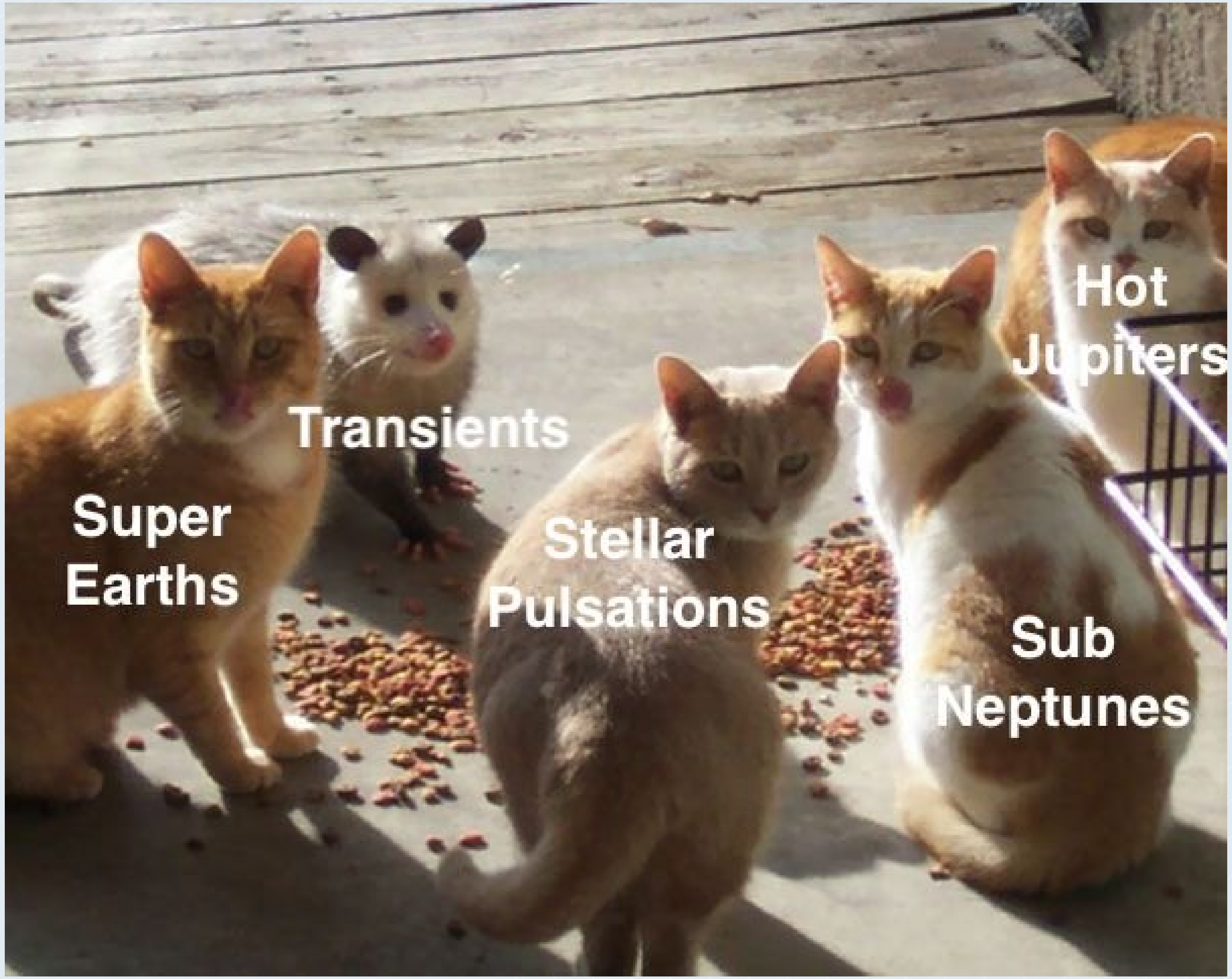
TESS in the Solar System

András Pál

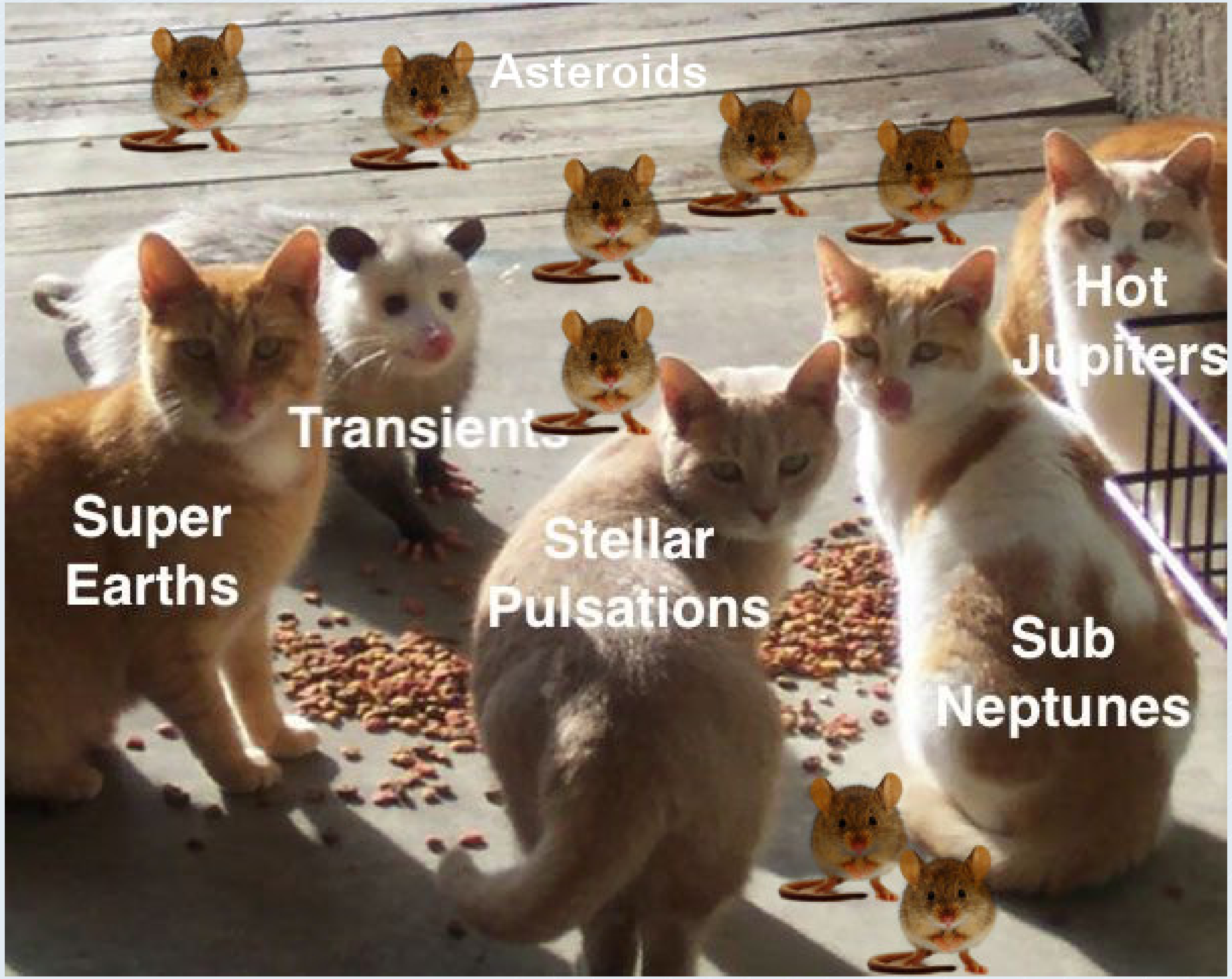
<apal@konkoly.hu>

– TESS Science Conference I, MIT, Cambridge, USA –

August 1, 2019


Transients
Super
Earths
Stellar
Pulsations
Hot
Jupiters
Sub
Neptunes

TESS in the Solar System



TESS in the Solar System

Outline of the next 22 ± 1 minutes:

