Centaurs (scatterers) as a Probe of the Inner Oort Cloud

Nathan Kaib
University of Oklahoma

Outline

- Scatterer dynamics background/motivation
- OSSOS / survey simulator
- Numerical simulations of scatterer production
- Results and conclusions

Outline

- Scatterer dynamics background/motivation

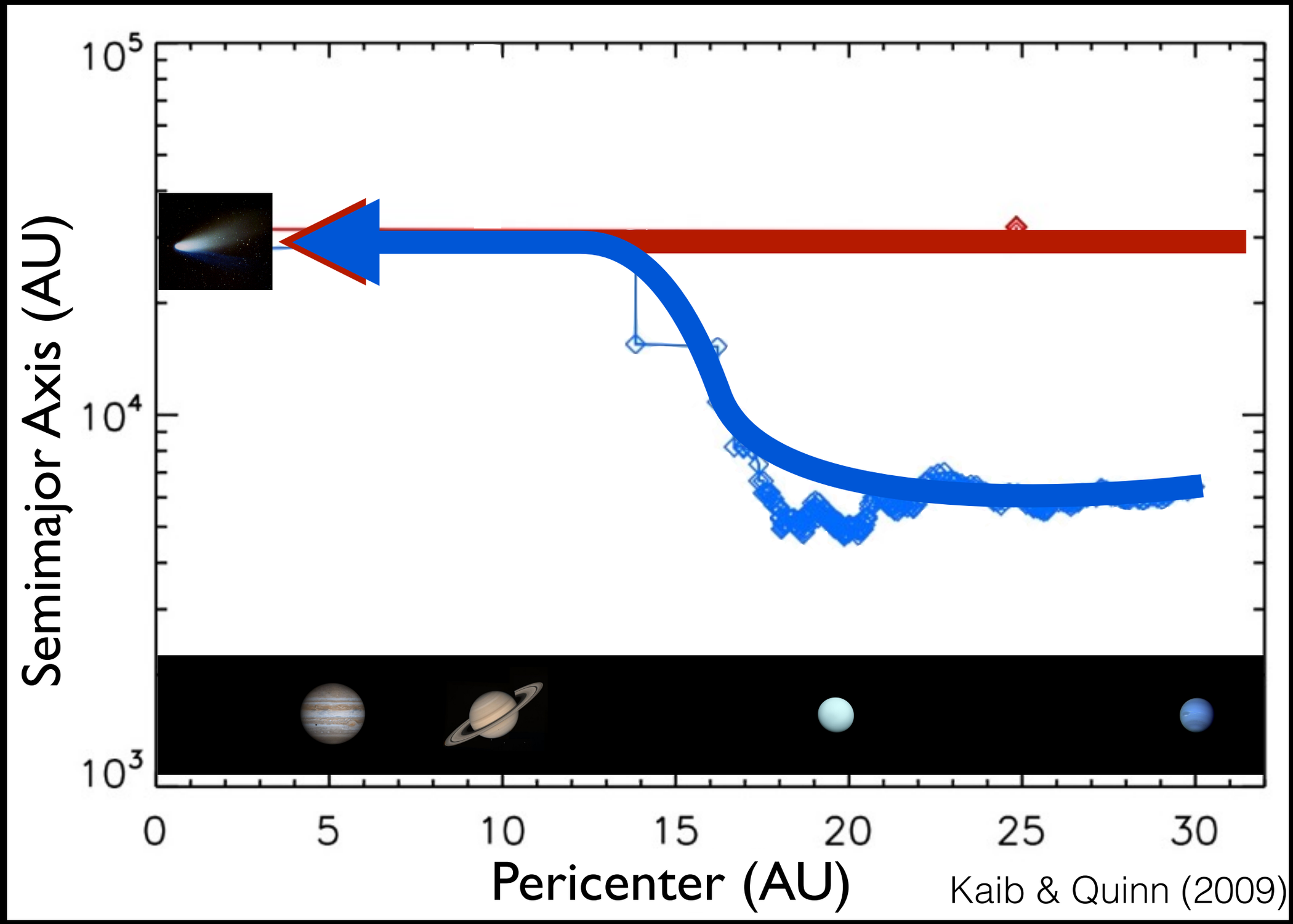
- OSSOS / survey simulator

- Numerical simulations of scatterer production

- Results and conclusions

Scattering Object Defintion

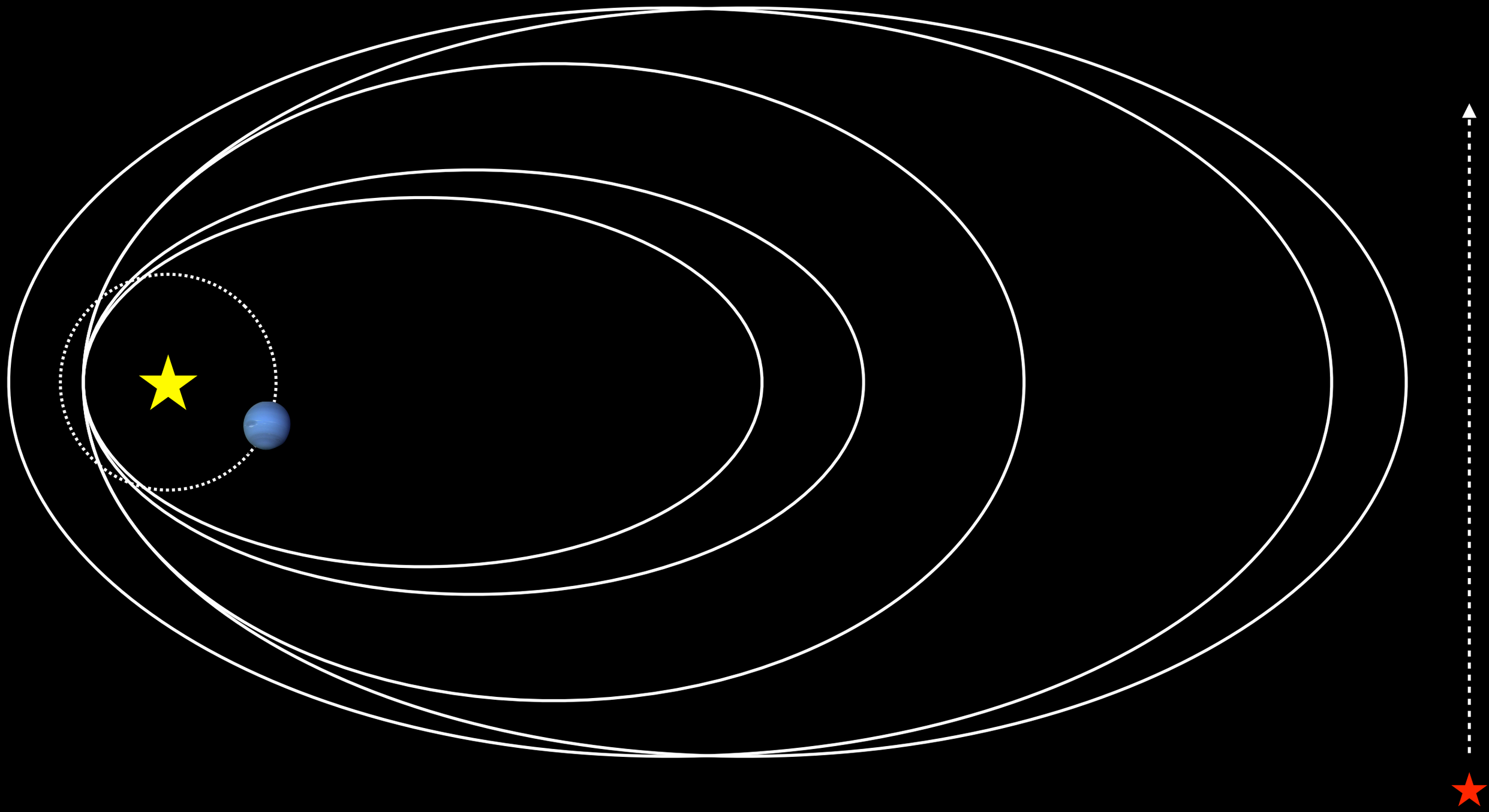
- Look for any orbit with $a < 10^3$ AU
- Integrate orbits in the presence of the giant planets for 10 Myrs
- If semimajor axis changes by 1.5 AU or more it is considered actively scattering off planets (Gladman et al. 2008)



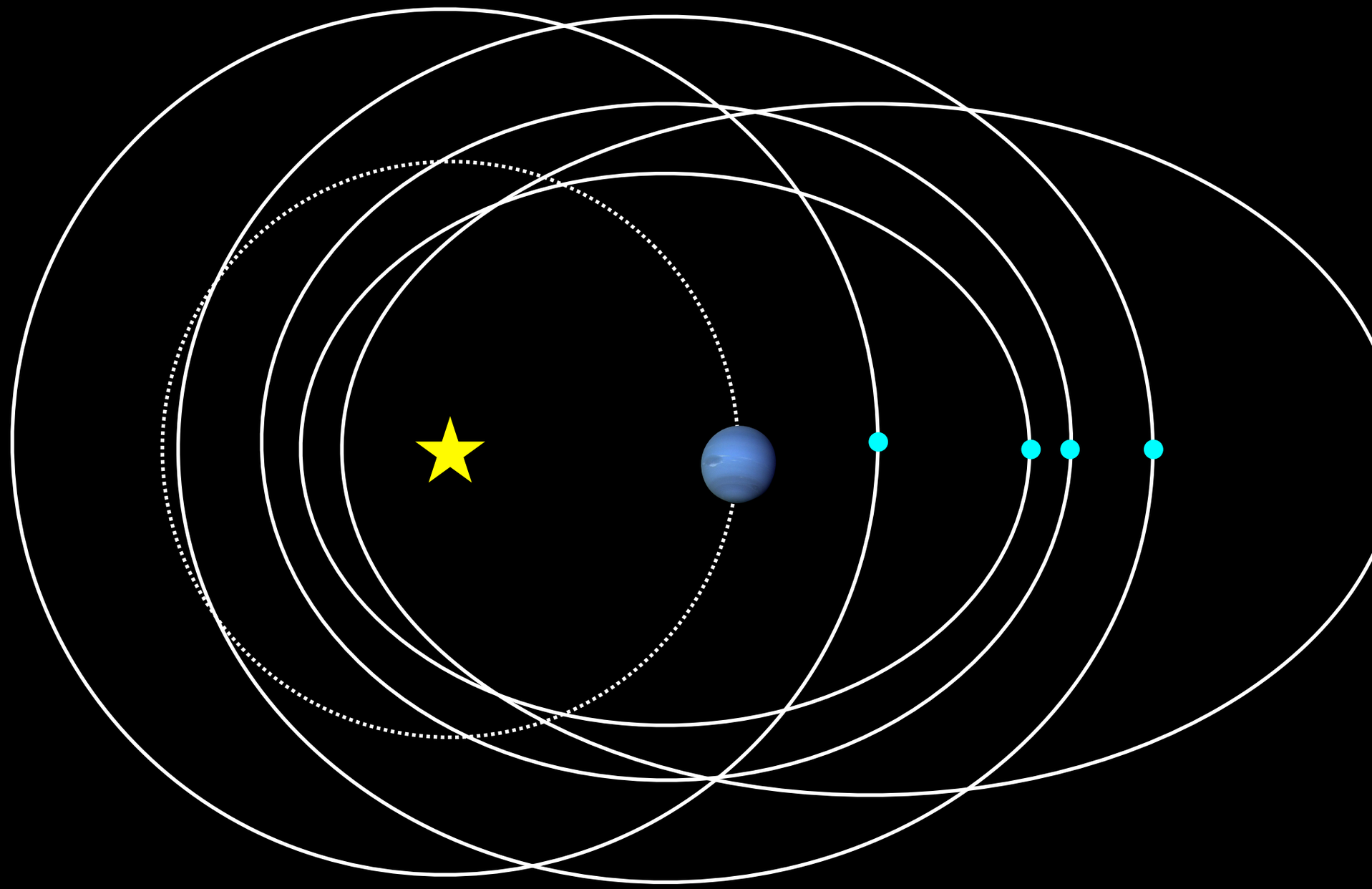
Expect comparable LPC contributions from all regions

