Earth's Mini-Moons

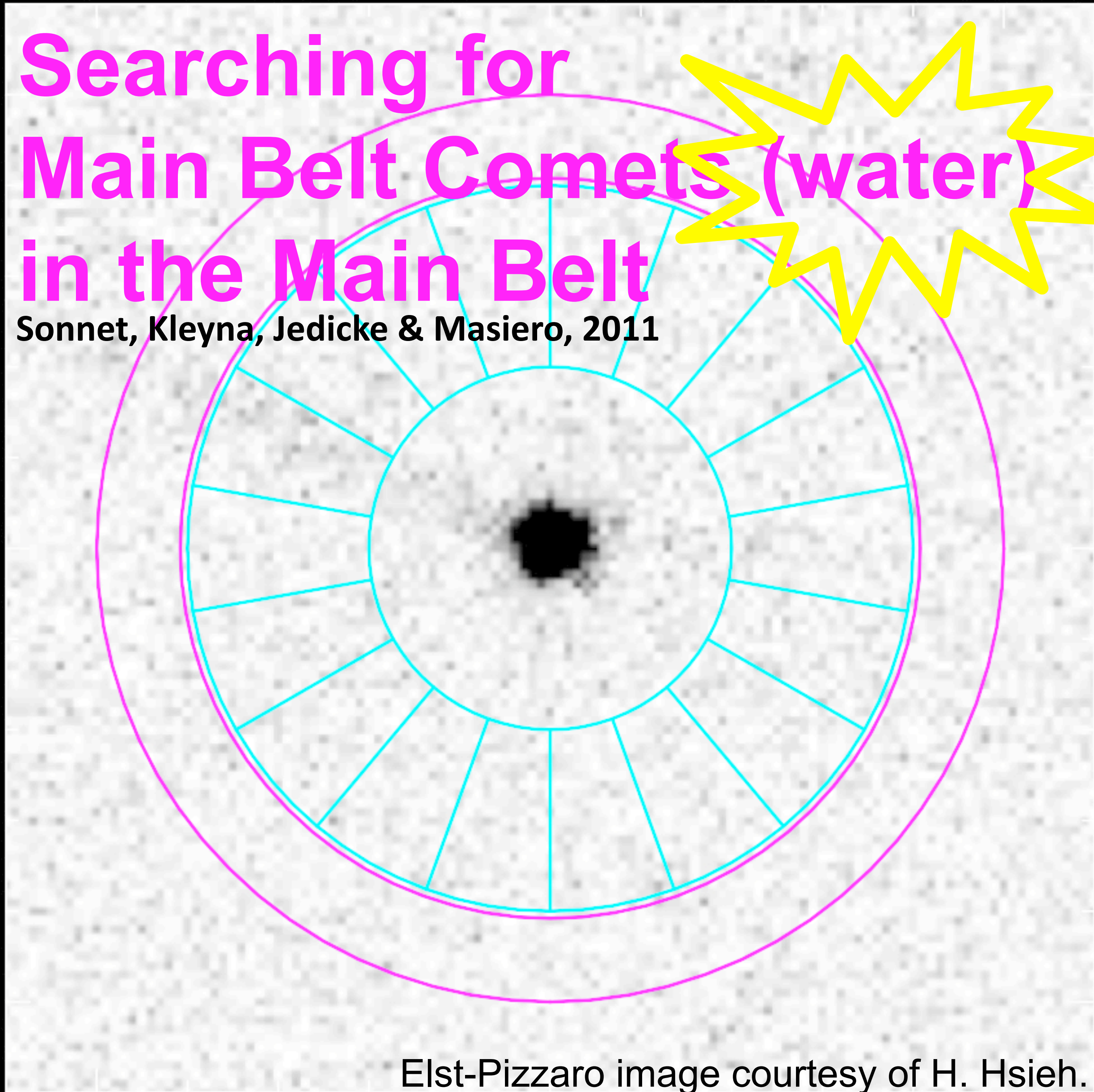
Granvik, Vaubaillon & Jedicke, 2012

Abstract Confusion

March 7th, Wednesday -- Session 2: Nature and Orbits of planetary bodies: Models and Observations (Cont'd)		
09:00 - 09:45	Morbidelli, Alessandro	Solar System evolution and the diversity of planetary systems (Invited Talk)
09:45 - 10:05	Jehin, Emmanuel	TRAPPIST: One year of robotic operations
10:05 - 10:30	Coffee Break	
10:30 - 11:15	Jewitt, David	Small Bodies and Primordial Ice in the Solar System (Invited Talk)
11:15 - 11:35	Hartogh, Paul	Ocean-like water in Jupiter- family comet 103P/Hartley 2
11:35 - 11:55	Jedicke, Robert	Earth's Mini-Moons
11:55 - 12:15	Dumas, Christophe	Ice on TNOs
12:15 - 12:35	Snodgrass, Colin	Observing water in our Solar System
12:35 - 14:10	LUNCH	

Searching for Main Belt Comets (water) in the Main Belt

Sonnet, Kleyna, Jedicke & Masiero, 2011



Elst-Pizzaro image courtesy of H. Hsieh.

Results

ZERO

Goals

- identify new main belt comets
- measure the MBC:MBA ratio
- locate the contemporary snow line

TALCS

(Masiero et al. 2009)

- Thousand Asteroid Light Curve Survey
  - 924 asteroids
  - 80% with >40 detections

Two Techniques

- Identify coma
  - target `fuzziness'
- Identify tails
  - directed flux near target

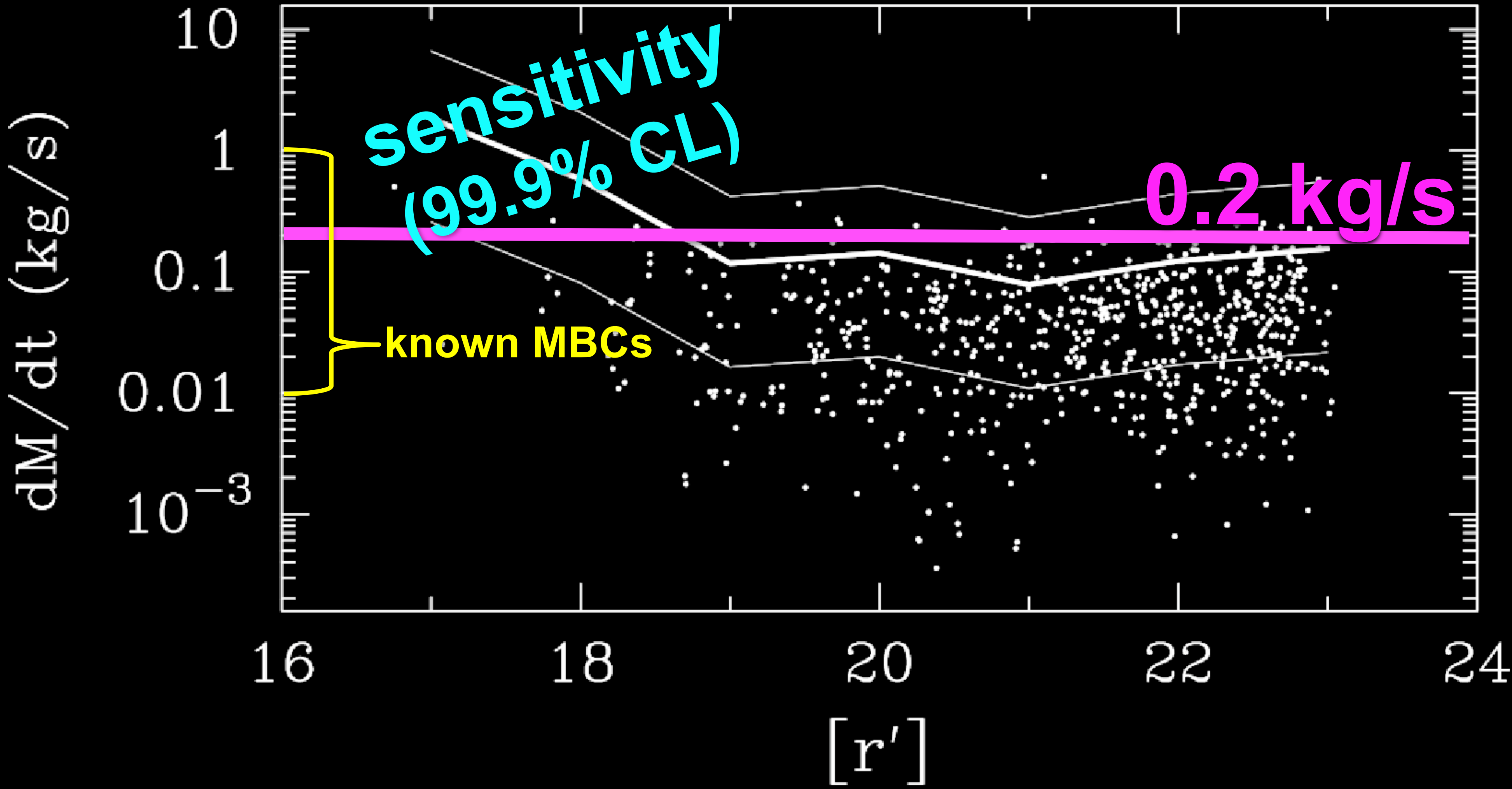
$f_{nucleus} + f_{coma} = 1$

Searching for Coma

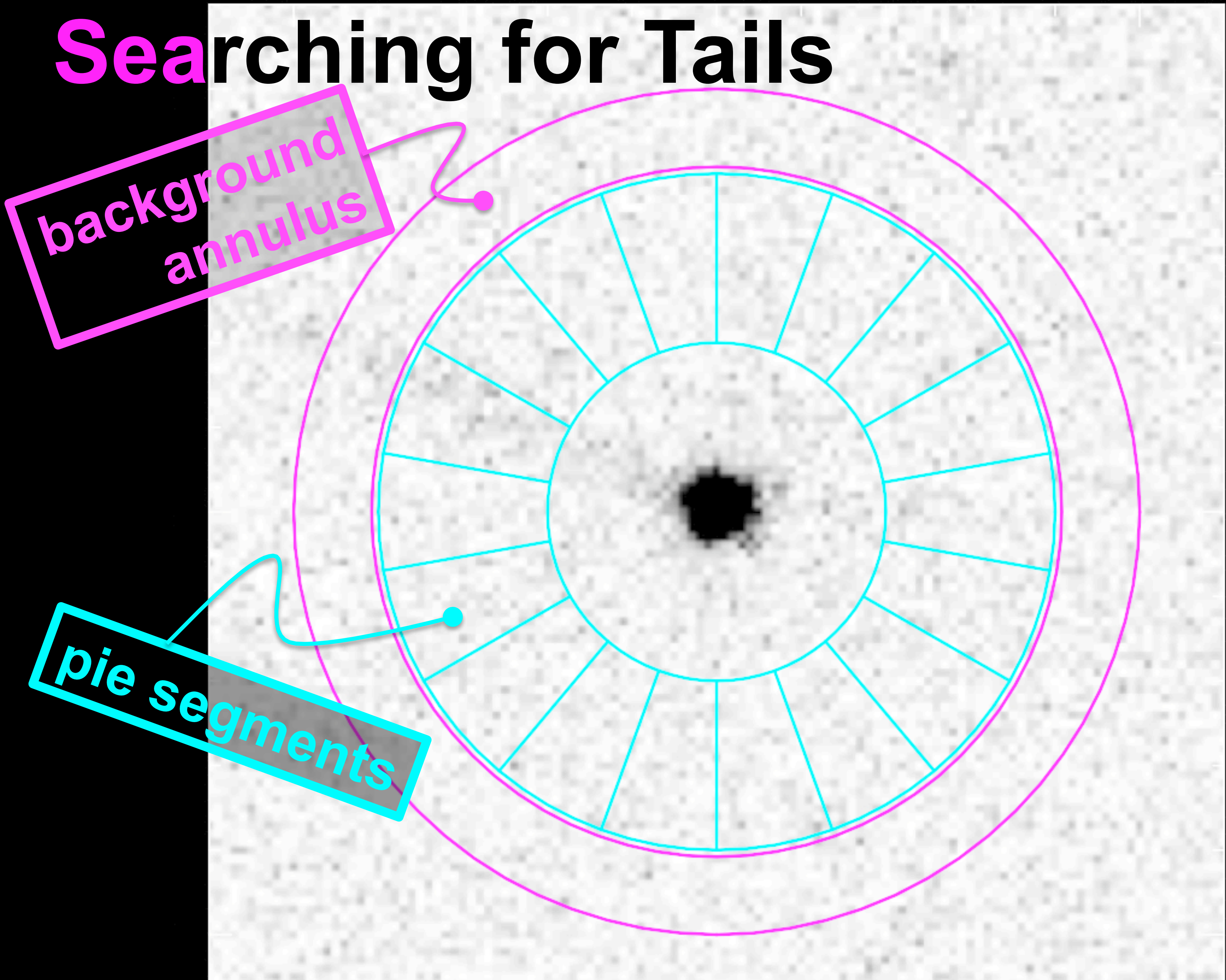
$$PSF_{target} = f_{nucleus} PSF_{nucleus} + f_{coma} PSF_{coma}$$