- Solar System
- Legacy of Kepler/K2 (in the context of Solar System studies)
- How does TESS work for Solar System objects?
- What are the interesting questions about the Solar System what can be answered by TESS?
- Some aspects of the data reduction: image subtraction, astrometry, stacking, and so on…!
- Known objects: Some nice preliminary results and displays/exhibitions of light curves, detections
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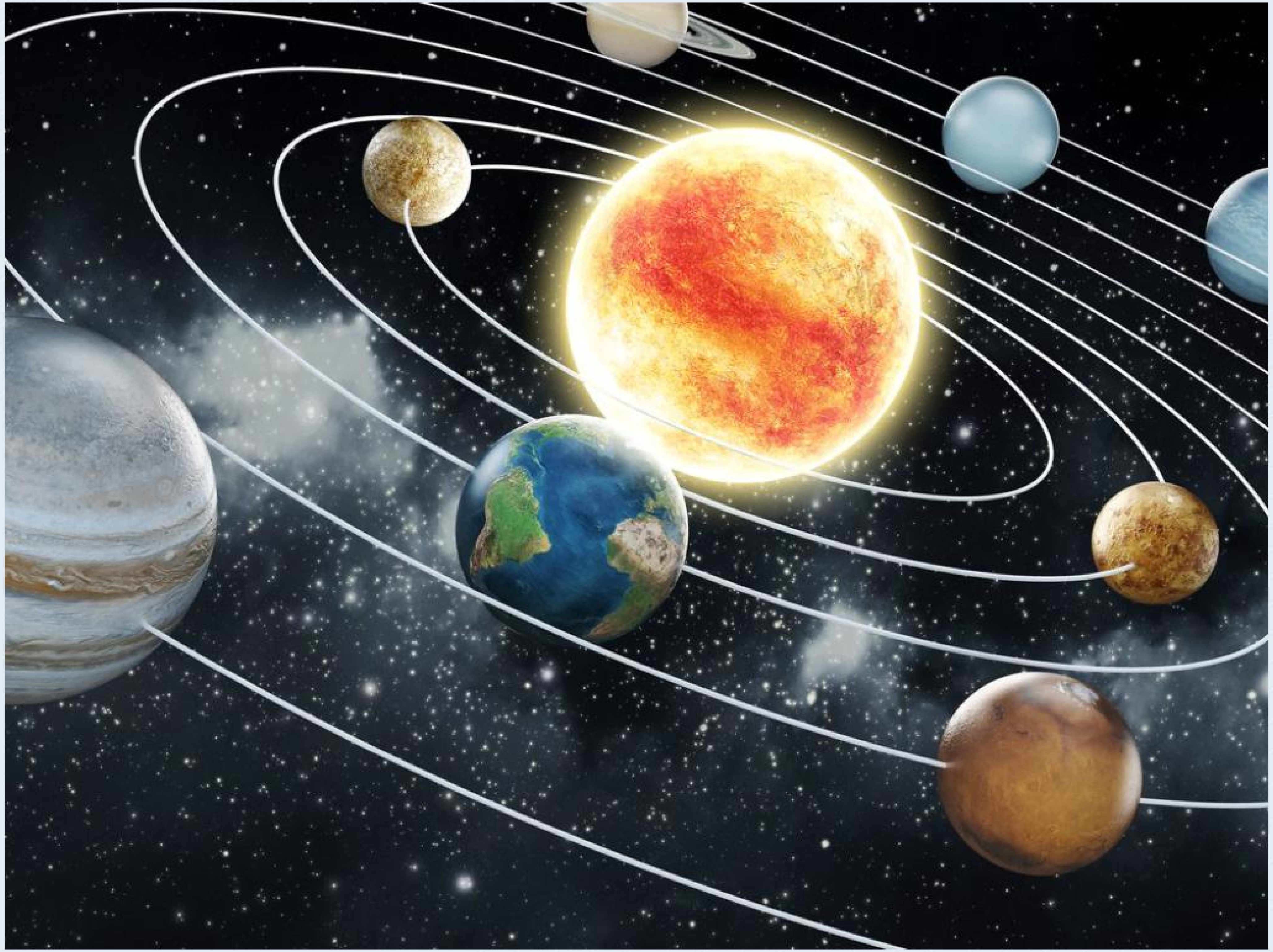

