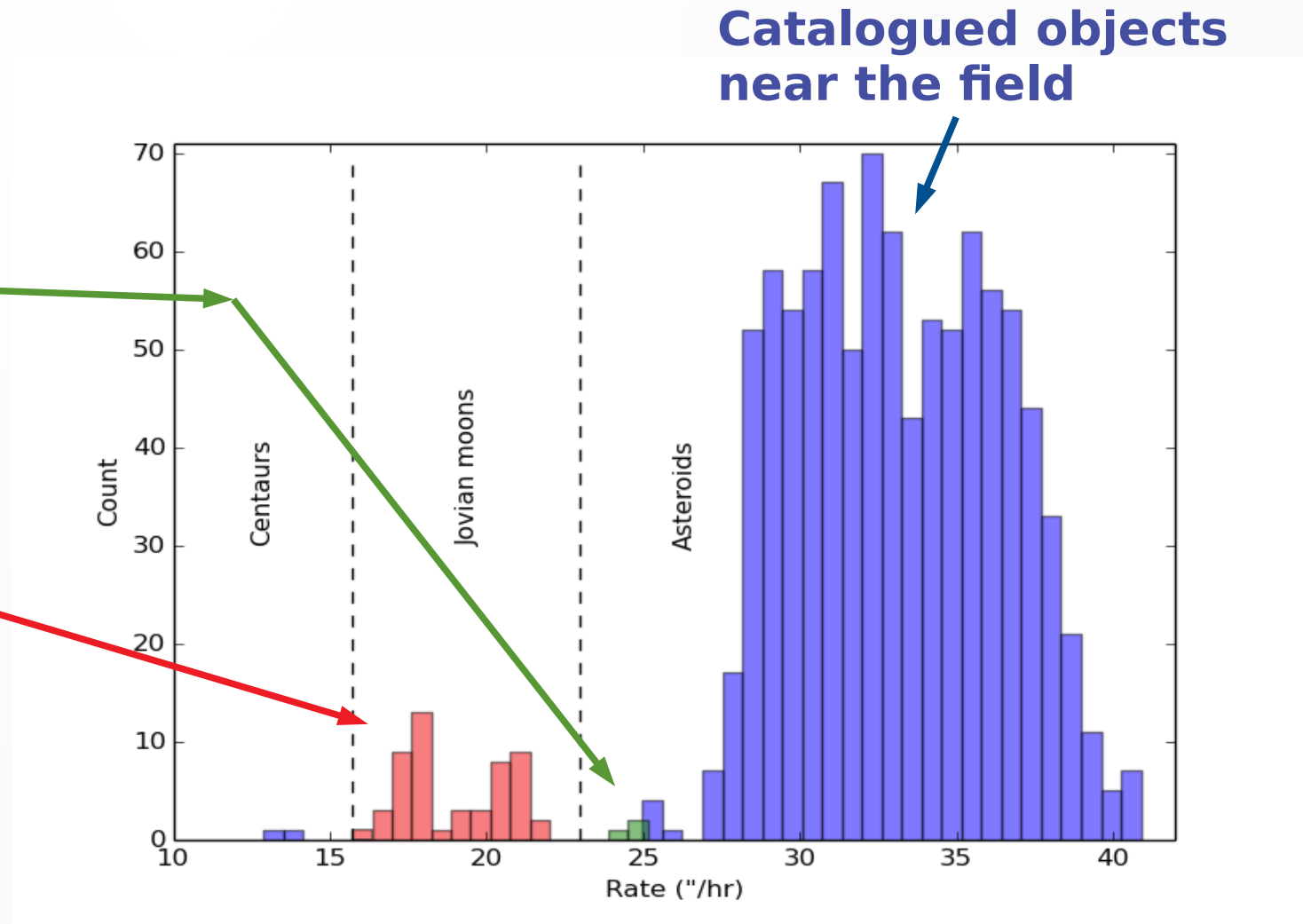


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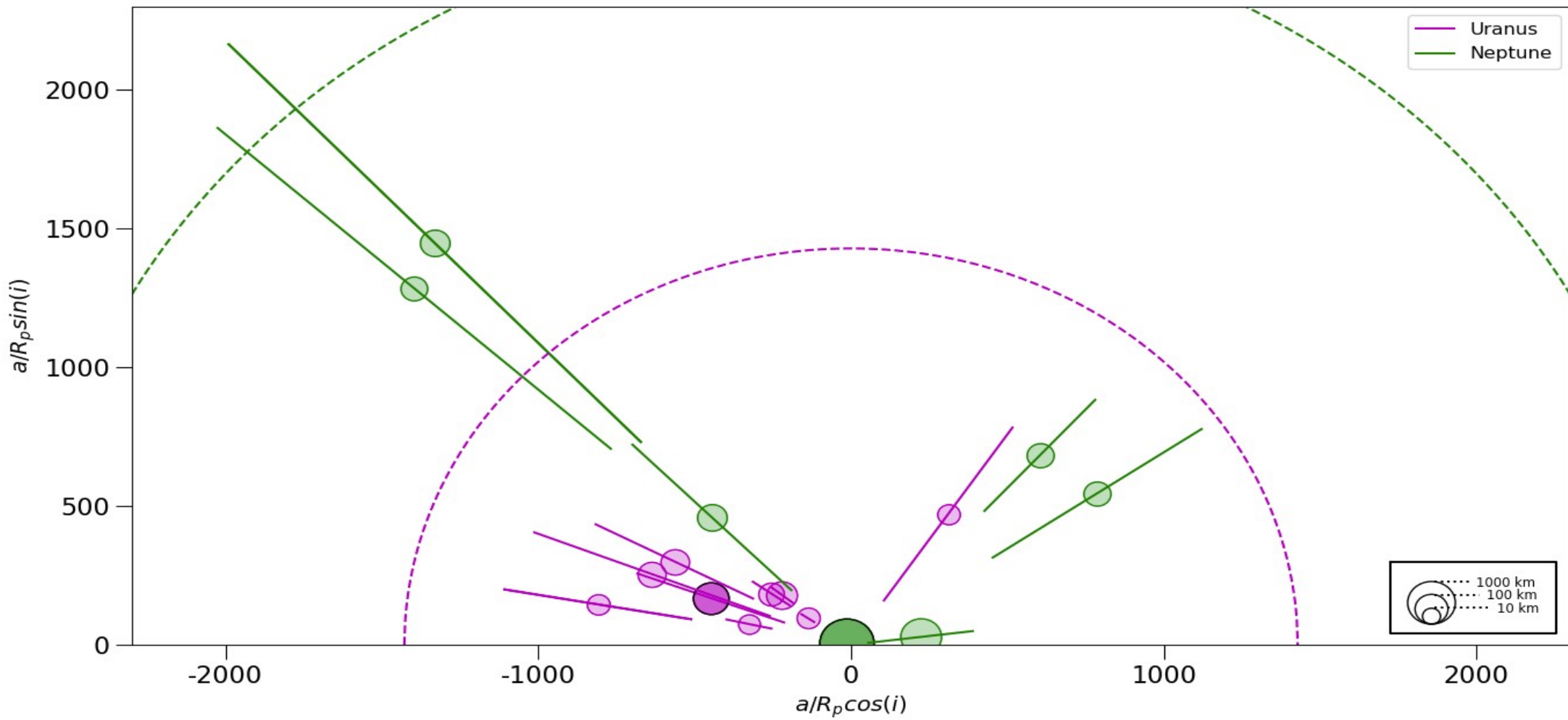