$$f_{nucleus} + f_{coma} = 1$$

Derived Mass Loss Rates

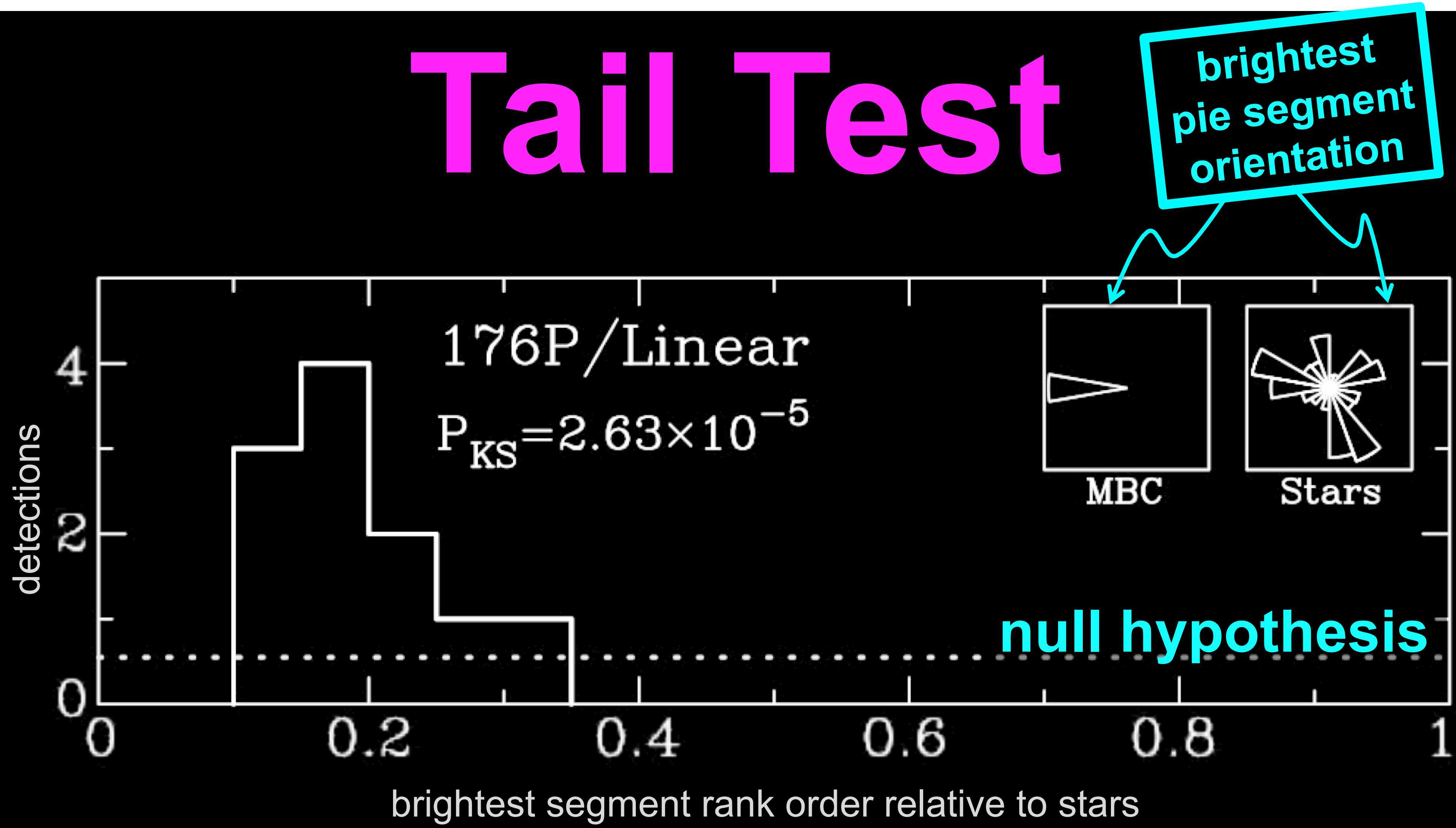


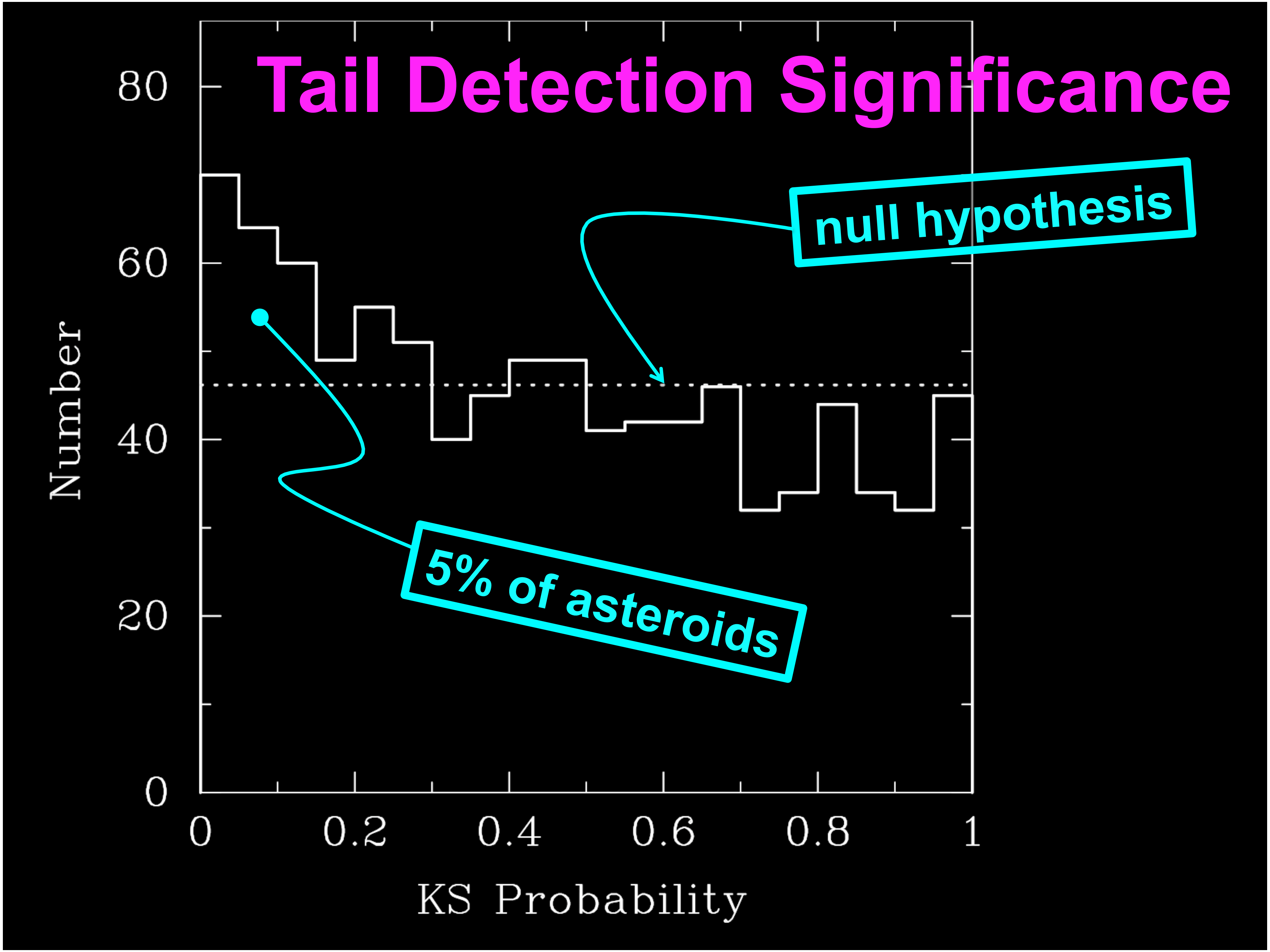
Searching for Tails



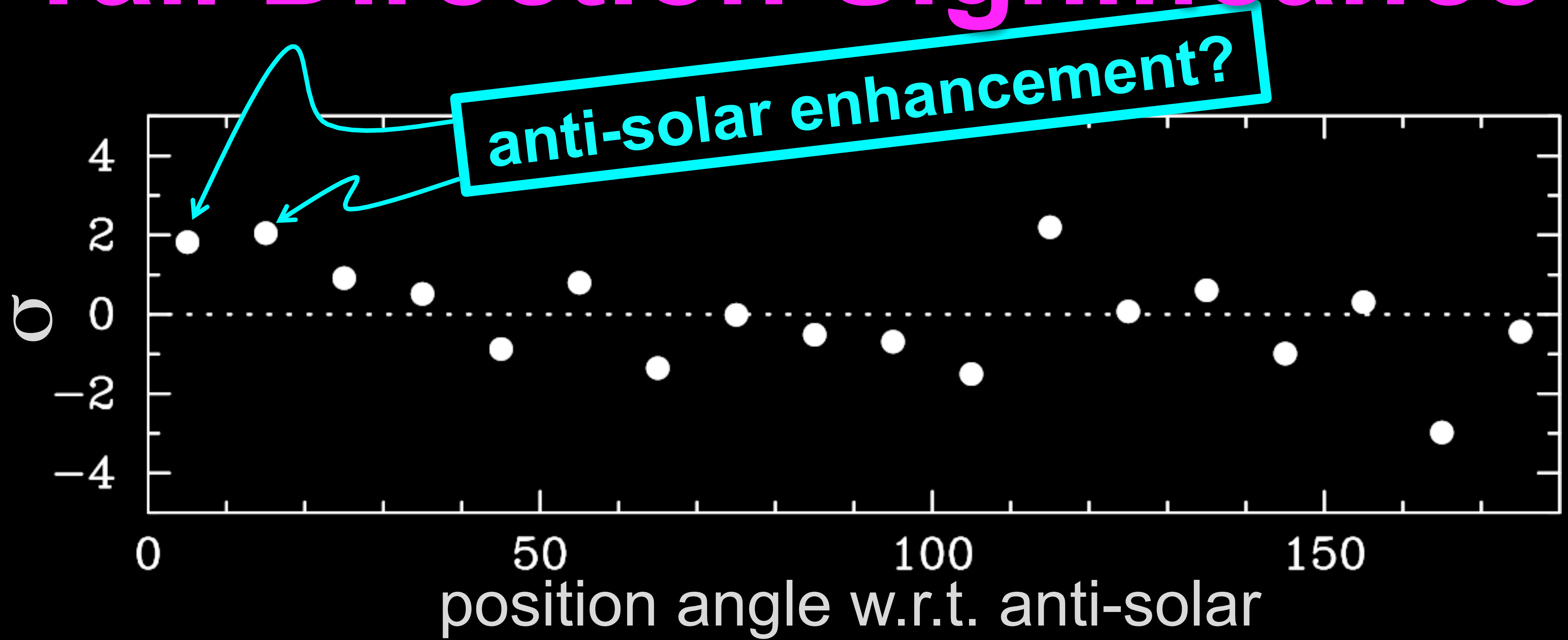
Elst-Pizzaro image courtesy of H. Hsieh.

Tail Test


brightest
pie segment
orientation
176P/Linear
P_{KS}=2.63×10^{-5}
MBC
Stars
null hypothesis
detections
4
2
0
0
0.2
0.4
0.6
0.8
1
brightest segment rank order relative to stars

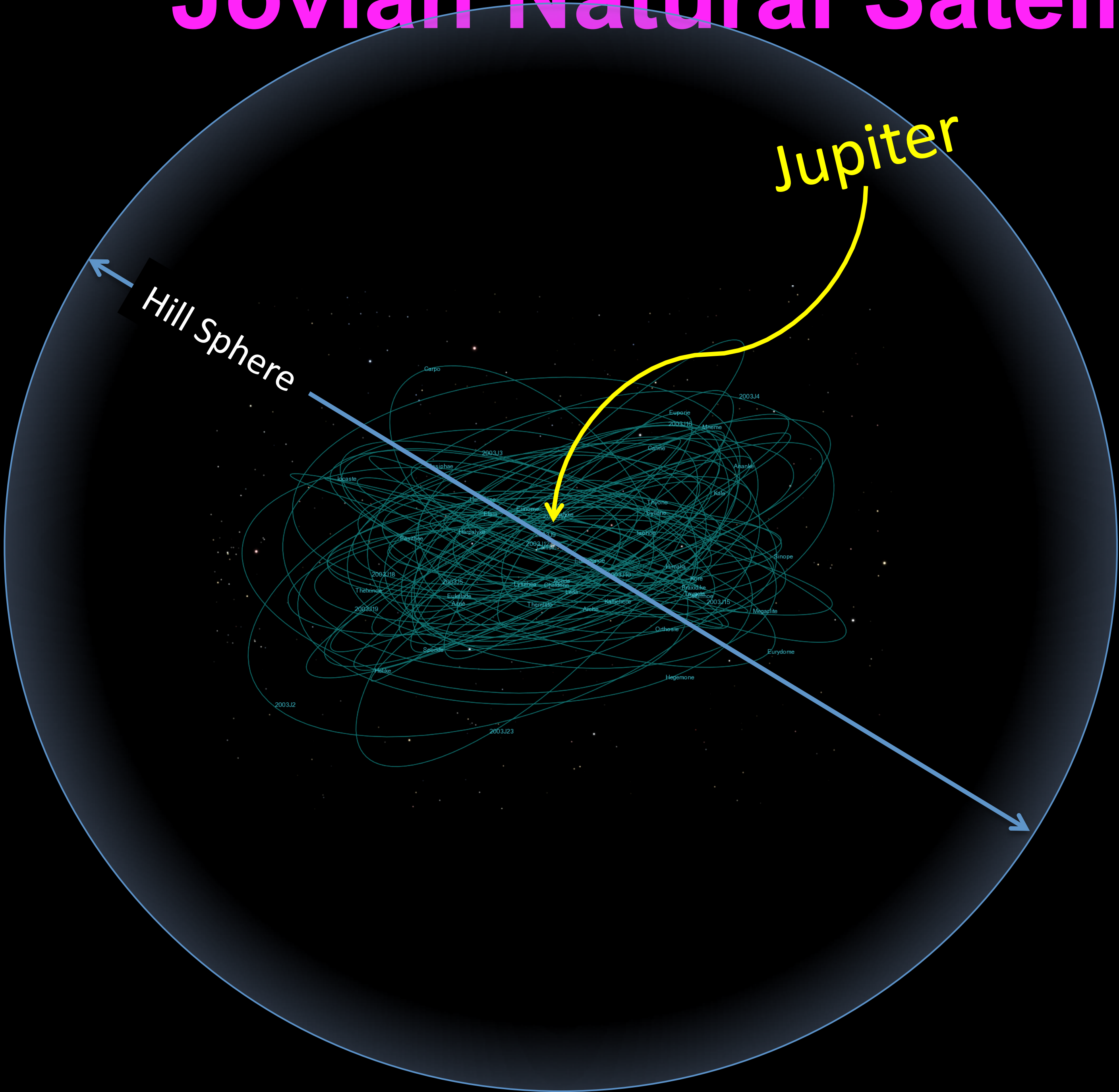

Tail Detection Significance
null hypothesis
5% of asteroids
Number
KS Probability
0
20
40
60
80
0
0.2
0.4
0.6
0.8
1

Tail Direction Significance




Earth’s Mini-Moons
Granvik, Vaubaillon & Jedicke, 2012

Jovian Natural Satellites



Earth's Other Natural Satellites?

Why Study Mini-Moons?

- provide strong constraints on Near Earth Object models
- intermediate source population for some meteoroids/meteorites
- natural space debris
- perfect targets for sample return mission

Early Work on Earth's Mini-Moons

- **Denning (1916):**
  - 'the large meteors that passed over Northern America on February 9, 1913, must have been temporary Earth satellites' because the orbits were 'concentric, or nearly concentric, with the Earth's surface.'
- **Baker (1958):**
  - artifical satellites 'may be accompanied in their journey through space by certain "natural" satellites'
- **Cassidy et al. (1965):**
  - suggested craters in Argentina and Chile were caused by a mini-moon
    on a decaying orbit
- **Cline (1979):**
  - analytical results suggest a possible capture mechanism via a very close encounter with the Moon
- **[illegible]amo[illegible]i et al. (1999):**
  - simulations suggest a possibility for a NES population on retrograde orbits
- **1991 VG (Tancredi 1997) and 2006 RH120 (Kwiatkowski et al. 2009):**
  - the first mini-moons

minimal

Other Work on Irregular Satellites

Searching for Saturn's dust swarms: limits on the size distribution of irregular satellites from km to micron sizes

2 2011JGRA..11612115 — Sonwalkar, V. S.; Reddy, A.; Carpenter, D. L. — 1.000 — 11/2011

3 2011MNRAS.416.1274K — Koch, F. Elliott; Hansen, Bradley M. S. — 1.000 — 09/2011 — On collisional capture rates of irregular satellites around the gas-giant planets and the minimum mass

4 2011Icar..215..260T — Tamayo, Daniel; Burns, Joseph A.; Hamilton, Douglas P.; Hedman, Matthew M. — 1.000 — 09/2011 — Finding the trigger to Iapetus' odd global albedo pattern: Dynamics of dust

5 2011MNRAS.415.1999G — Gaspar, H. S.; Winter, O. C.; Vieira Neto, E. — 1.000 — 08/2011 — Irregular satellites of Jupiter: capture configurations of binary asteroids

6 2011A&A...532A..44F — Frouard, J.; Vienne, A.; Fouchard, M. — 1.000 — 08/2011 — The long-term dynamics of the Jovian irregular satellites

7 2011Obs...131..187H — Hinse, T. C. — 1.000 — 06/2011 — Dynamical aspects of Jovian irregular satellites

8 2011GeoRL..3810104D — Dao, E.; Kelley, M. C.; Roddy, P.; Retterer, J.; Ballenthin, J. O.; de La Beaujardiere, O.; Su — 1.000 — Longitudinal and seasonal dependence of nighttime equatorial plasma density irregularities during solar minimum detected on the C/NOFS satellite

9 2011MNRAS.412.2137K — Kennedy, G. M.; Wyatt, M. C. — Collisional evolution of irregular satellite swarms: detectable dust around Solar system and extrasolar planets

10 2010Icar..208..824P — Philpott, Catherine M.; Agnor, Craig B. — 2010 — Three-body capture of irregular satellites: Application to Jupiter

11 2010MNRAS — Hinse, T. C.; Christou, A. A.; Alvarellos, J. L. A.; Goździewski, K. — 1.000 — 05/2010 — Application of the MEGNO technique to the dynamics of Jovian irregular satellites

12 2010MNRAS.402.1959C — Correa Otto, J. A.; Giuppone, C. A.; Beaugé, C. — 1.000 — 03/2010 — Mapping the $\nu_{\odot}$ secular resonance for retrograde irregular satellites

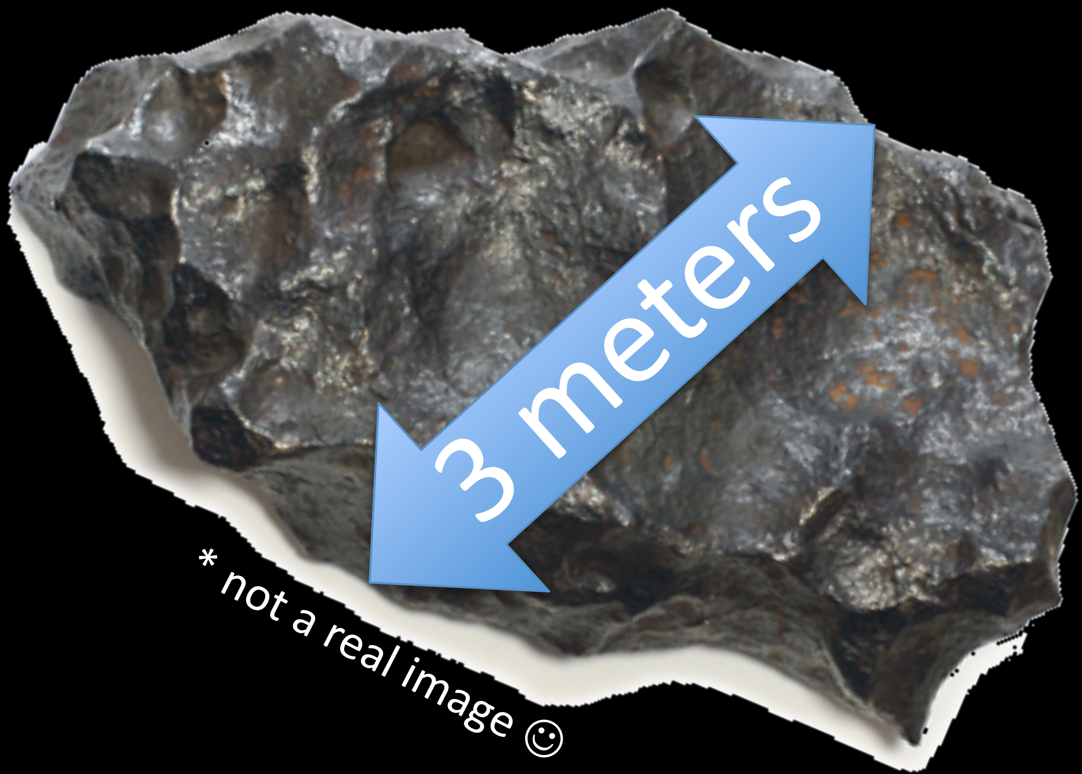
13 2010AJ....139..994B — Bottke, William F.; Nesvorný, David; Vokrouhlický, David; Morbidelli, Alessandro — 1.000 — 03/2010 — The Irregular Satellites: The Most Collisionally Evolved Populations in the Solar System