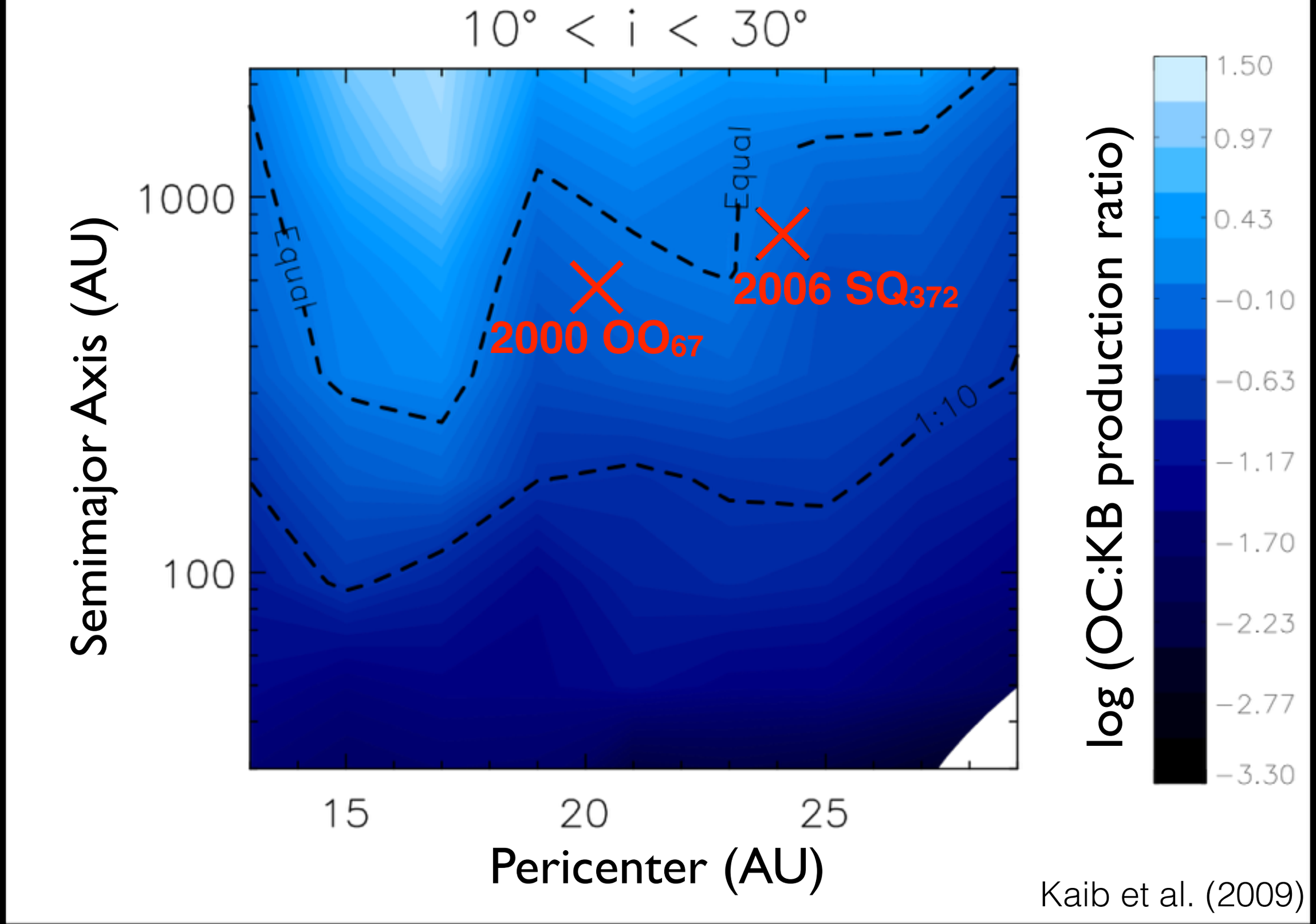
Would be nice to have an additional constraint with a > ~5000 AU (Kaib & Quinn 2009)

$a \geq \sim 10^3$ AU



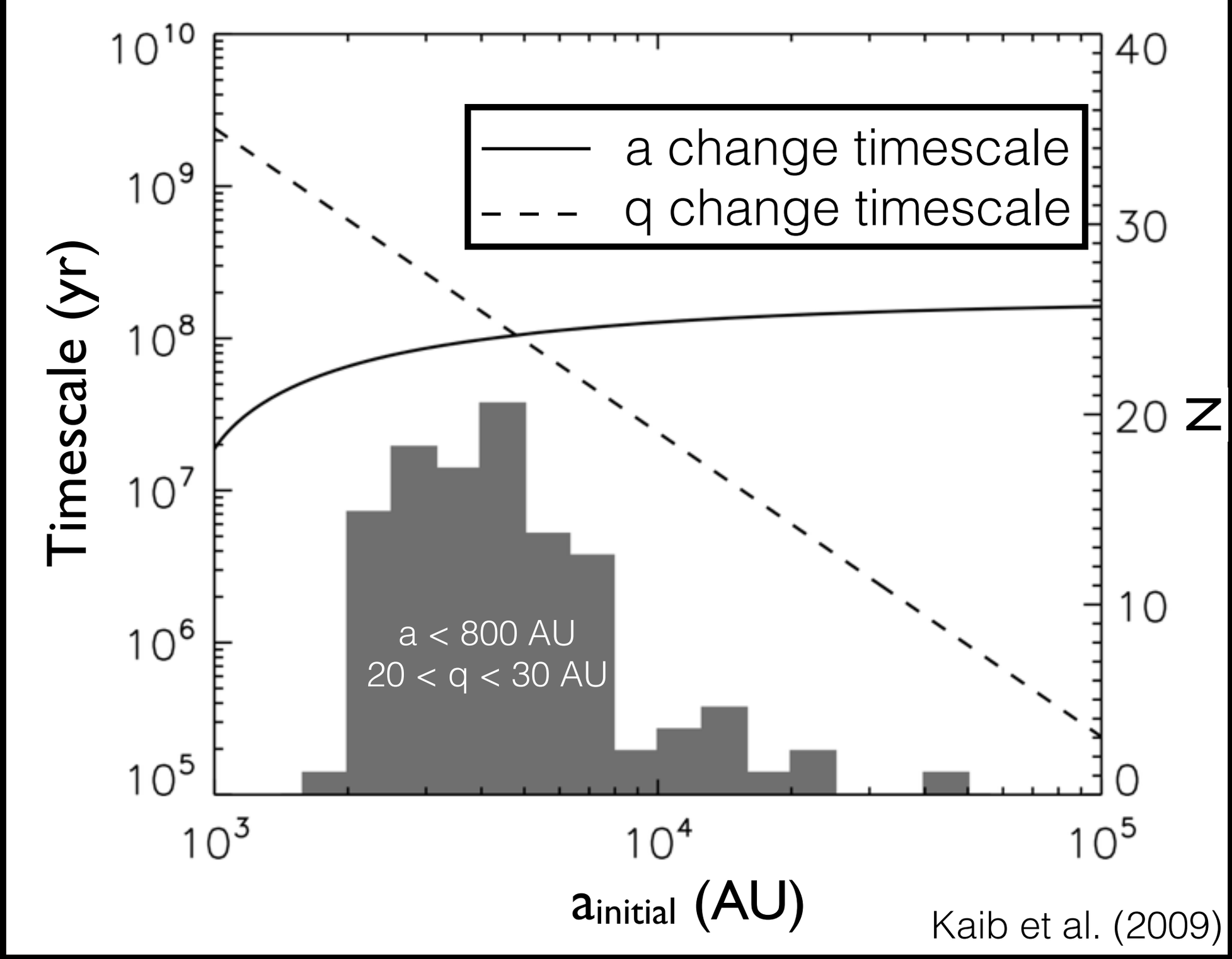
Pathway outlined in Emel'yanenko et al. (2005)