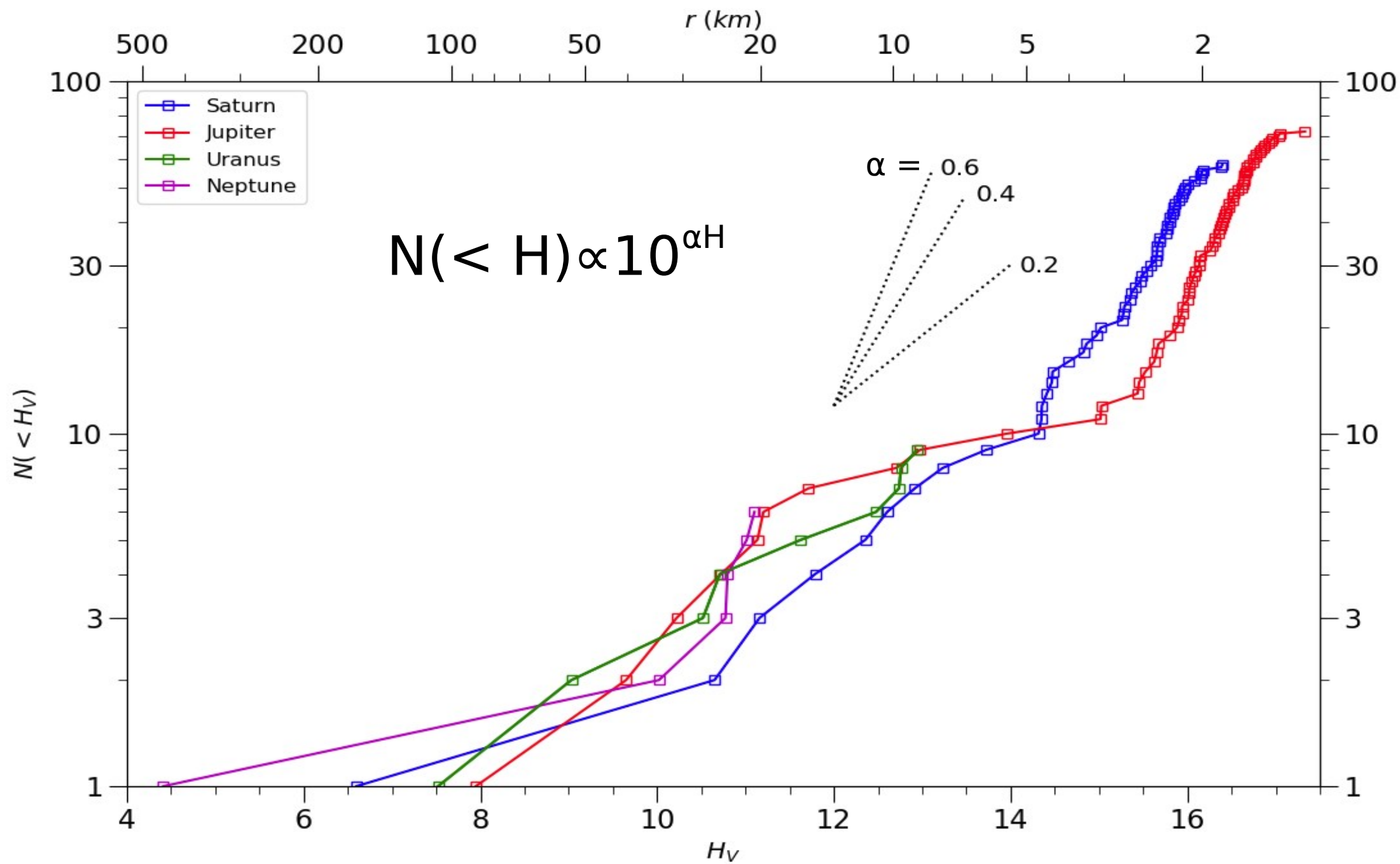
# Jovian Results

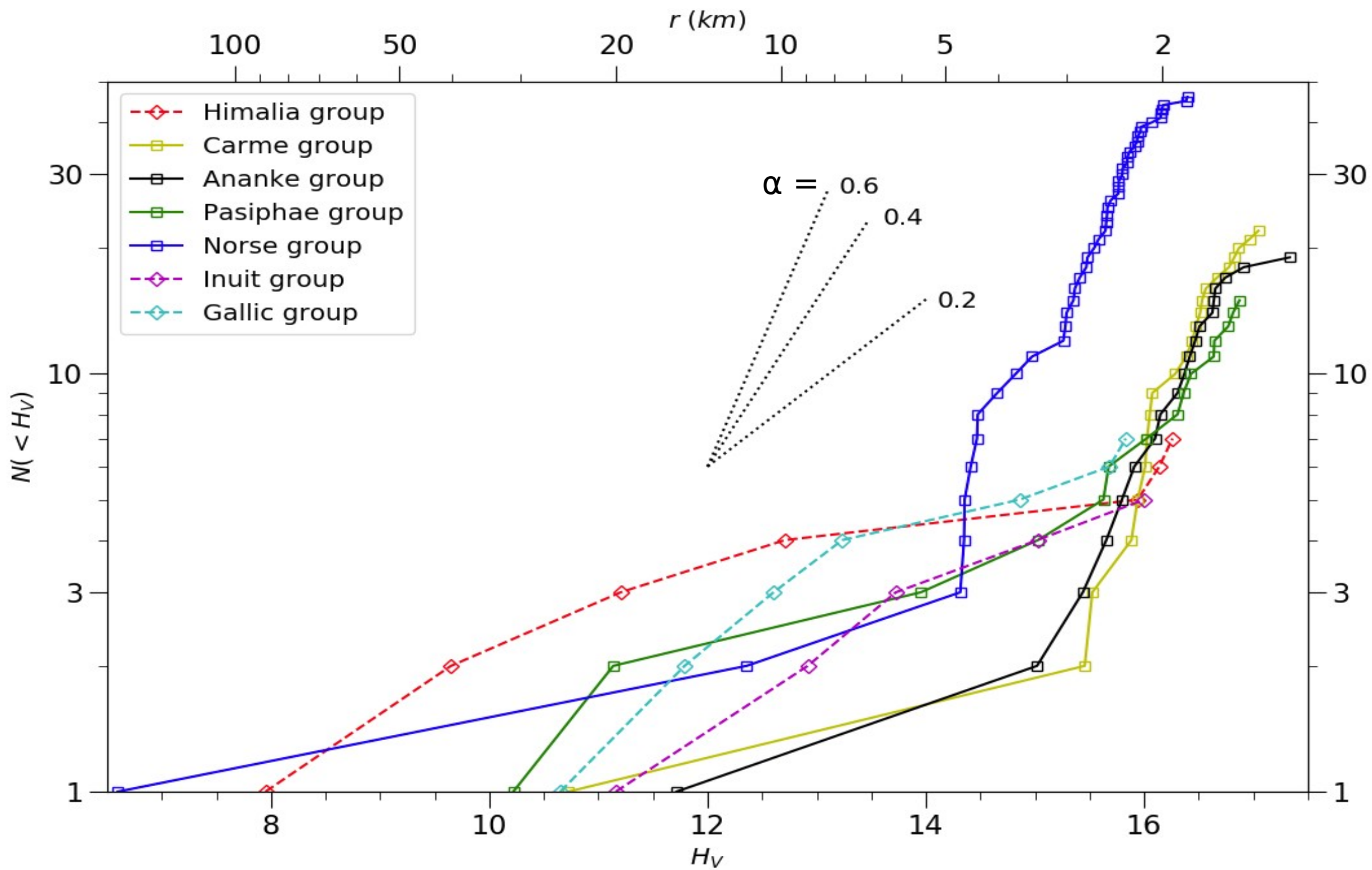
- 55 non-implanted were found.
- 3 travelling fast outer main asteroids).
- Thus 52 moon candidates