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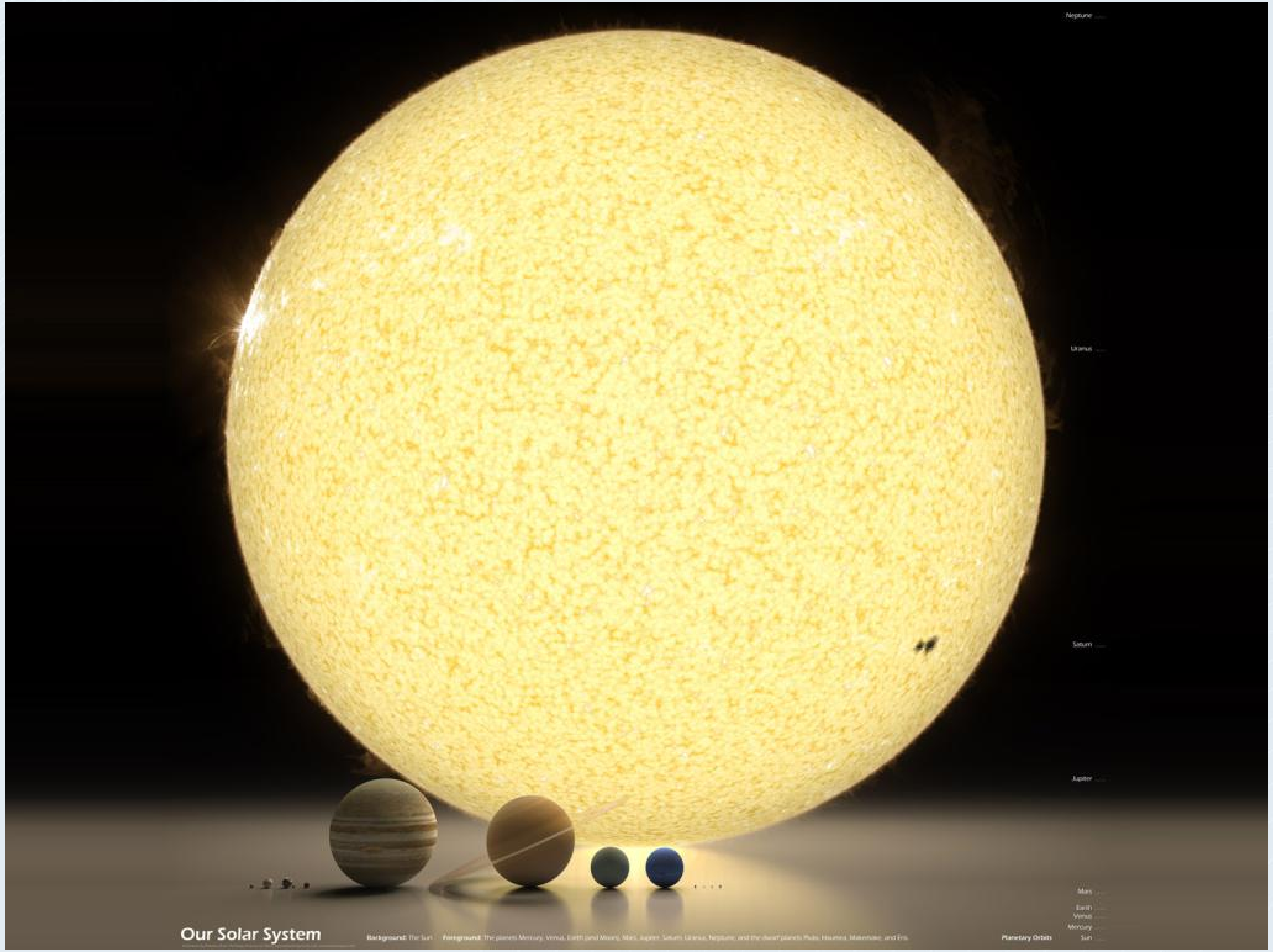