14 2010PhDT.......119P

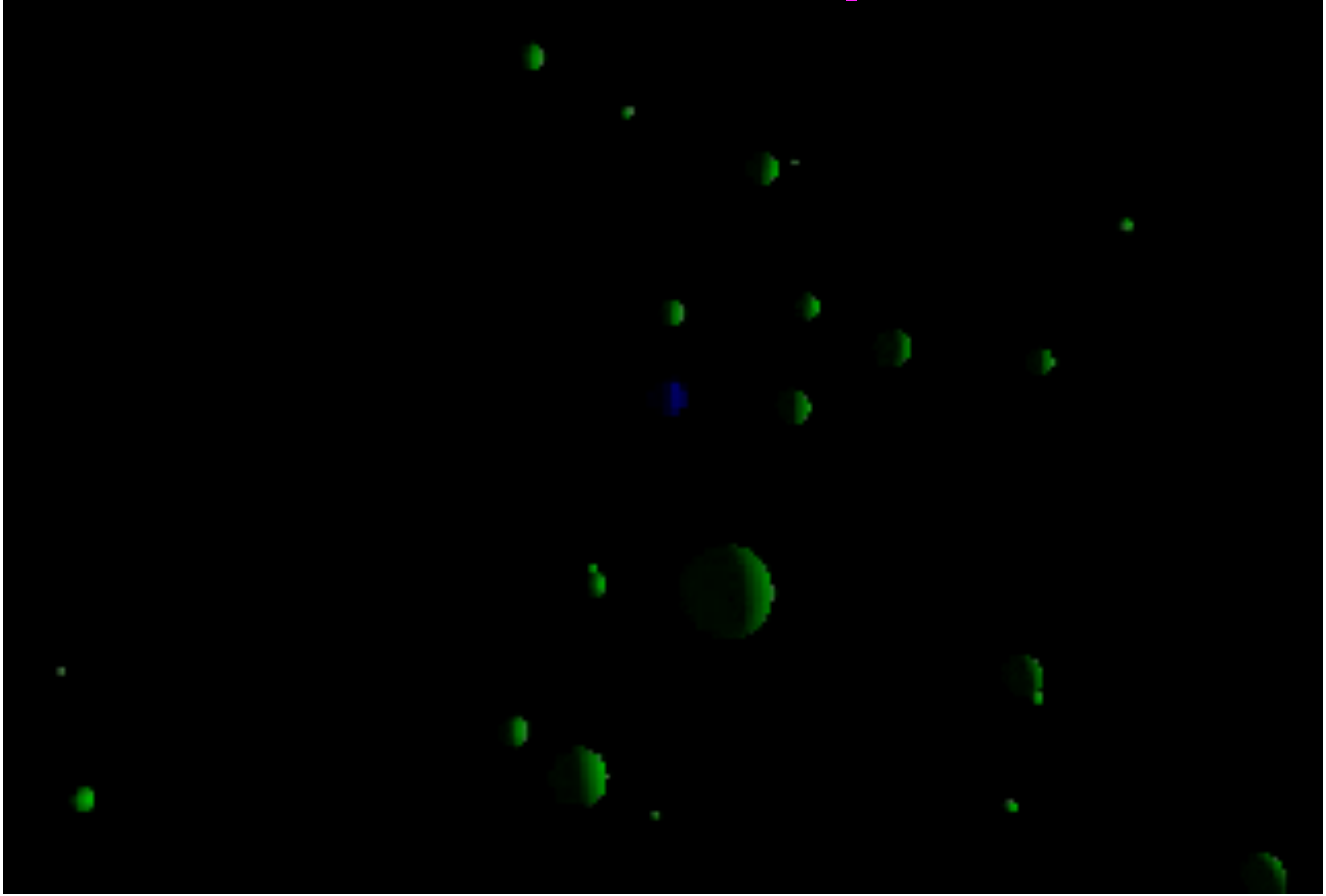
extensive

2006 RH$_{120}$

Earth's first known irregular satellite

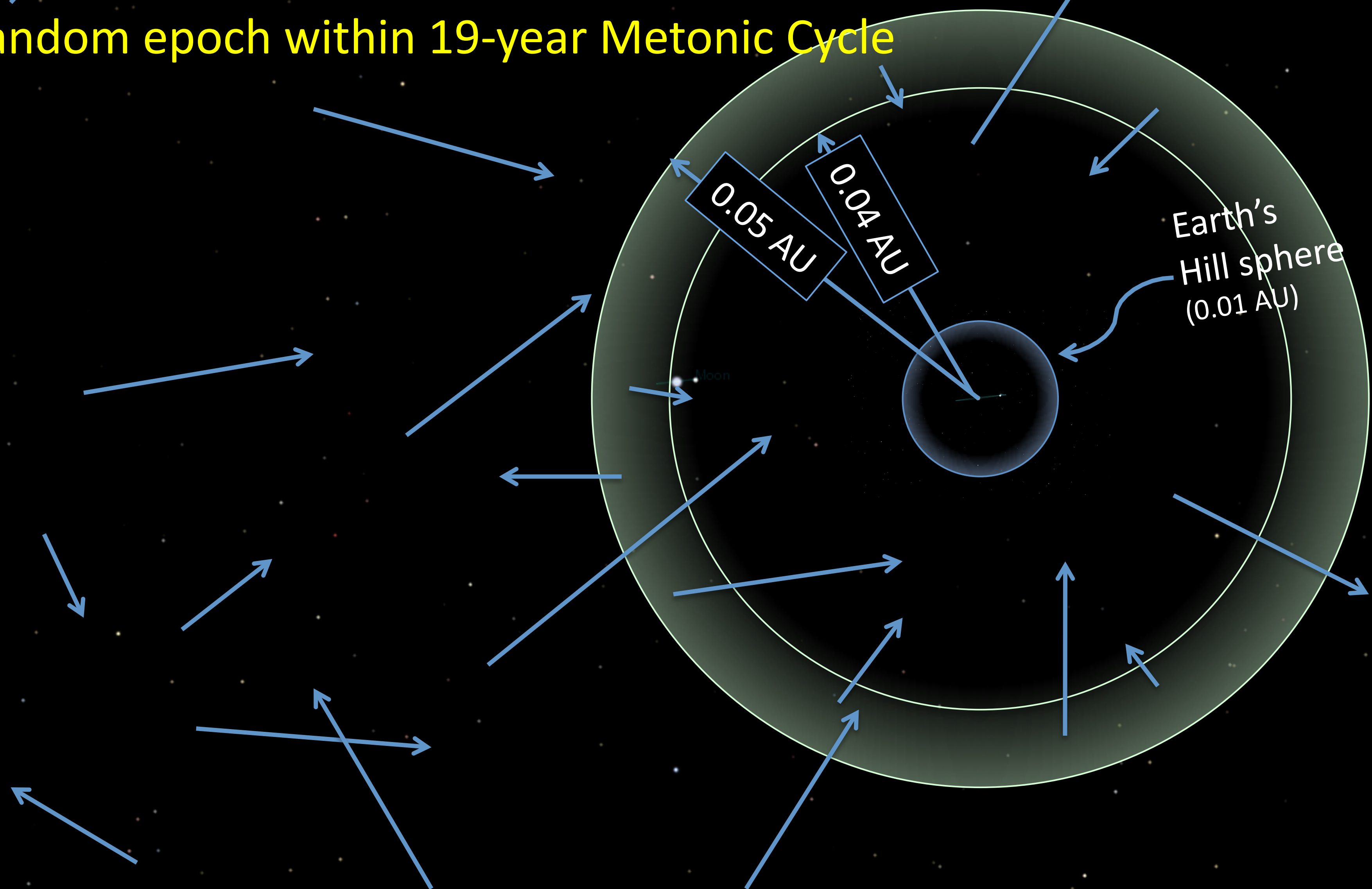


Mini-Moon Source Population



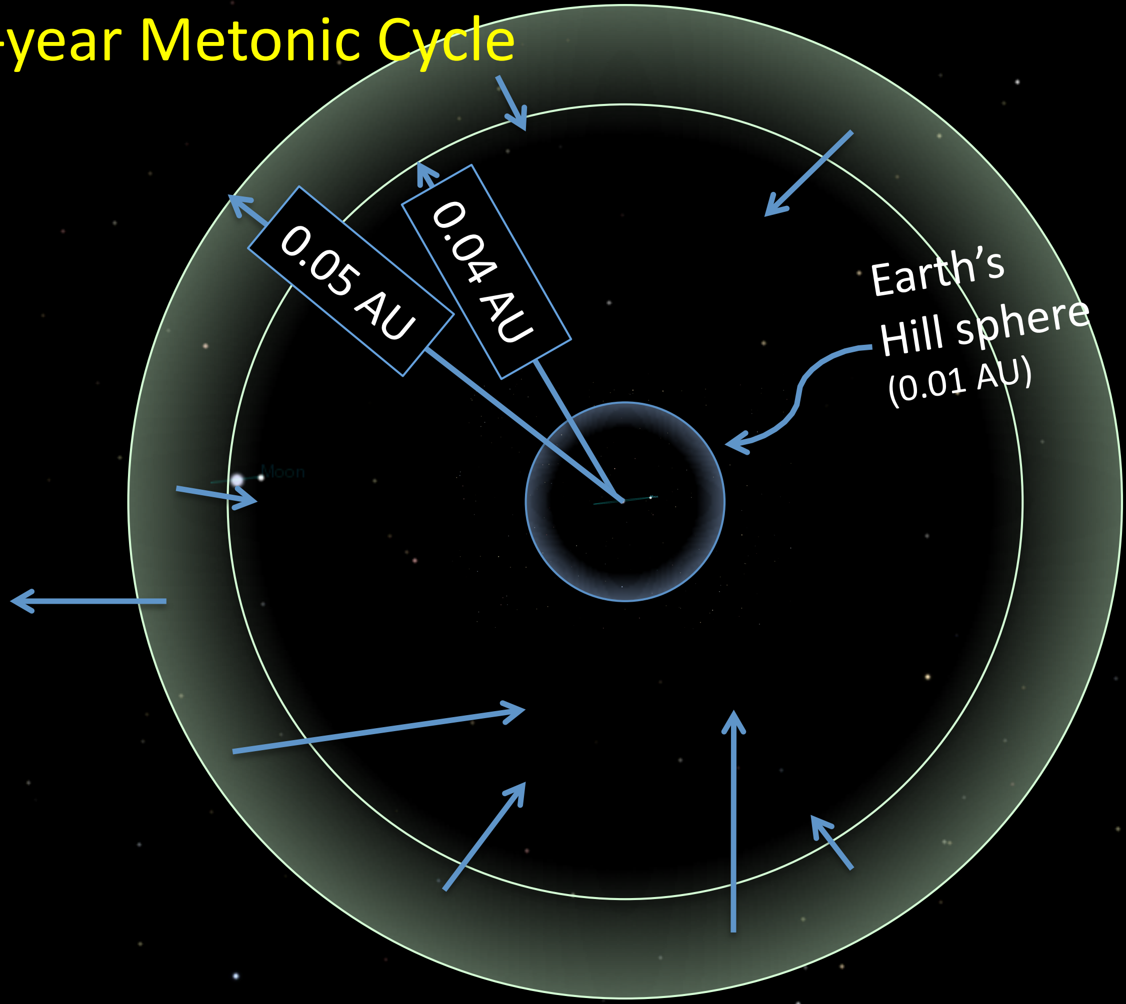
Generating NEO mini-moon Candidates

- a, e, i, randomly selected from NEO population
- random angular elements (Ω, ω, M) from flat distribution
- random epoch within 19-year Metonic Cycle



Generating NEO mini-moon Candidates

- a, e, i, randomly selected from NEO population
- random angular elements (Ω, ω, M) from flat distribution
- random epoch within 19-year Metonic Cycle
- 0.04 AU < Δ < 0.05 AU



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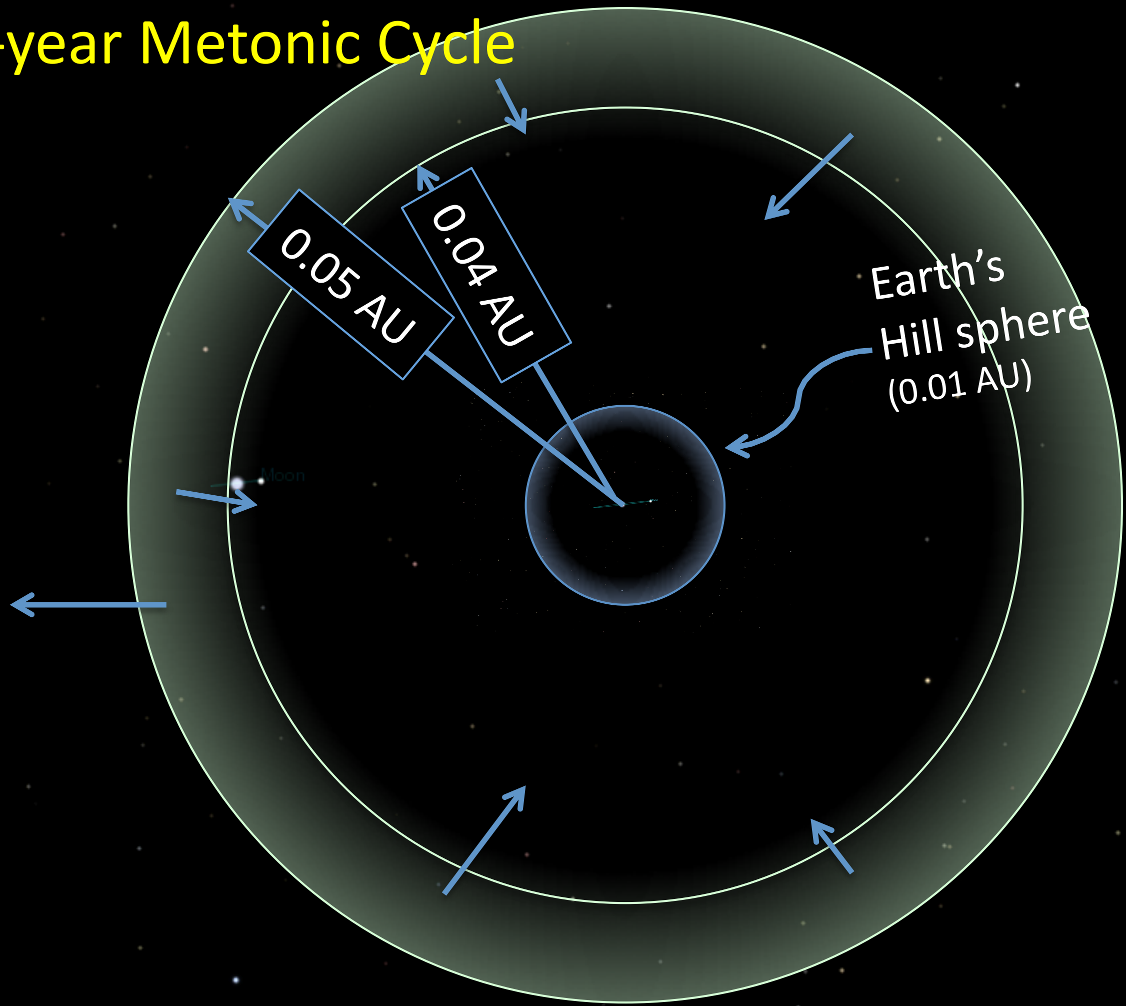
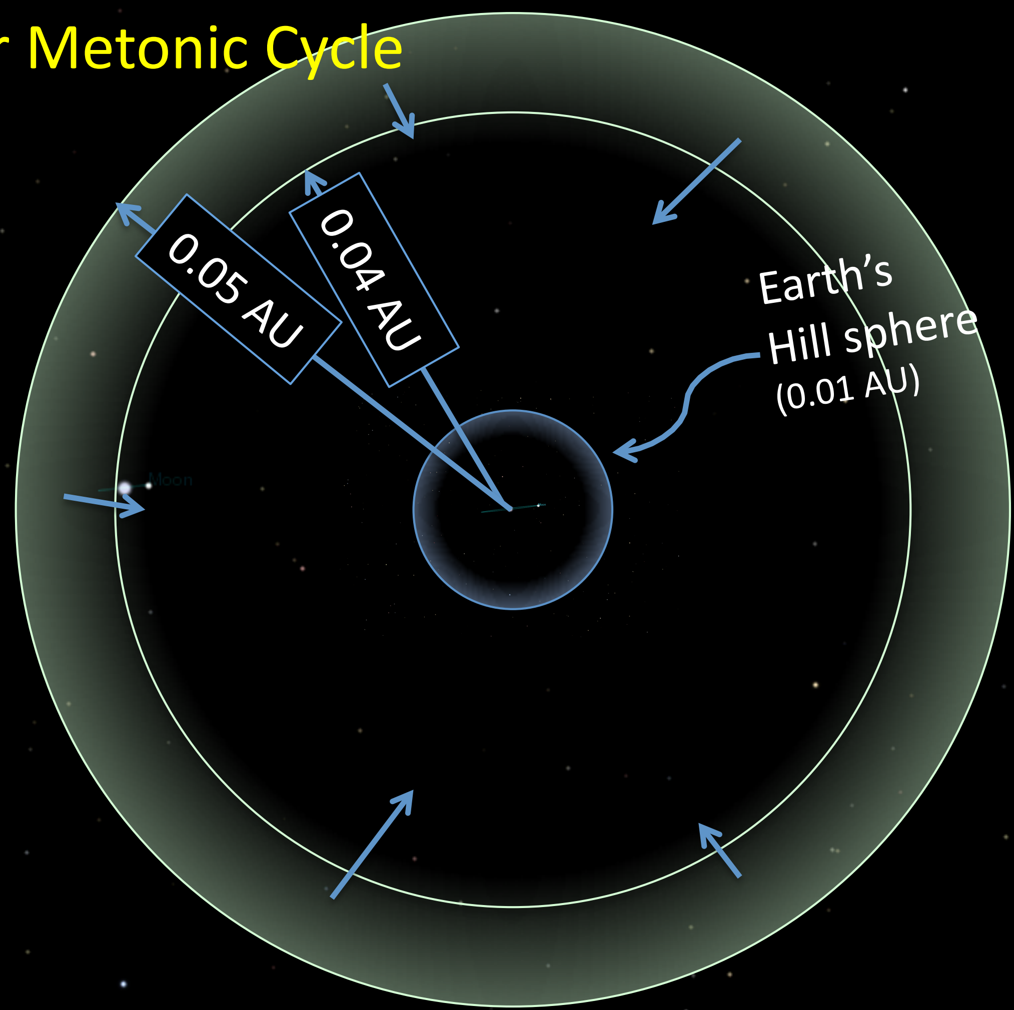
- a, e, i, randomly selected from NEO population
- random angular elements (Ω, ω, M) from flat distribution
- random epoch within 19-year Metonic Cycle
- 0.04 AU < Δ < 0.05 AU
- v_{Earth} < 3 km/s



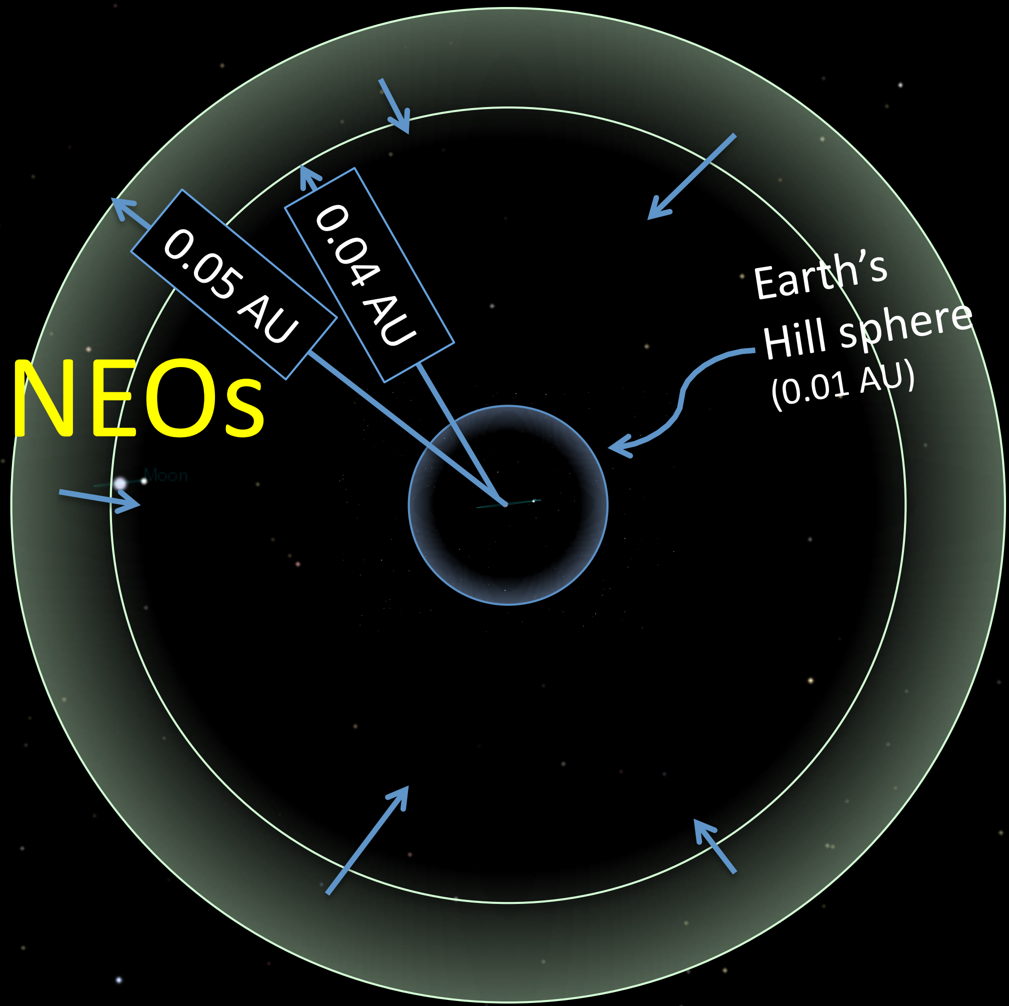
Generating NEO mini-moon Candidates

- a, e, i, randomly selected from NEO population
- random angular elements (Ω, ω, M) from flat distribution
- random epoch within 19-year Metonic Cycle
- 0.04 AU < Δ < 0.05 AU
- v_{Earth} < 3 km/s
- Direction angle < 120 deg



