ASSESSING THE AVAILABILITY OF LOW DELTA-V TARGETS FOR ISRU DEVELOPMENT AND WATER EXTRACTION.

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Space Resources Roundtable
Golden, Colorado
2016

Mars landing
Near-Earth asteroids
Mars moons
Most-accessible known near-Earth asteroids.
Mars orbit
Missions to increasingly distant bodies would build human-spaceflight capabilities towards Mars.
Moon
Mars flyby
Asteroid Redirect Mission
A thorough survey would discover thousands more asteroids for astronauts to visit in the next two decades.
International Space Station
Total propulsion required for round trip (kilometres per second)
26
24
22
20
18
16
14
12
10
8
0
100
200
300
400
500
600
Round-trip mission duration (days)
SOURCE: BRENT W. BARBEE/NASA GODDARD SPACEFLIGHT CENTER

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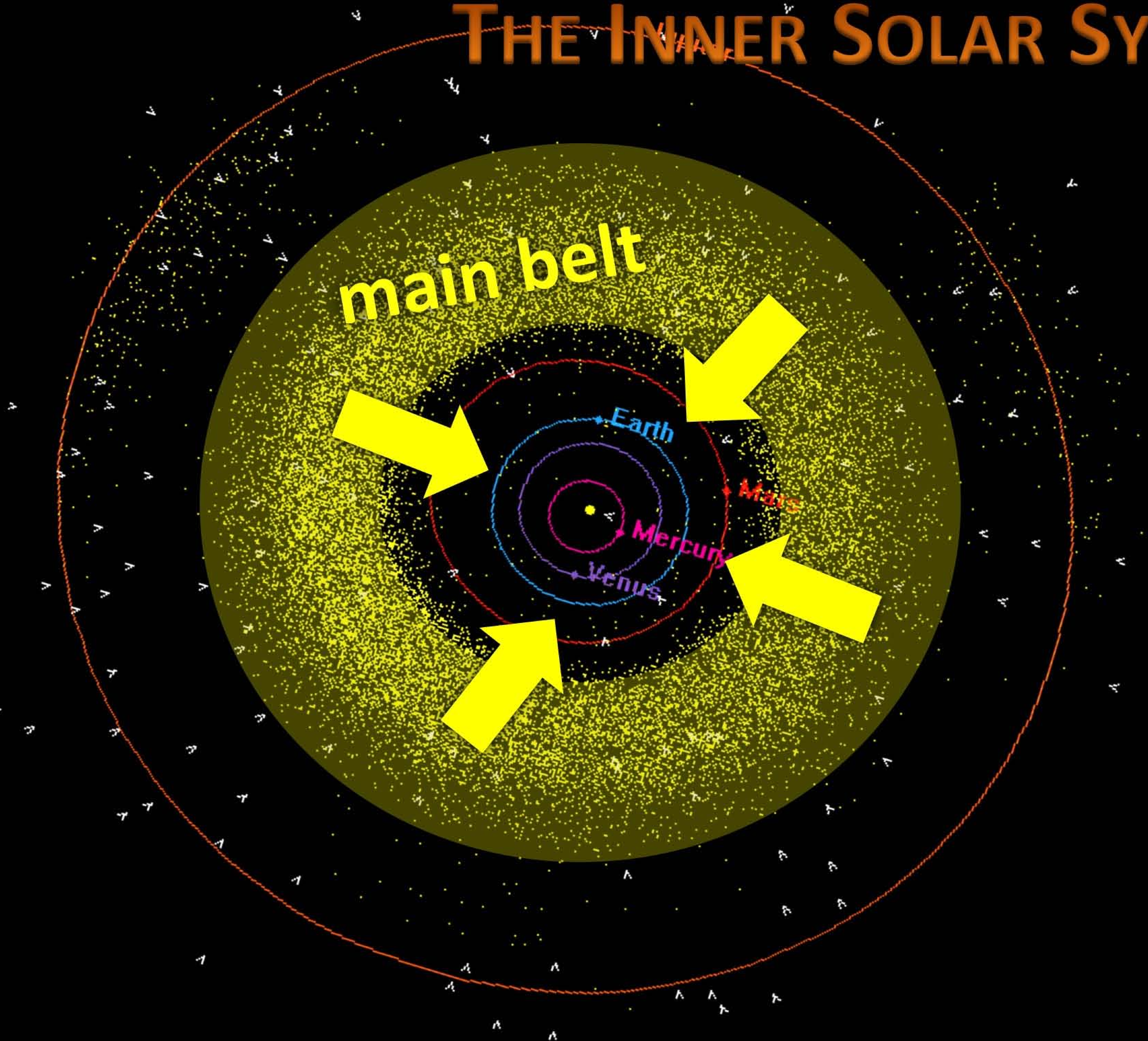
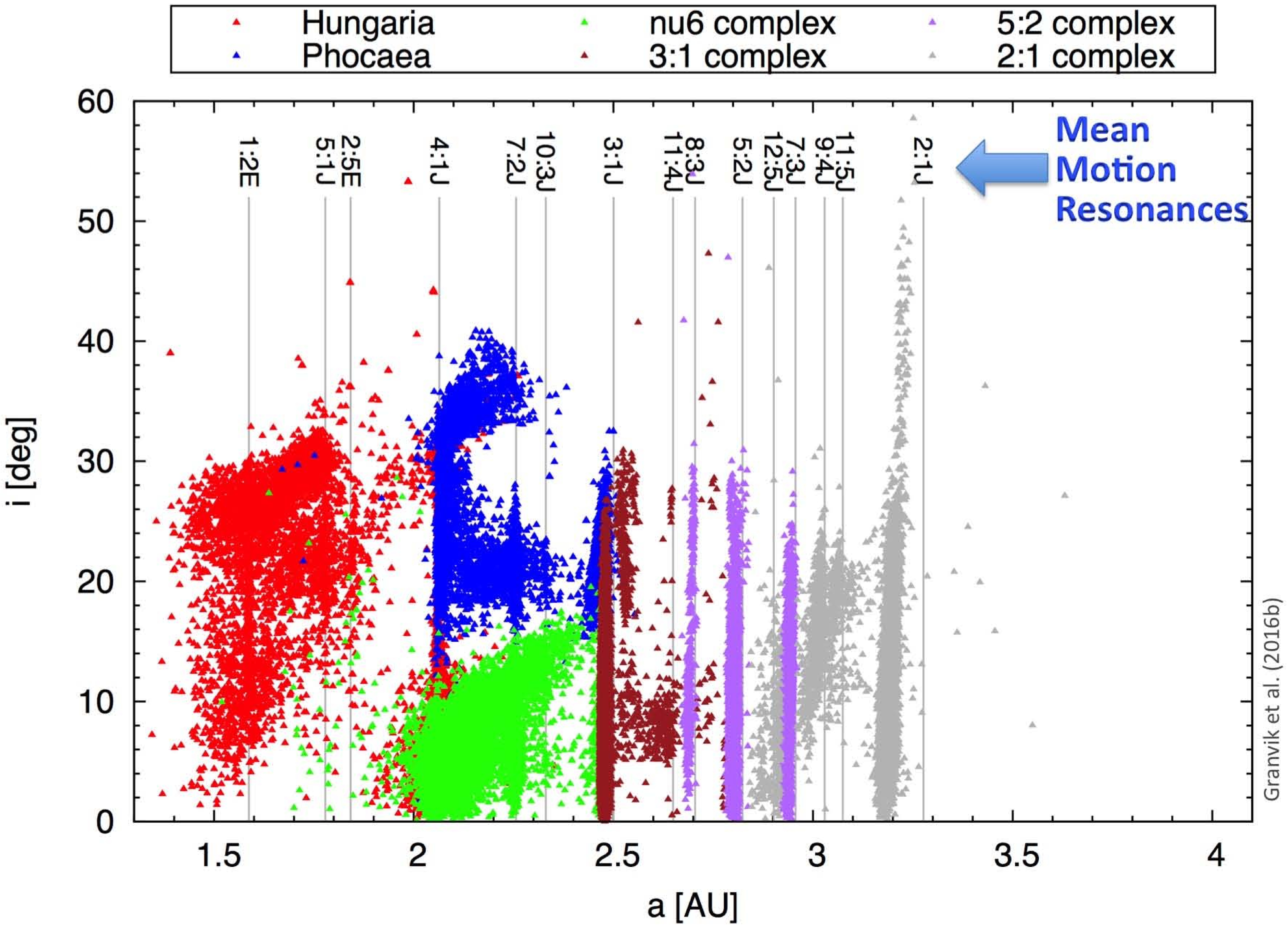
A thorough survey would discover thousands more asteroids for astronauts to visit in the next two decades.
International Space Station
THIS TALK
Round-trip mission duration (days)
Total propulsion required for round trip (kilometres per second)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
0
100
200
300
400
500
600
SOURCE: BRENT W. BARBEE/NASA GODDARD SPACEFLIGHT CENTER