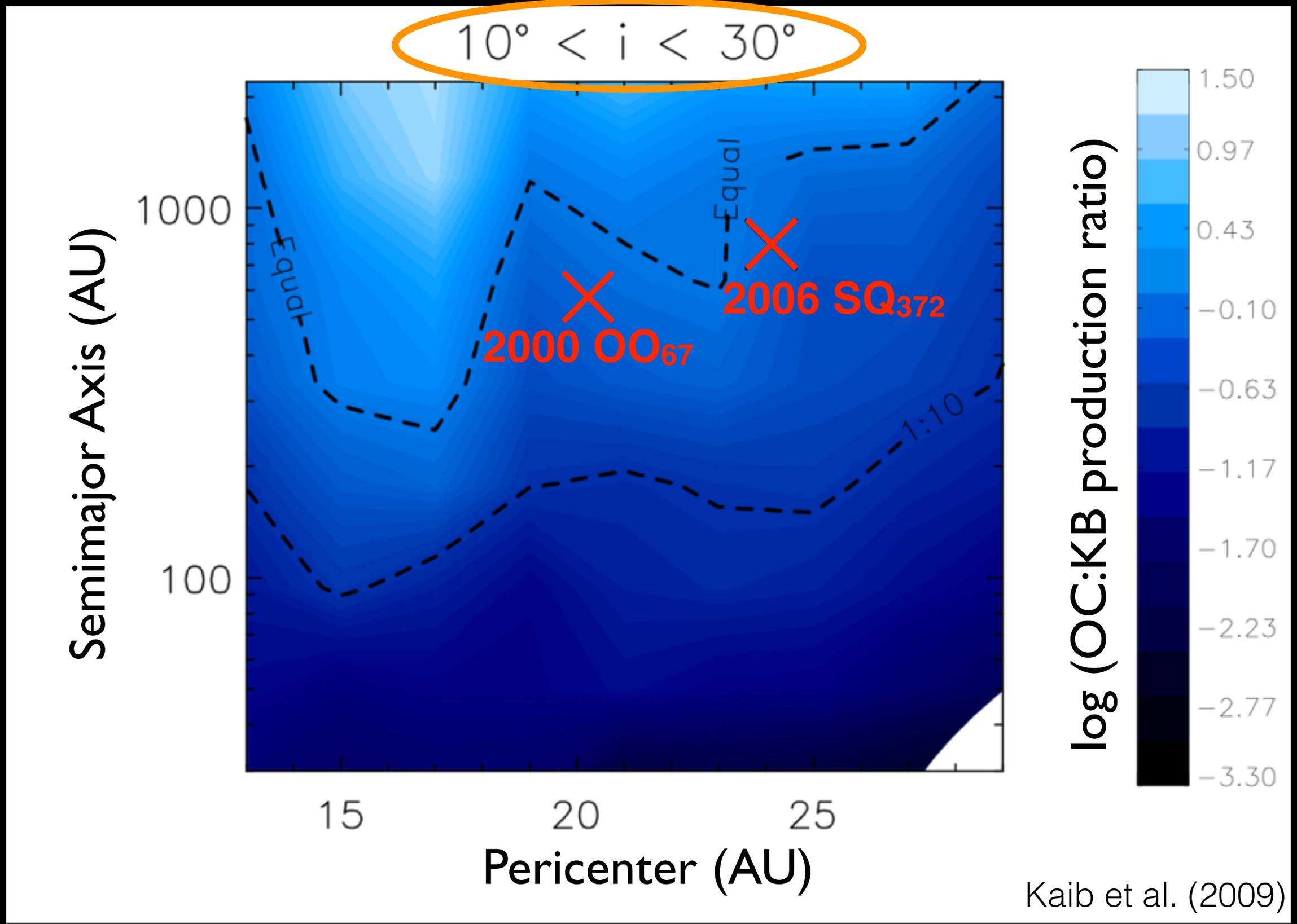
Kaib et al. (2009)

Both objects are more likely to be from Oort cloud



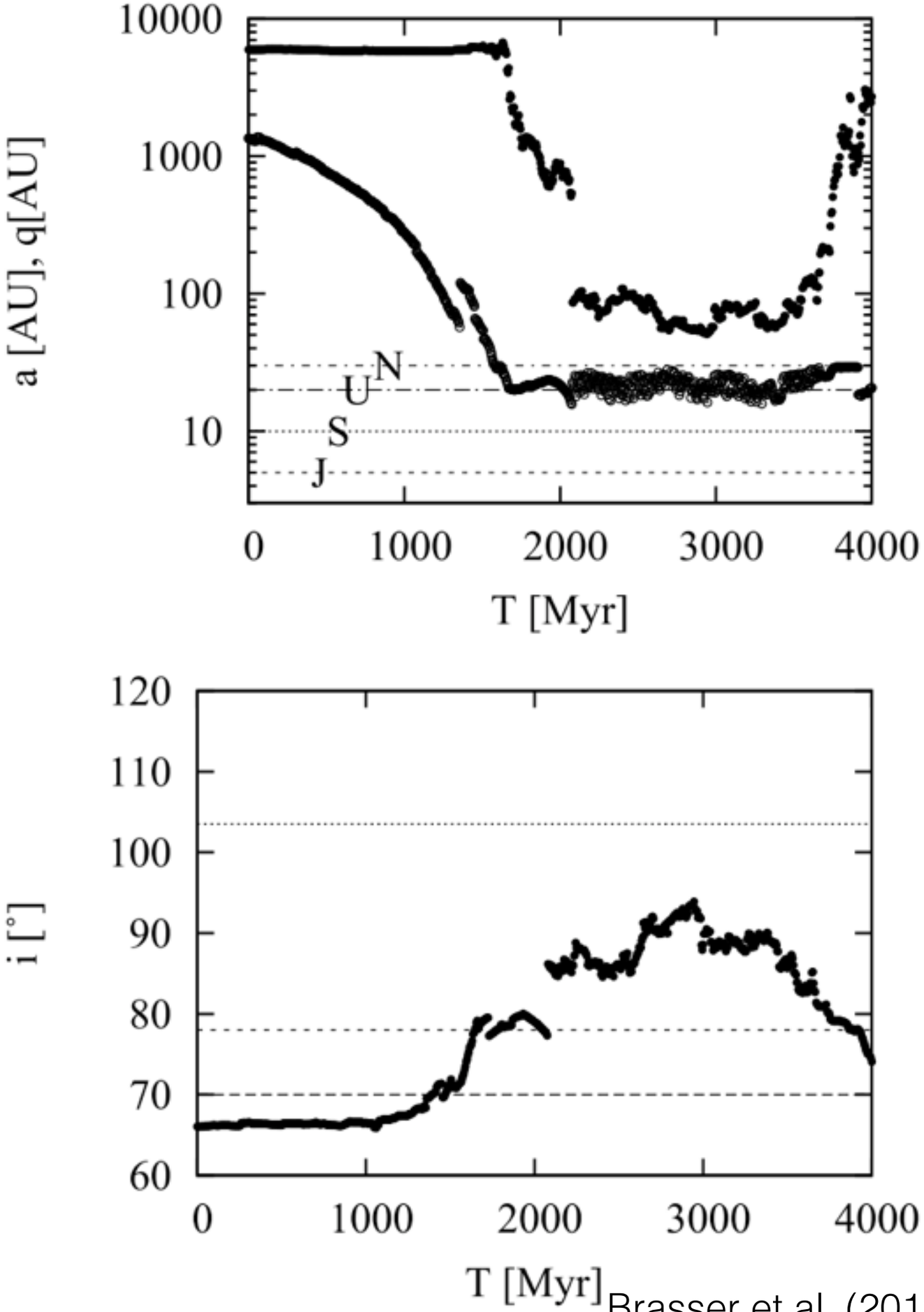
- Centaurs/scatterers almost exclusively constrain inner 10^4 AU of Oort cloud

- Also probe a larger size range than LPCs



Kaib et al. (2009)

Both objects are more likely to be from Oort cloud

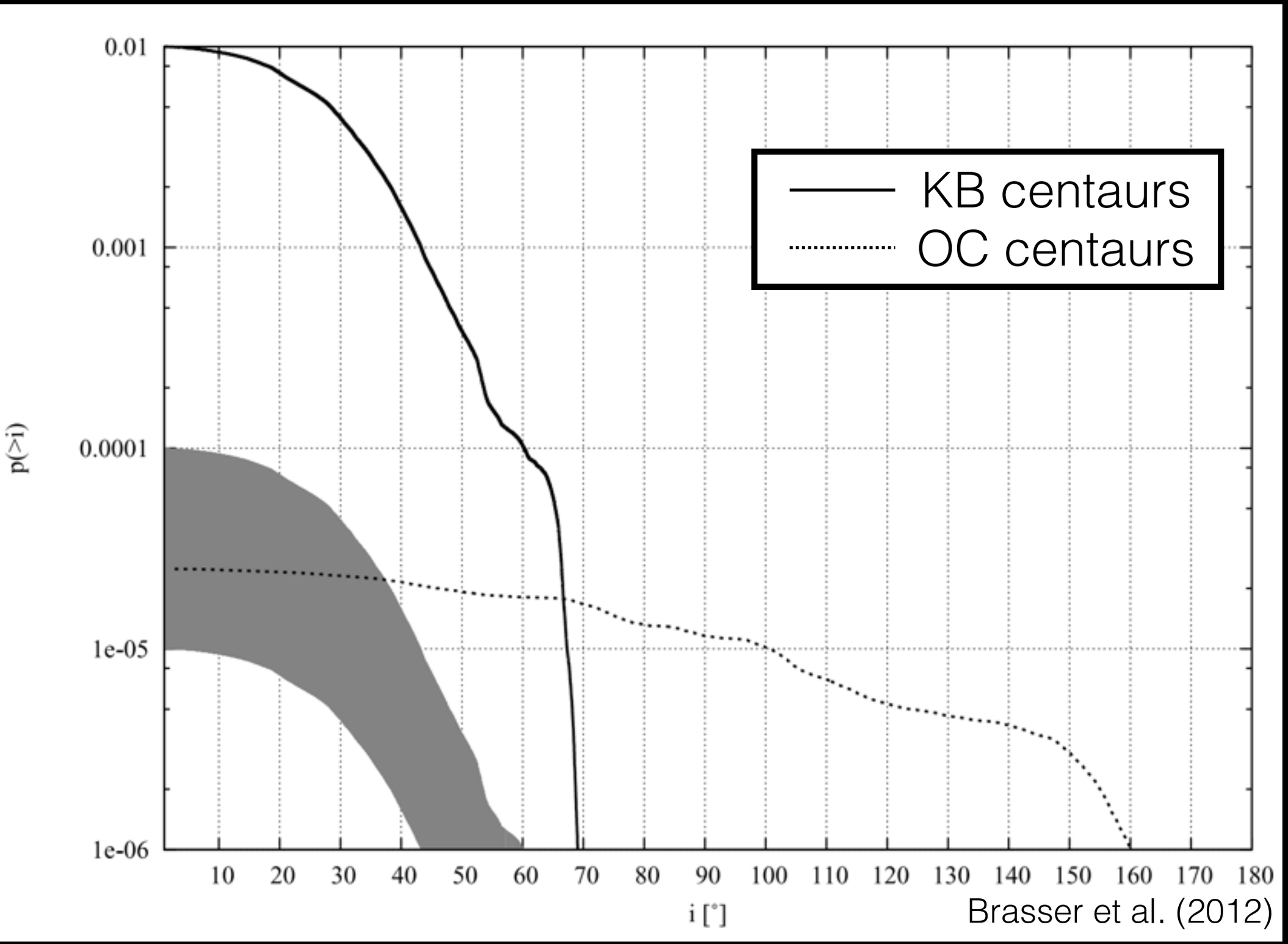


- 13 centaurs/scattering objects have inclination over 65°

- Expect low-i objects from the Kuiper belt

- Higher-i objects may be from Oort cloud

Brasser et al. (2012)



Brasser et al. (2012)

Caveats

- Centaurs database compiled with an amalgam of different surveys with different biases