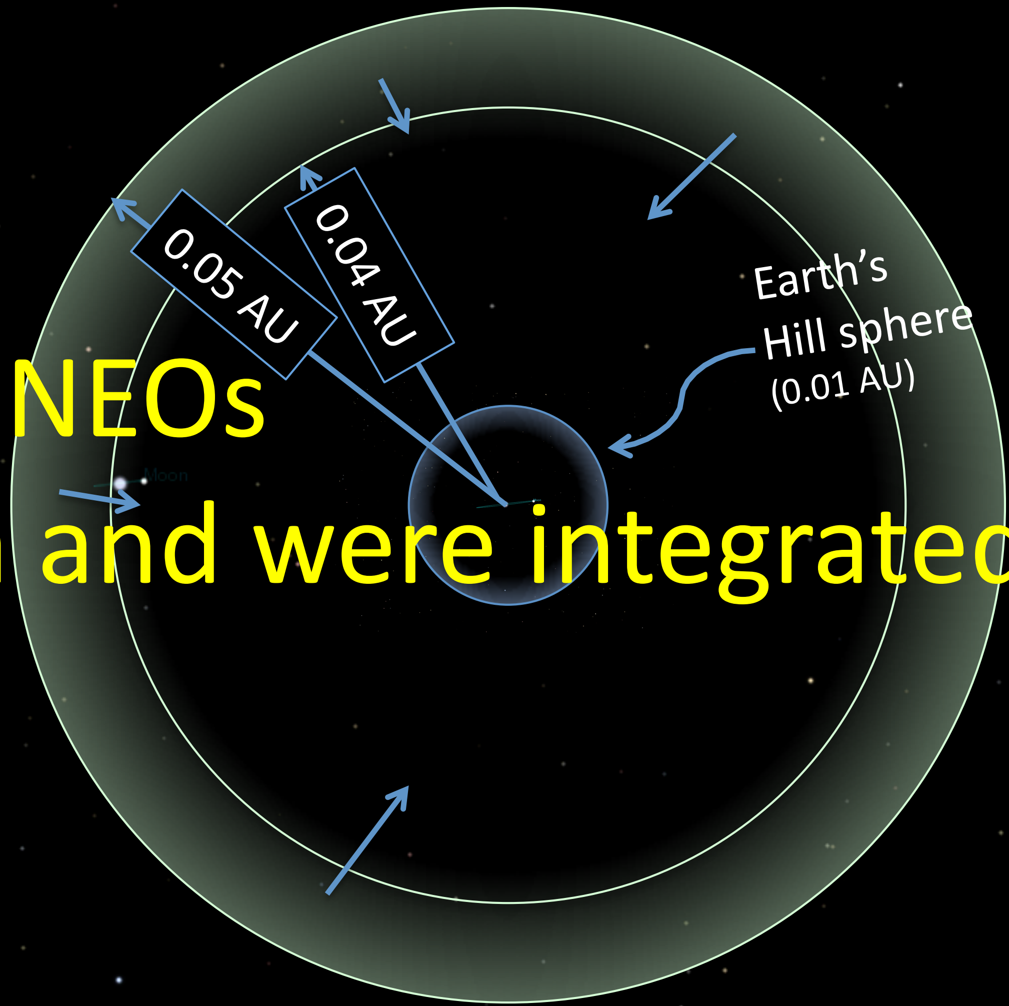
Generating NEO mini-moon Candidates

- 10^{10} generated NEOs



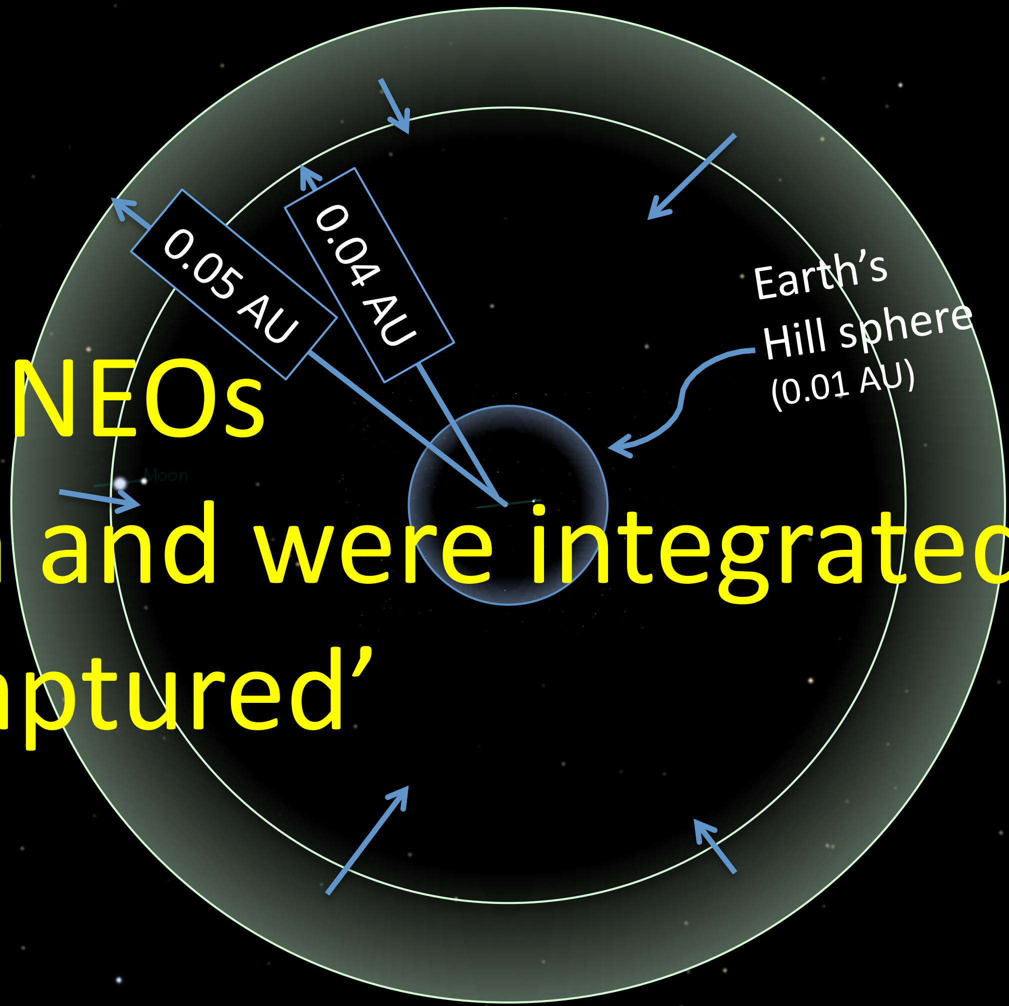
Generating NEO mini-moon Candidates

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



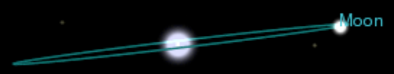
Generating NEO mini-moon Candidates

- 10^{10} generated NEOs
- 10^{7} met criteria and were integrated
- 16,000 were ‘captured’



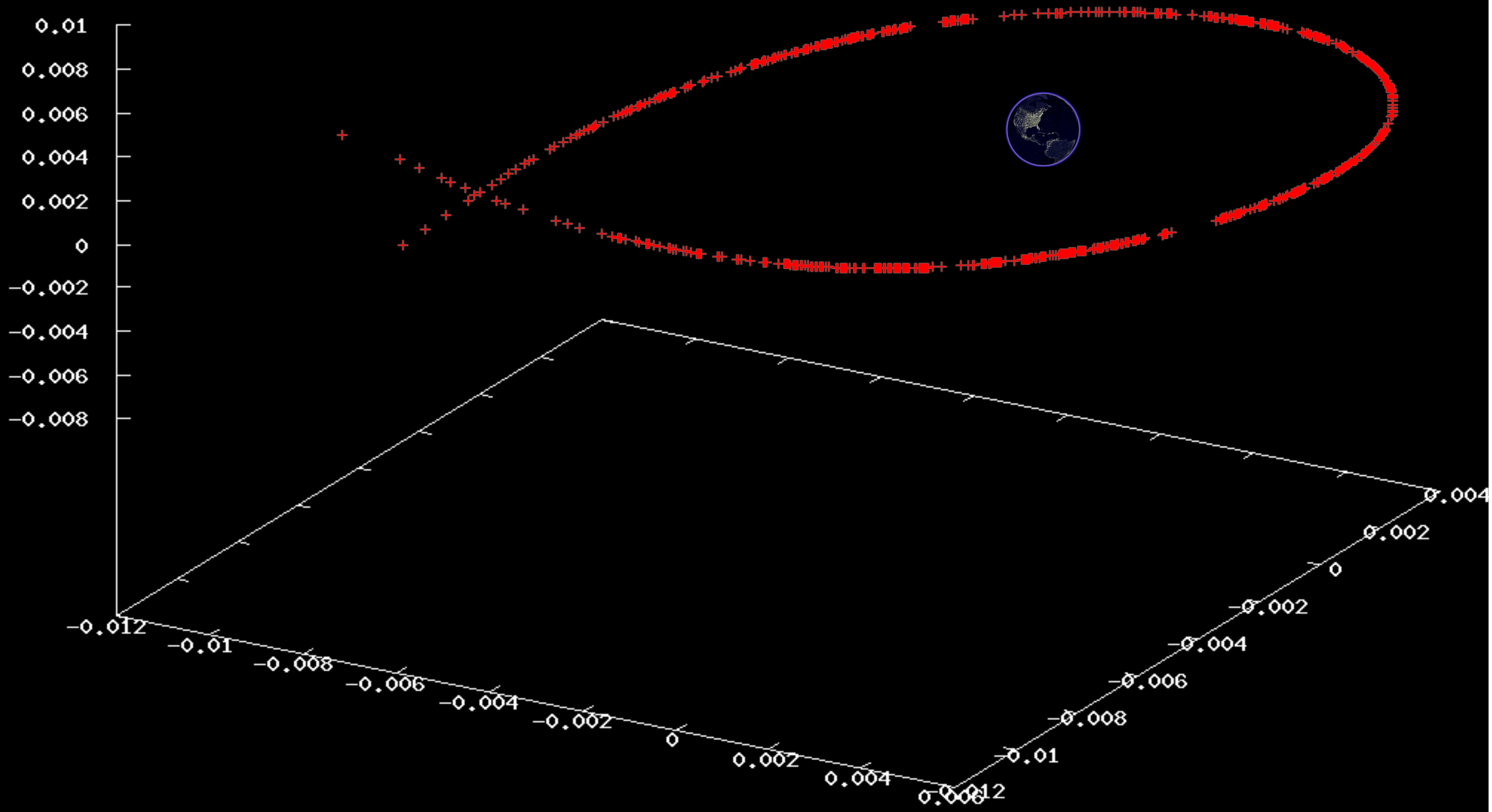
Capture Definition

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

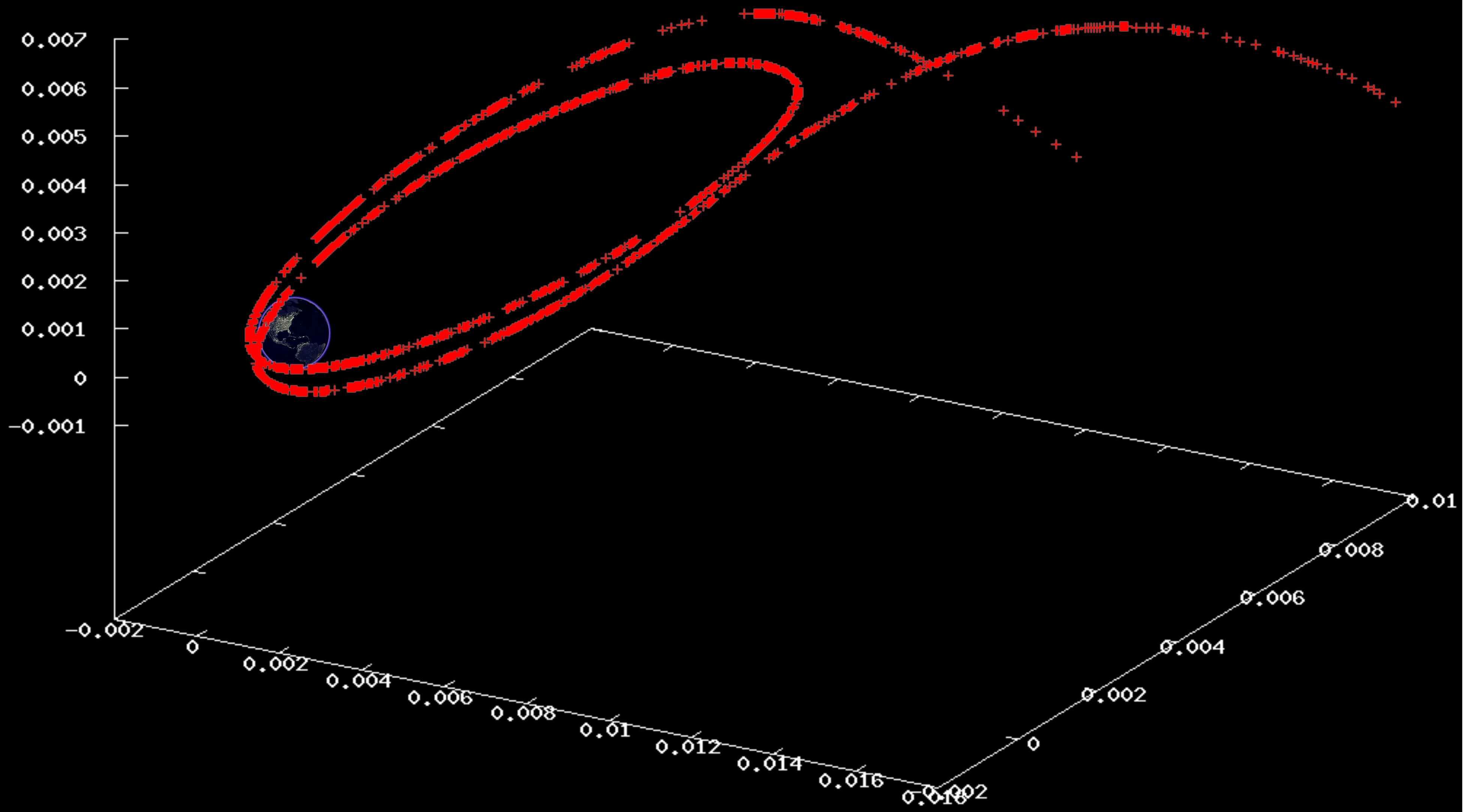


within the hill sphere

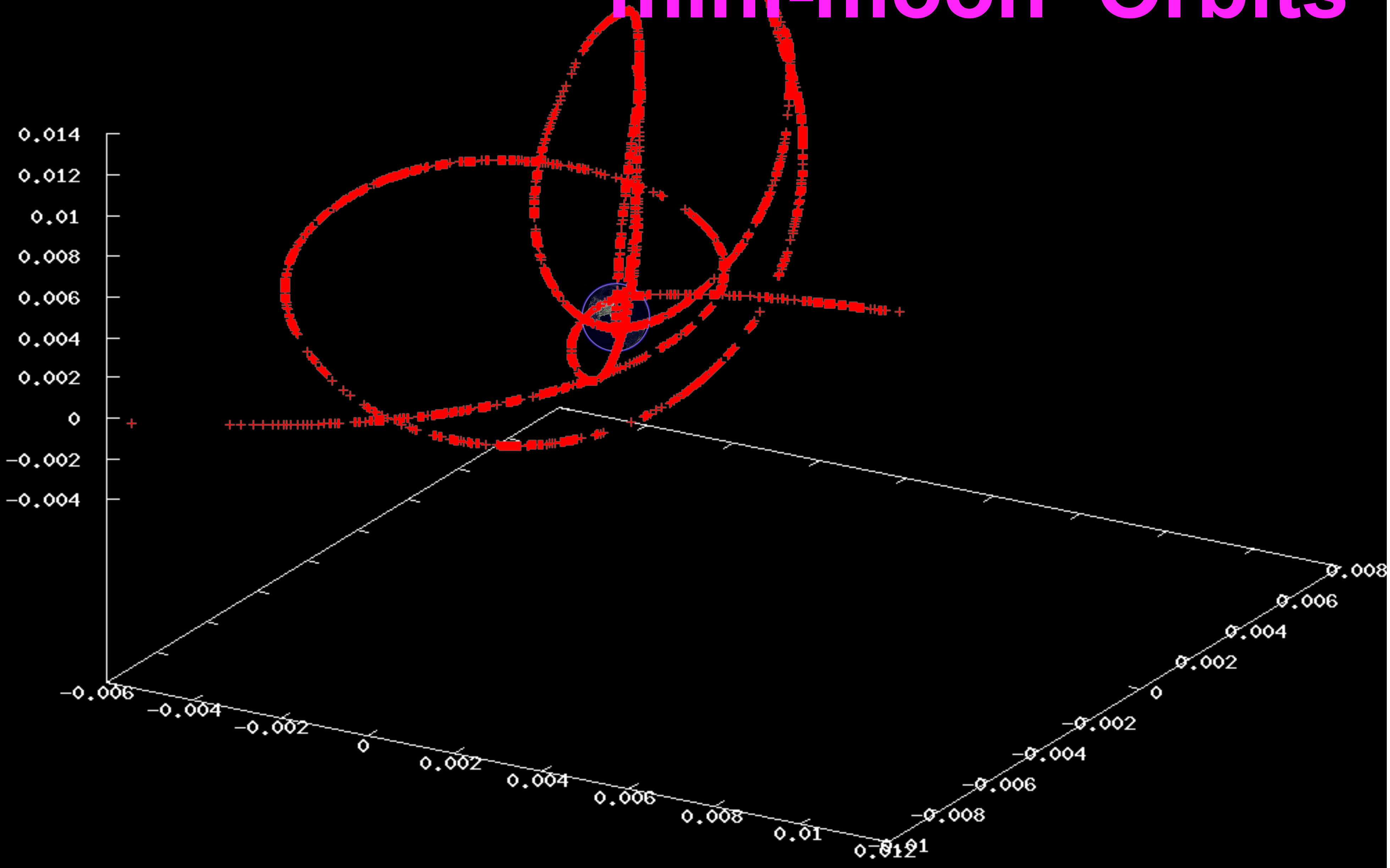
mini-moon ‘Orbits’