The Inner Solar System



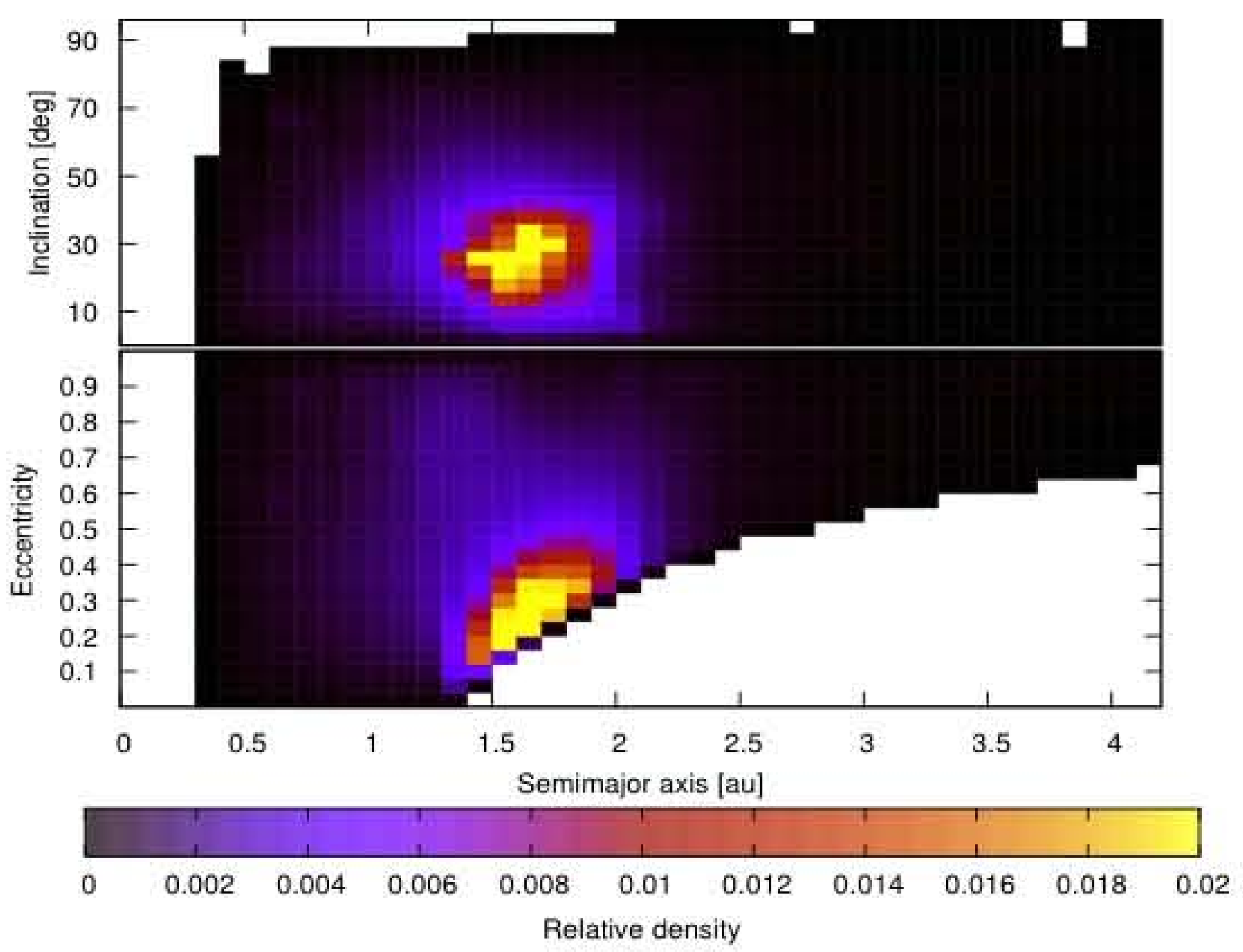
The Inner Solar System

Main Belt NEO Sources

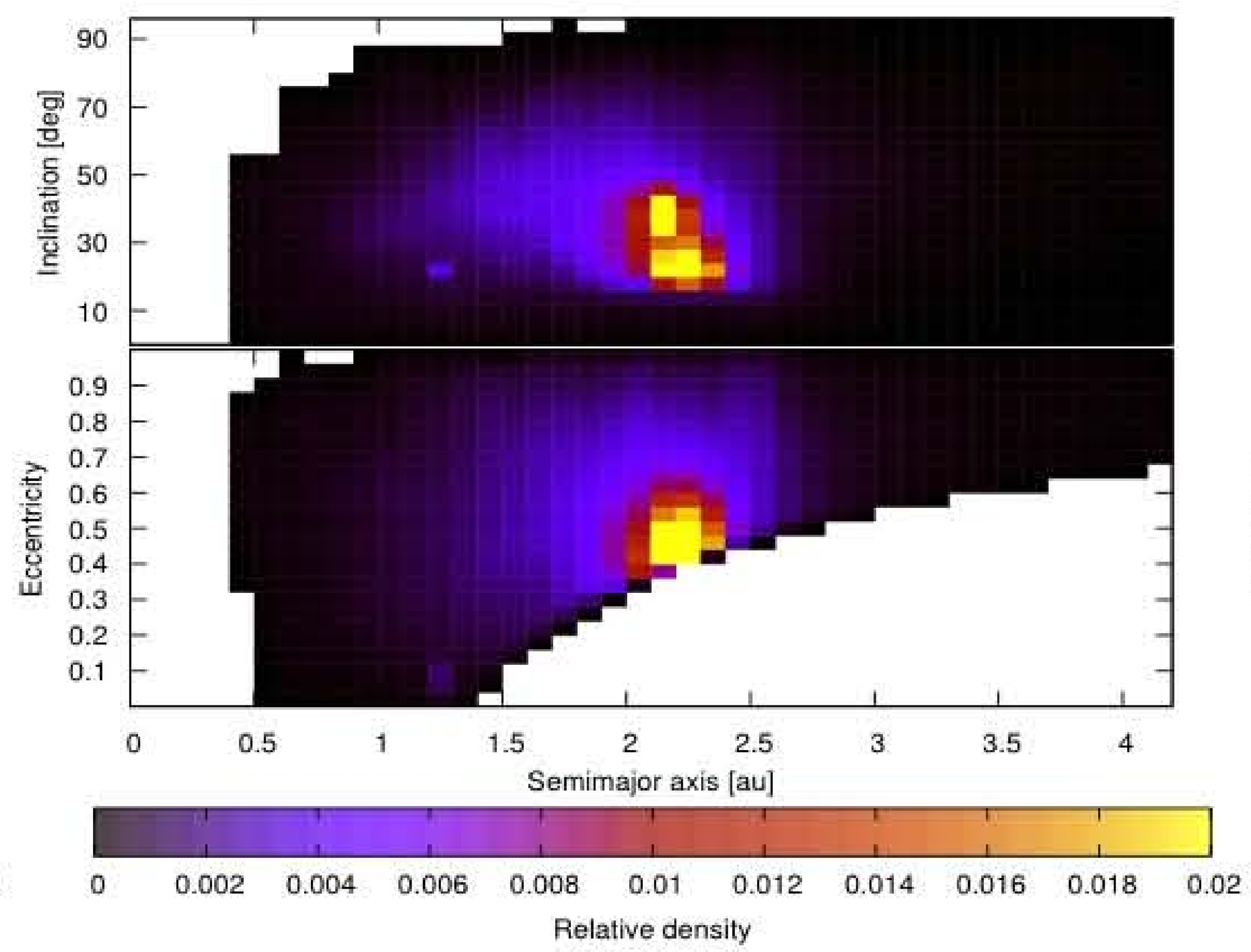


NEO SOURCE ORBITAL STEADY-STATE DISTRIBUTIONS

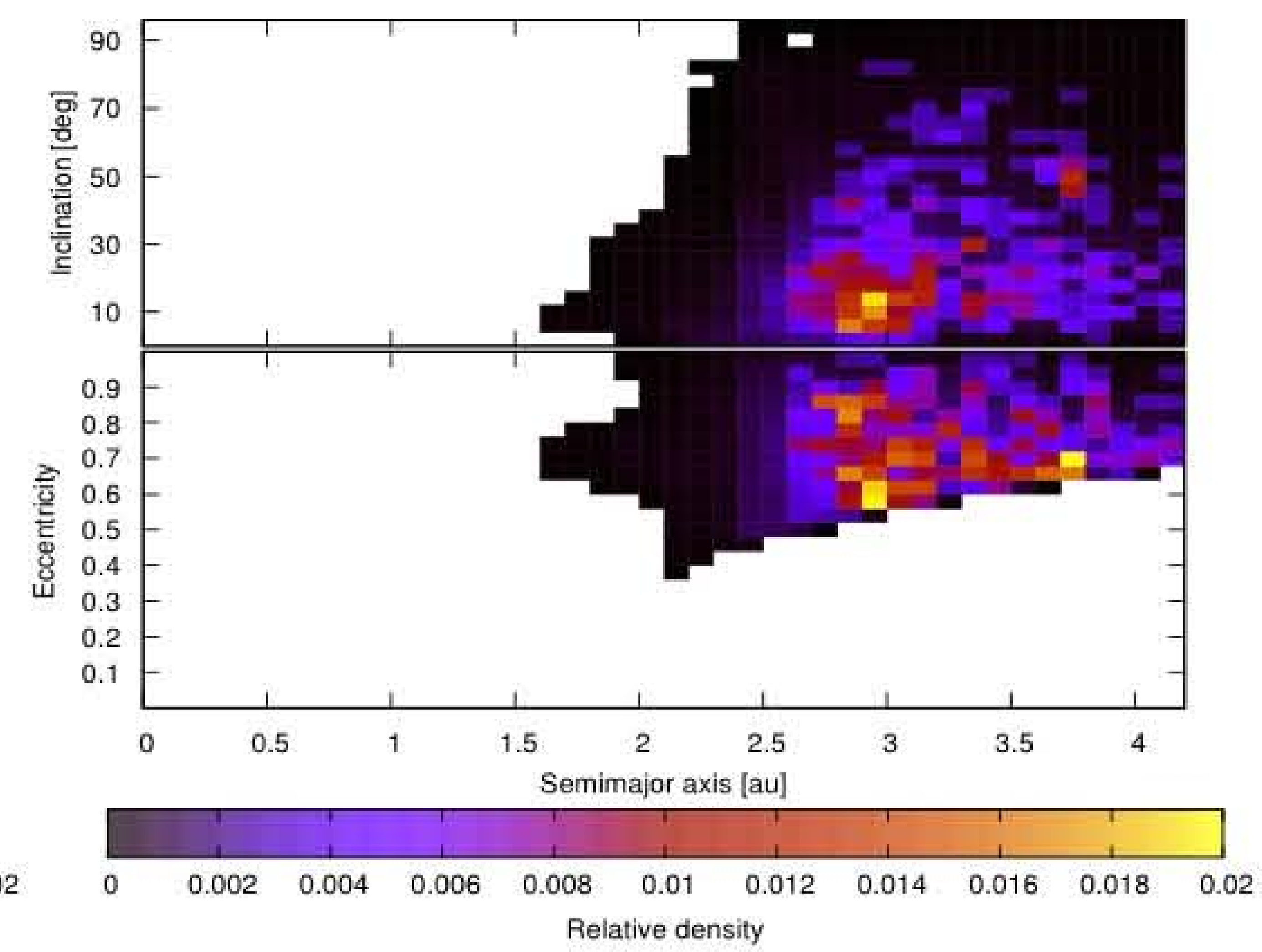
Hungaria



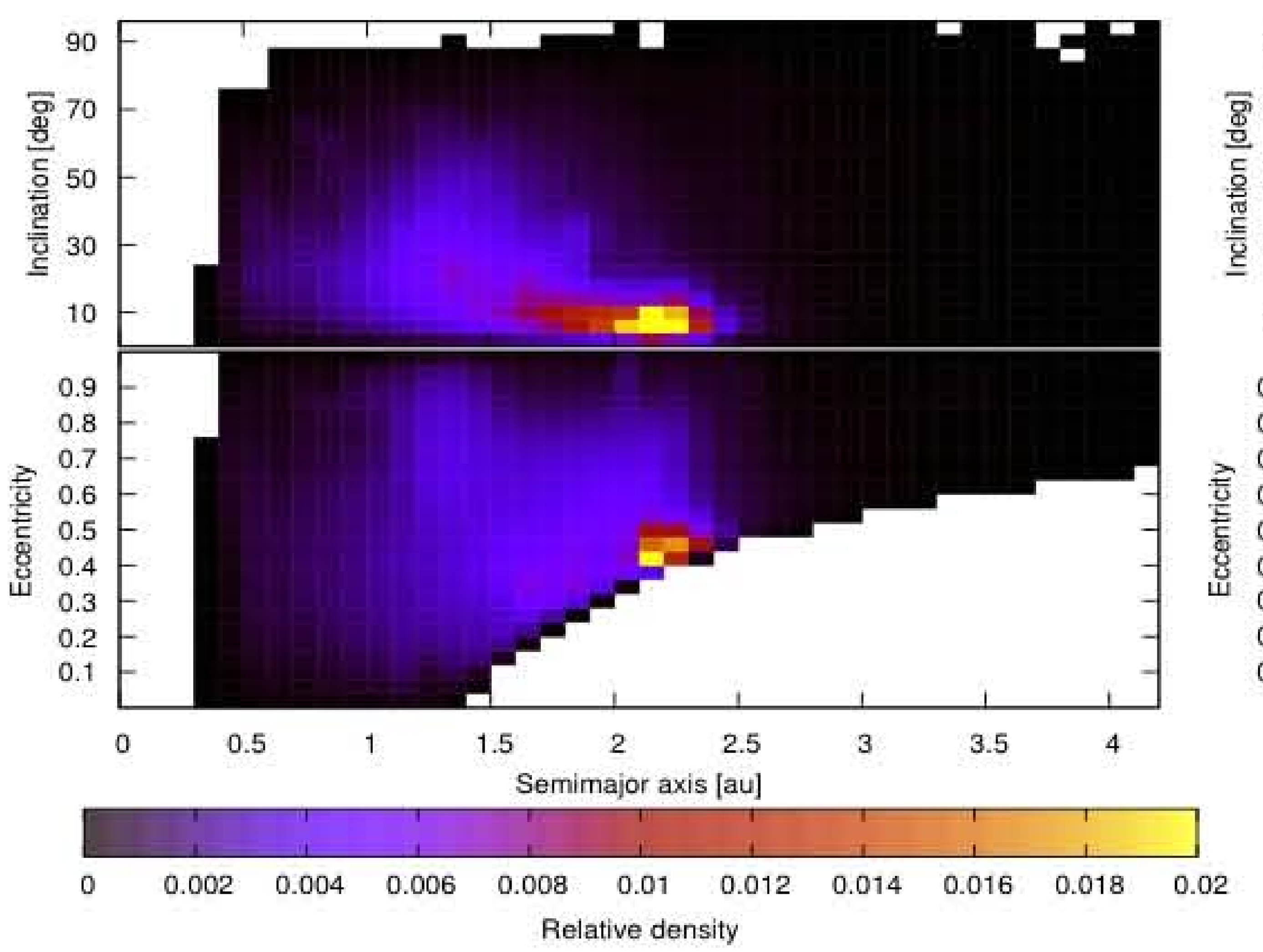
Phocaea



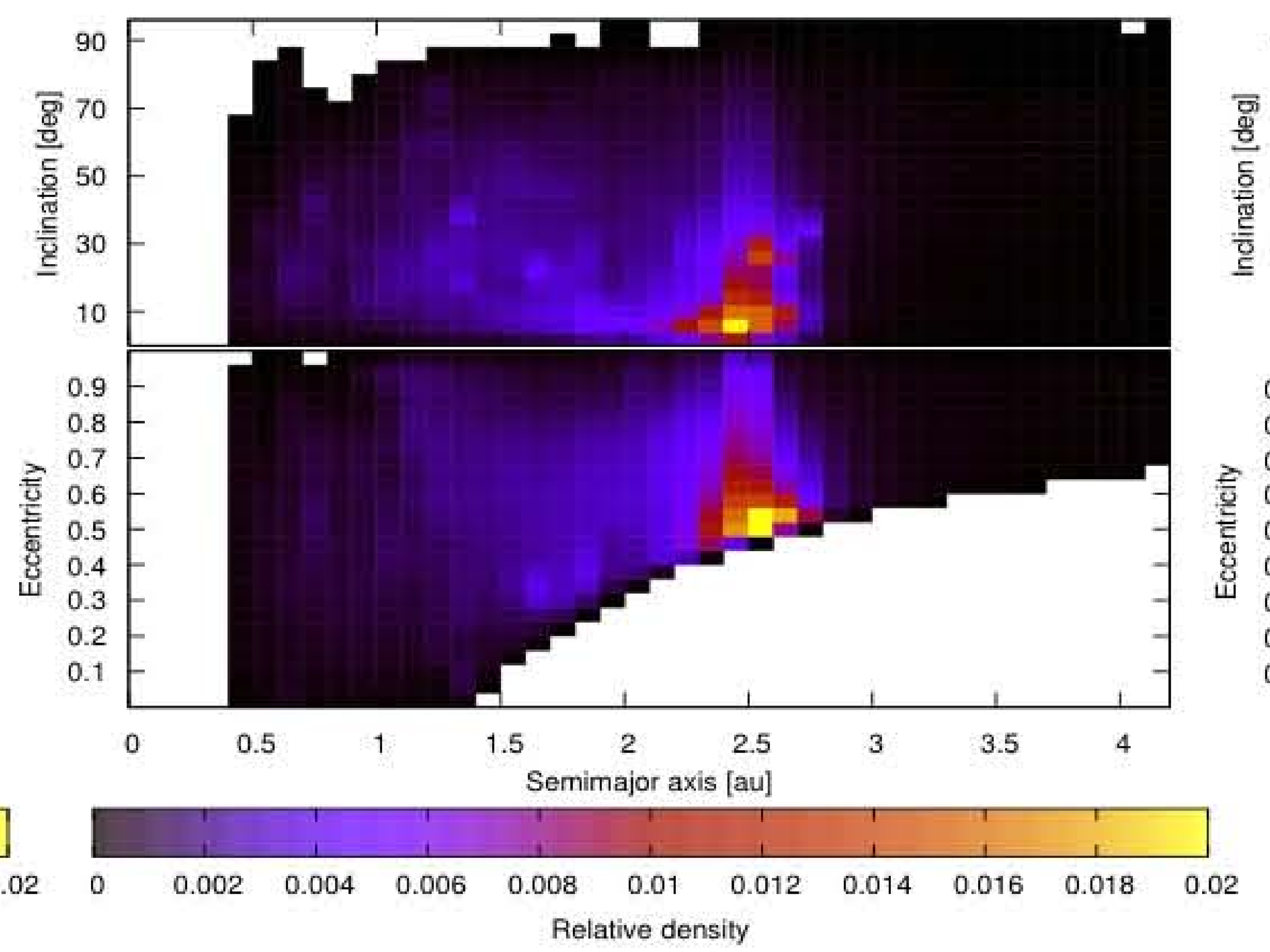
JFC



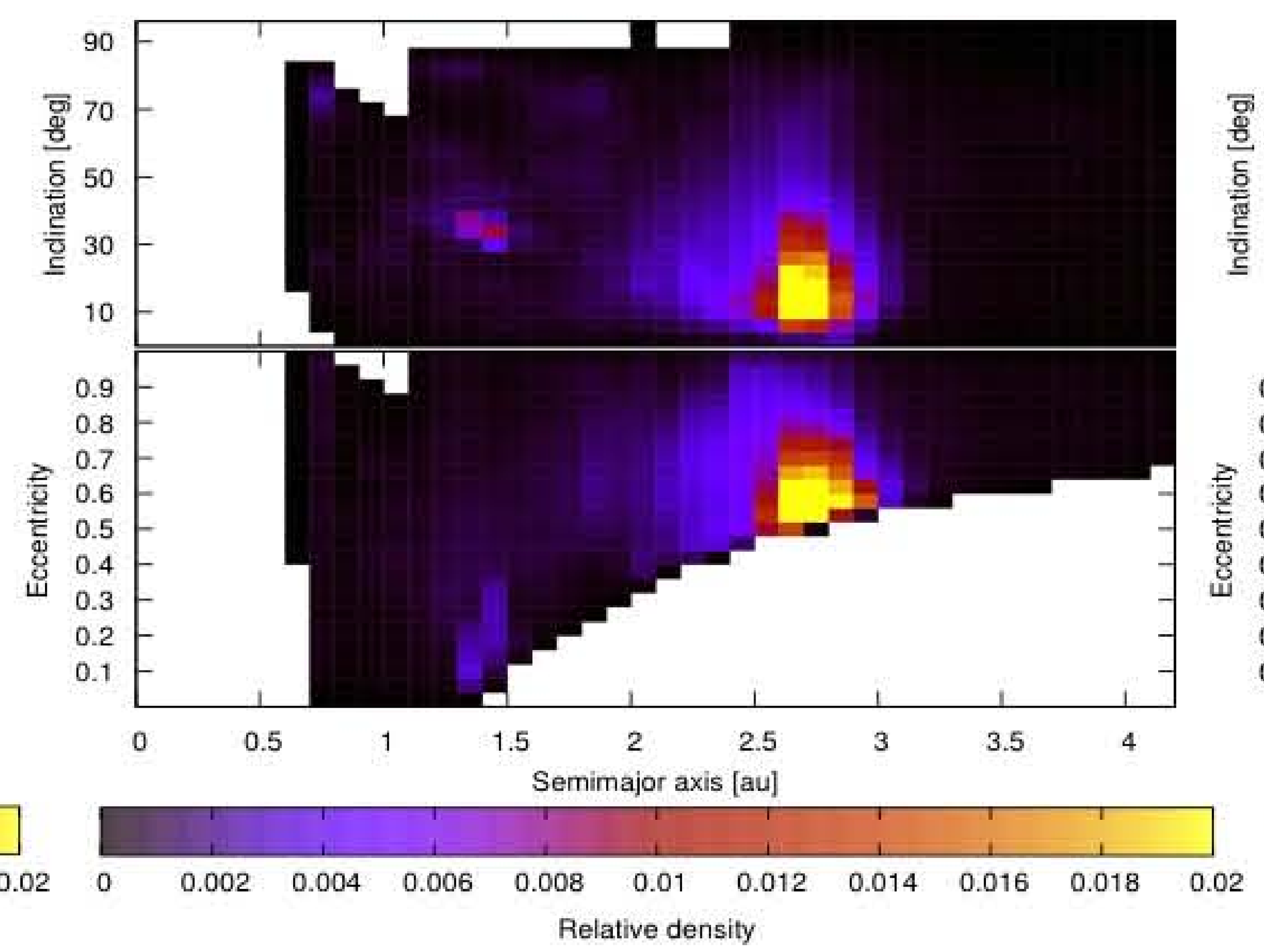