- Many of the surveys detection limits and pointings are not published

- We have no idea what the biases in the observational sample are

Outline

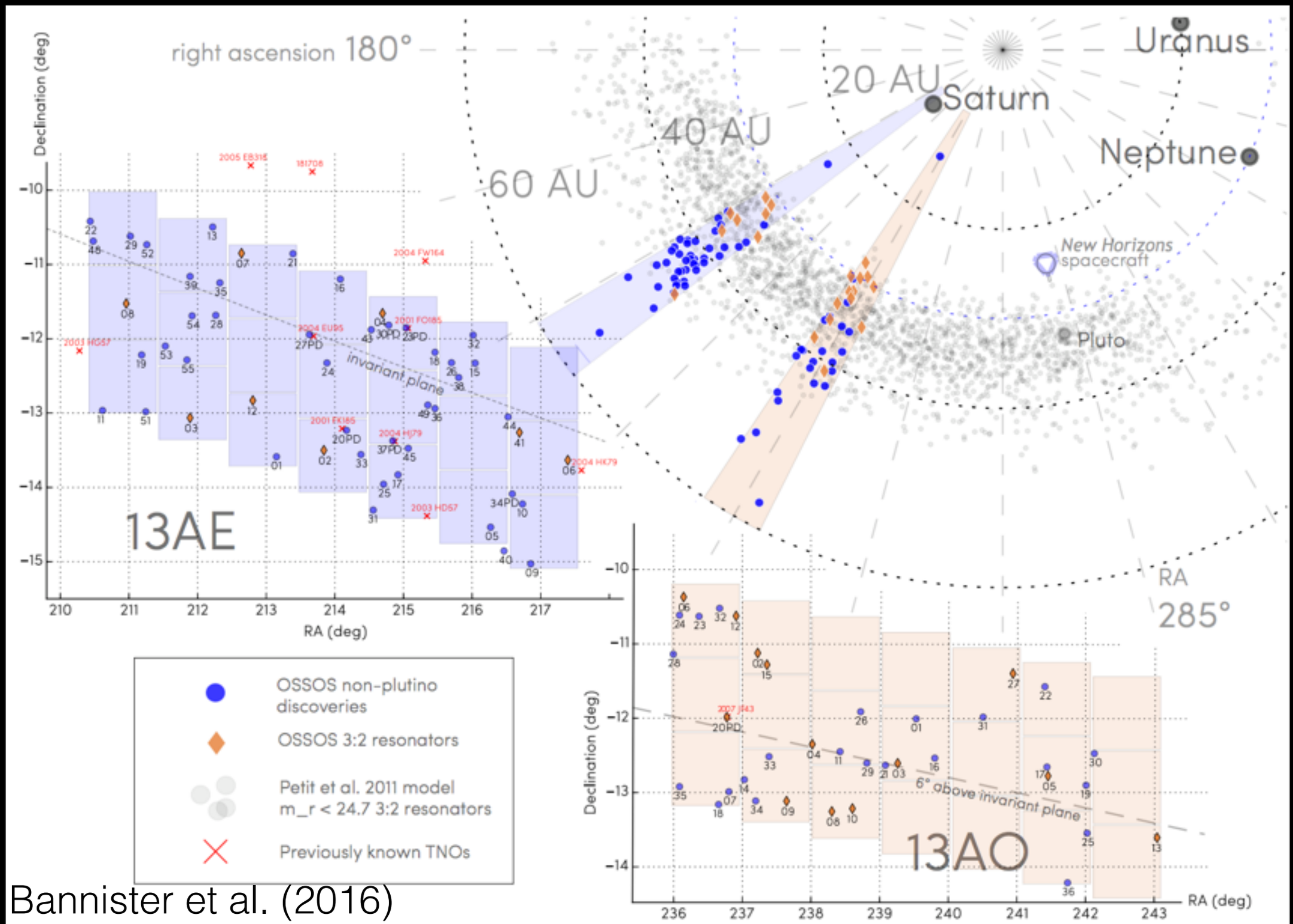
- Scatterer dynamics background/motivation

- OSSOS / survey simulator

- Numerical simulations of scatterer production

- Results and conclusions

Outer Solar System Origins Survey



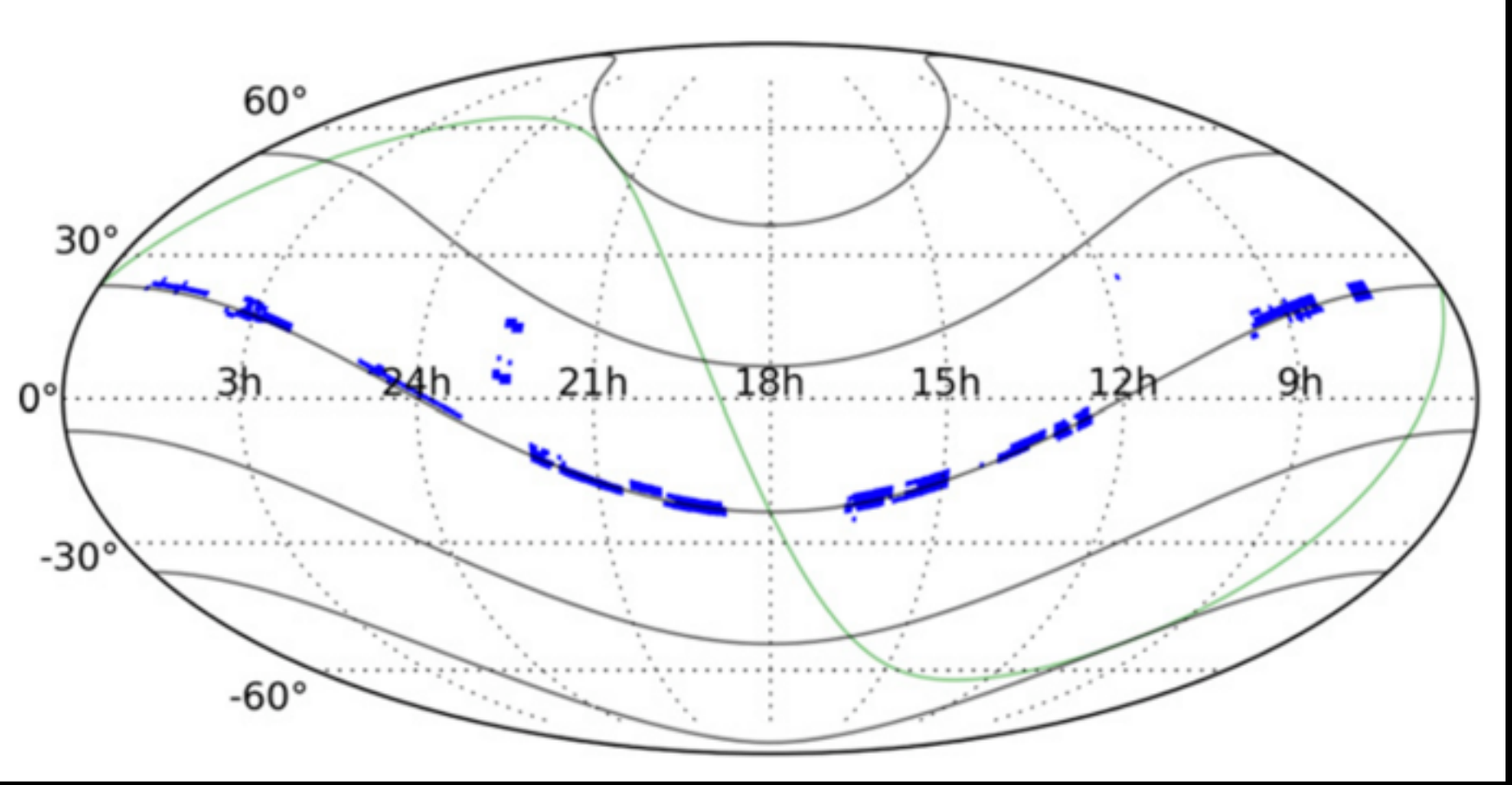
Bannister et al. (2016)

Outer Solar System Origins Survey

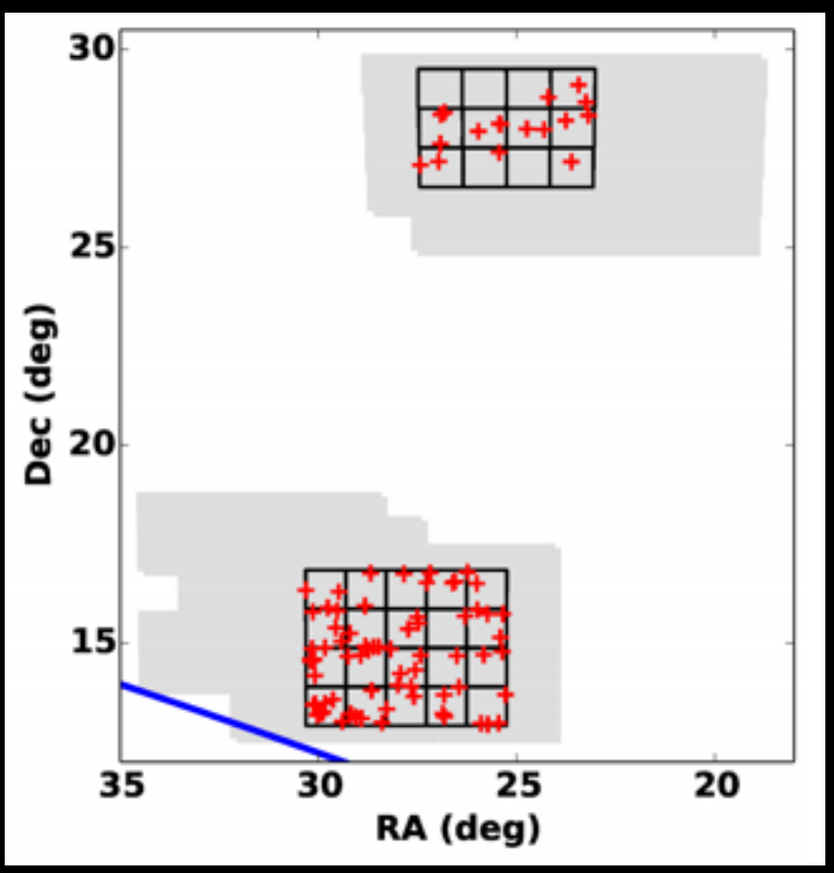
- Observe 148 sq. degrees of sky between 2013 and 2017

- By embedding thousands of artificial PSFs, detection efficiency as a function of magnitude is known for each field

- Typical limiting magnitudes are ~24



CFEPS
321 sq. degrees



HiLat
600 sq. degrees

Alexandersen et al. (2014)
32 sq. degrees

Survey Simulator

- Observations of 1100 square degrees are highly characterized

- Survey simulator is constructed from this

- Given an orbital track, albedo, and size, simulator predicts whether it is detected