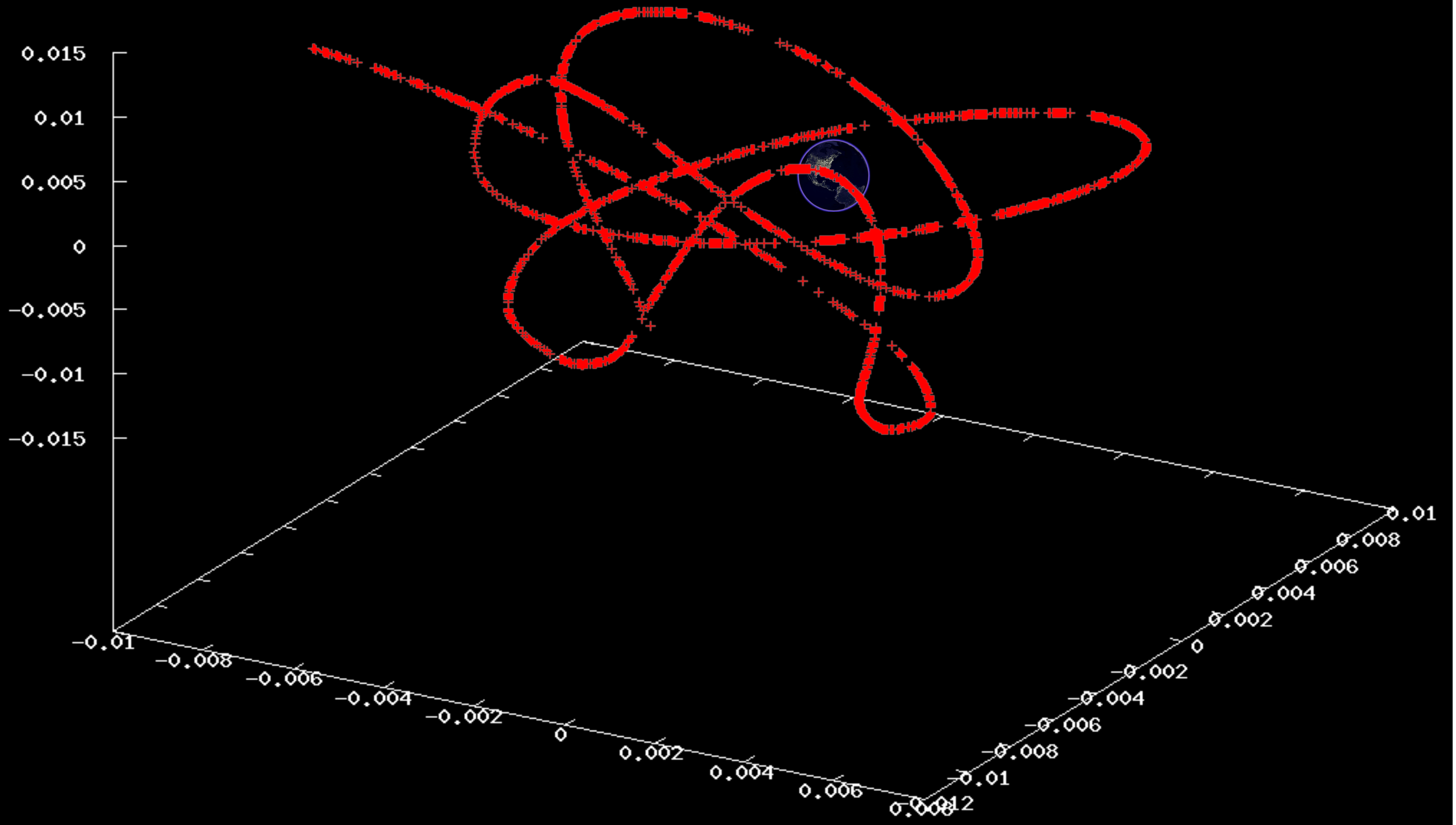
mini-moon ‘Orbits’



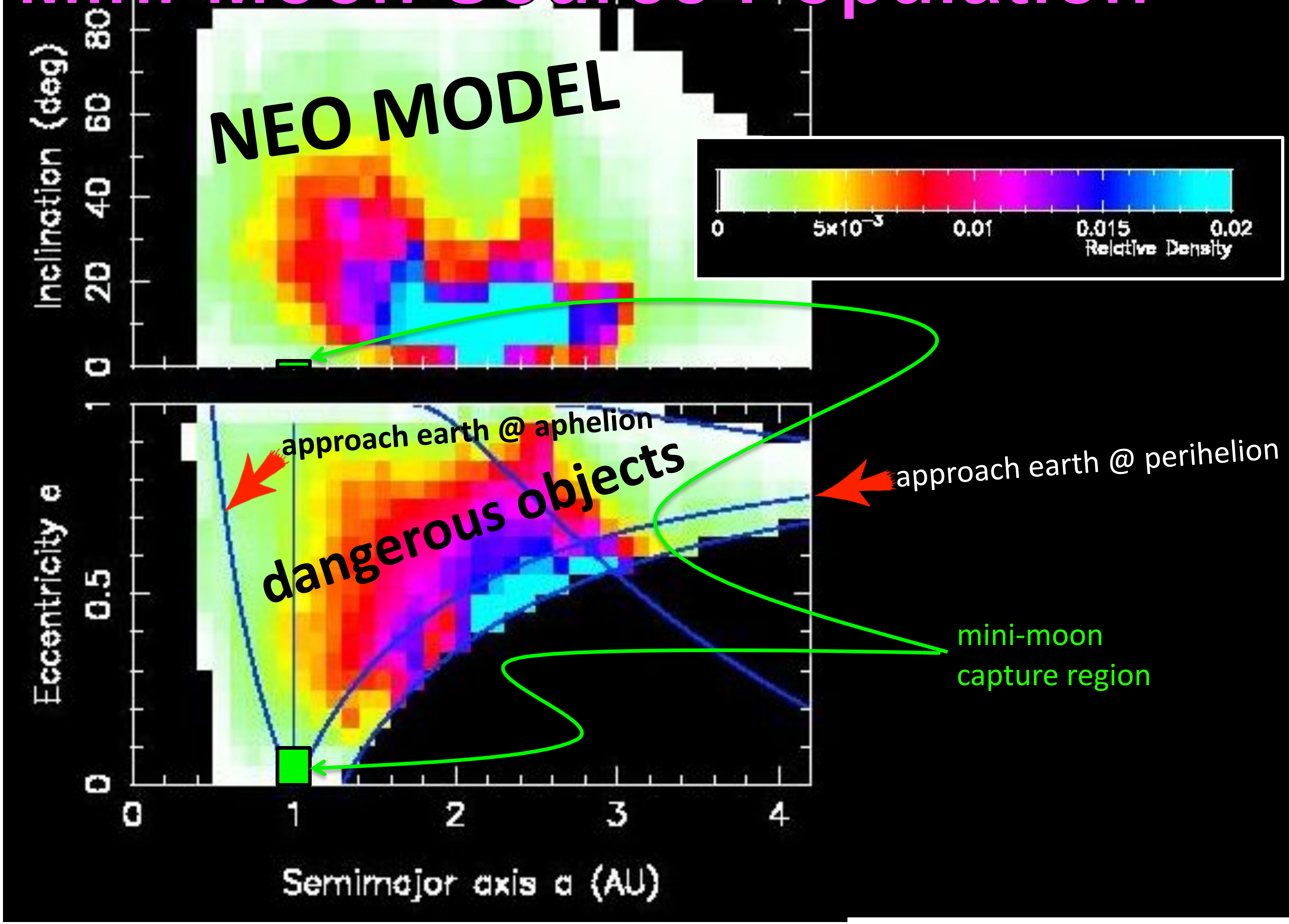
mini-moon ‘Orbits’

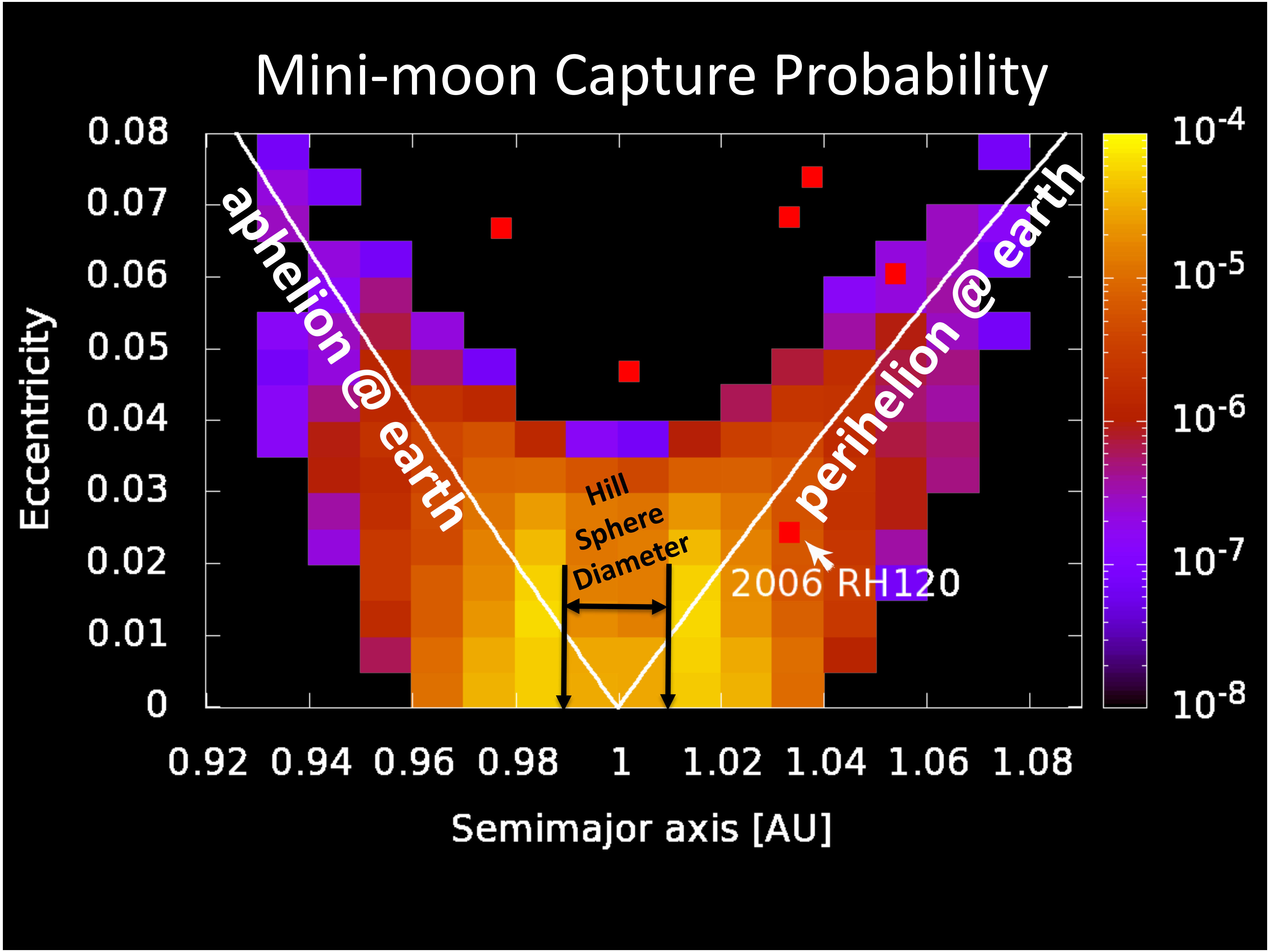


mini-moon 'Orbits'