ν_6 complex



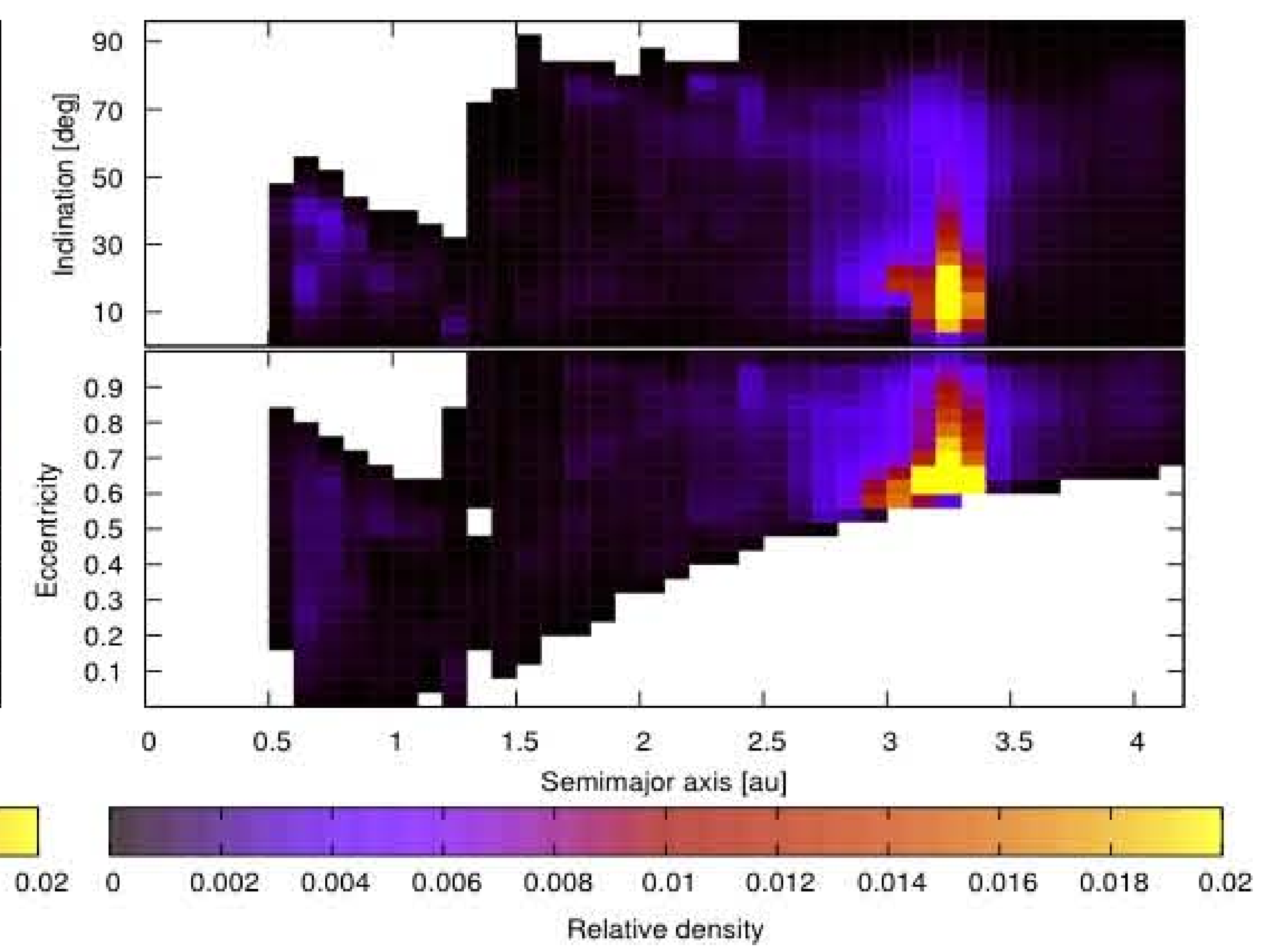
3:1 complex



5:2 complex

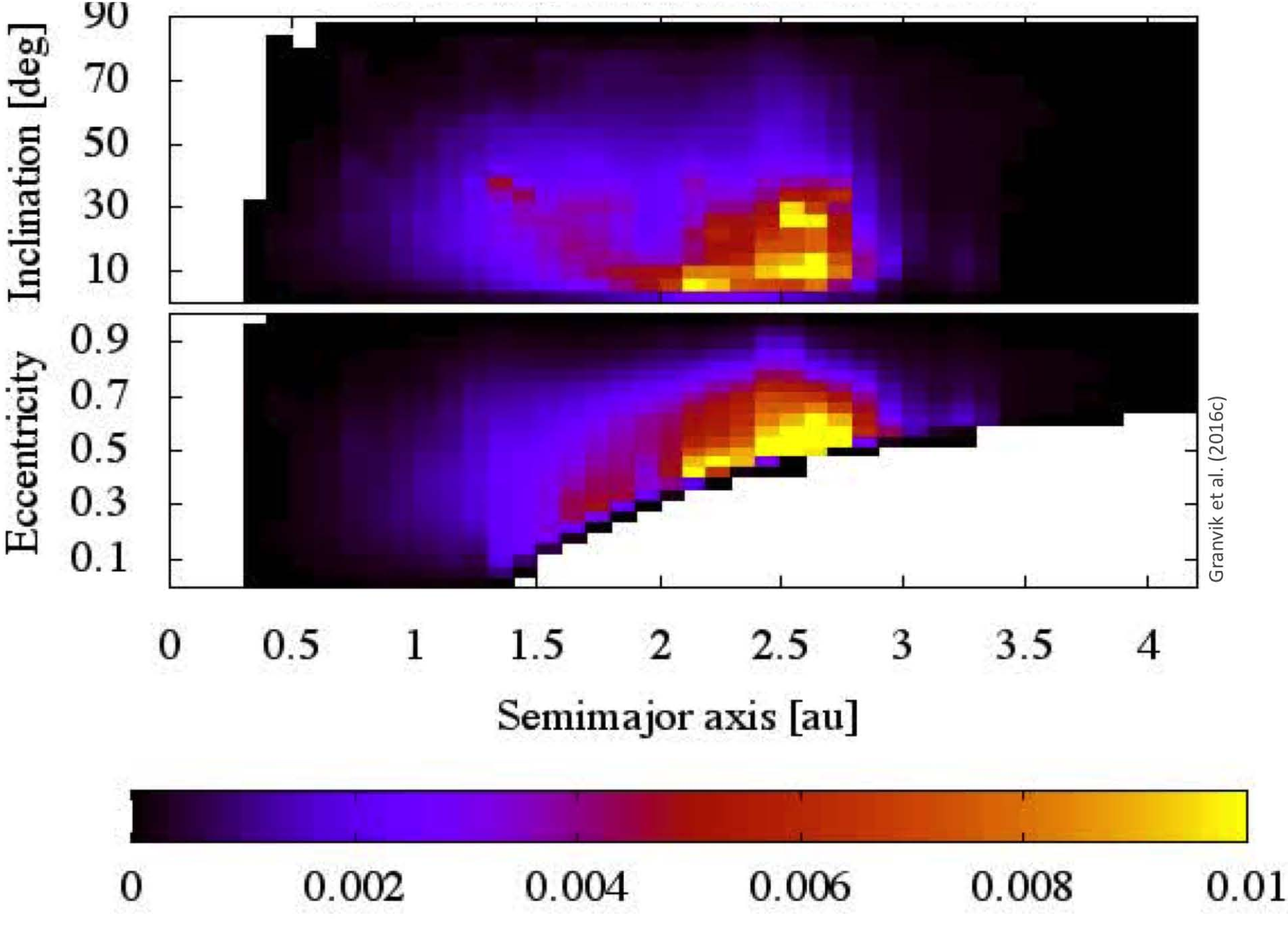


2:1 complex



Granvik et al. (2016c)

Size Dependent NEO Orbit Distribution



DEBIASED *SOURCE-SPECIFIC* H (SIZE) DISTRIBUTIONS

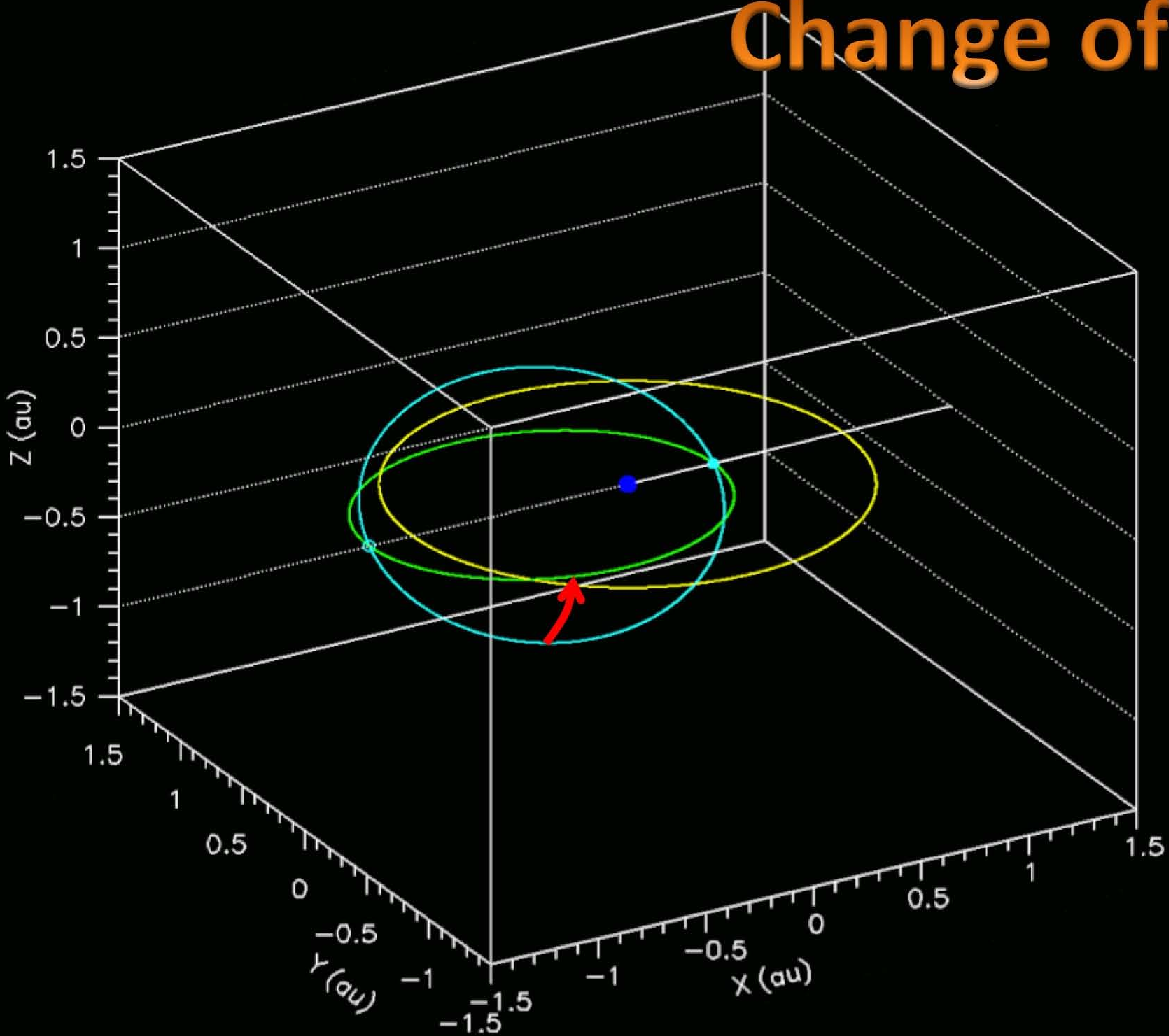
Percentage contribution of NEOs by source region vs. H (size)