Outline

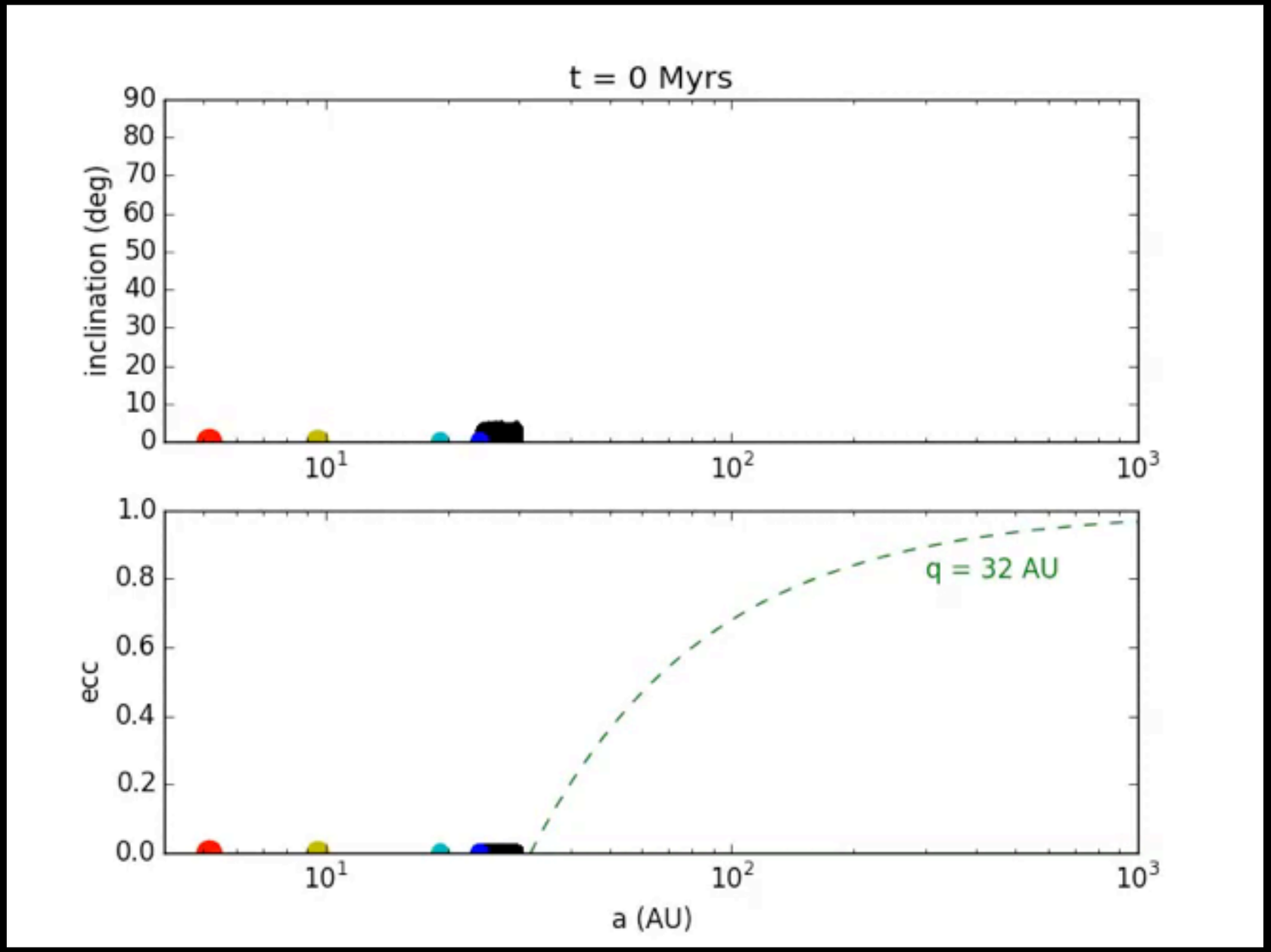
- Scatterer dynamics background/motivation
- OSSOS / survey simulator
- Numerical simulations of scatterer production
- Results and conclusions

Simulations

- Model the formation of the Kuiper belt
  - Collect centaurs/scatterers produced from diffusion from the Kuiper belt
- Model the formation of the Oort cloud
  - Collect centaurs/scatterers produced from re-injected Oort cloud orbits

Kuiper Belt Simulations

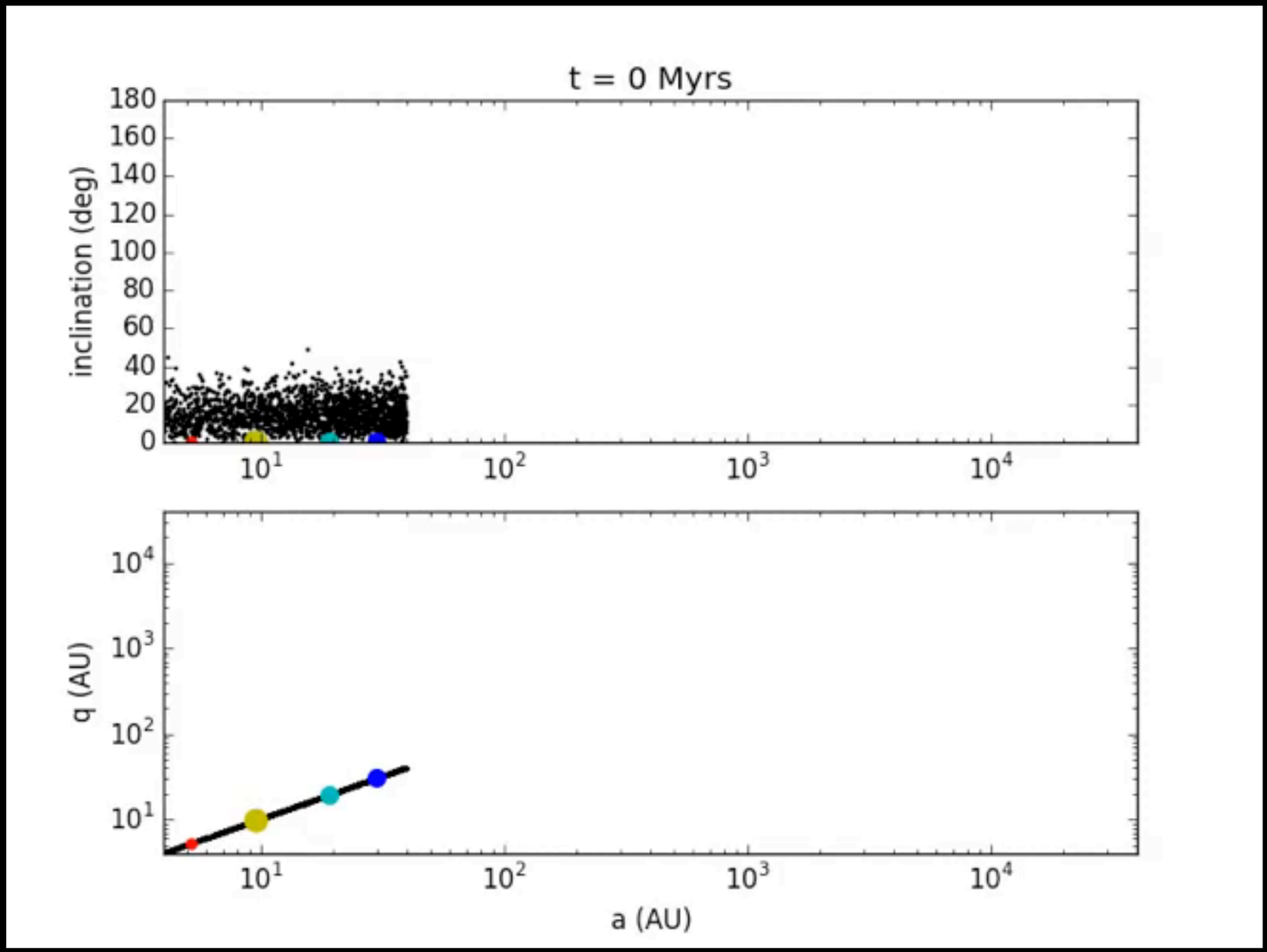
- Based on Nesvorny (2015)
- Migrating Neptune that jumps 0.5 AU at t = 10 Myrs
- 10^6 particles



- Integrated for 4 Gyrs with SWIFT RMVS4 (Levison & Duncan 1994)

Oort Cloud Simulations

- 2000 particles
- Cloned 10x when they attain a>100 AU and again at q>45 AU
- Static planets and static galactic environment



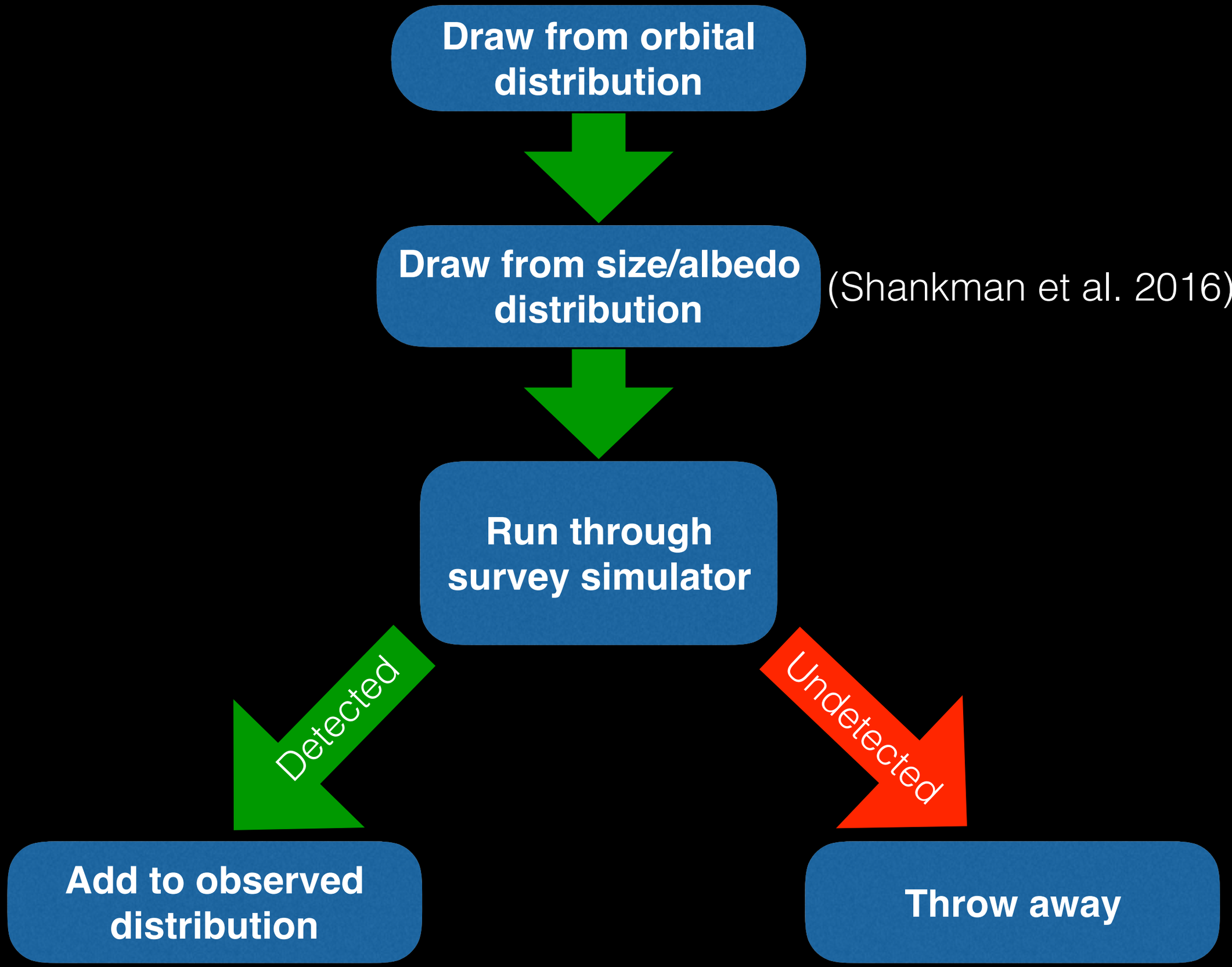
- Integrated for 4 Gyrs with SCATR (Kaib et al. 2011)