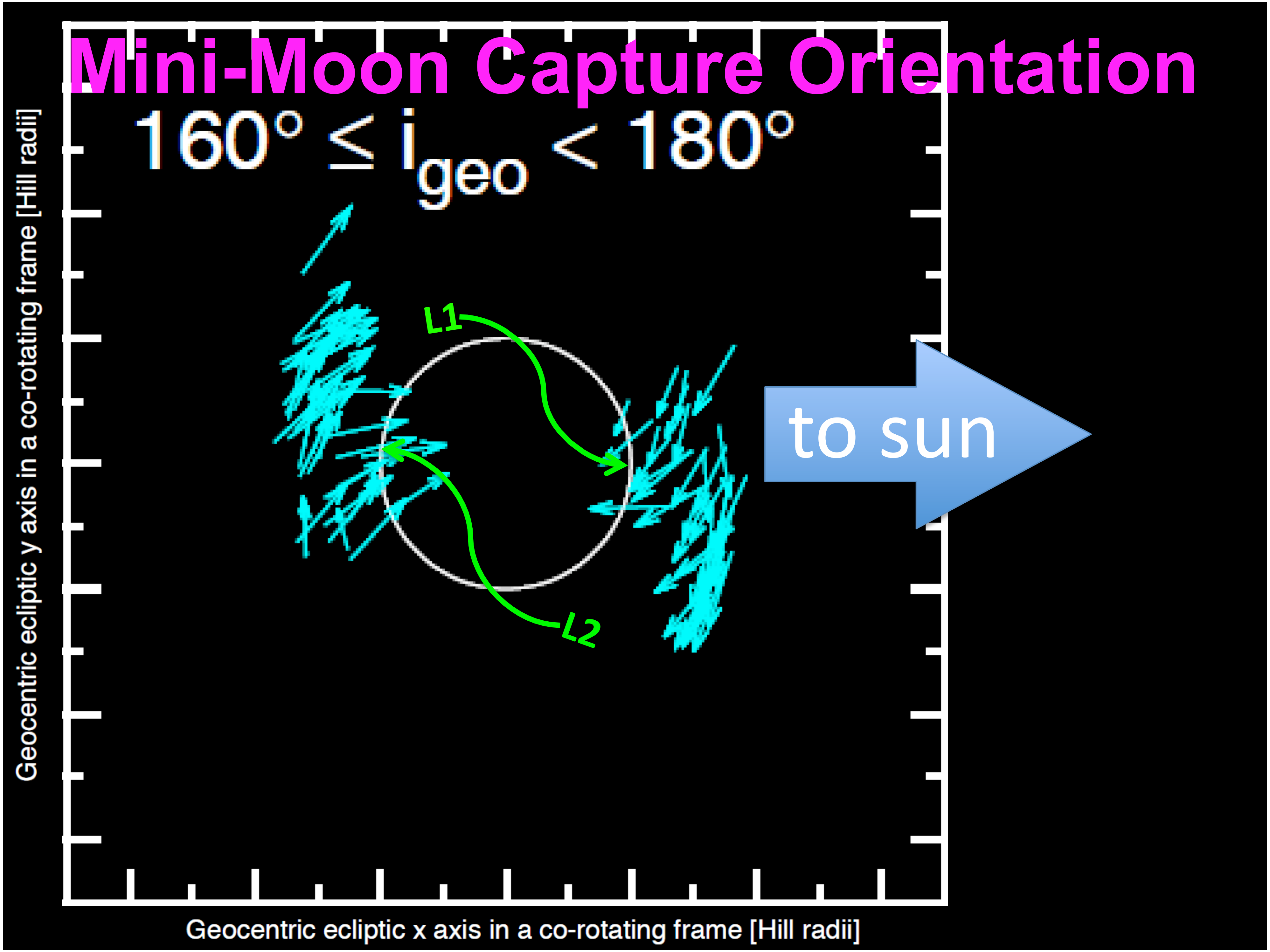
Mini-Moon Source Population



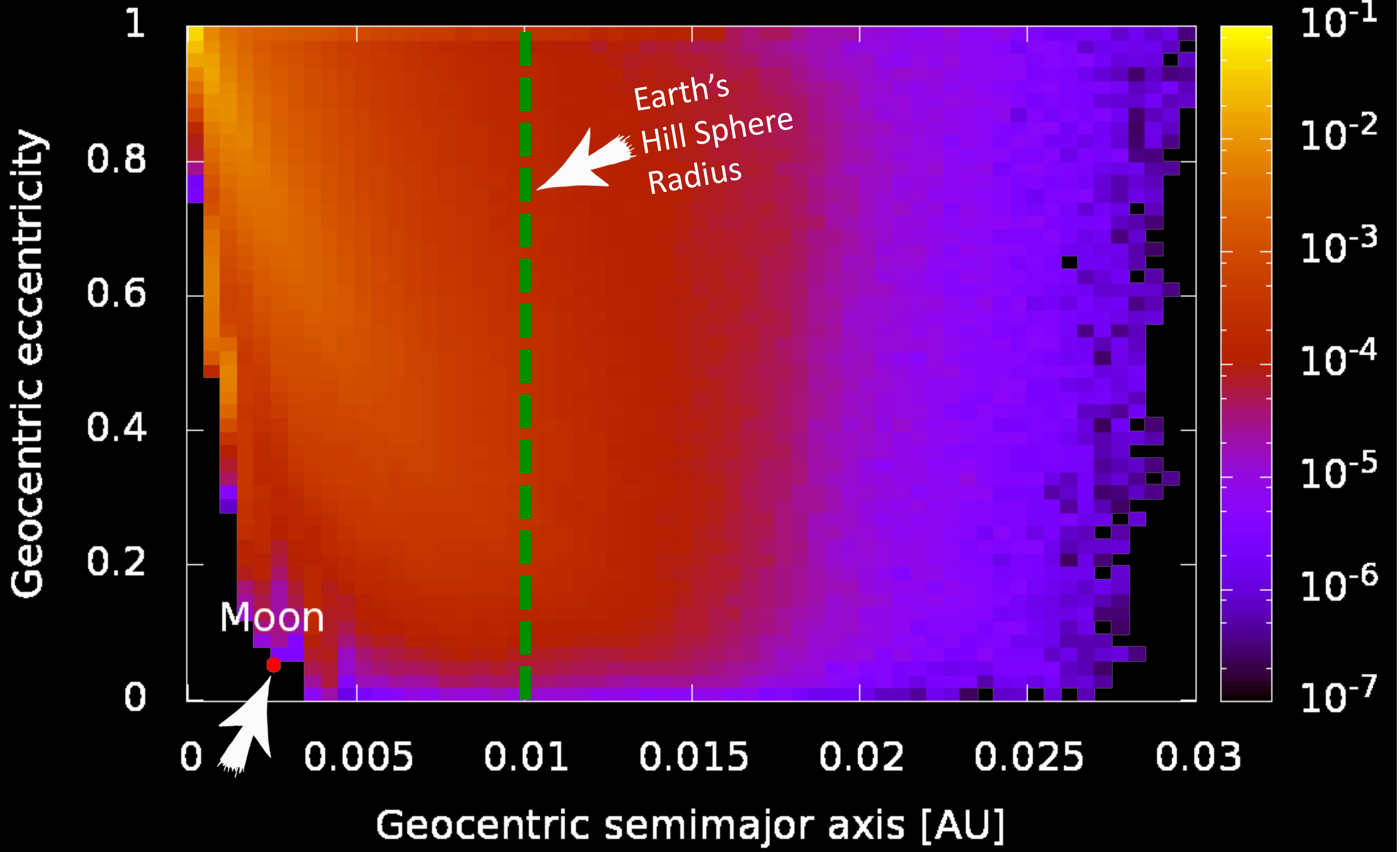


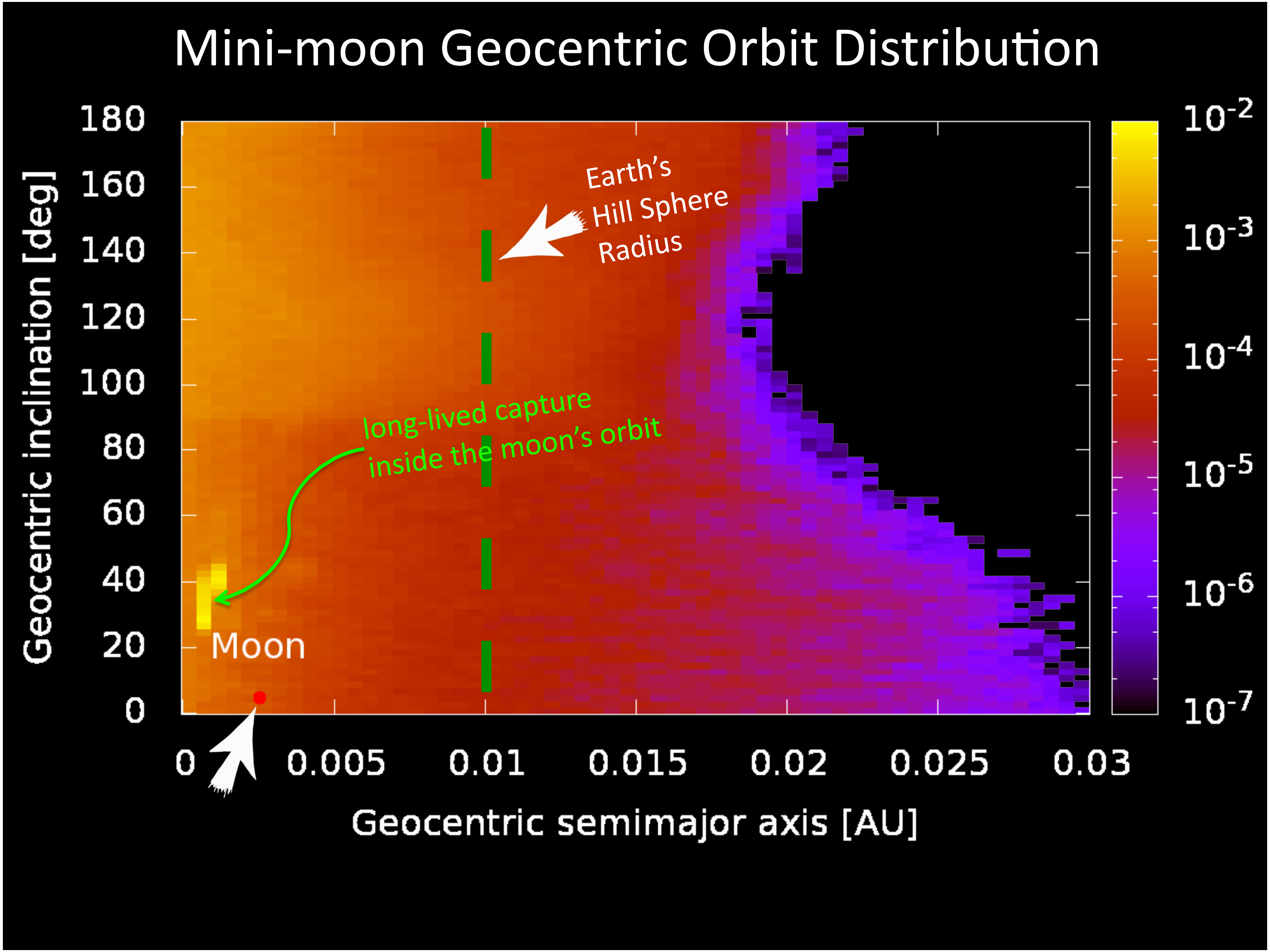
Mini-moon Capture Probability
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
Eccentricity
0.92
0.94
0.96
0.98
1
1.02
1.04
1.06
1.08
Semimajor axis [AU]
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
aphelion @ earth
perihelion @ earth
Hill Sphere Diameter
2006 RH120

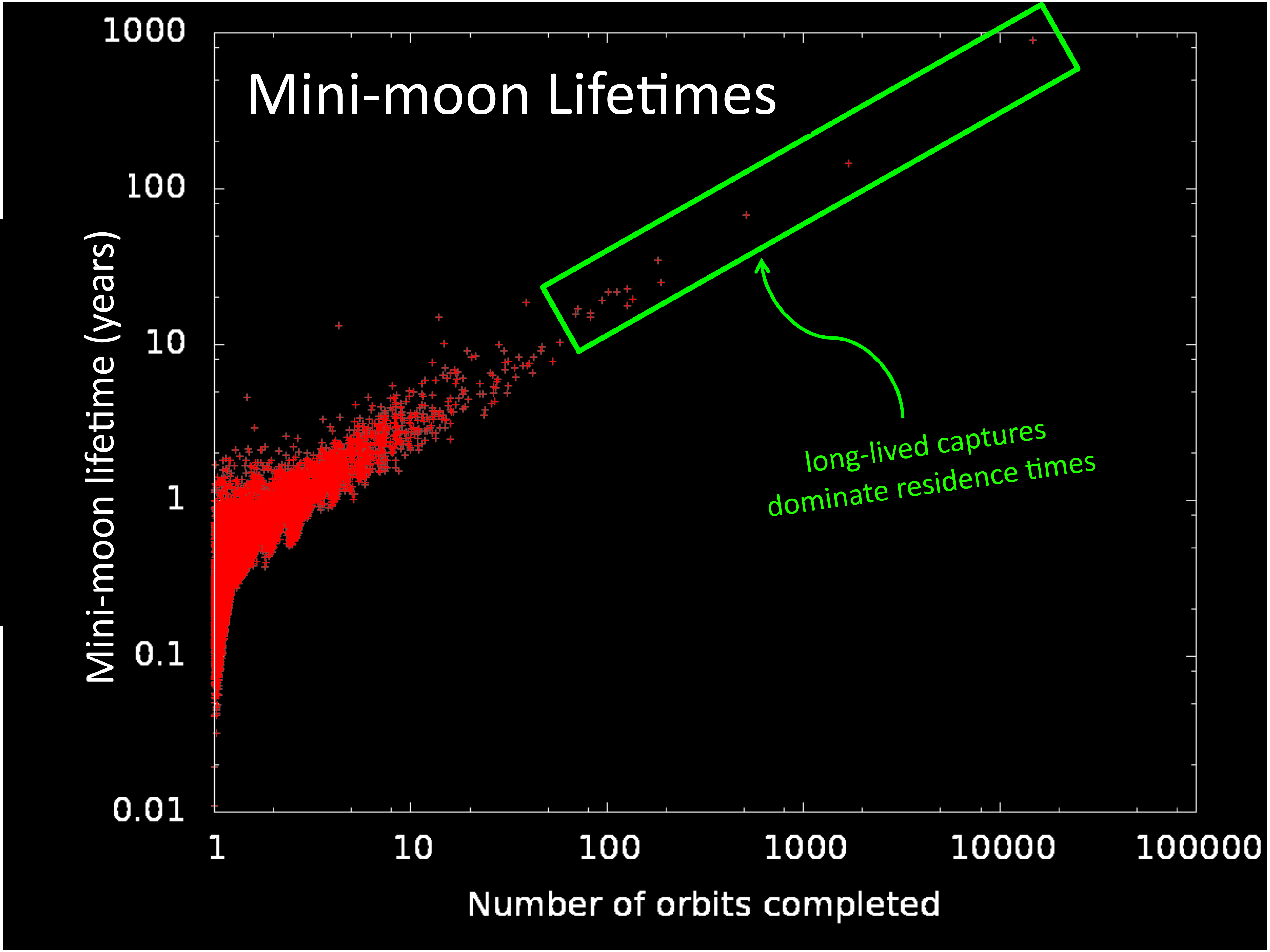
Mini-Moon Capture Orientation



Mini-moon Geocentric Orbit Distribution

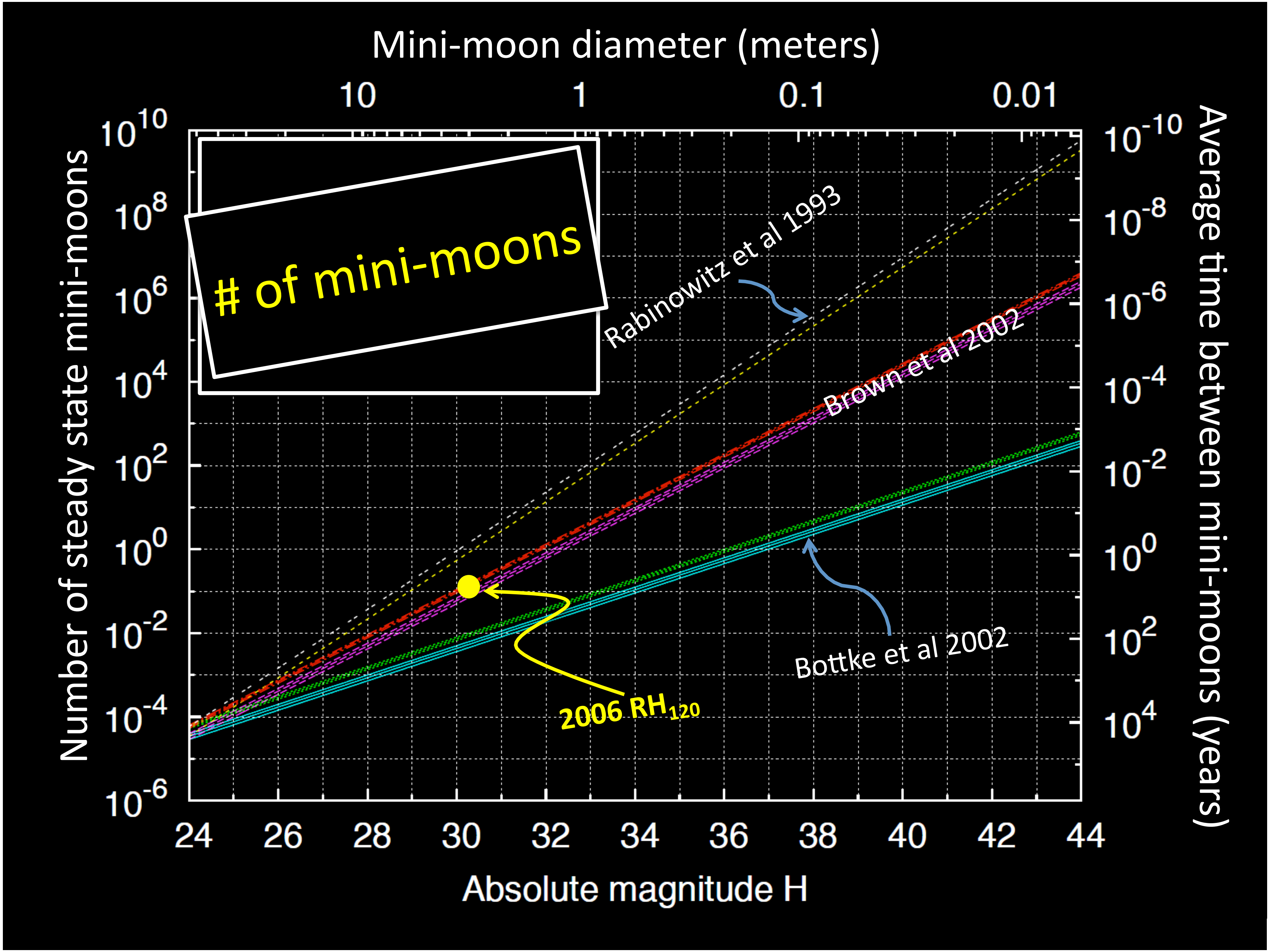



Mini-moon Geocentric Orbit Distribution
Geocentric inclination [deg]
180
160
140
120
100
80
60
40
20
0
Geocentric semimajor axis [AU]
0
0.005
0.01
0.015
0.02
0.025
0.03
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
Earth's Hill Sphere Radius
long-lived capture inside the moon's orbit
Moon



Mini-moon Lifetimes
Mini-moon lifetime (years)
1000
100
10
1
0.1
0.01
1
10
100
1000
10000
100000
Number of orbits completed
long-lived captures
dominate residence times


How many Mini-Moons are there?



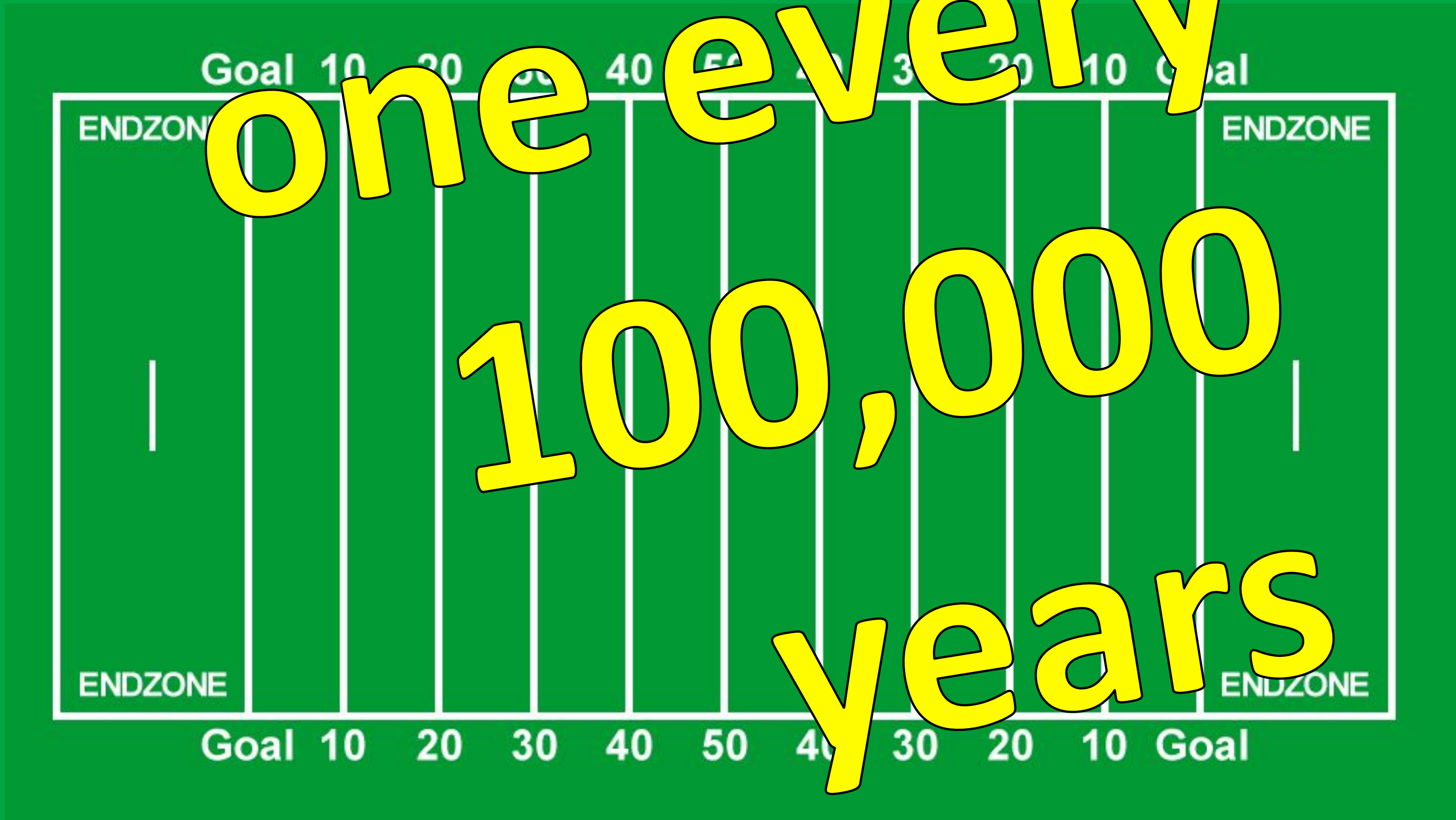
Mini-moon diameter (meters)
10
1
0.1
0.01
# of mini-moons
Rabinowitz et al 1993
Brown et al 2002
Bottke et al 2002
2006 RH120
Number of steady state mini-moons
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}
Average time between mini-moons (years)
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
24
26
28
30
32
34
36
38
40
42
44
Absolute magnitude H

How many Mini-Moons are there?