ΔV From Heliocentric Orbit to LDRO

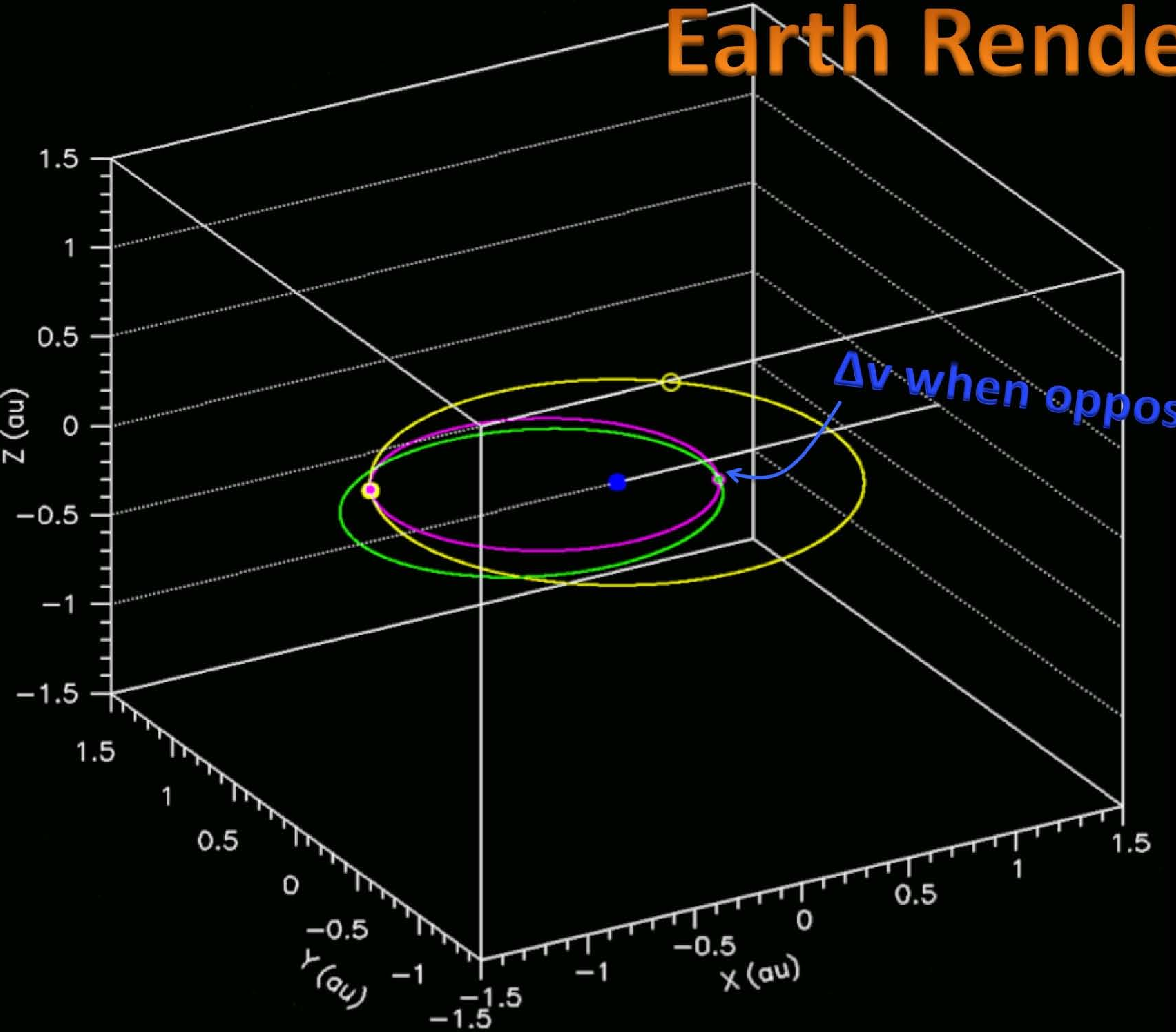
- designed to provide conservative over-estimate
- 4 burns
  1. rotate into Earth's orbital plane
  2. rendezvous with Earth position
  3. match Earth-Moon velocity
  4. capture into Lunar Distant Retrograde Orbit

We are now implementing a more optimal broken plan maneuver that should provide up to a 40% ΔV reduction and reduce the resource delivery time

Change of Plane



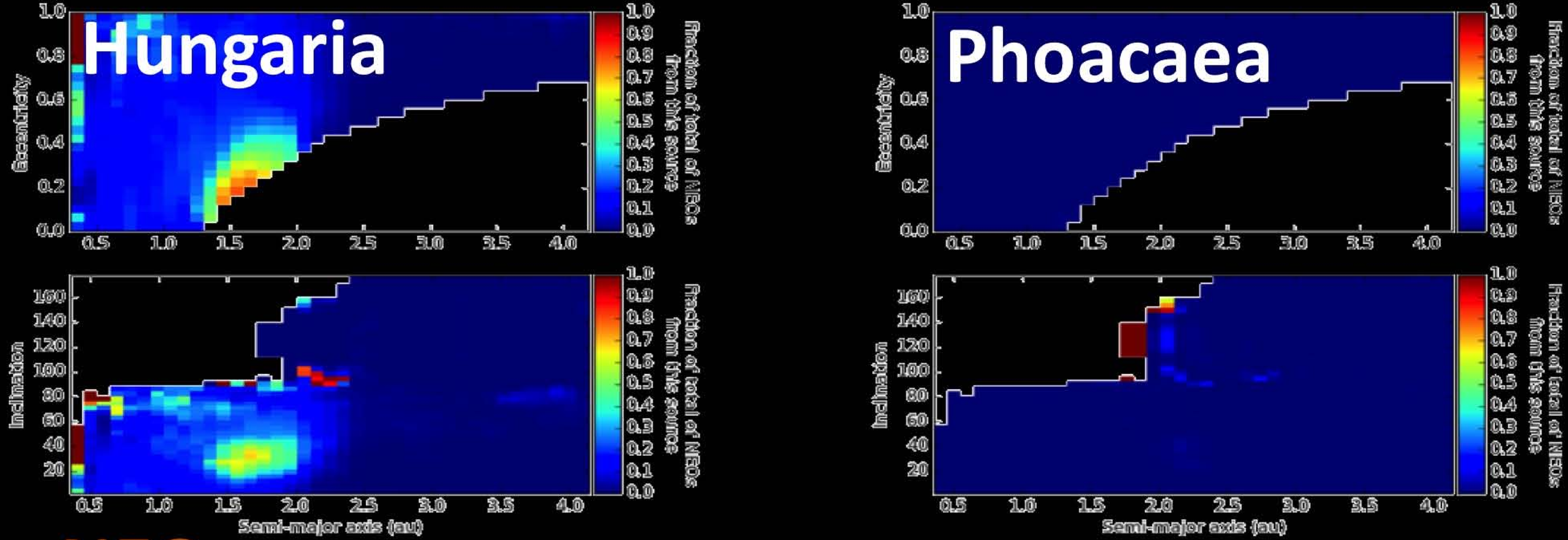
Earth Rendezvous



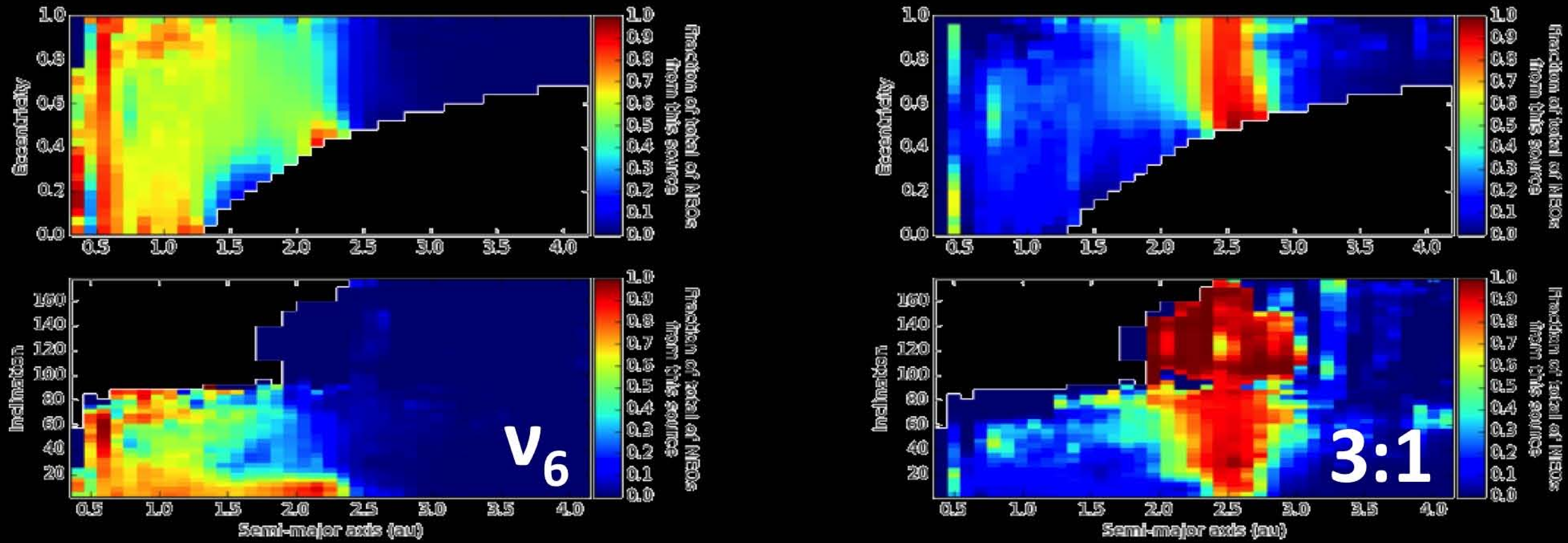
low Δv targets
>4 meters diameter
about 1,000
about 200
cumulative number of objects
delta–v (km/s)
0
1000
2000
3000
4000
5000
6000
1
1.25
1.5
1.75
2
2.25
2.5
2.75
3

low Δv target inclinations

low Δv target eccentricity
vs. semi-major axis
but explore a range
of eccentricity and
semi-major axis
eccentricity
semi-major axis (au)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5



NEO STEADY-STATE SOURCE DISTRIBUTION FRACTIONS



Main Belt Mass and Taxonomic Distribution

Taxonomic Properties

Tholen Taxonomic class (c)	SMASSII Taxonomic class (c)	Bulk density[a] ($\mathrm{g\,cm^{-3}}$) $[\rho_{Mc}]$	Associated Meteorite	Meteorite density ($\mathrm{g\,c}$[illegible]$^{-3}$) $[\rho$[illegible]	Water Weight[g] % $[f_{H_20}, c]$	Bulk porosity[j] $[P_c]$	NEO Albedo[l] $[A_c]$
S	[illegible]	[illegible]	[illegible]	[illegible]	1	$.08 \pm 0.02$	0.26
C	[illegible]	[illegible]	[illegible]	[illegible]	13-20	$.34 \pm 0.18$ $.38 \pm 0.20$	0.13
D	[illegible]	[illegible]	[illegible] CI[b]	[illegible] $2.26 \pm$ [illegible]2[g]	13-20	undef.[k] undef.[k]	0.02

[a]From Table 3, Carry (2012) but given here with reduced precision; ρ_{50} for S and C types, ρ_{∞} for D type.

[b]Trigo-Rodríguez *et al.* (2014)

[d]Cloutis *et al.* (2011), Cloutis *et al.* (2011)

[e]Hiroi *et al.* (2001)

[g]Mason (1963)

[h]Britt and Consolmagno (2003)

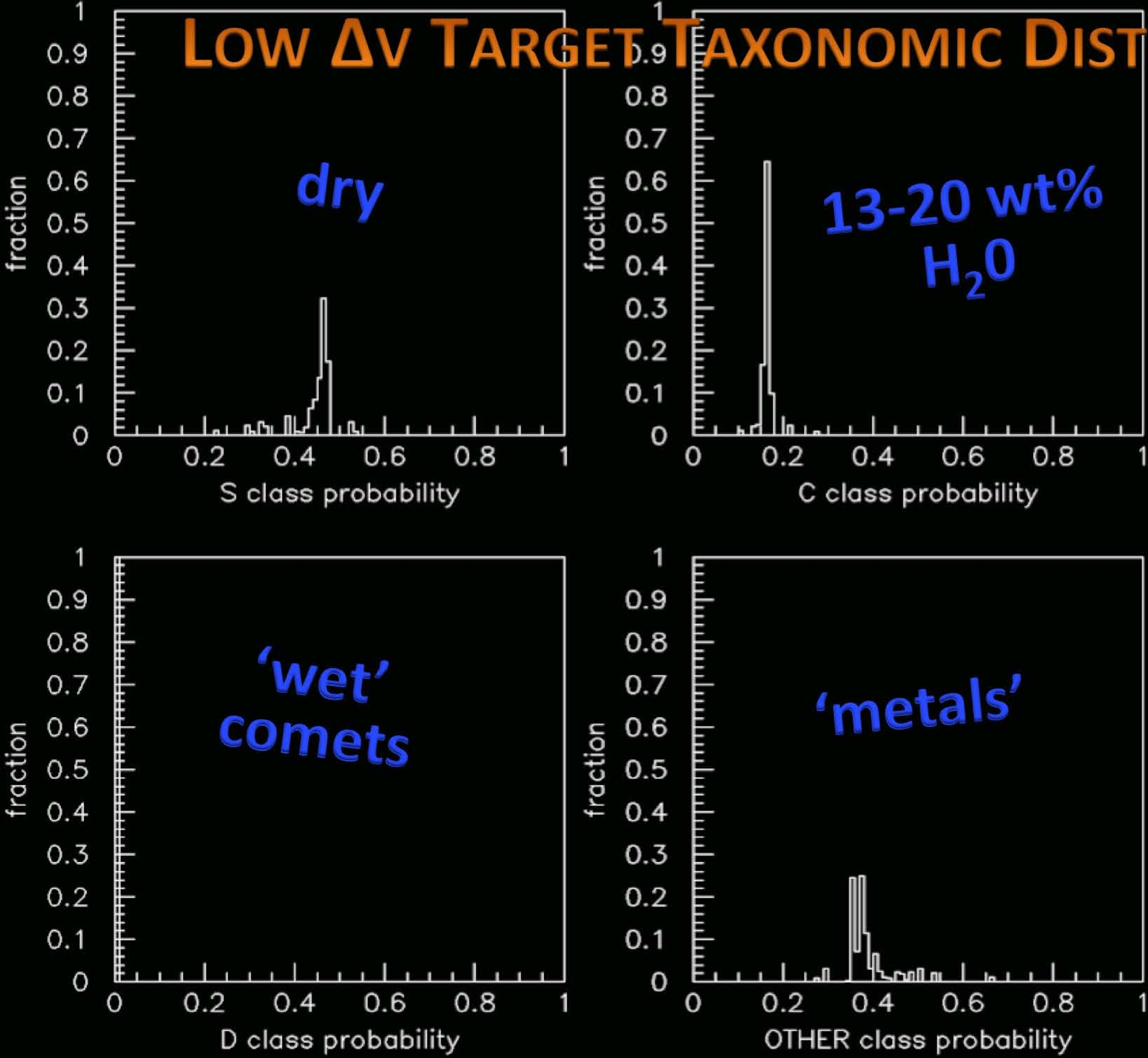
[i]Grady *et al.* (2002)

[j] $P_c = 1 - \rho_{Mc}/\rho_c$

[k]Undefined since the reported asteroid density is up to 6× higher than the constituent meteorite!