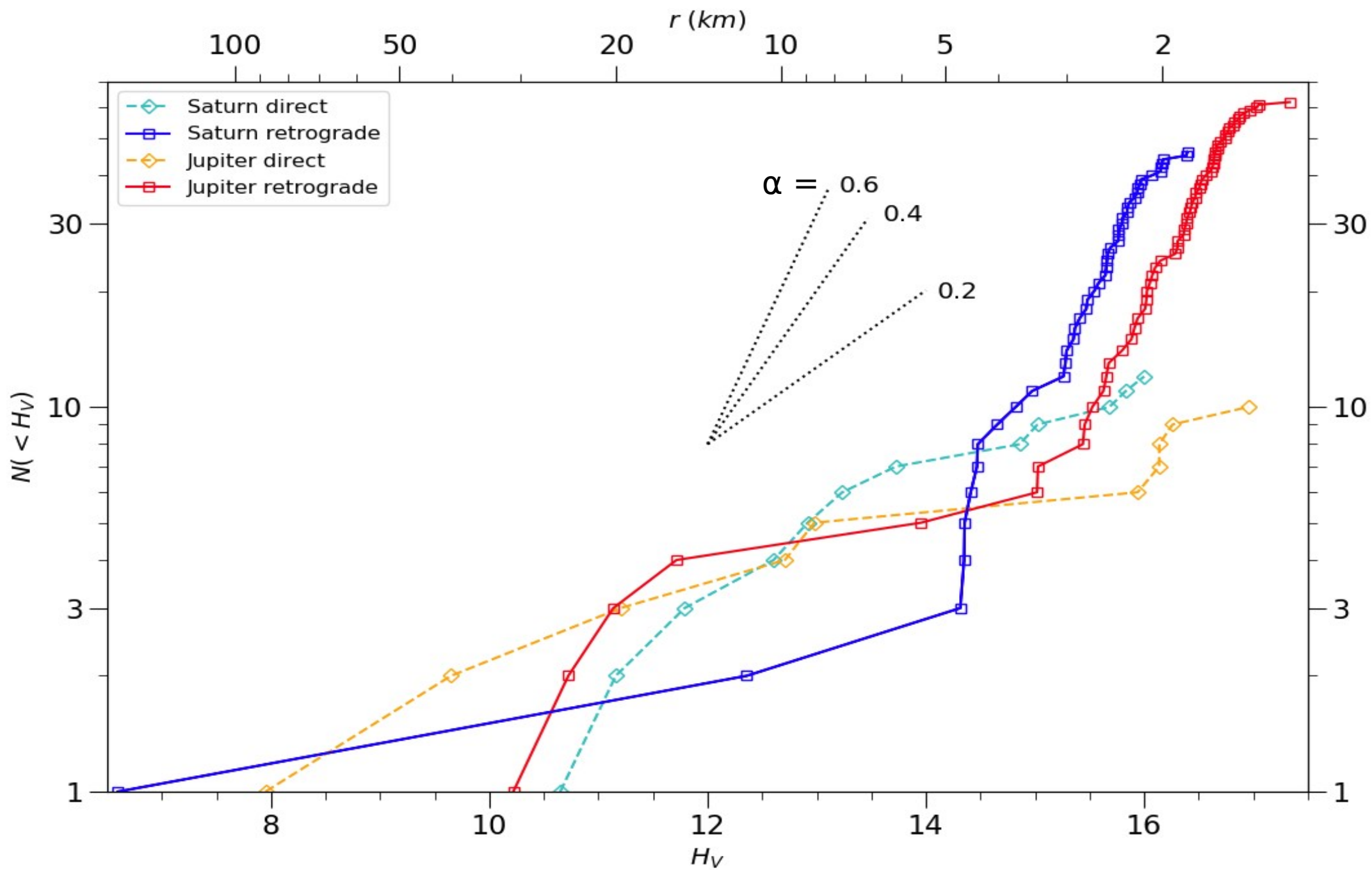


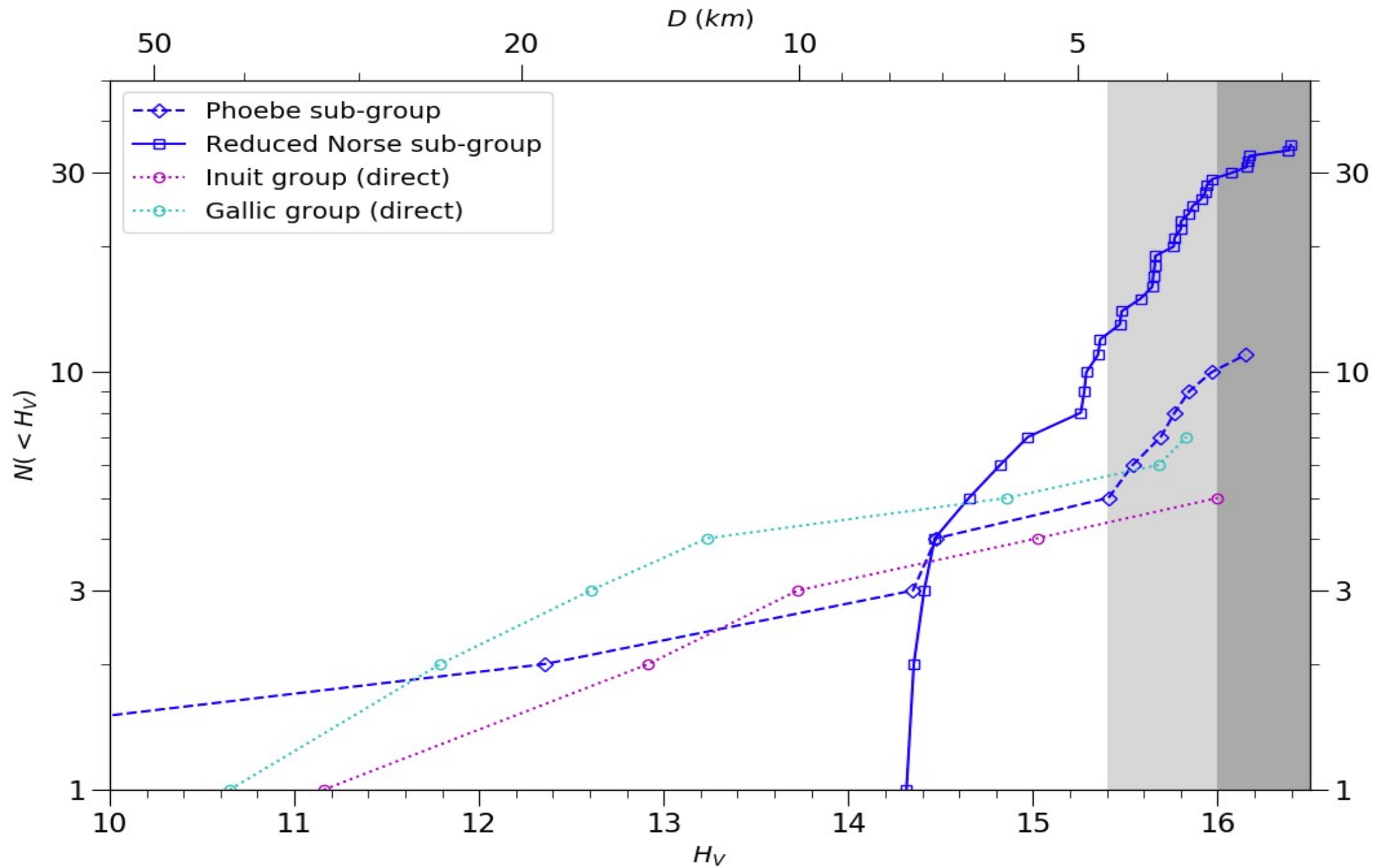
# Uranian and Neptunian irregulars

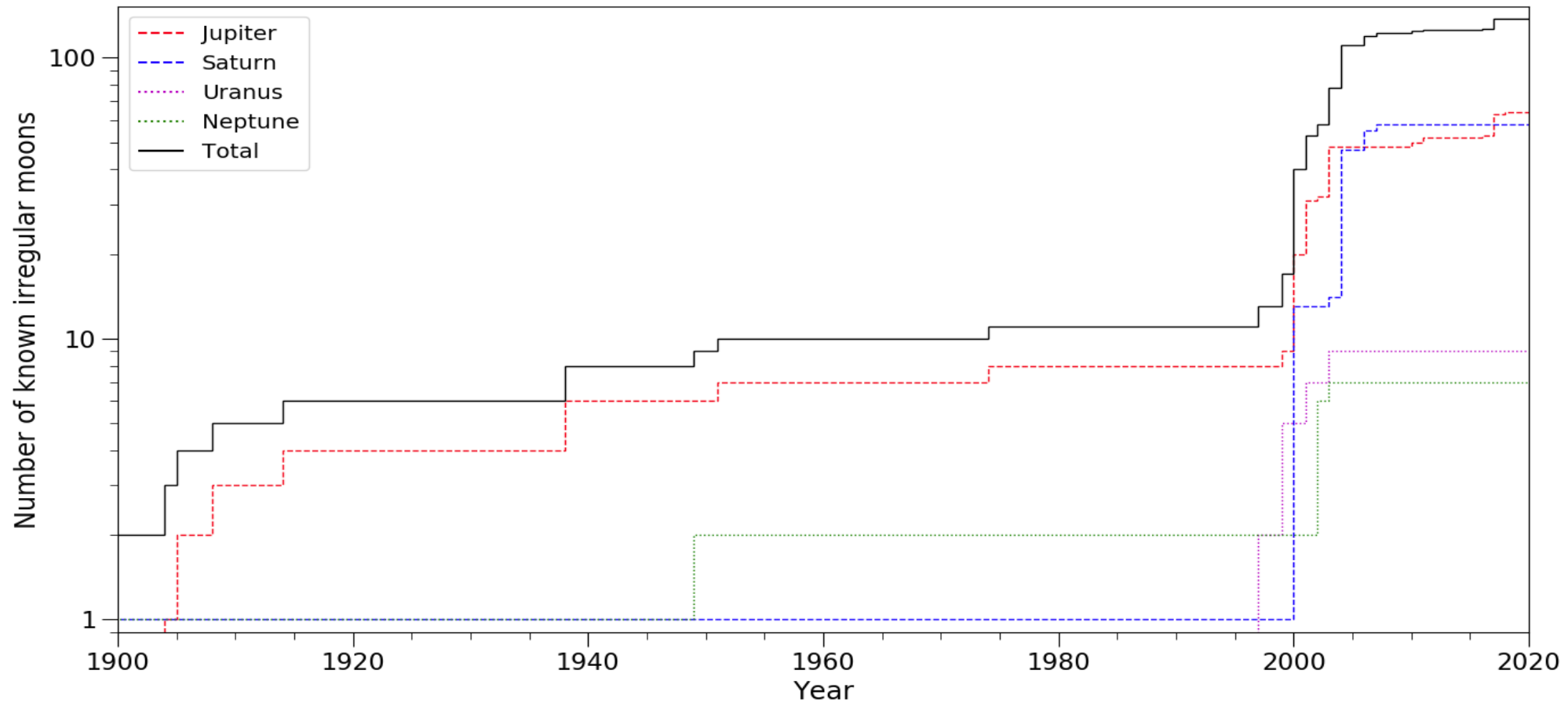














# Irregular Moons – PROB NOT

- Usually irregular moons are smaller in size and have larger orbits compared with regular moons.
- They typically have inclined, non-circular orbits.
- Regular moons formed around their host planet, whereas irregular moons were captured from a heliocentric orbit.
- Two popular capture mechanisms
  - Gas drag from a ‘puffy’ planet
  - Binary exchange reaction

# Archival jovian data

- Done essentially as a `warm up' for the Saturnian search, but yielded interesting new result.
- Consisted of a single one square-degree CFHT field.
- Acquired on 8<sup>th</sup> Sept 2010 for bright jovian recovery.
- The field centre was 1.5° west of Jupiter
- There were 60 sequential 140-second exposures (3 hours total)
- This data set had never been `shifted and stacked' because of the large parameter space this entailed.

# Saturnian data

- Consisted of a two 1.1 square-degree CFHT fields.
- The two fields were east and west of Saturn.
- Both fields were visited twice on sequential nights.
- Acquired on 1<sup>st</sup> to 4<sup>th</sup> July 2019.
- Each visit consisted of 44 sequential 205-second exposures (3 hours total).

# Implanted moons

- Artificial moons were implanted into the images to measure the efficiency of the operators.
- The artificial moons were made to look indistinguishable from the real ones (time variable PSF, trailing included).
- There were  $\sim 600$  implanted moons per CCD for the jovian search and  $\sim 150$  per CCD for the saturnian search

# Jovian Results

- 52 candidates
- 4 fainter than our characterisation limit.