2

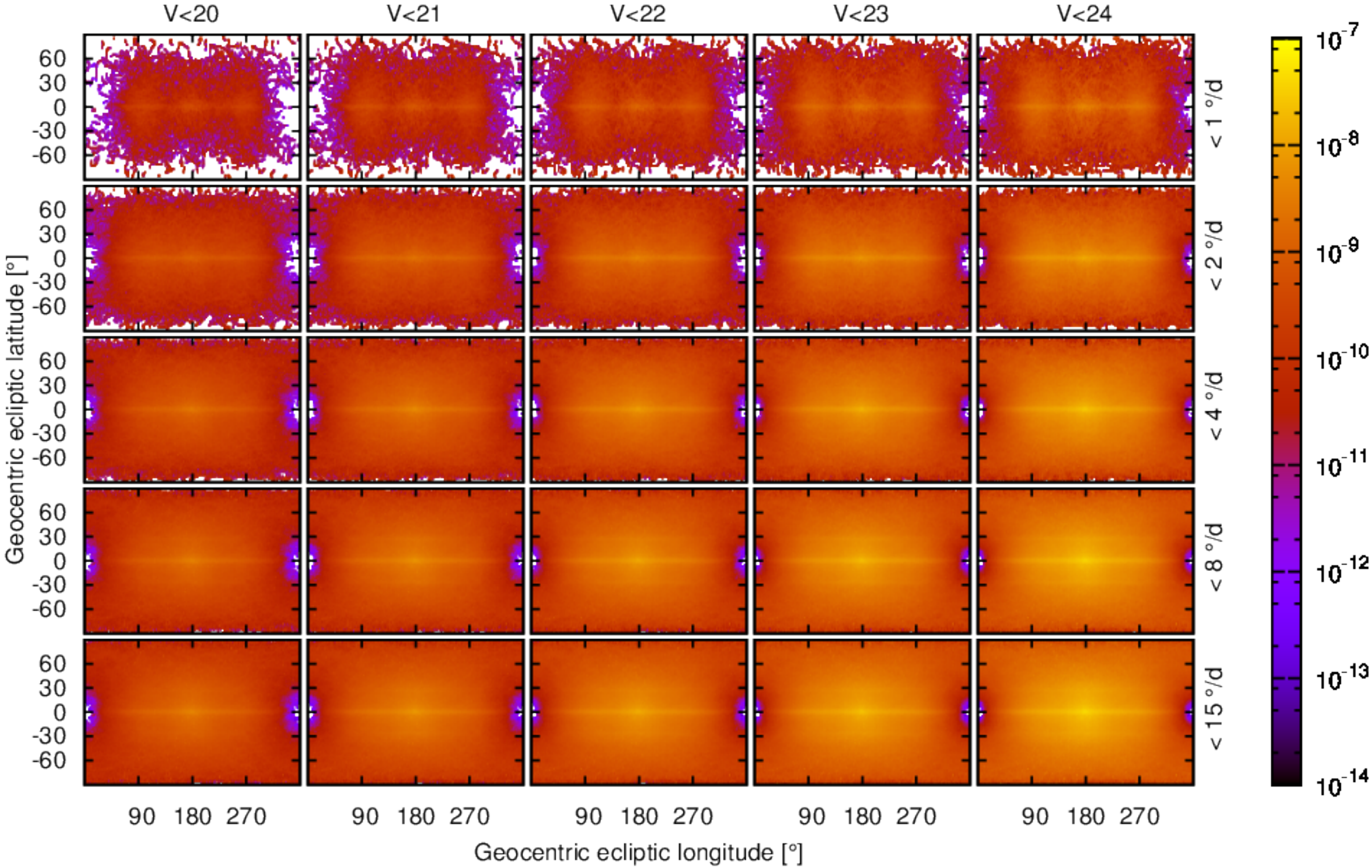
one every 50 years

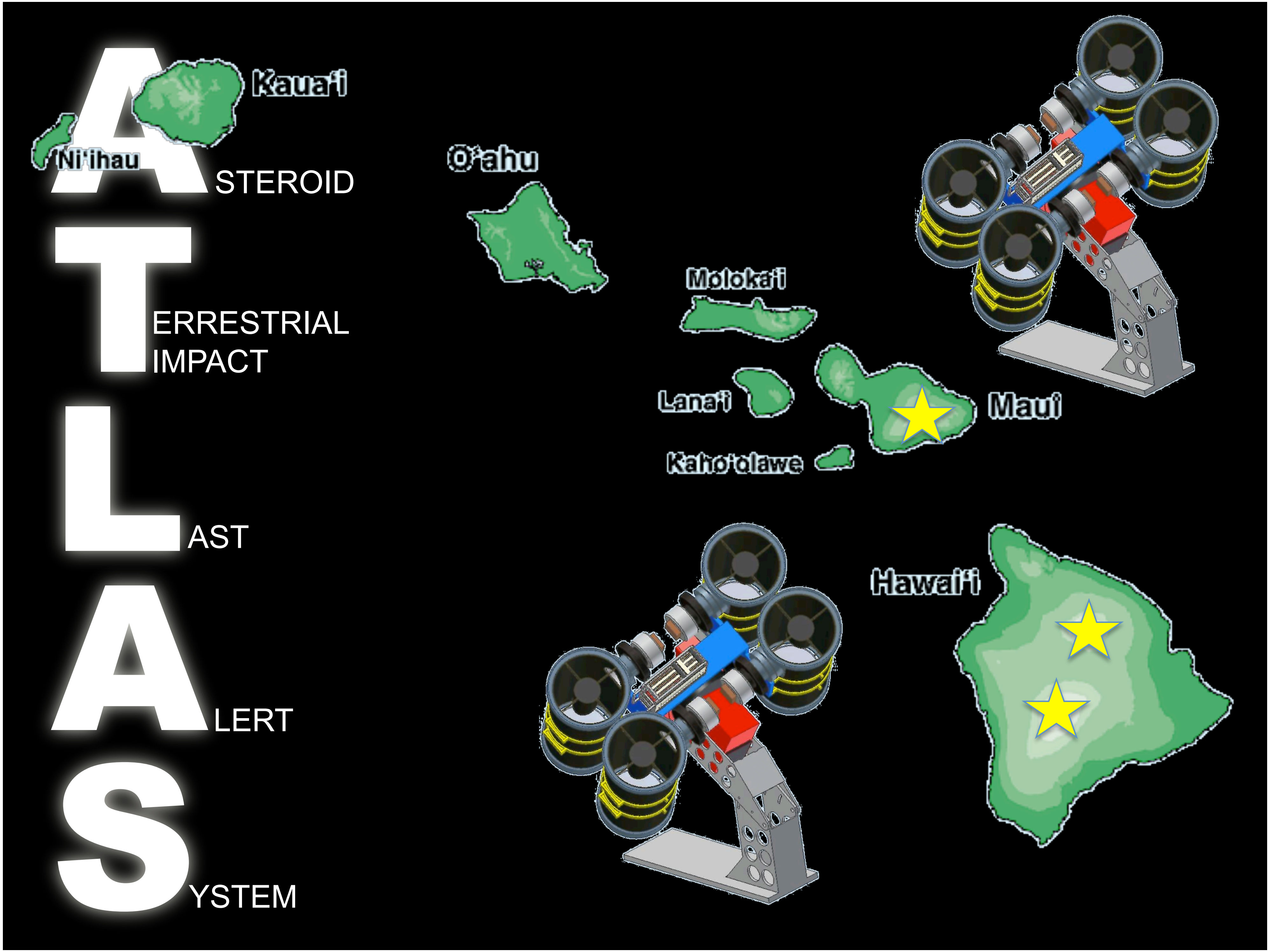
How many Mini-Moons are there?

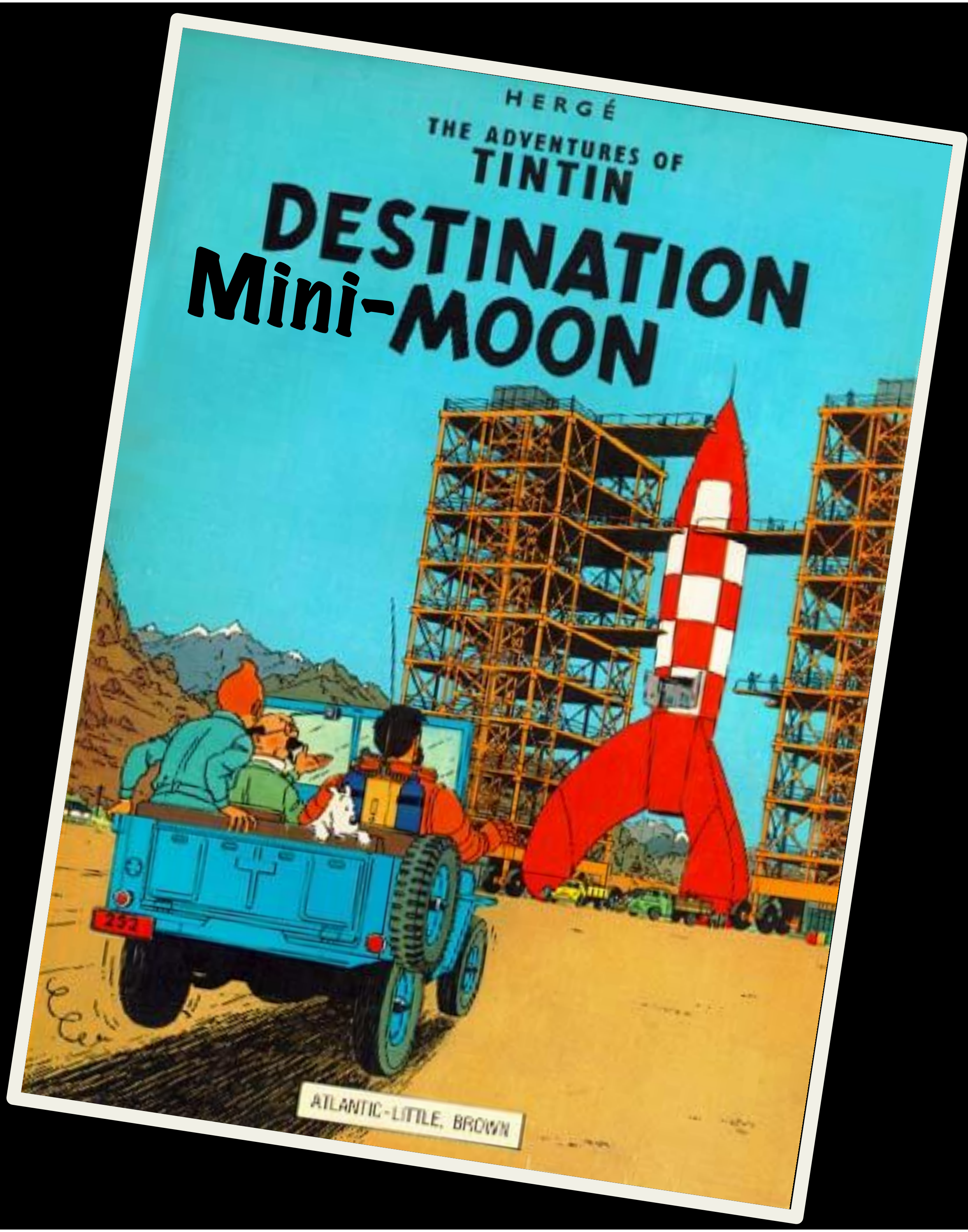


one every 100,000 years

Mini-moon Sky-Plane Distribution




ASTEROID
TERRESTRIAL
IMPACT
LAST
ALERT
SYSTEM
Kaua'i
Ni'ihau
O'ahu
Moloka'i
Lana'i
Maui
Kaho'olawe
Hawai'i

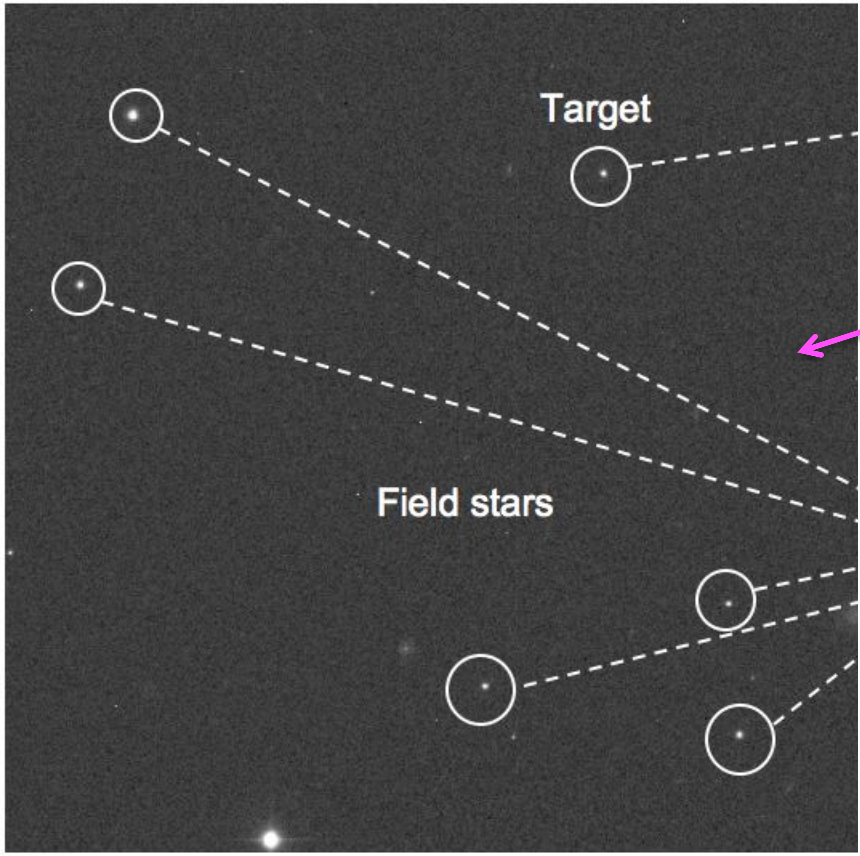

HERGÉ
THE ADVENTURES OF
TINTIN
DESTINATION
Mini-MOON
ATLANTIC-LITTLE, BROWN

Summaries

- ZERO main belt comets
- measured MBC:MBA ratios (m>0.2kg/s) •
  - 1:300 – inner belt (H<21)
  - 1:350 – middle belt (H<19.5)
  - 1:500 – outer belt (H<18)
- low S/N detection of tails for 5% of main belt asteroids

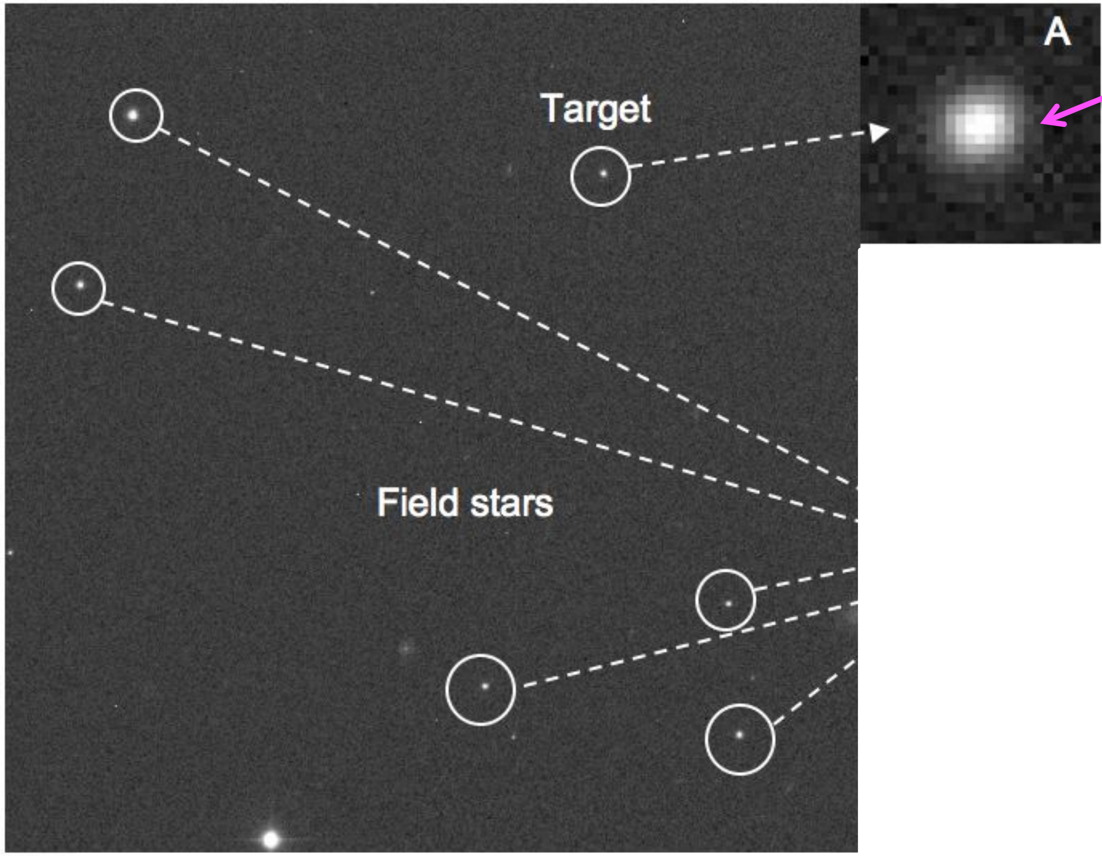
- MANY mini-moons
- 1-2 one-meter diameter mini-moons at any time