[l]Thomas *et al.* (2011)

Low Δv Target Taxonomic Distribution




EARTH'S *OTHER* (TEMPORARY)
NATURAL SATELLITES
MINIMOONS

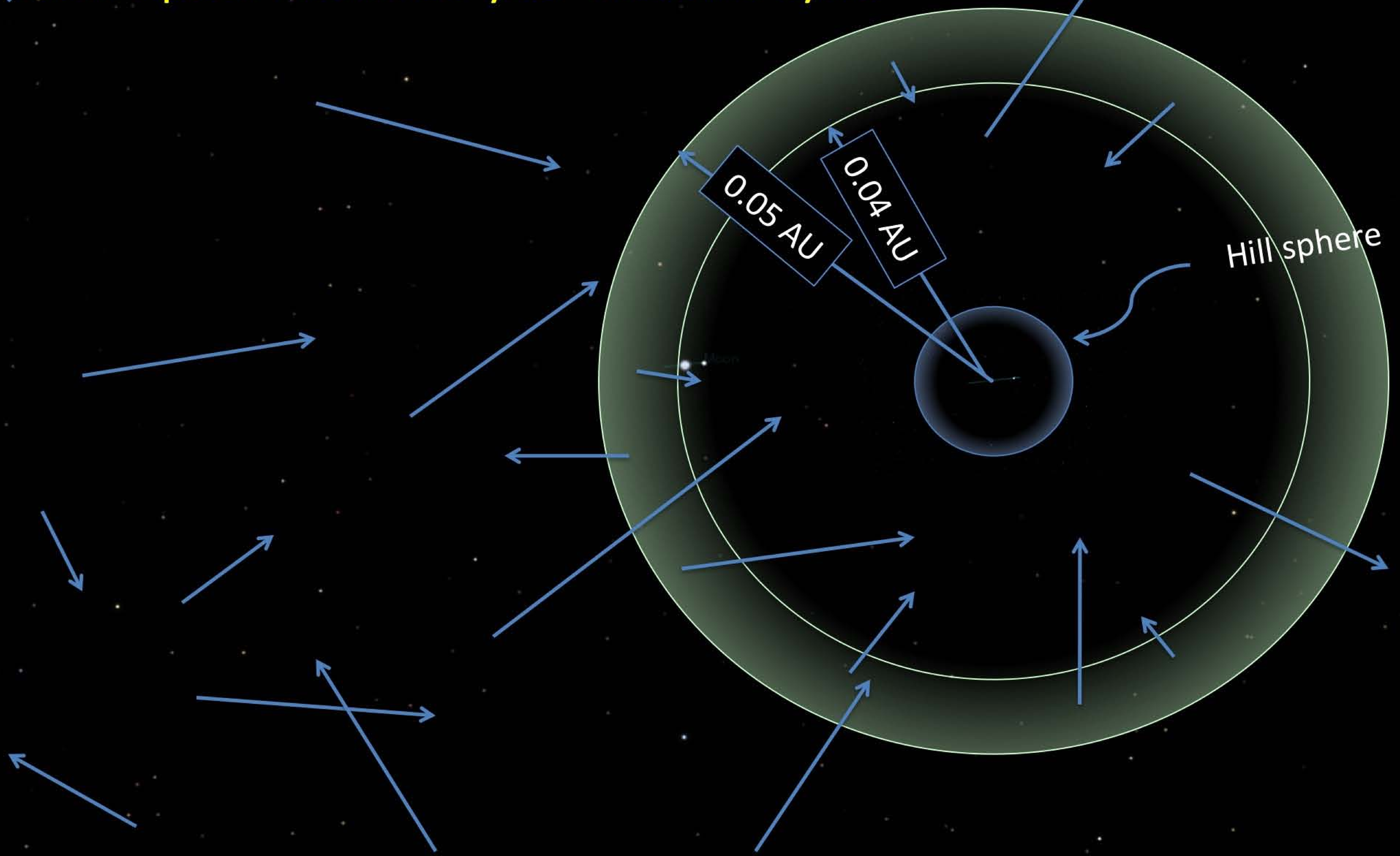
MINIMOON SOURCE POPULATION


EARTH'S *OTHER* (TEMPORARY)
NATURAL SATELLITES
NOT MINIMOONS
ONE 10 METER DIAMETER NEO
CLOSER THAN THE MOON
AT ALL TIMES

MINIMOON SOURCE POPULATION

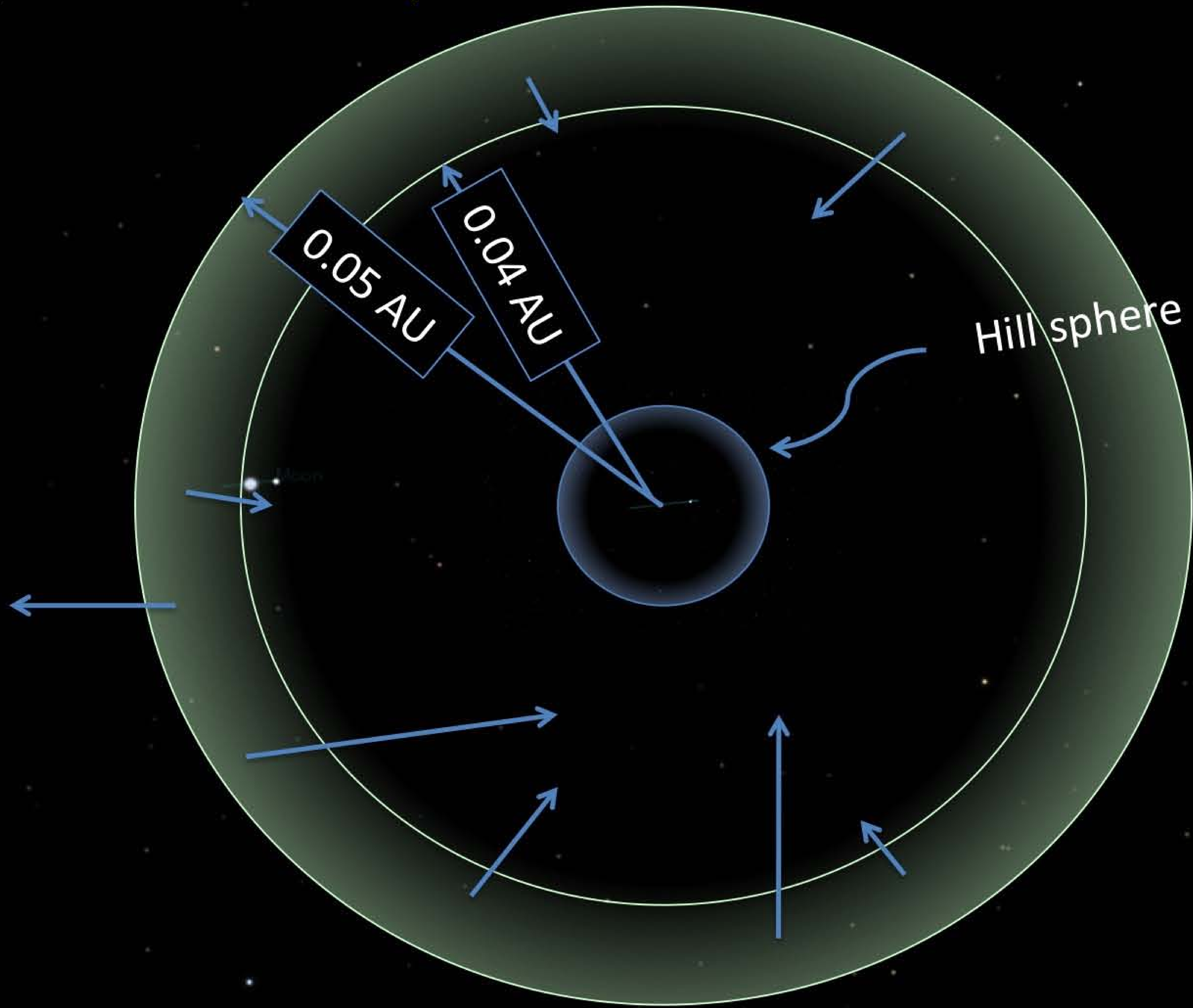
Generating NEO Minimoon Candidates

- orbits randomly selected from NEO population
- random epoch within 19-year Metonic Cycle



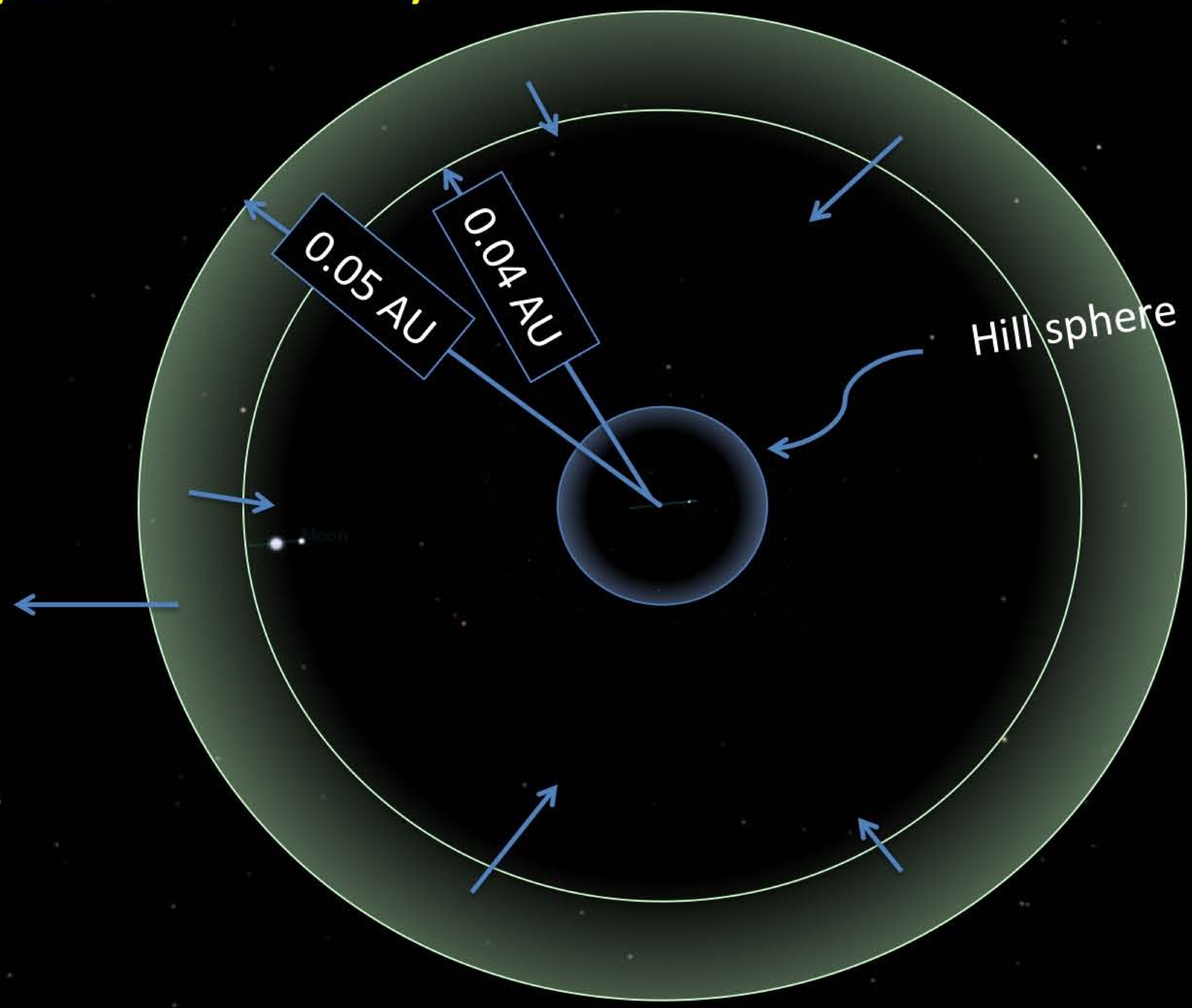
Generating NEO Minimoon Candidates

- orbits randomly selected from NEO population
- random epoch within 19-year Metonic Cycle
- 0.04 AU < Δ < 0.05 AU



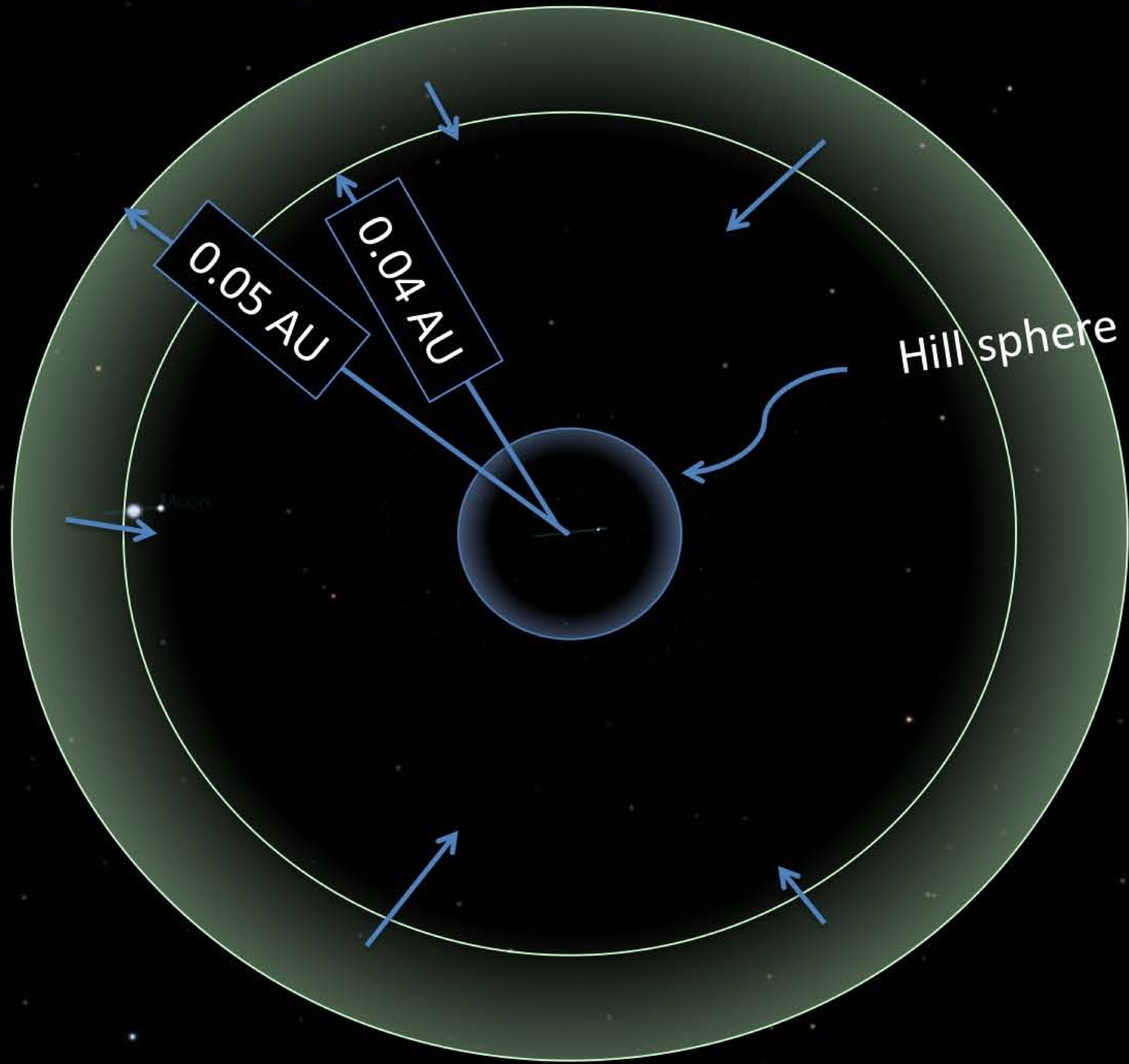
Generating NEO Minimoon Candidates

- orbits randomly selected from NEO population
- random epoch within 19-year Metonic Cycle
- $0.04\ \text{AU} < \Delta < 0.05\ \text{AU}$
- $v_{Earth} < 3$ km/s