Outline

- Scatterer dynamics background/motivation
- OSSOS / survey simulator
- Numerical simulations of scatterer production
- Results and conclusions

Building distributions

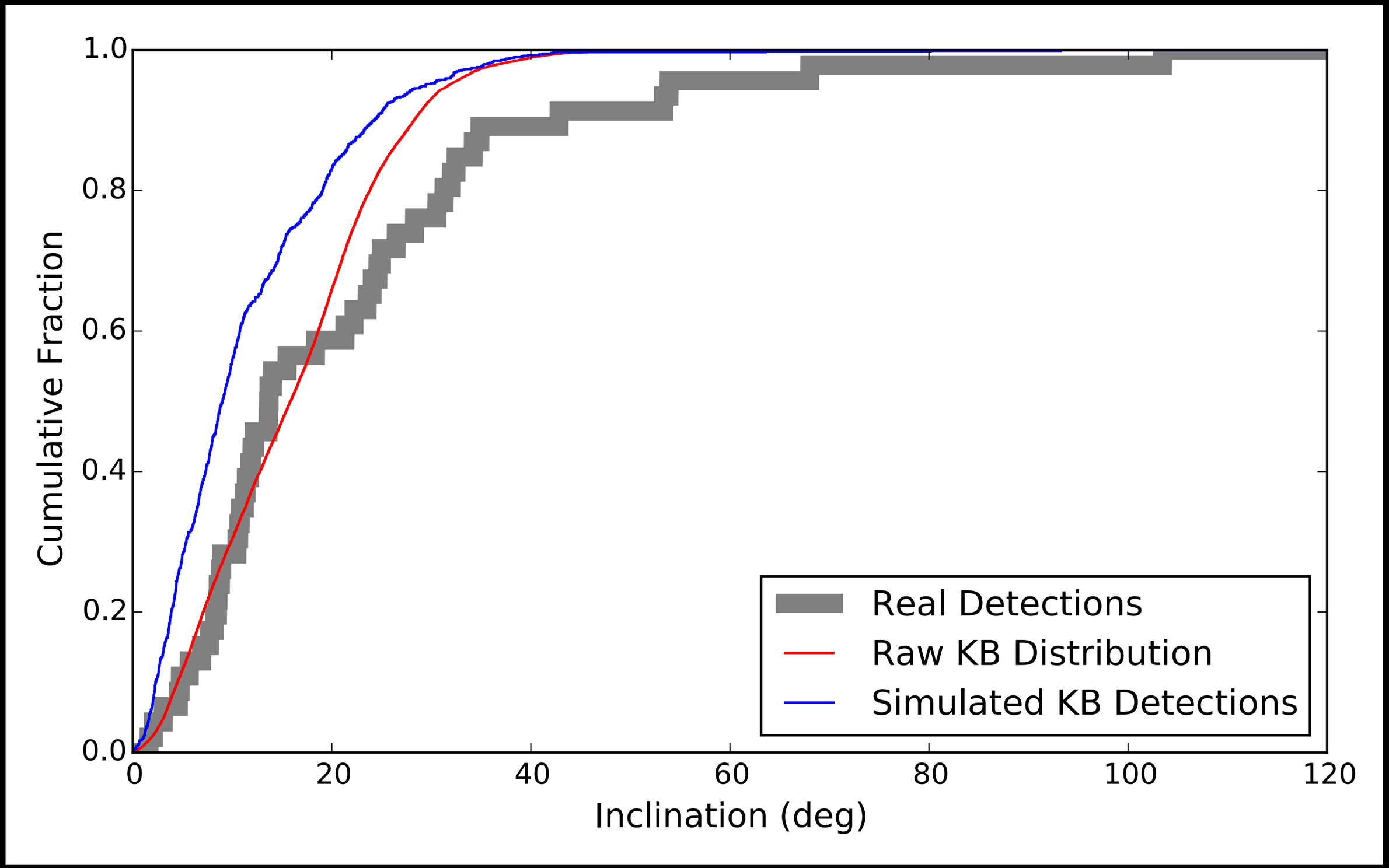
- Cull simulations for particles with $a < 10^3$ AU and $q < 40$ AU for last 500 Mrs
- If particle's semimajor axis changes by 1.5 AU after 10-Myr integration classify it as scattering
- Build separate orbital databases for Kuiper belt and Oort Cloud simulations



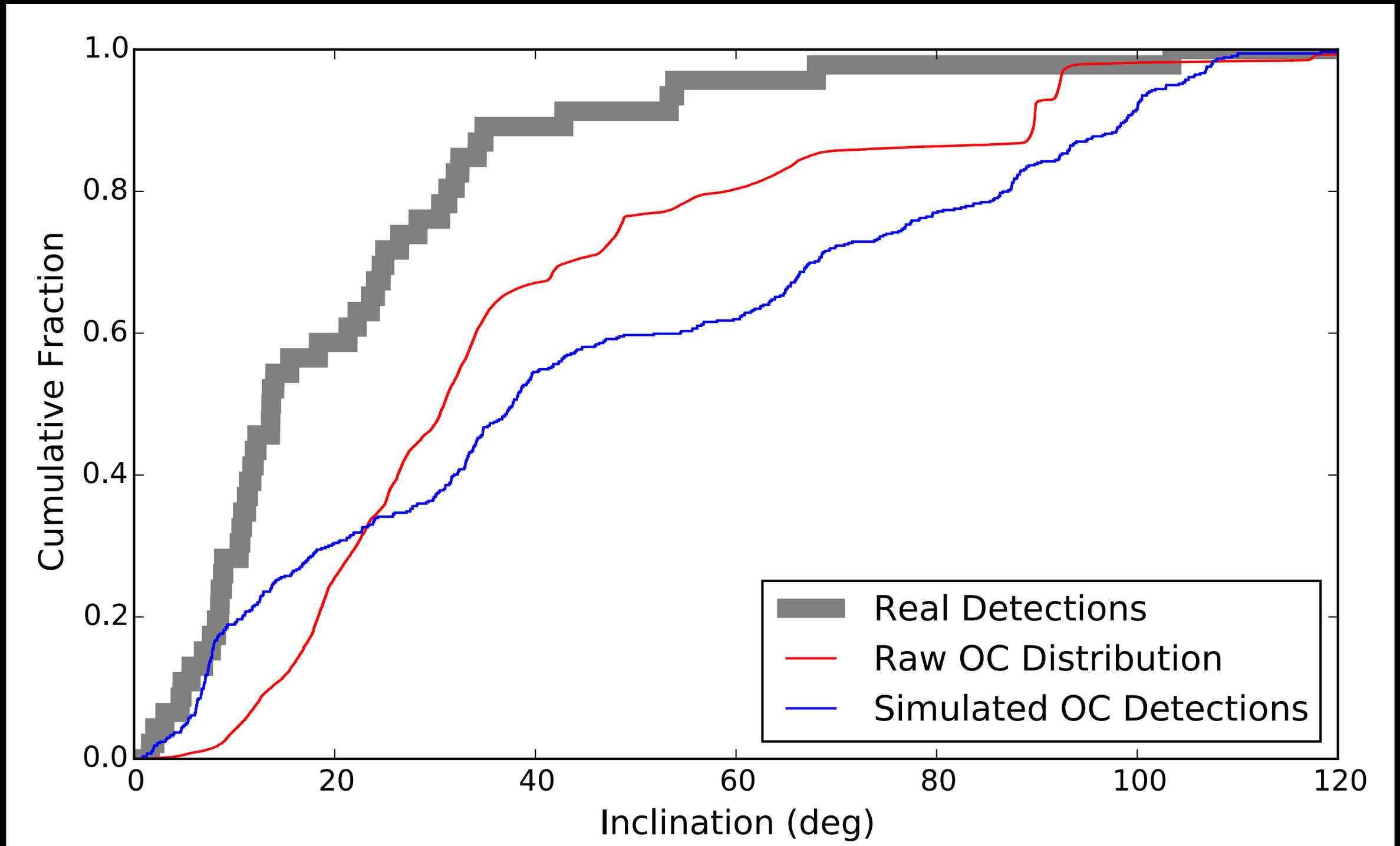
(Shankman et al. 2016)

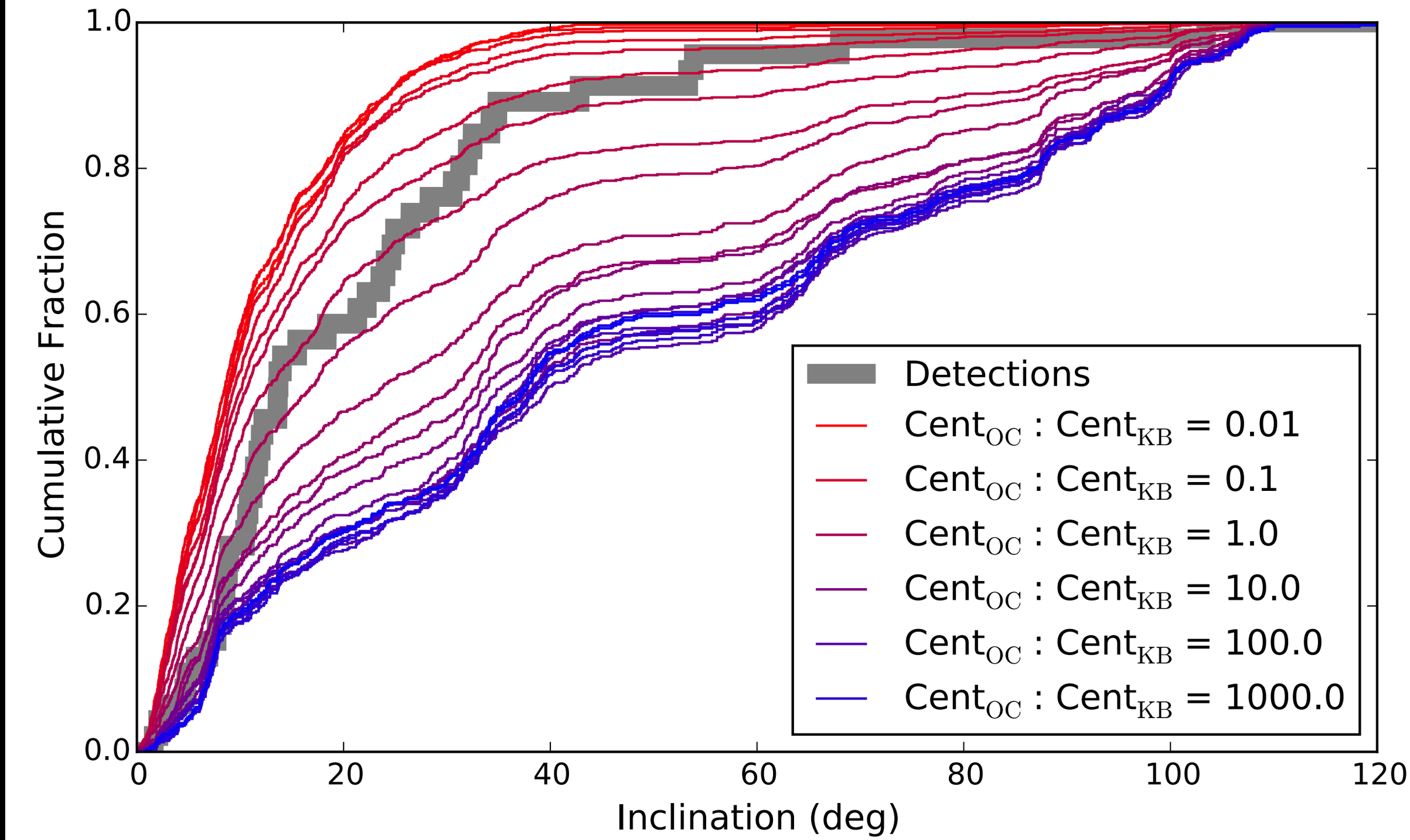
Repeat until 1000 detections are generated