- 1 found, by chance, while performing astrometry on another candidate moon.
- Thus 47 characterised moons.
- Of which, 7 (of the brightest) were linked to previously known moons.

# Extrapolation

- Almost all of our moons are likely retrograde since
  - Only a small fraction of known jovians are direct (10/71)
  - Most (8 of 10) direct jovians never, or only just, make it far enough away from Jupiter to appear in our field.
- On average there 1/**11** of known retrograde jovians would be in our offset sky coverage.

# Jovian size distribution

- Fitting  $N(< H) \propto 10^{\alpha H}$  yields:
  - $\alpha = 0.6 \pm 0.3$  for known moons,  $m_r = 21.9$  to  $23.1$ .
  - $\alpha = 0.29 \pm 0.15$  for our detections,  $m_r = 23.7$  to  $25.7$
- This is not a surprise, as simulations (Bottke et al. 2010) produce ‘waves’ in the luminosity function as the exponential index fluctuates around the collisional equilibrium value of  $\alpha = 0.5$  (Dohnanyi 1969) as one descends the size distribution.
- Note that this work is 2 mags deeper.

# Saturnian Results

- 120 non-implanted objects were found.
  - 74 were characterised detections.
  - 38 were linked to previously known moons.



# Saturnian size distribution

- We estimate 150 saturnians with  $D > 3\text{km}$ , about **3 times** larger than the same-scale jovian population.
- Fitting size distribution, between  $D = 3$  and  $4\text{ km}$ , yields  $\alpha = 0.78^{+0.12}_{-0.14}$ .
- Were  $\alpha = 0.78$  to continue to  $D = 1\text{ km}$ , there will be  $\sim 10,000$  multi-km saturnian irregulars.
- This slope is greater than collisional equilibrium ( $\alpha = 0.5$ ).
- We believe this is due to recent large collisions in the retrograde population.