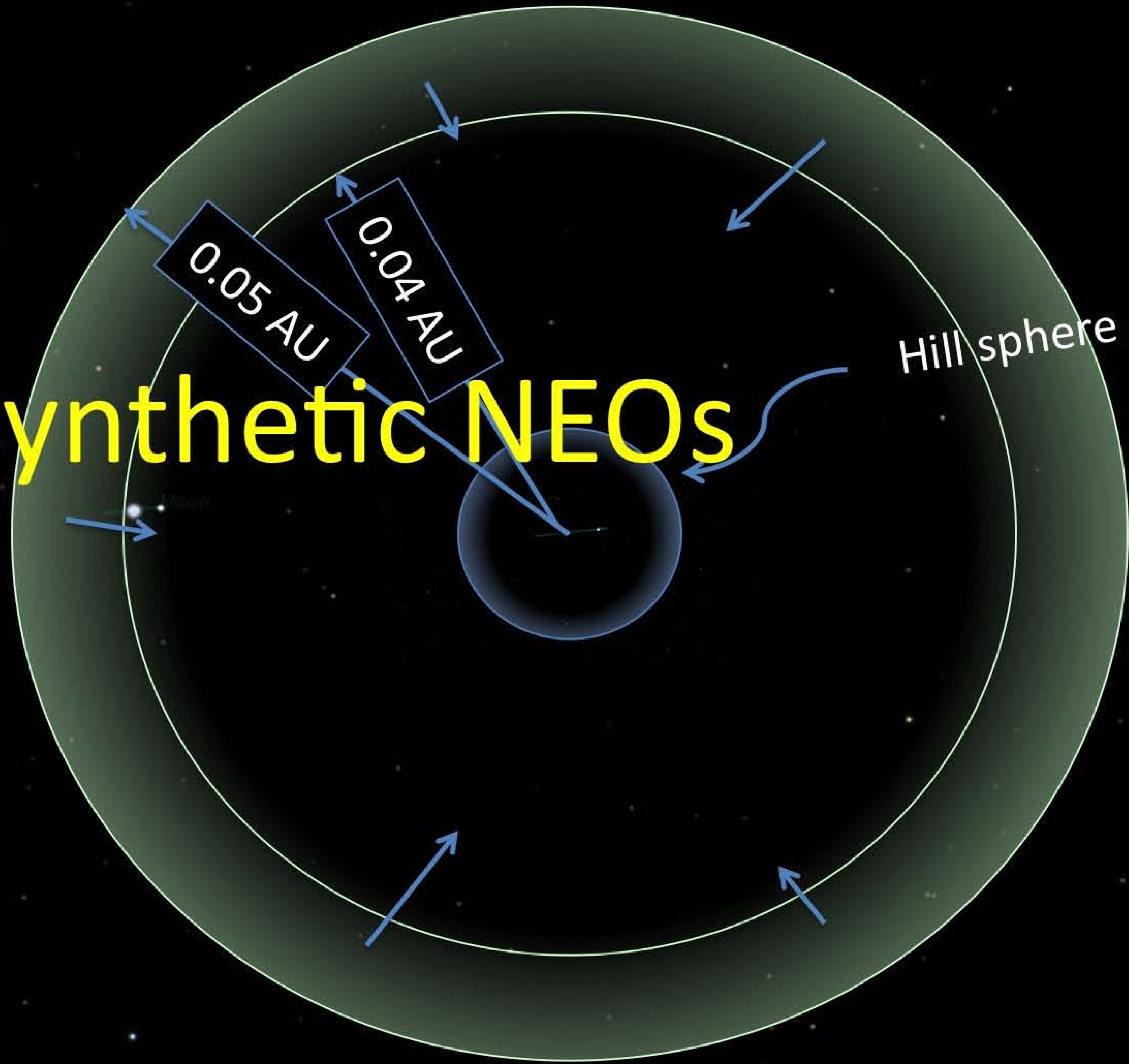
Generating NEO Minimoon Candidates

- orbits randomly selected from NEO population
- random epoch within 19-year Metonic Cycle
- 0.04 AU < Δ < 0.05 AU
- v_{Earth} < 3 km/s
- direction angle < 120 deg



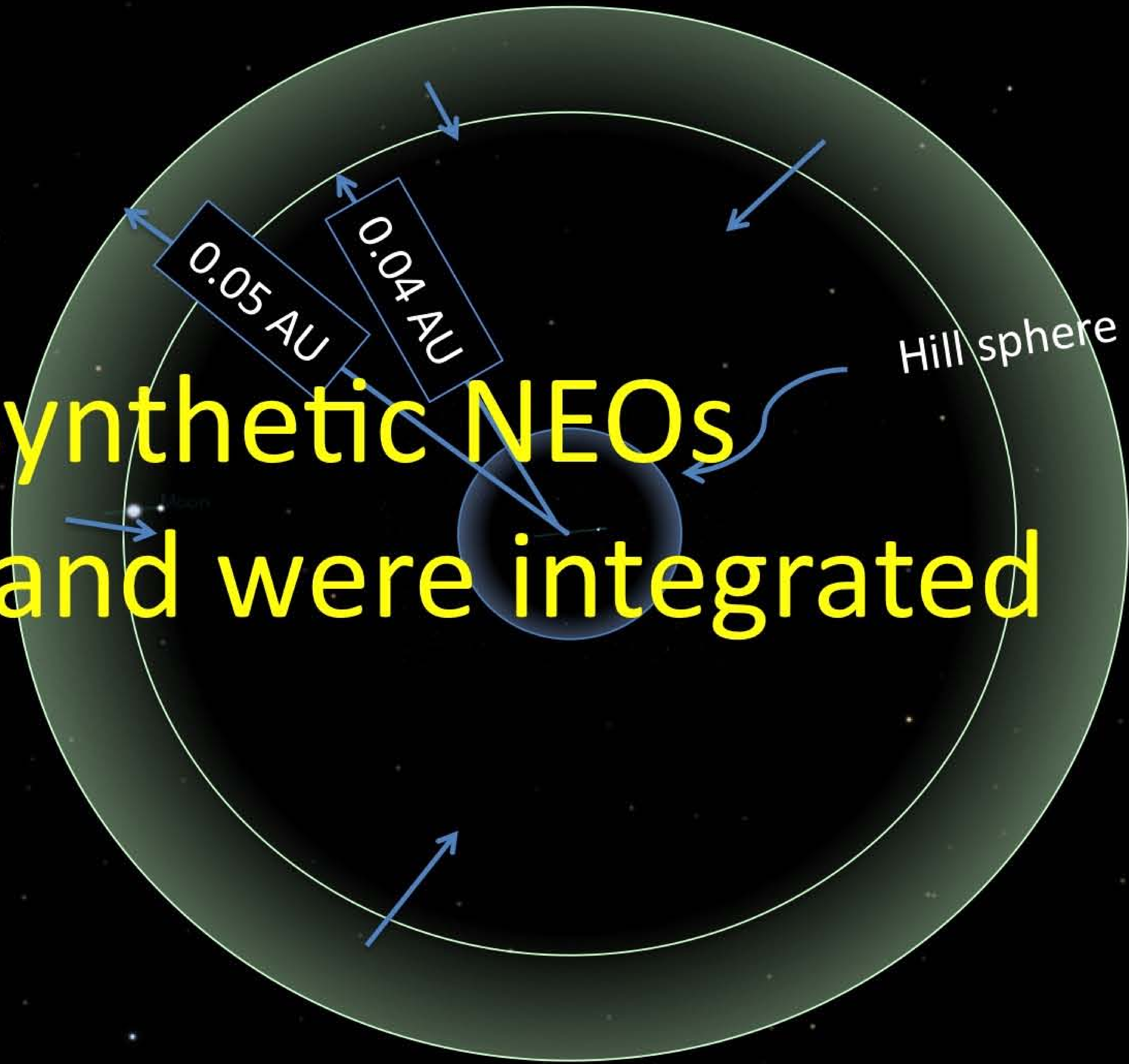
GENERATING NEO MINIMOON CANDIDATES

- 10^{11} generated synthetic NEOs

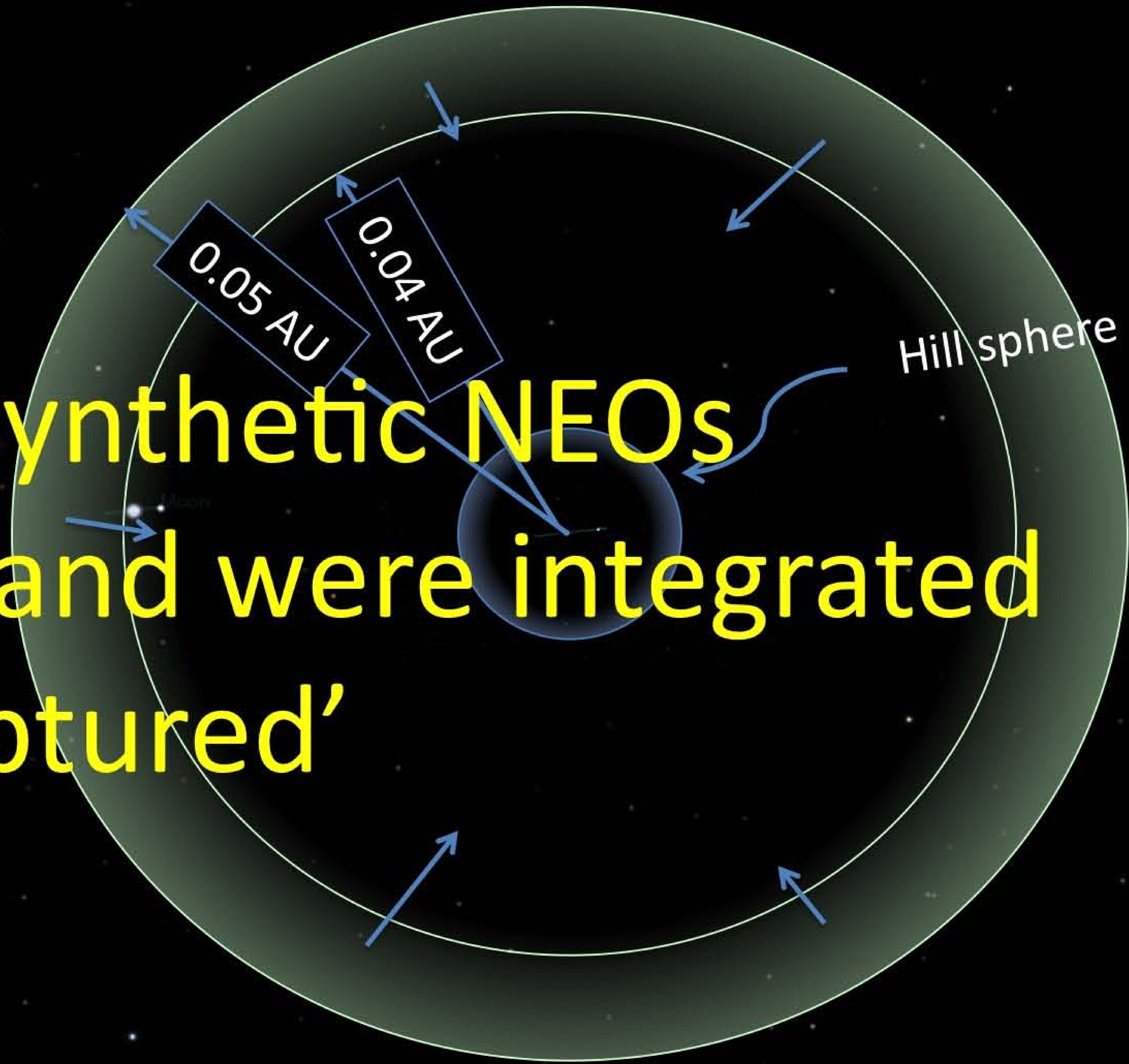


Generating NEO Minimoon Candidates

- 10^{11} generated synthetic NEOs
- 10^{7} met criteria and were integrated



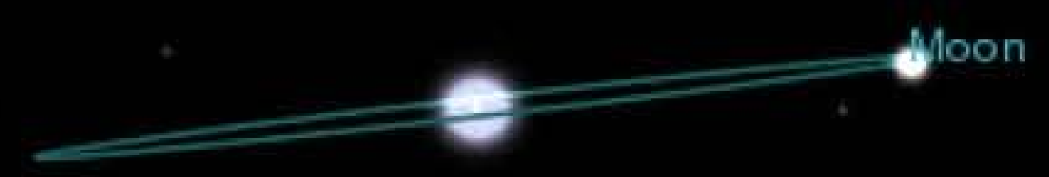
Generating NEO Minimoon Candidates



- 10^{11} generated synthetic NEOs
- 10^{7} met criteria and were integrated
- 16,000 were 'captured'

Capture Definition

$$E_{kinetic} + E_{potential} < 0$$



within the hill sphere

MINIMOON TRAJECTORIES

Granvik et al. (2012)

MINIMOON TRAJECTORIES

Granvik et al. (2012)

MINIMOON TRAJECTORIES

Granvik et al. (2012)

MINIMOON TRAJECTORIES

Granvik et al. (2012)

Synthetic Minimoon Orbit

How Many Minimoons are there?

How Many Minimoons are there?

Granvik et al. (2012)