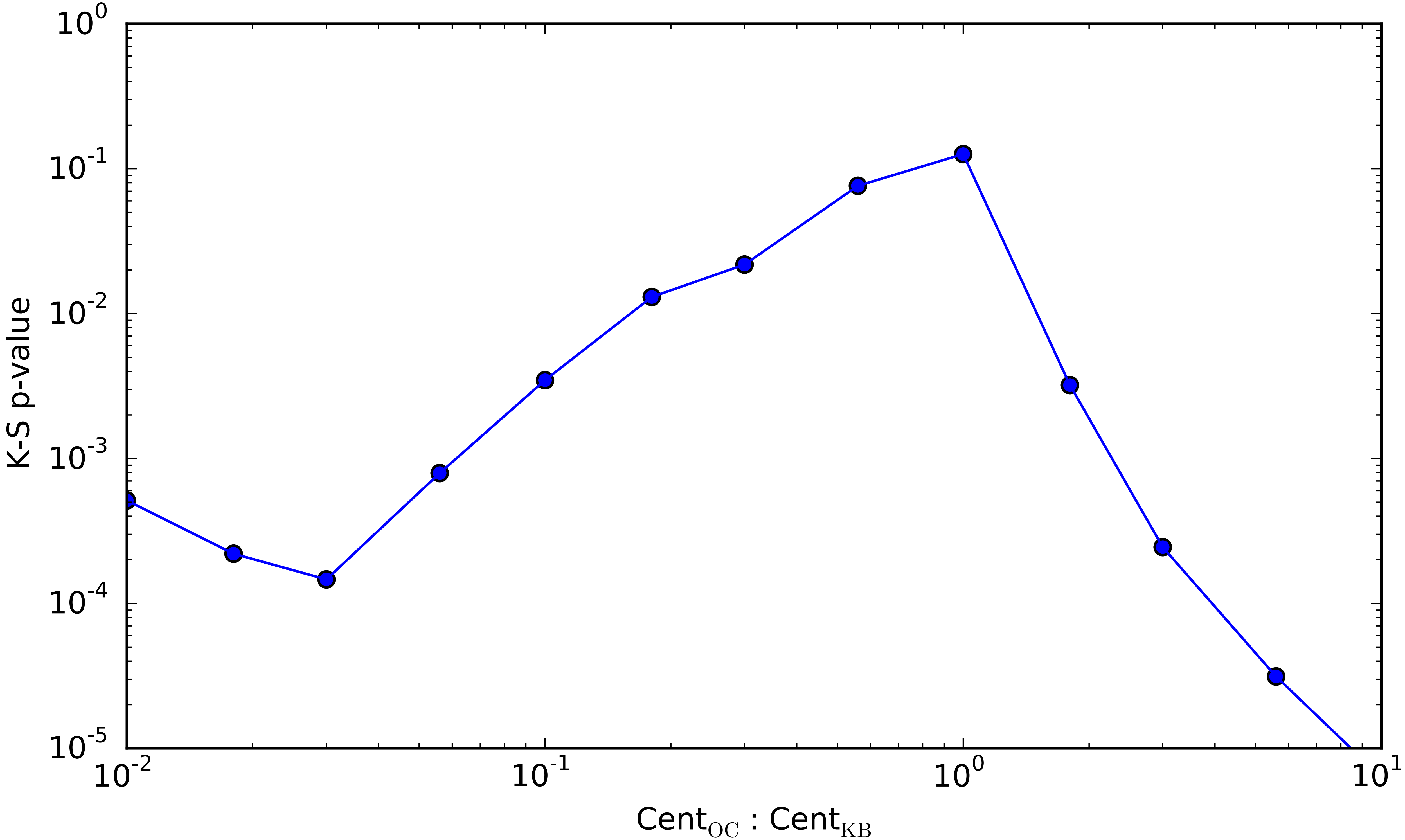
Kuiper Belt Distribution



Oort Cloud Distribution

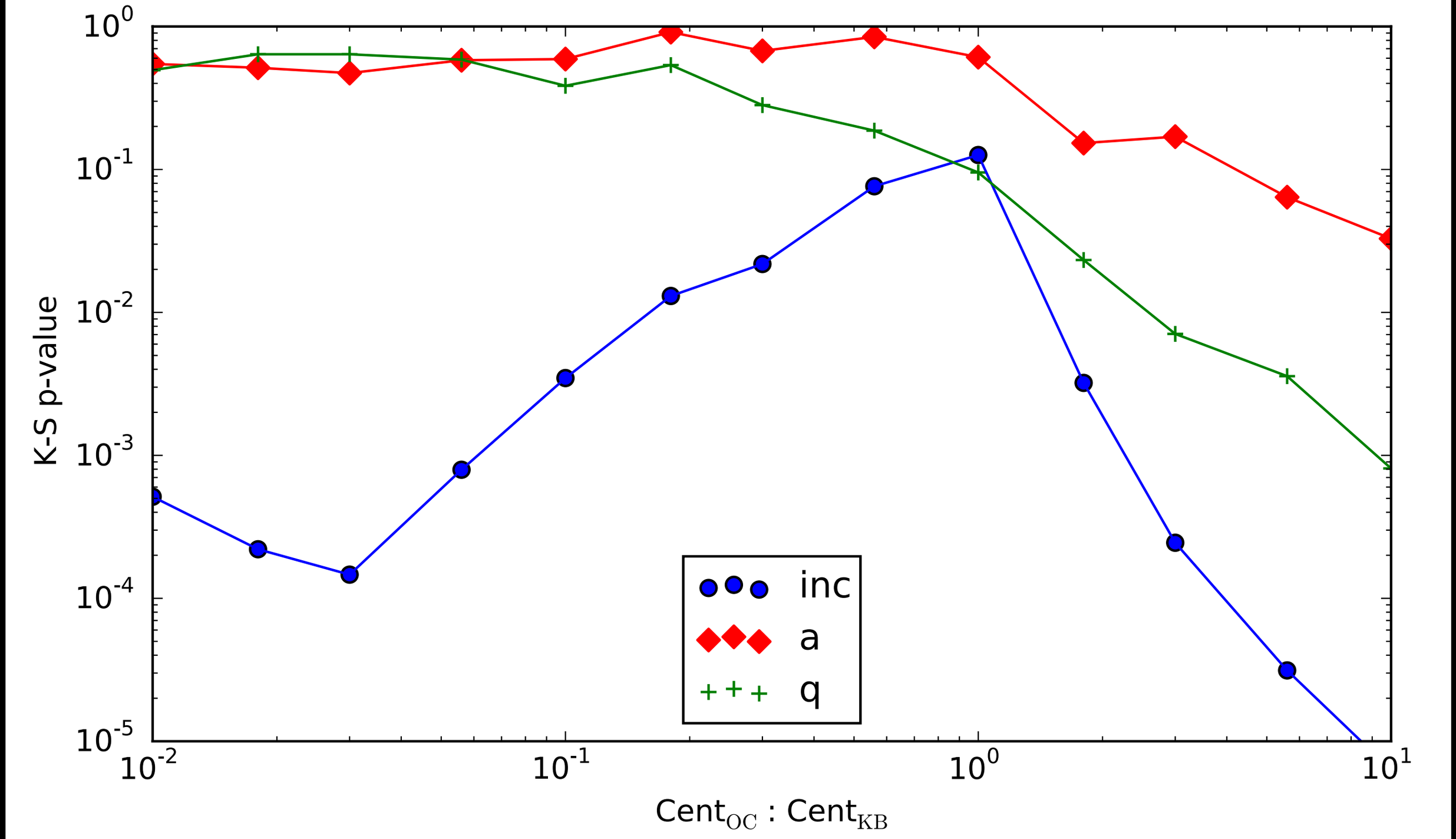



1.0
0.8
0.6
0.4
0.2
0.0
Cumulative Fraction
0
20
40
60
80
100
120
Inclination (deg)
Detections
Cent$_{OC}$: Cent$_{KB}$ = 0.01
Cent$_{OC}$: Cent$_{KB}$ = 0.1
Cent$_{OC}$: Cent$_{KB}$ = 1.0
Cent$_{OC}$: Cent$_{KB}$ = 10.0
Cent$_{OC}$: Cent$_{KB}$ = 100.0
Cent$_{OC}$: Cent$_{KB}$ = 1000.0