# A collision in the saturnian system

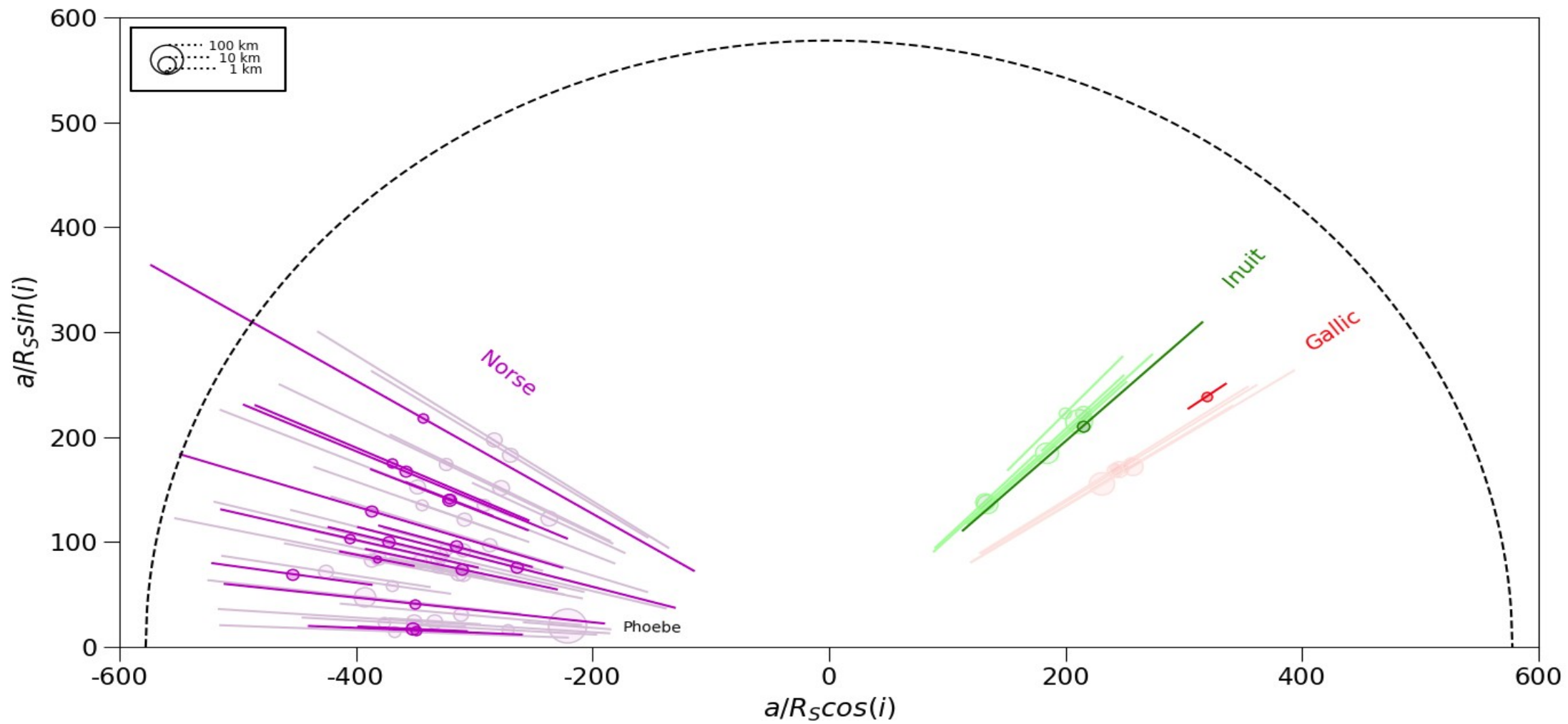
- In Chapter 5 of the thesis we look at which group did this recent collision occur in, and conclude that it likely involved the non-Phoebe-like members of the Norse group.
  - Need orbits to say for sure (which will involve 5x as much telescope time).
- The simple  $n\sigma v$  collision rate approximation is used to get a timescale of 0.11-2.8 Gyr for how recent the collision is.

# Conclusions

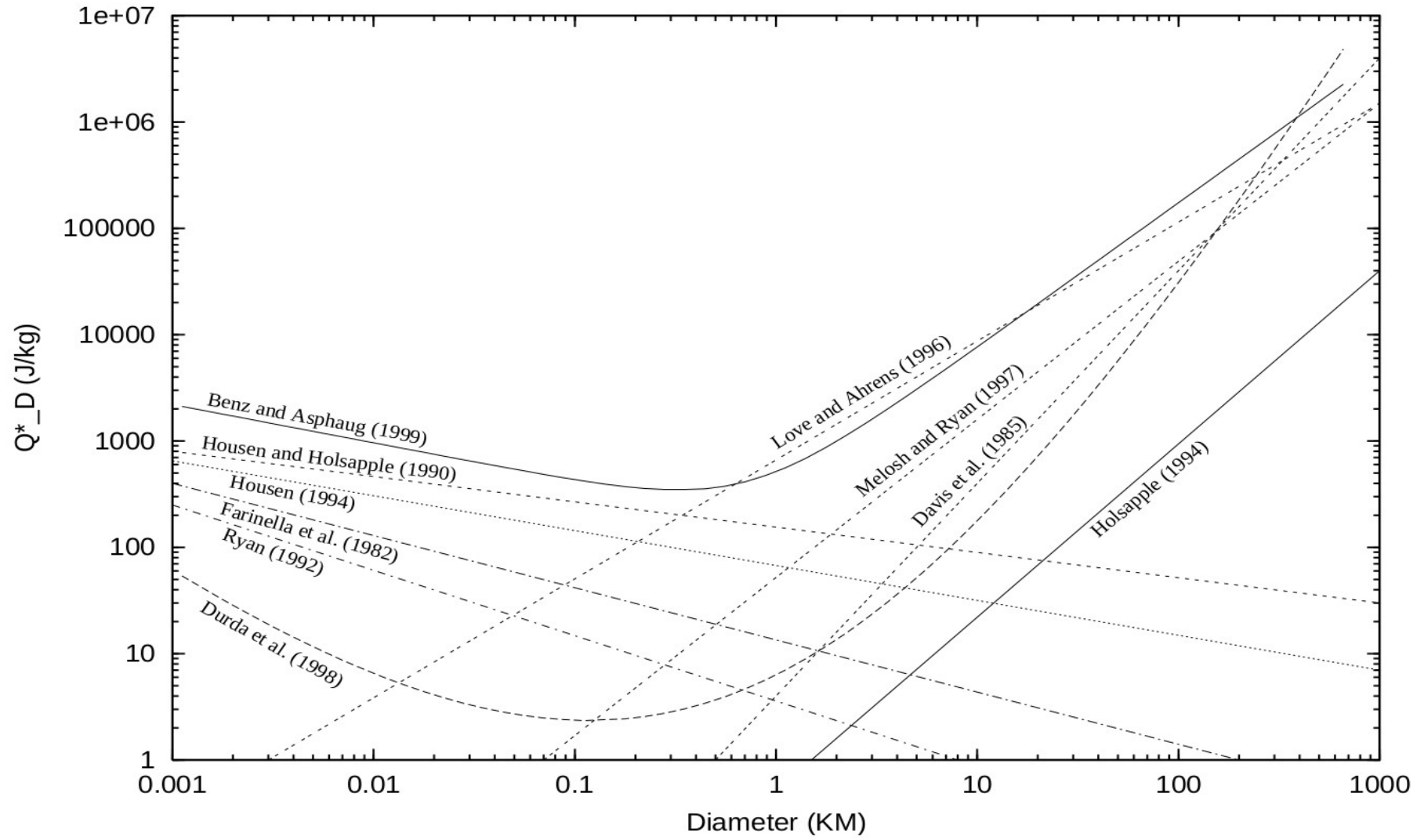
- Shifting and stacking two different data sets produced 52 jovian and 120 saturnian irregular moon candidates.
- The jovian size distribution becomes shallower, to  $\alpha = 0.29$  beyond the completion limit.
- The saturnian size distribution appears to steepen to  $\alpha = 0.78$  beyond the completion limit, which we believe to be due to a recent (0.11 – 2.8 Gyr) collision in the retrograde population.