>1 meter

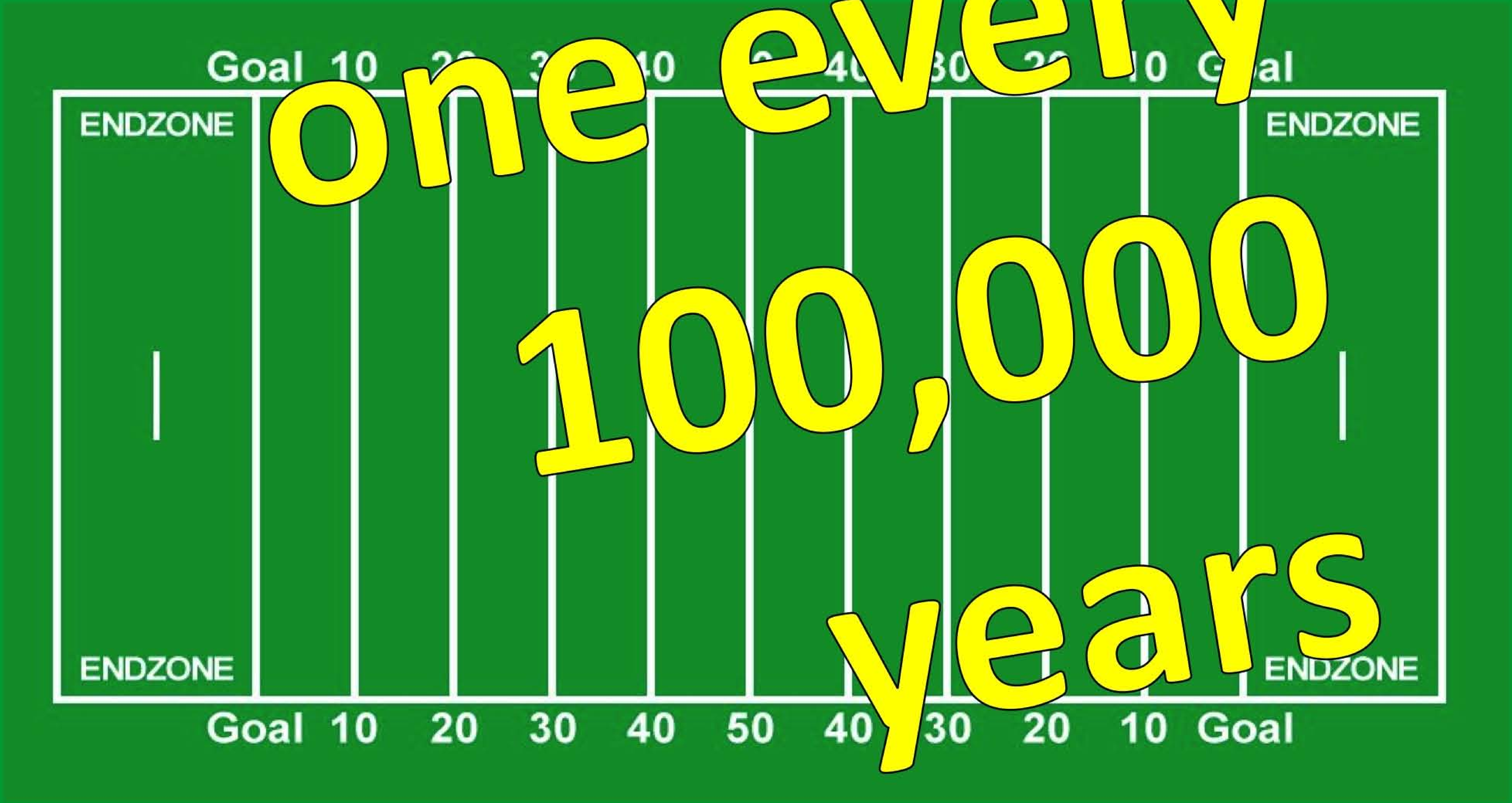
3

>½ meter

dozen

one every 50 years

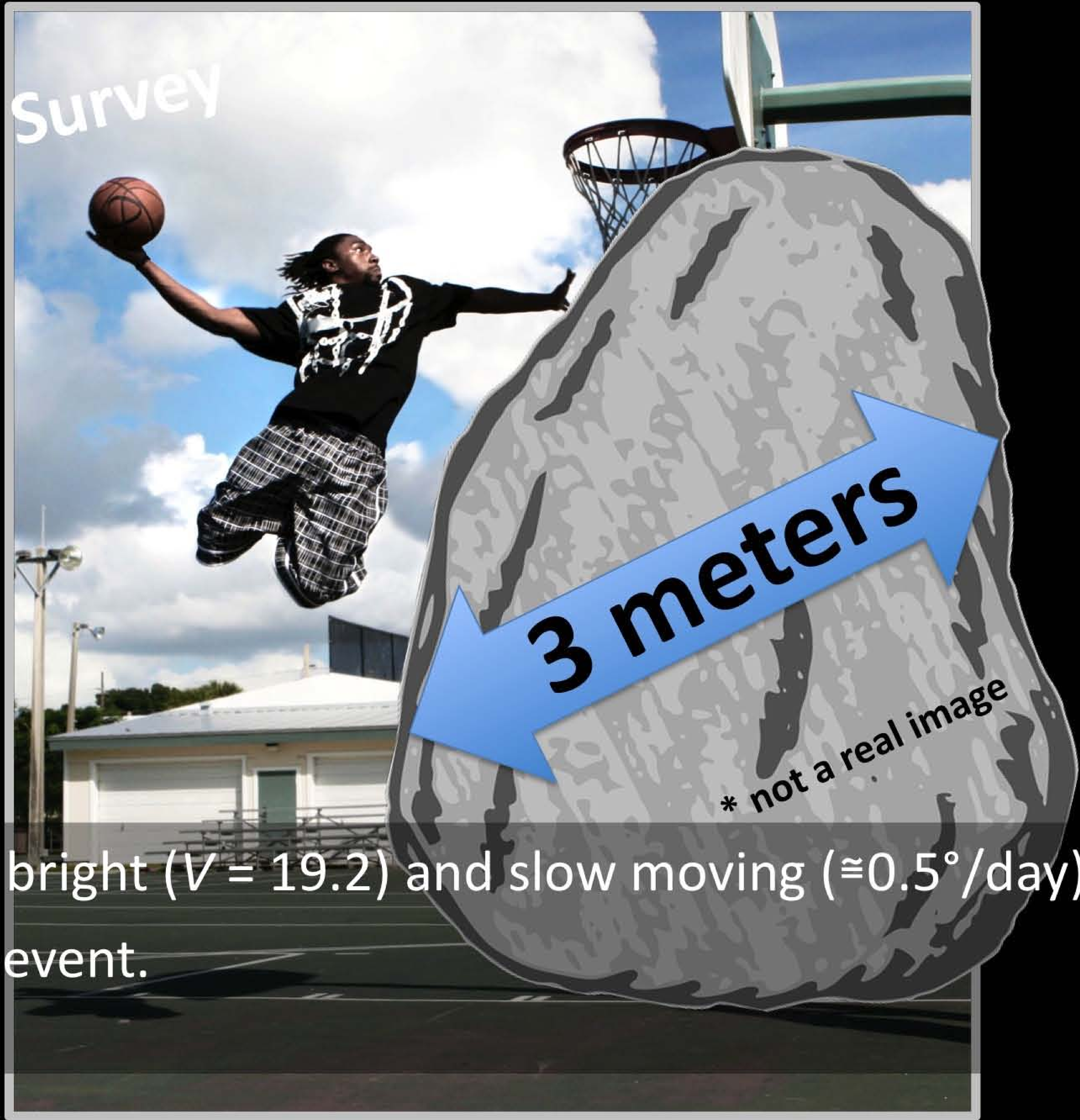
How Many Minimoons are there?



one every 100,000 years

Where are they???

First Minimoon: 2006 RH$_{120}$



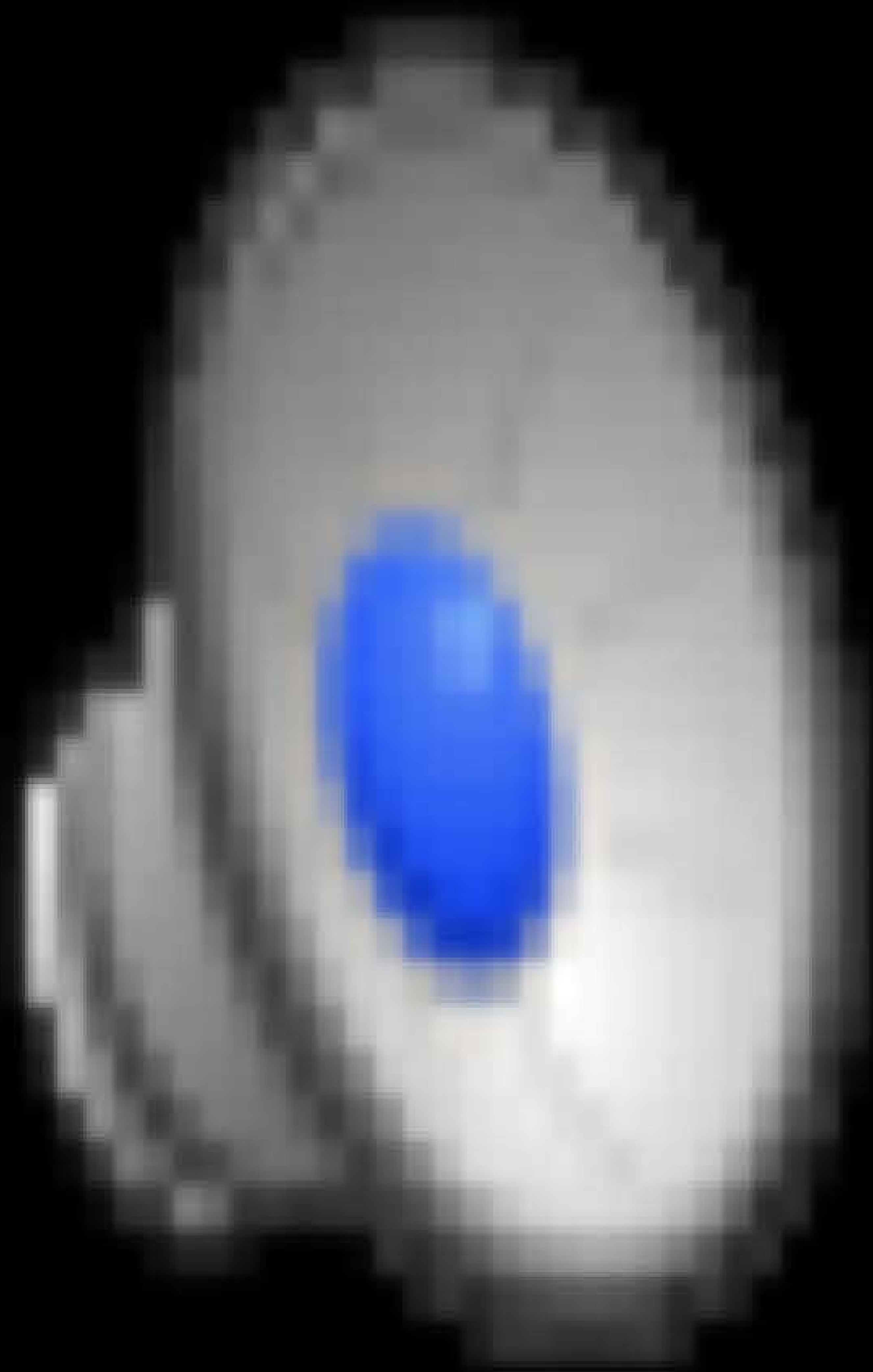
- discovered when bright (V = 19.2) and slow moving (≅0.5°/day).
- a one in ten year event.

Detecting Minimoons

Bolin et al. (2014)

Canadian Automated Meteor Observatory

Weryk et al. (2013)



Second Minimoon: EN130114

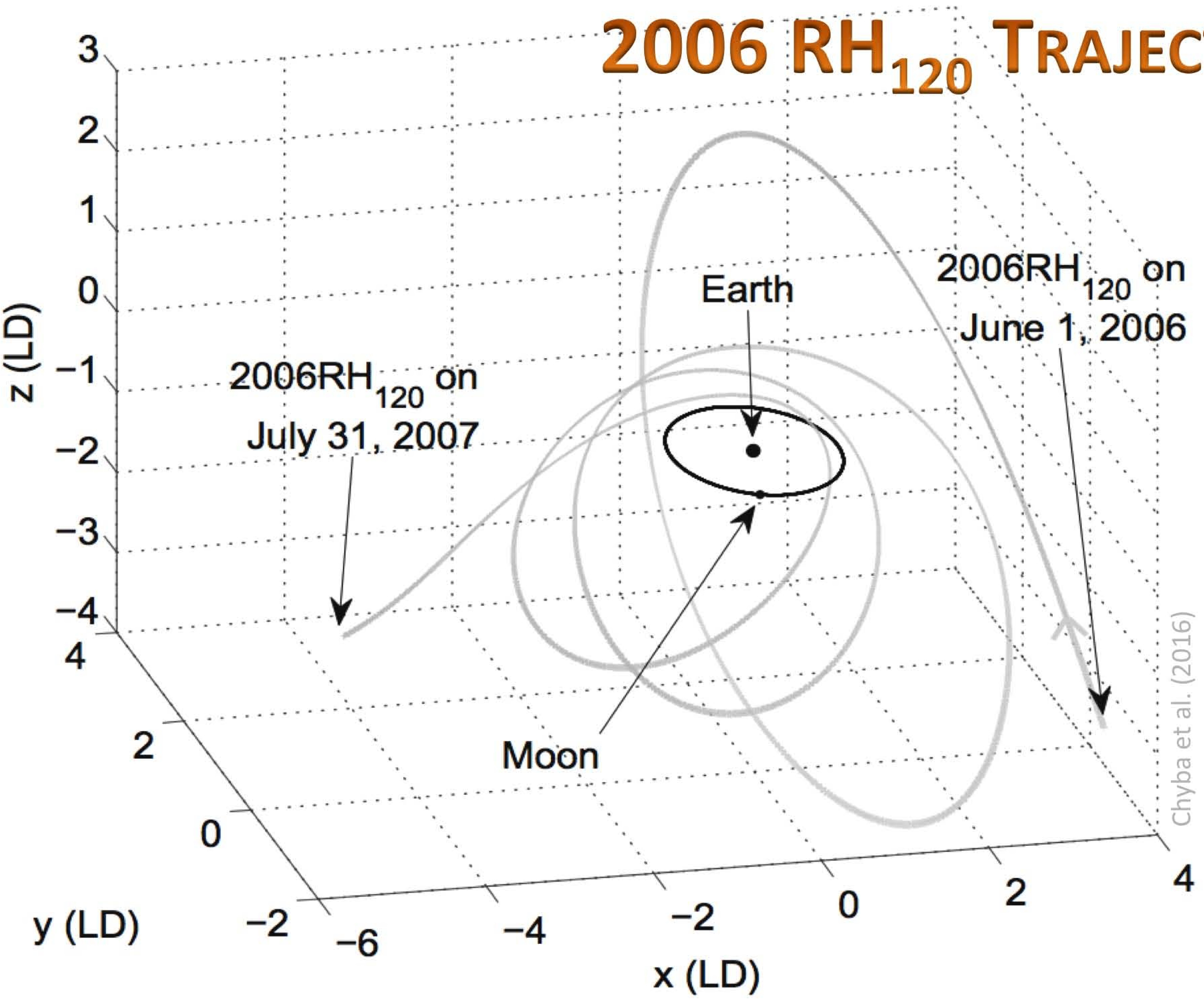
credit: European Fireball Network (Kuncak station, Czech Republic)

Optimized Minimoon Rendezvous

Optimized for 2006 RH_{120}

- CR3BP (Sun-Earth-Moon-spacecraft)
- all start dates after minimoon discovery
- all rendezvous dates
- 3 burn mission
- $T_{max} = 22N$
- $I_{sp} = 230$ s
- $m_0 = 350$ kg

2006 RH_{120} TRAJECTORY



EARTH-MOON L_2 HALO PARKING ORBIT

OPTIMIZING ΔV

Optimal 2006 RH_{120} 3-Burn Return

Chyba et al. (2016)

OPTIMAL 2006 RH_{120} 3-BURN RETURN

Chyba et al. (2016)

Optimal 2006 RH_{120} 3-Burn Return

Chyba et al. (2016)

Optimal 2006 RH_{120} 3-Burn Return

Chyba et al. (2016)

Optimal 2006 RH_{120} 3-Burn Return

Chyba et al. (2016)

OPTIMAL 2006 RH_{120} 3-BURN RETURN

Chyba et al. (2016)