Creating the PSFs



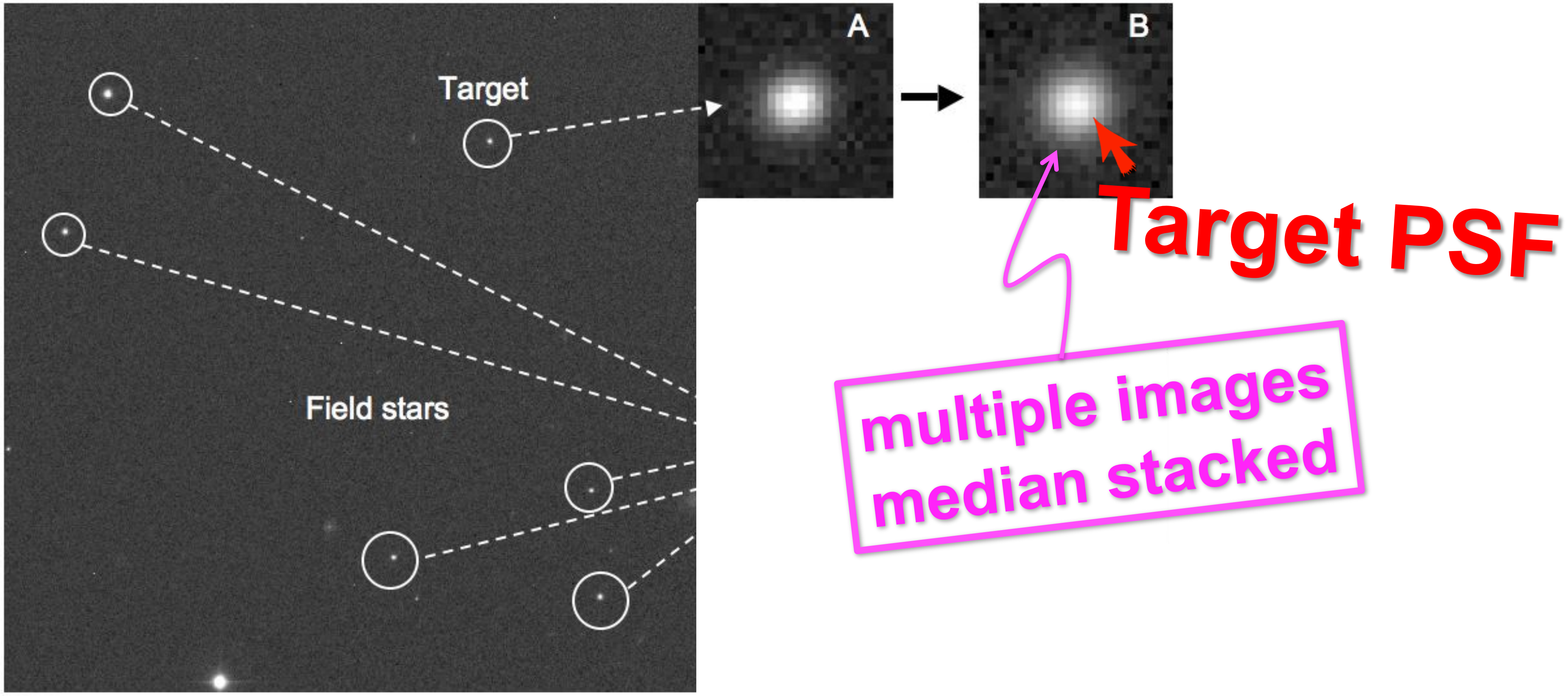
TALCS image

Creating the PSFs

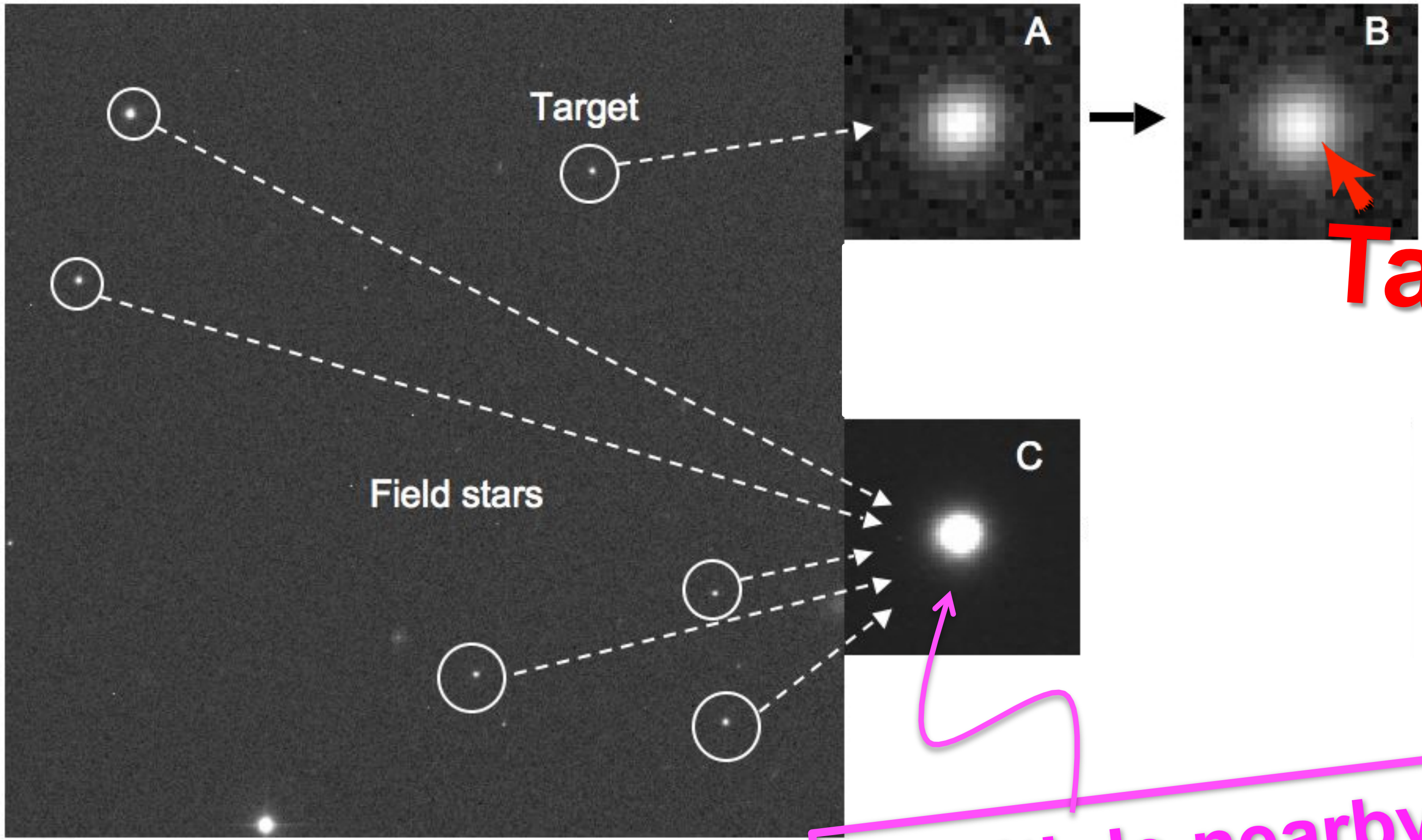


single target image

Creating the PSFs



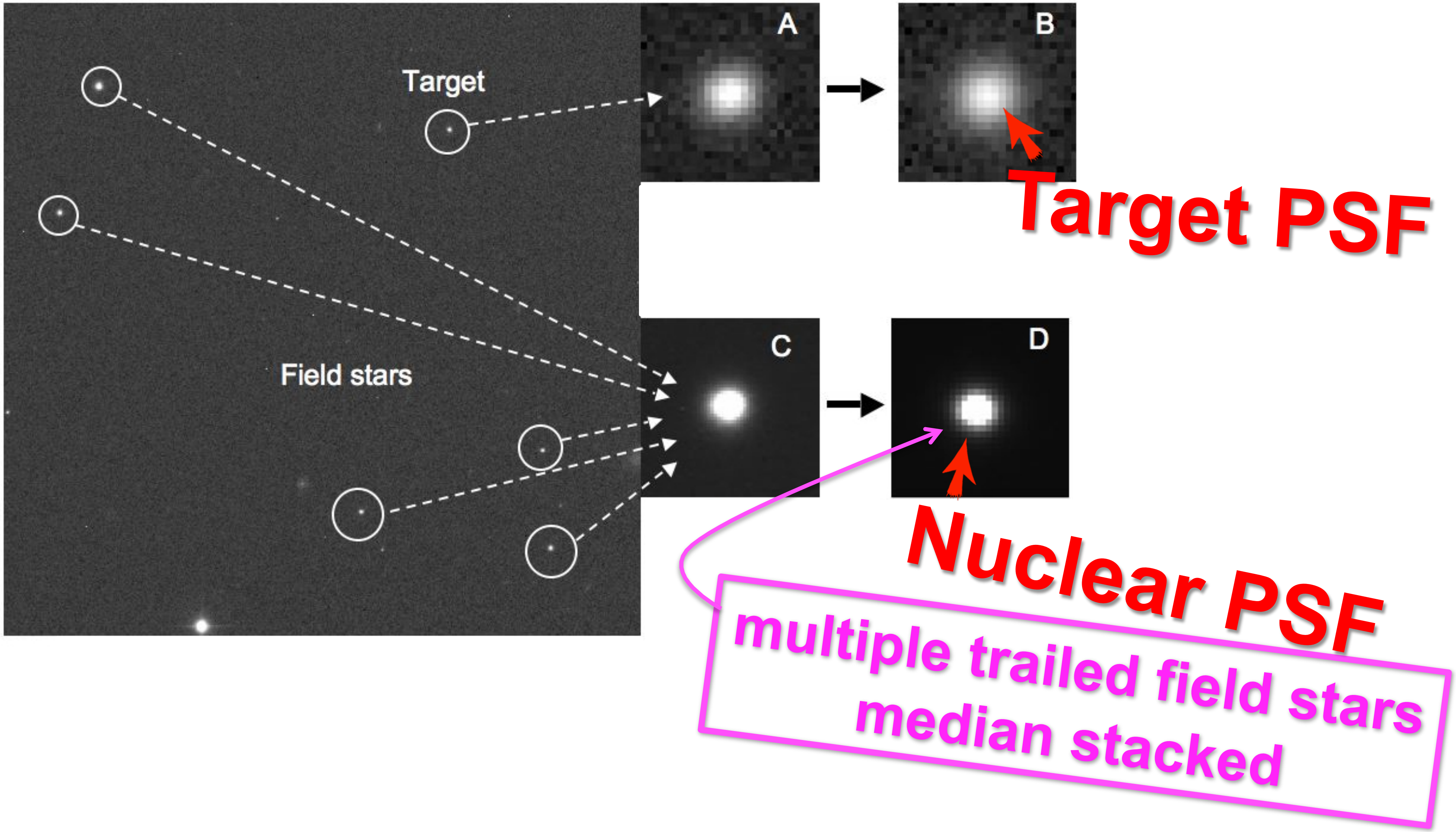
Creating the PSFs



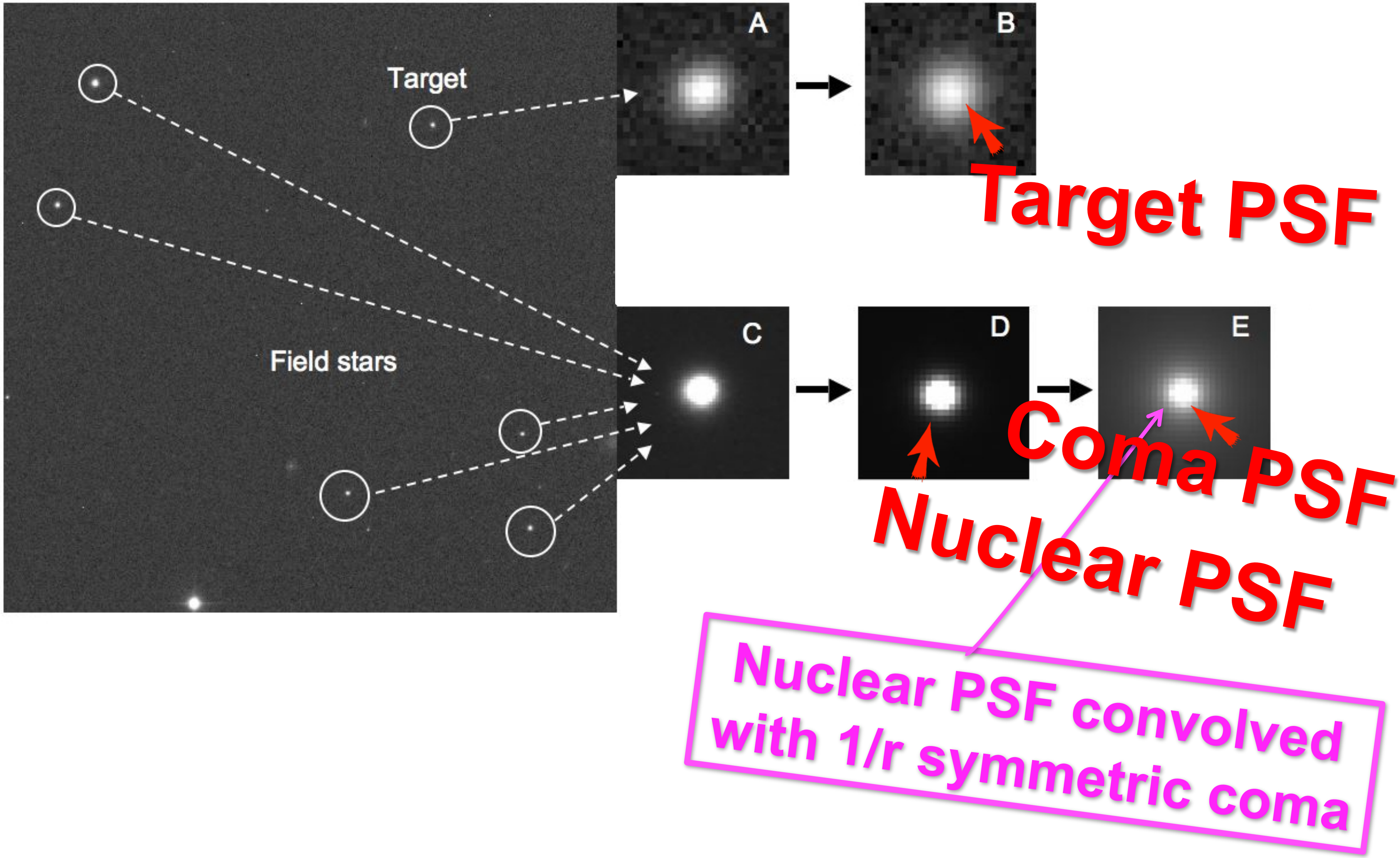
Target PSF

multiple nearby field stars trailed & median stacked

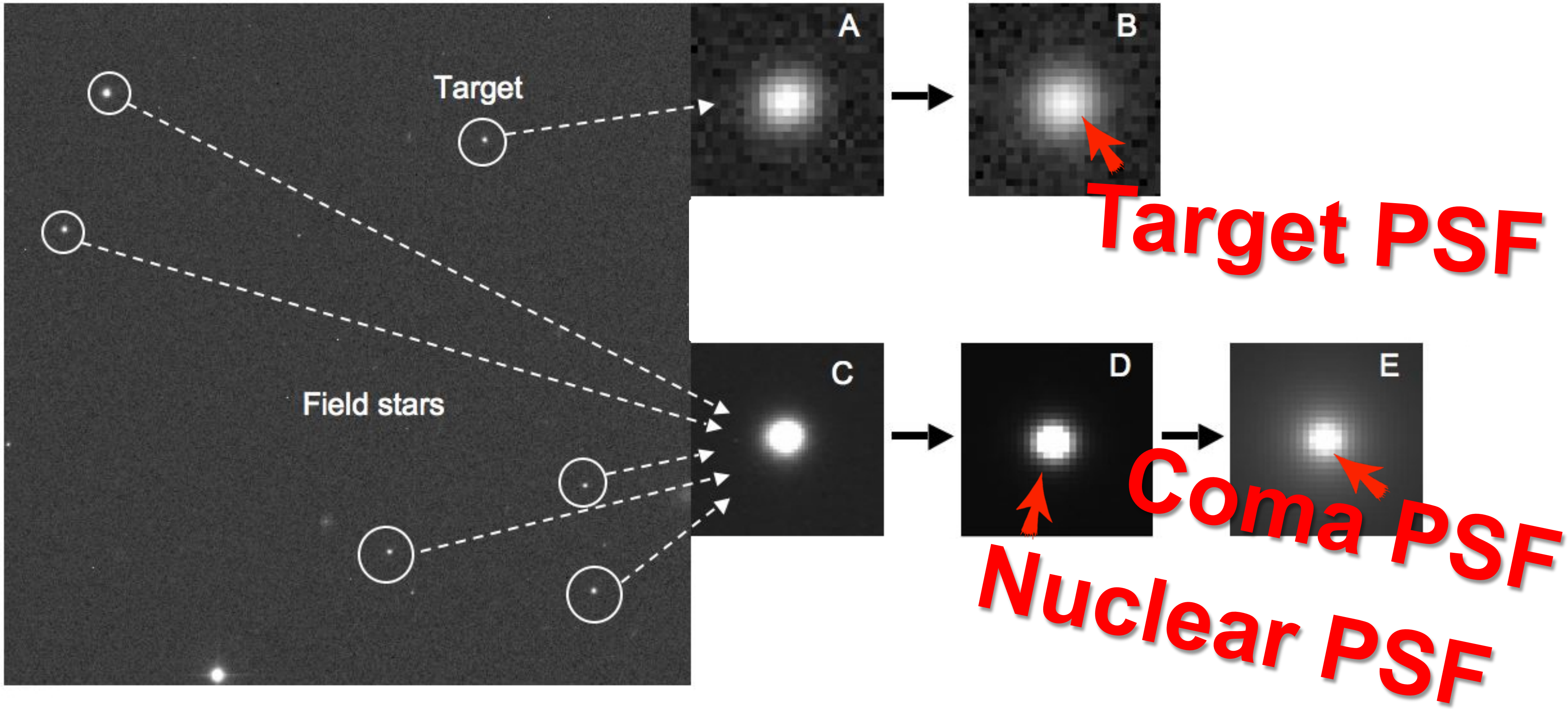
Creating the PSFs



Creating the PSFs



Creating the PSFs



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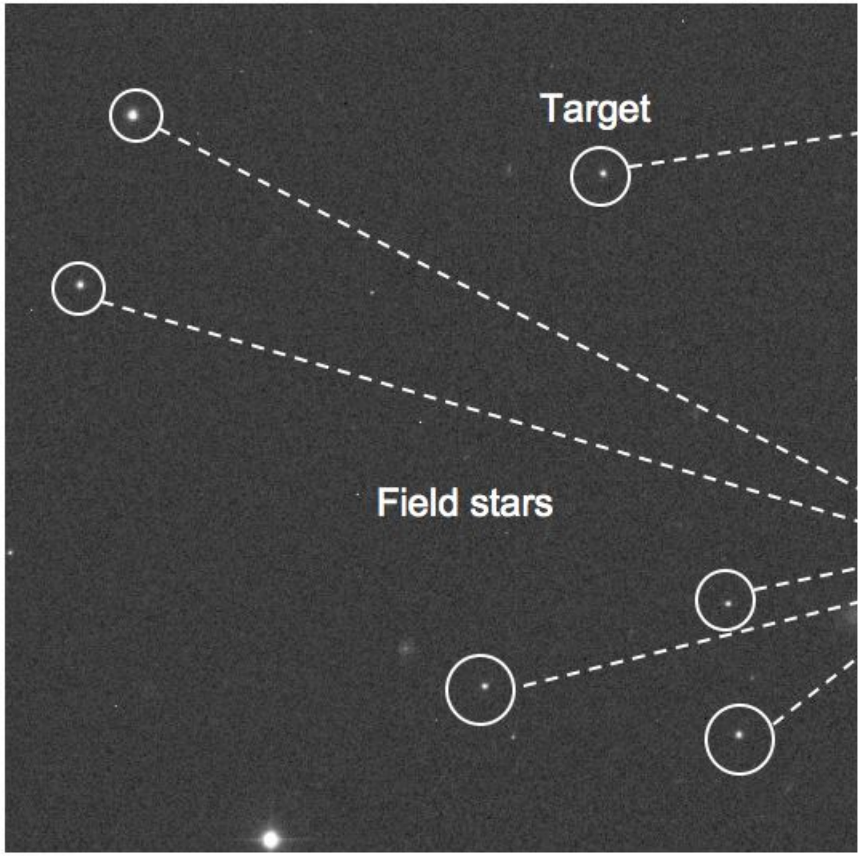

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