# Extra Slides

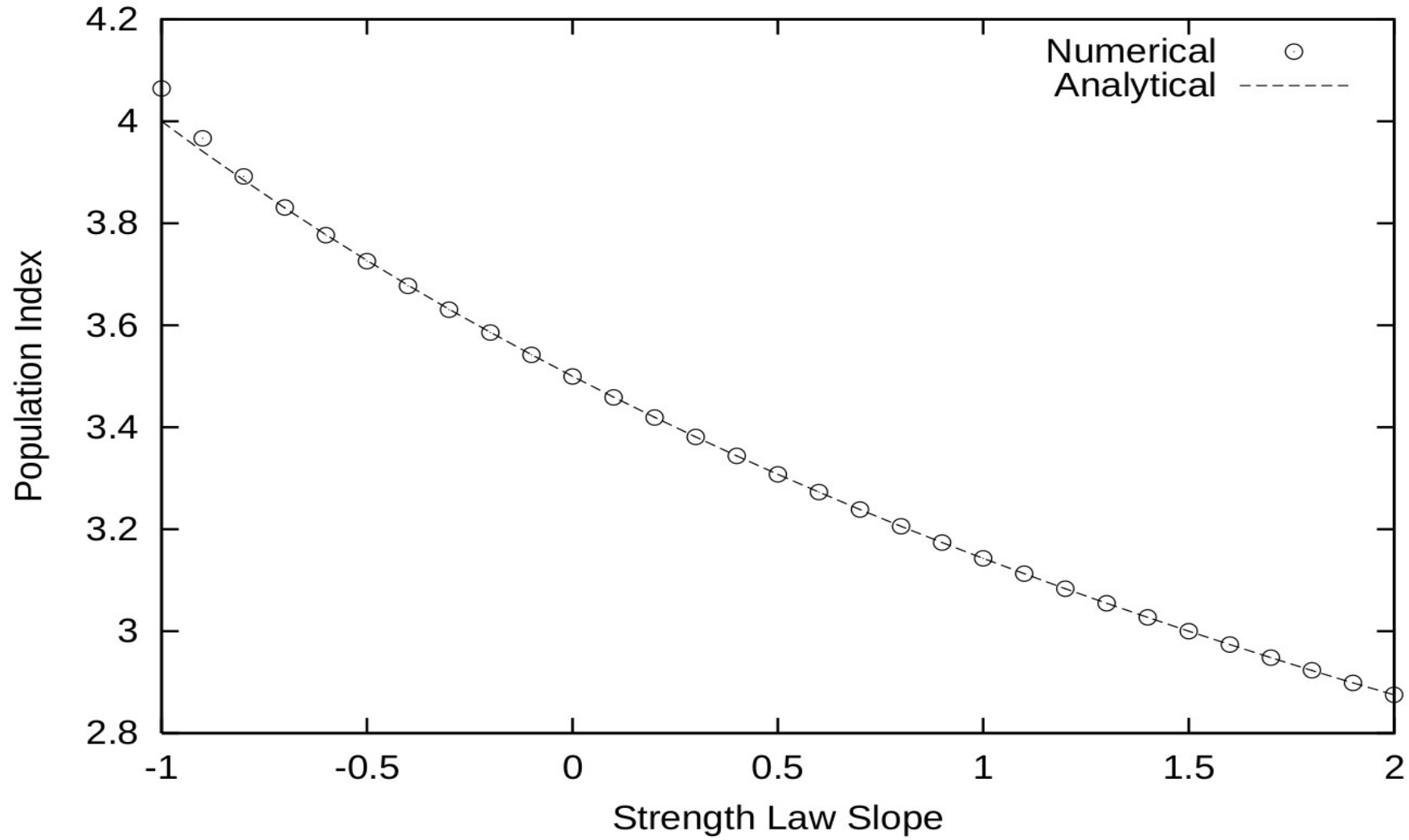
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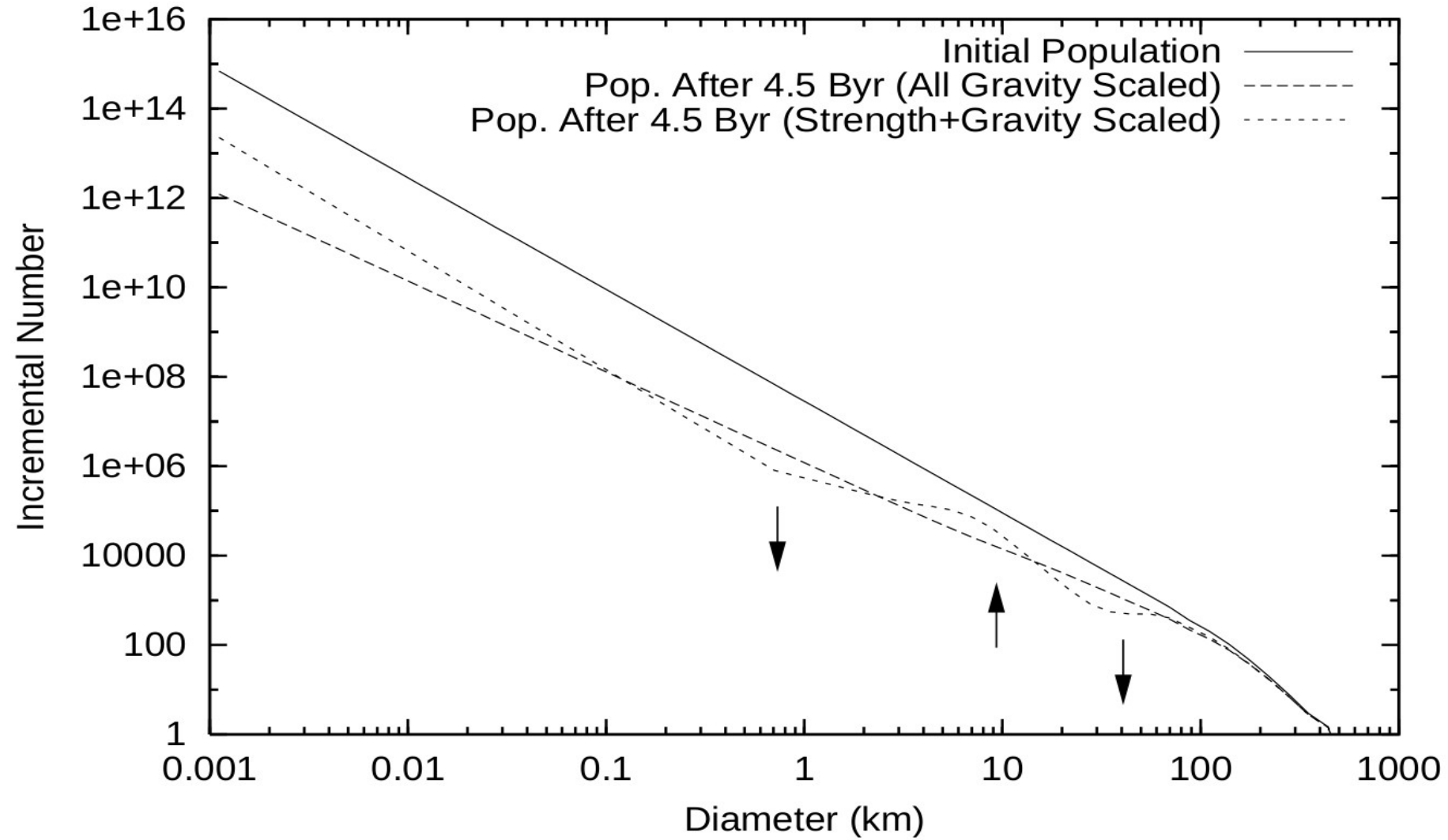
Estimates of Asteroid Strength