Optimal 2006 RH_{120} Round Trip

900 m/s < Δv < 1,600 m/s

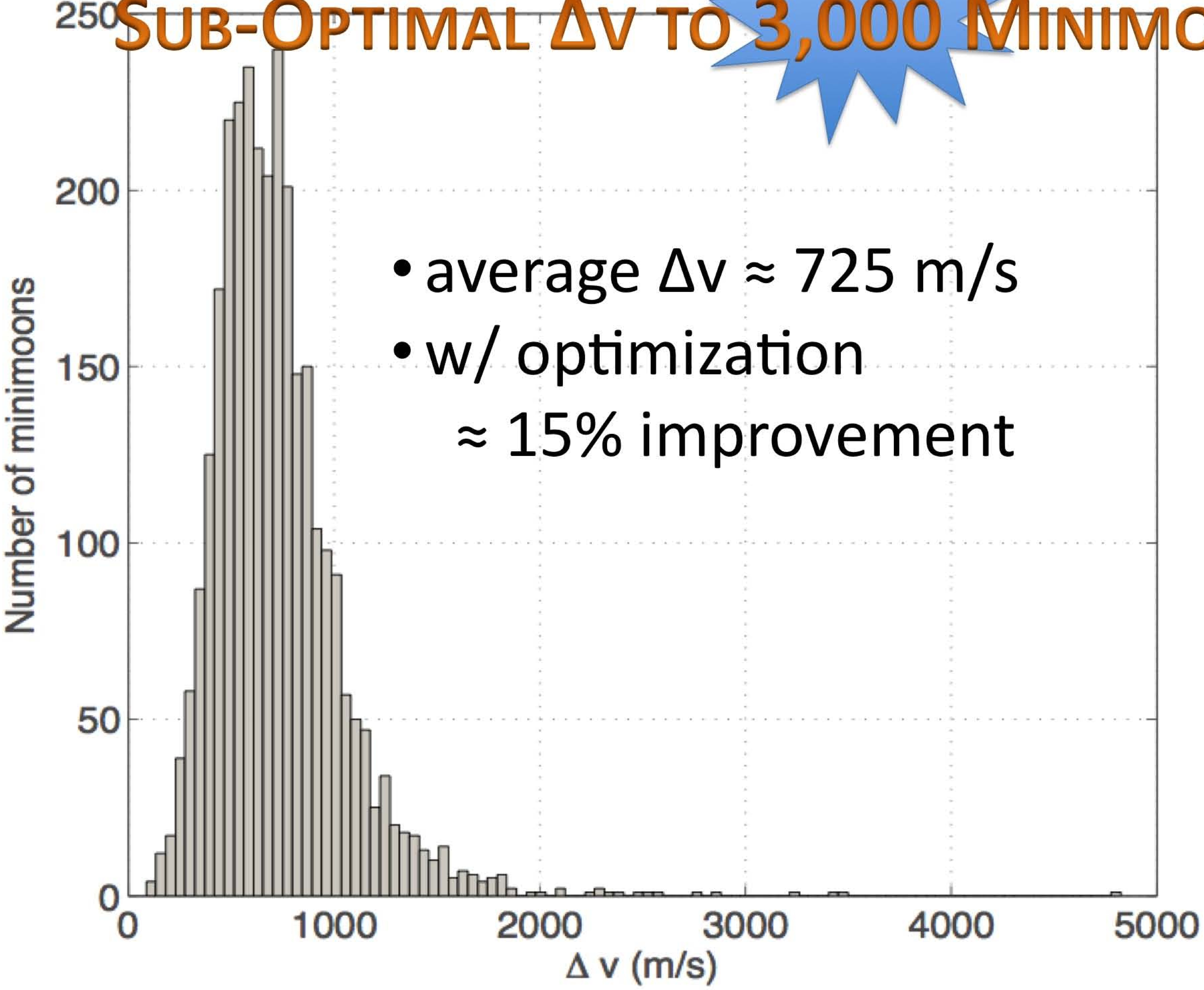
depending on time of discovery and rendezvous duration

OPTIMAL 2006 RH_{120} ROUND TRIP

allows multiple minimoon missions
or direct minimoon-to-minimoon transfers

Sub-Optimal Δv to 3,000 Minimoons

- average Δv ≈ 725 m/s
- w/ optimization
  ≈ 15% improvement



Searching for Minimoons

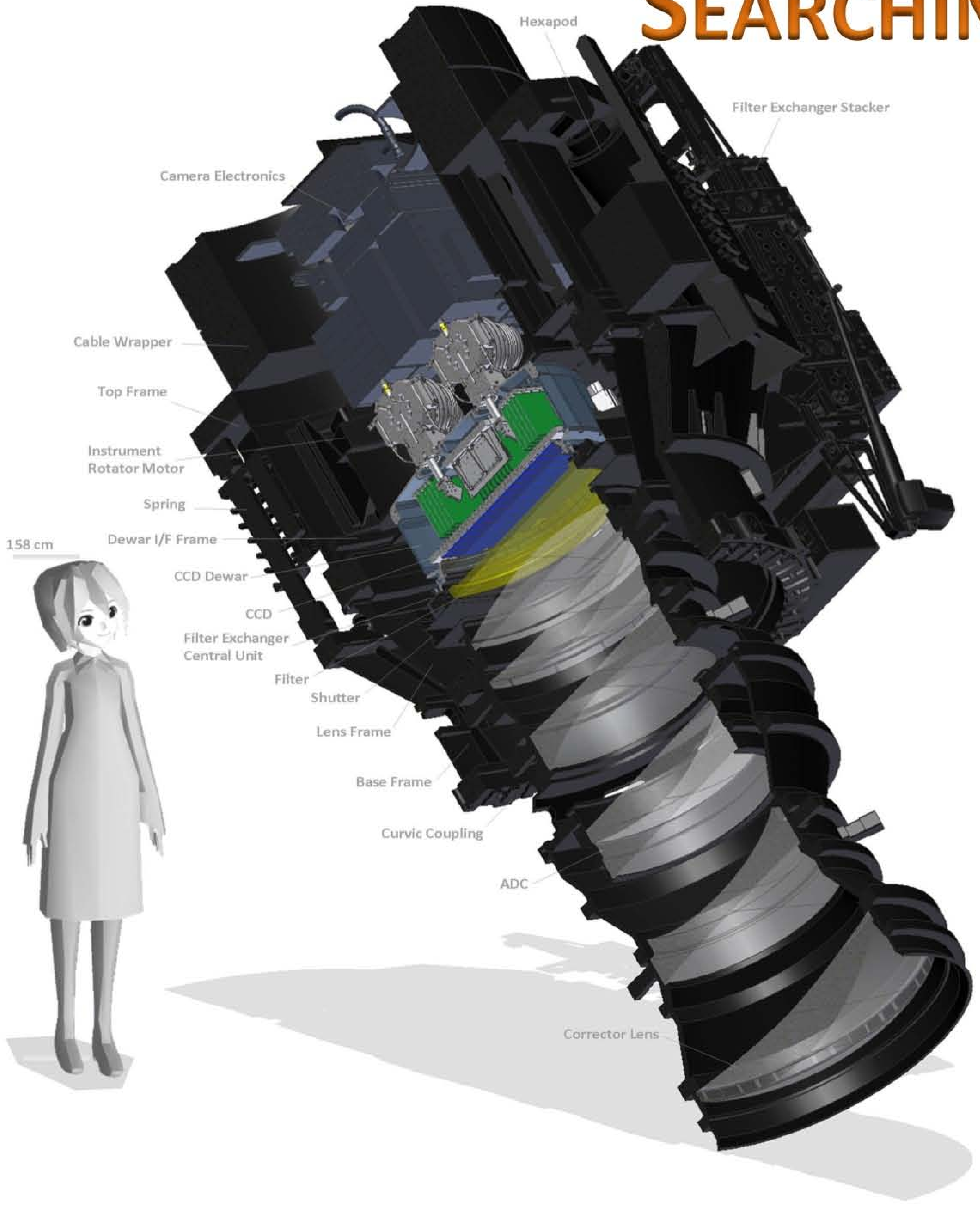
Bolin et al. (2014)

Searching for Minimoons

Bolin et al. (2014)

SEARCHING FOR MINIMOONS

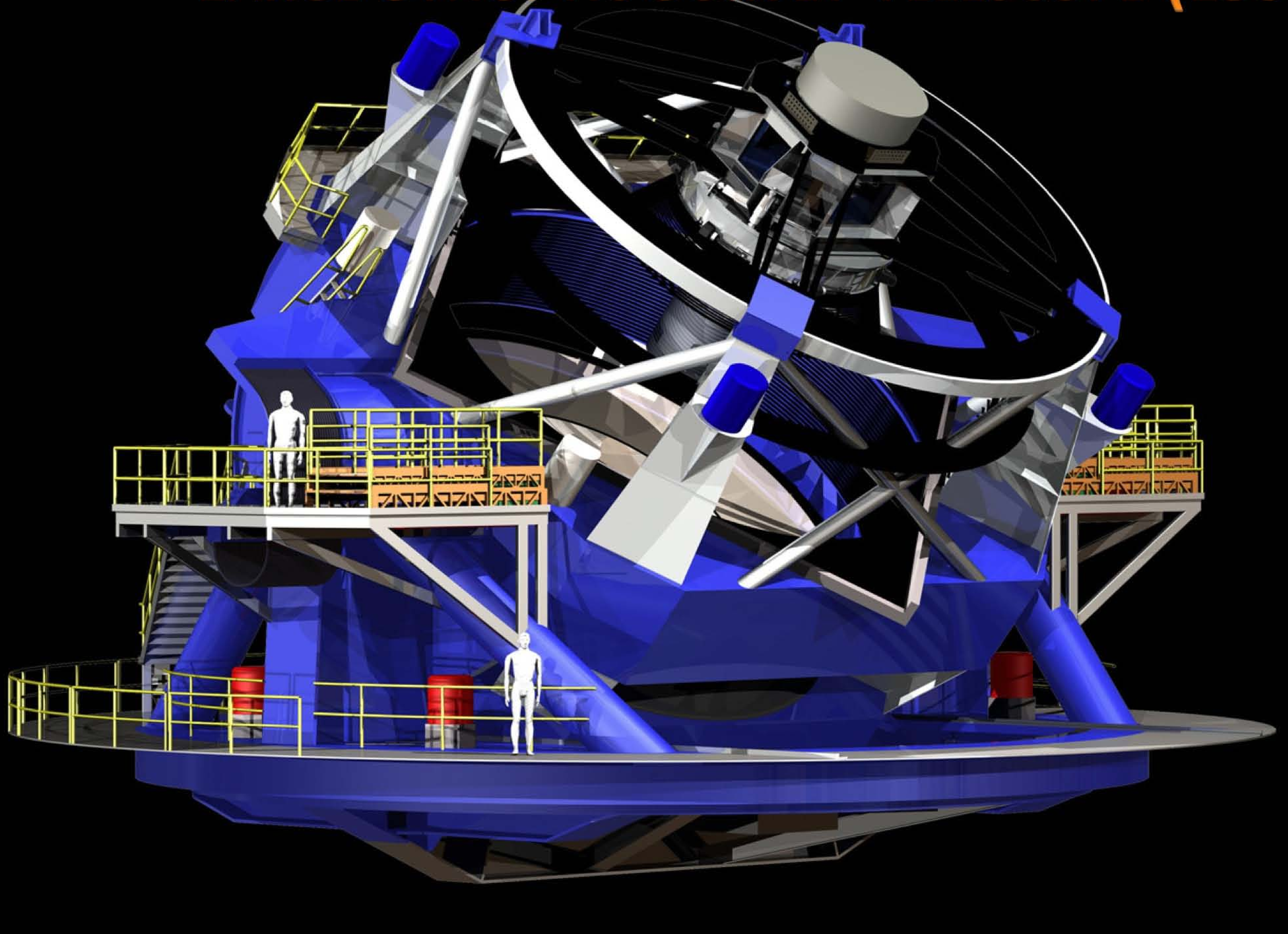
SEARCHING FOR MINIMOONS

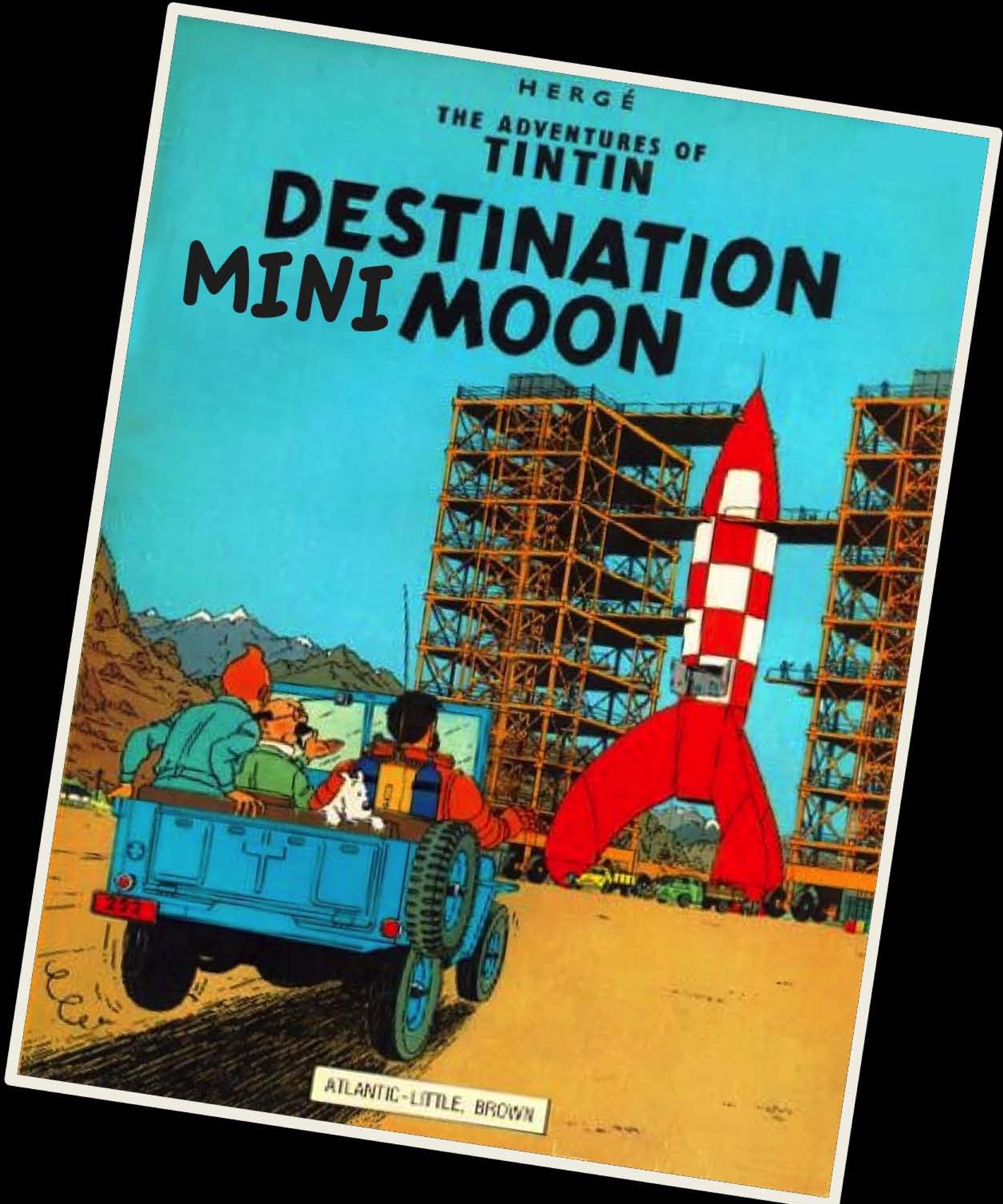


Searching for Minimoons

RESULTS: still processing

LARGE SYNOPTIC SURVEY TELESCOPE (LSST)




HERGÉ
THE ADVENTURES OF
TINTIN
DESTINATION
MINI MOON
ATLANTIC-LITTLE, BROWN