Oort cloud supplies between 1/4 and 2/3 of all centaurs and scattering objects

But Kuiper belt scatter production is about 500x more efficient than Oort cloud



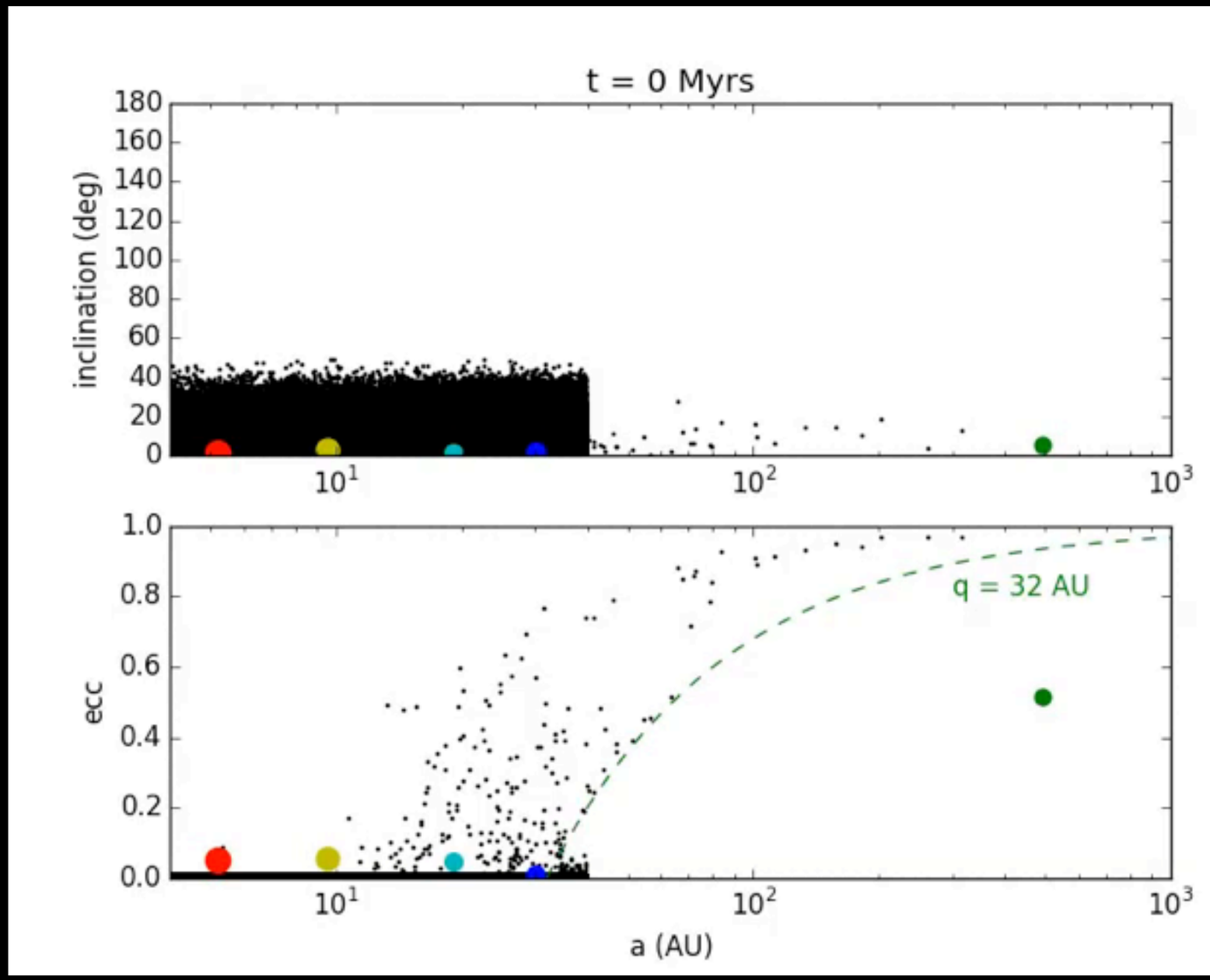
These ratios are not ruled about by a- or q-distributions

Conclusions

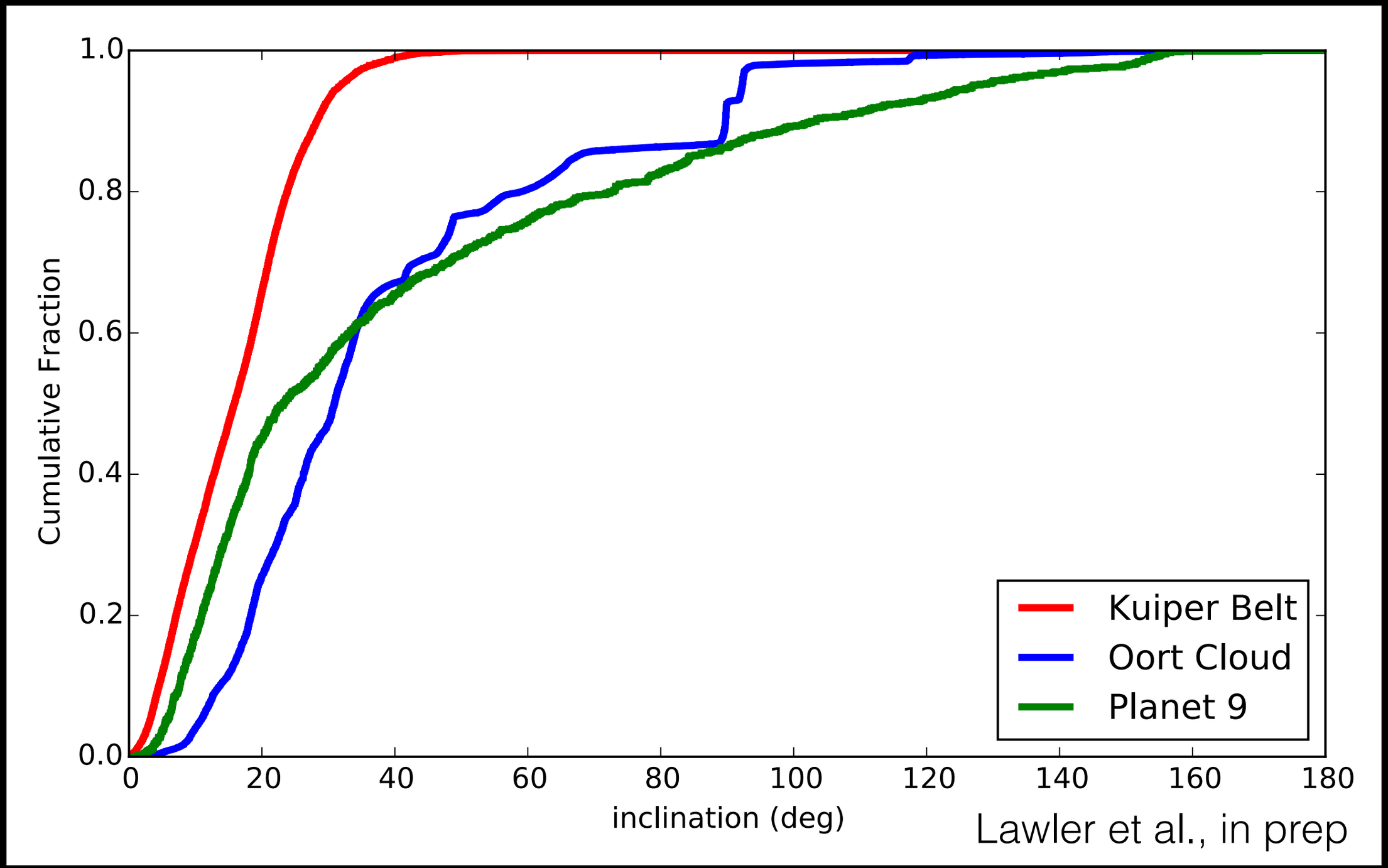
- Kuiper belt cannot be sole source of centaurs/ scattering objects
- If we assume a uniform size distribution, survey detections favor a OC:KB population ratio of ~500:1
- This ignores effects of a distant super-earth (Batygin & Brown 2016), but initial results don’t indicate this will replicate scattering inclinations

Complications of Planet 9

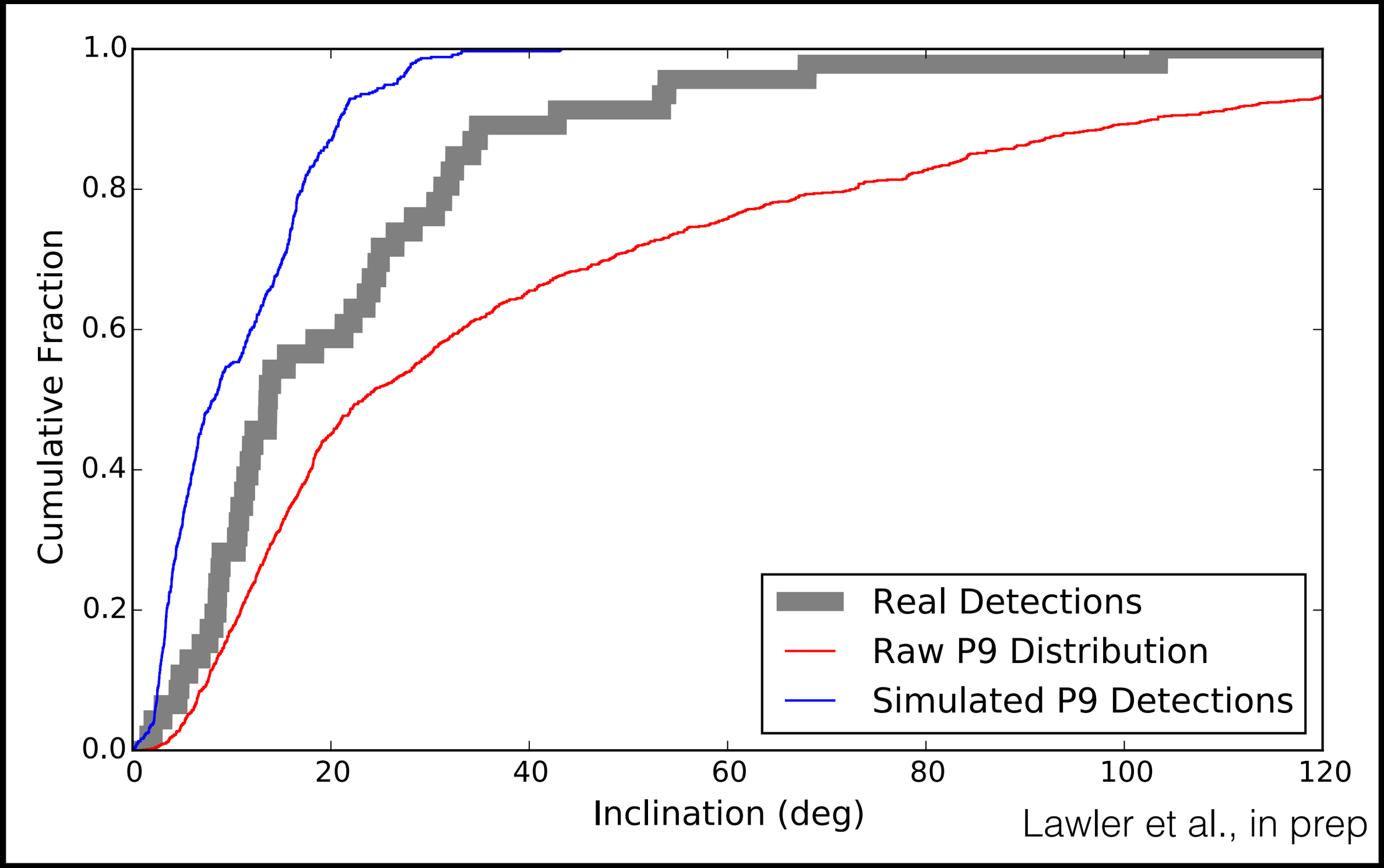
- 500,000 particles
- Static planets and static galactic environment
- Planet 9 with q = 250 AU, a = 500 AU (Batygin & Brown 2016)
- Integrated for 4 Gyrs with SWIFT RMVS4



Raw Distributions



Planet 9 Distribution



p-value = 10^{-4}