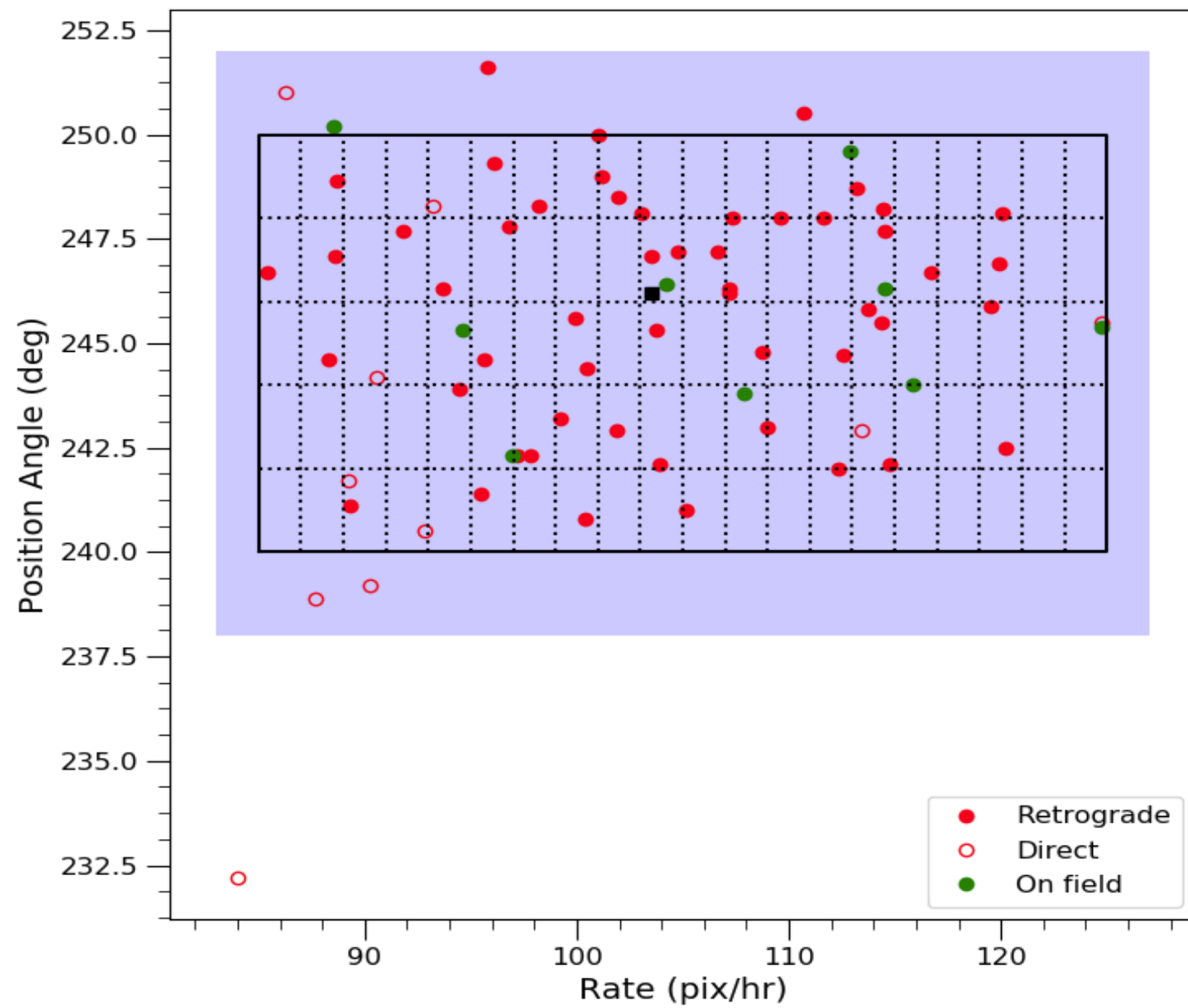
Population Index vs. Strength Law Slope

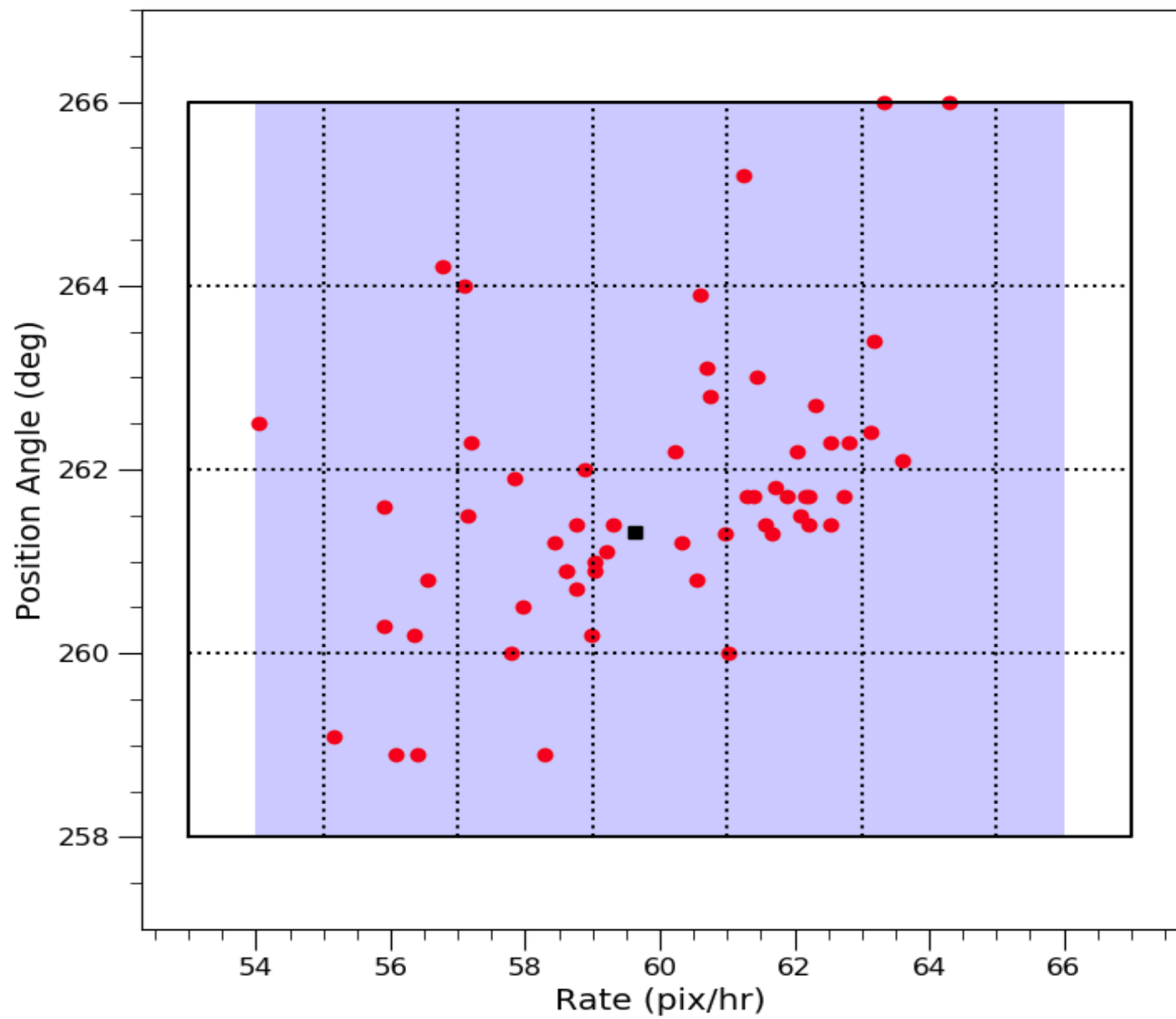


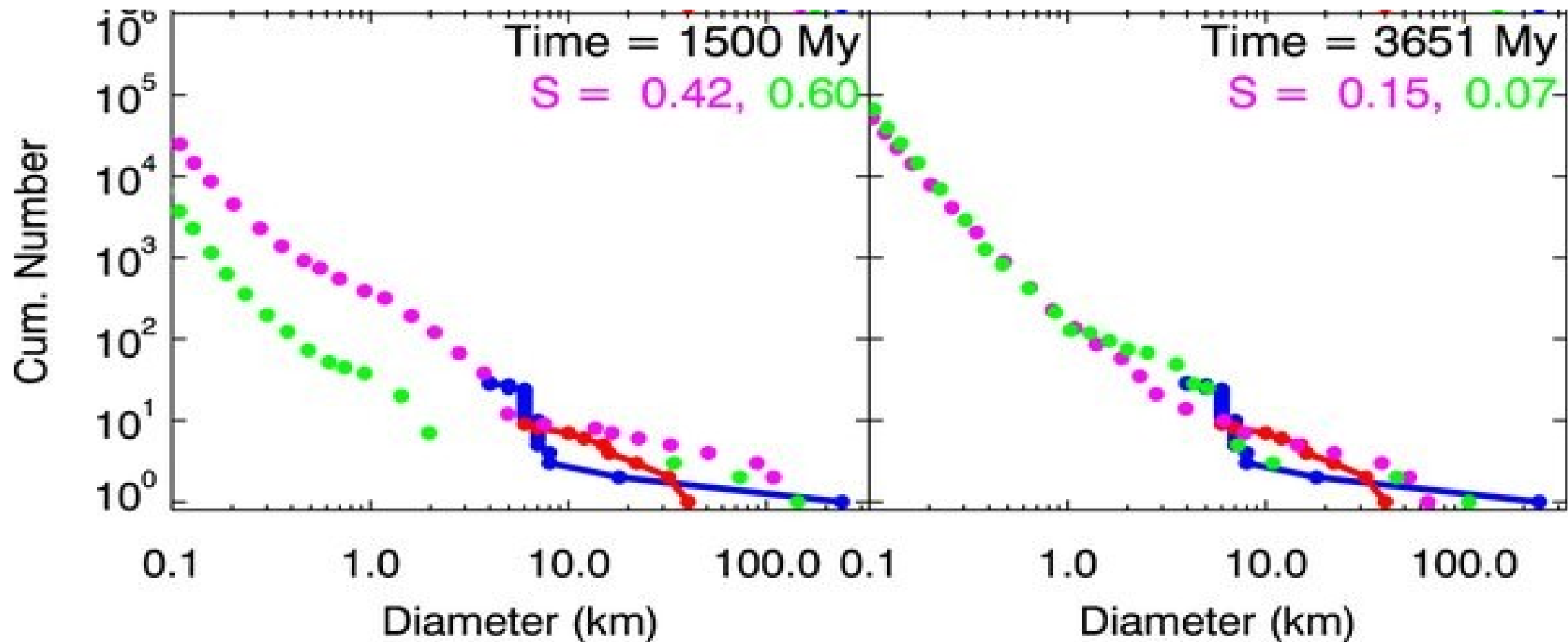
# 4.5 Byr Numerical Simulation

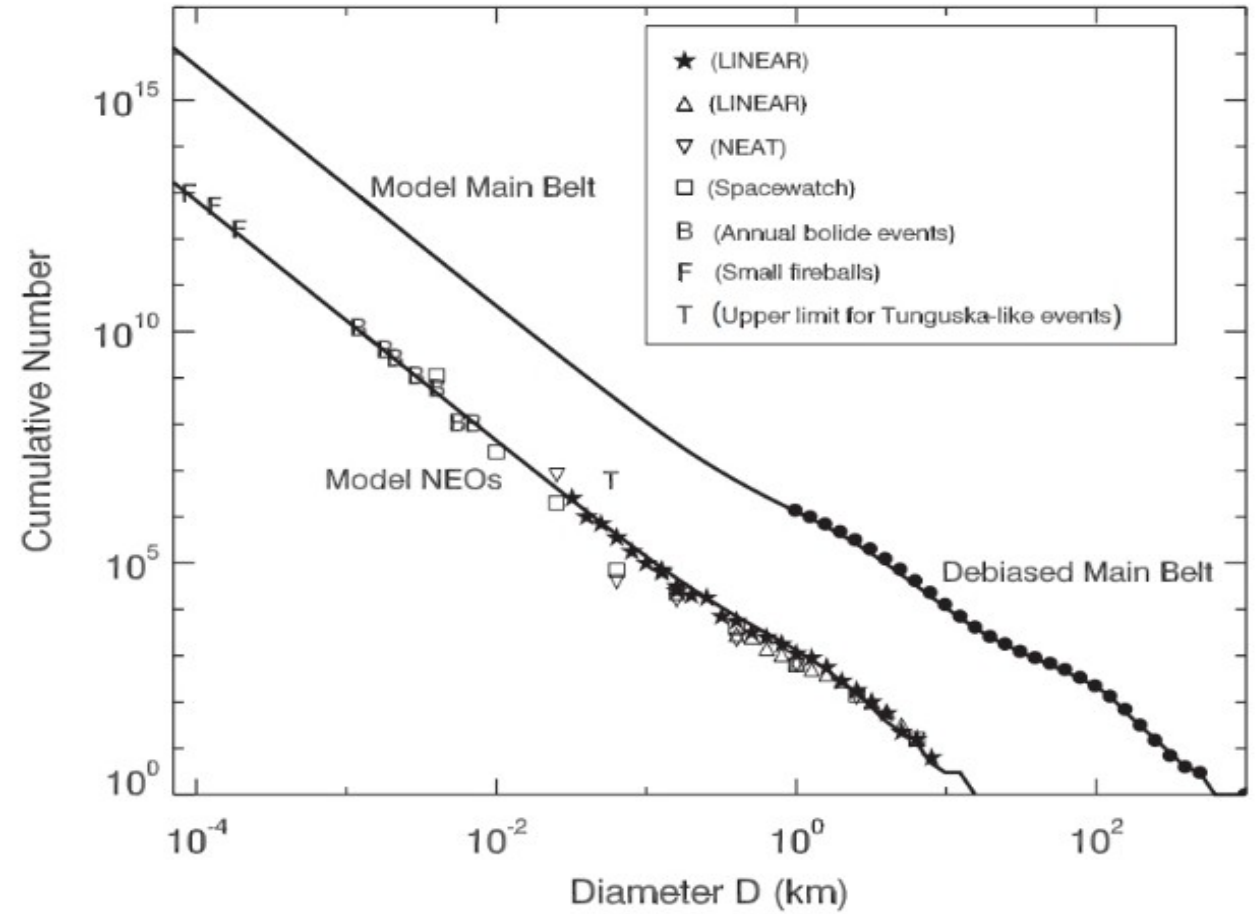












# Efficiency Function

An efficiency function is created by fitting the binned fraction of implanted moons found by the following function:

$$\eta(m_r) = \frac{A}{2} \left( 1 - \tanh \left( \frac{m_r - \mu}{\delta} \right) \right)$$

$$A = 0.998, \mu = 25.69 \text{ and } \delta = 0.31$$