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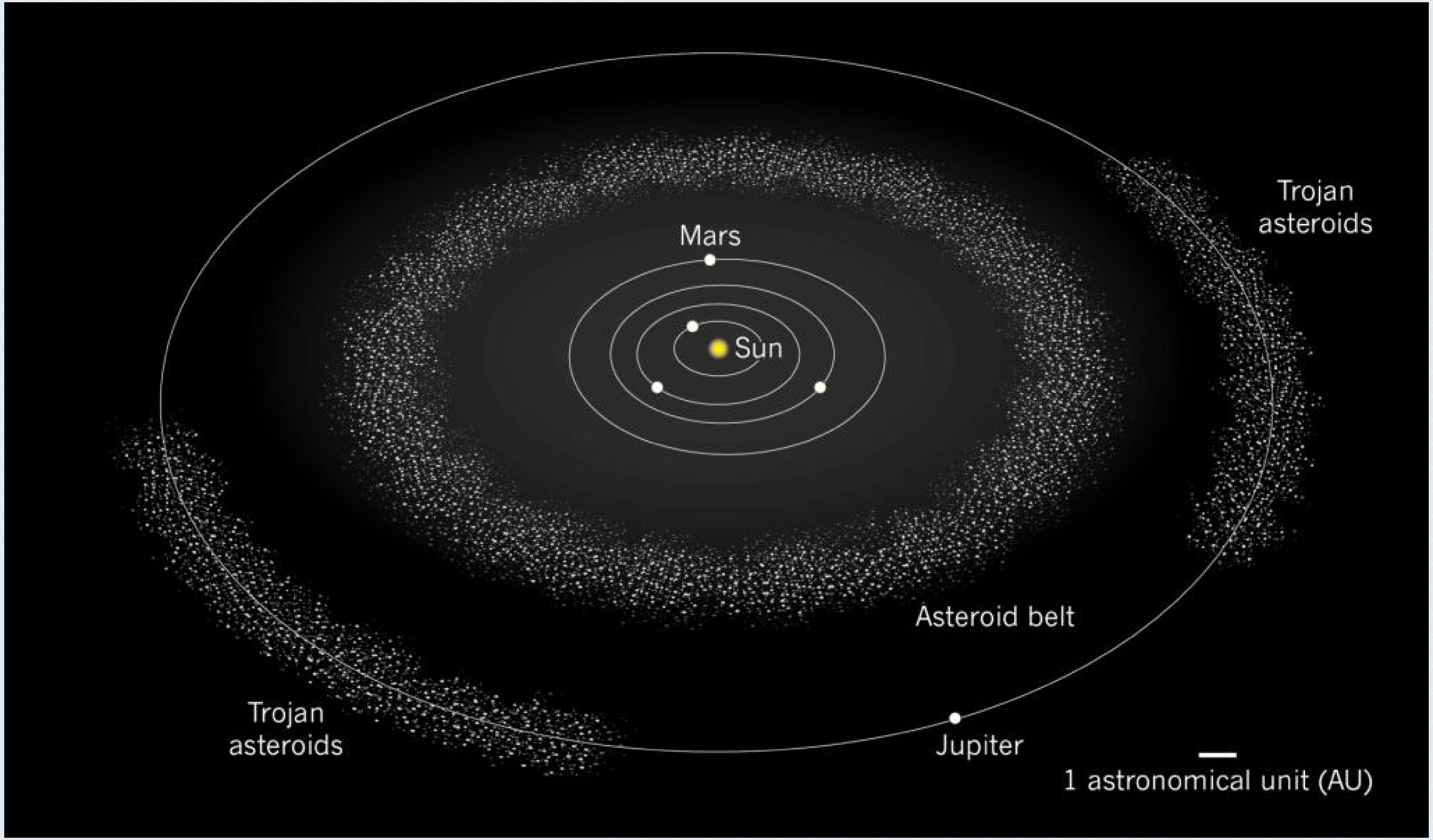

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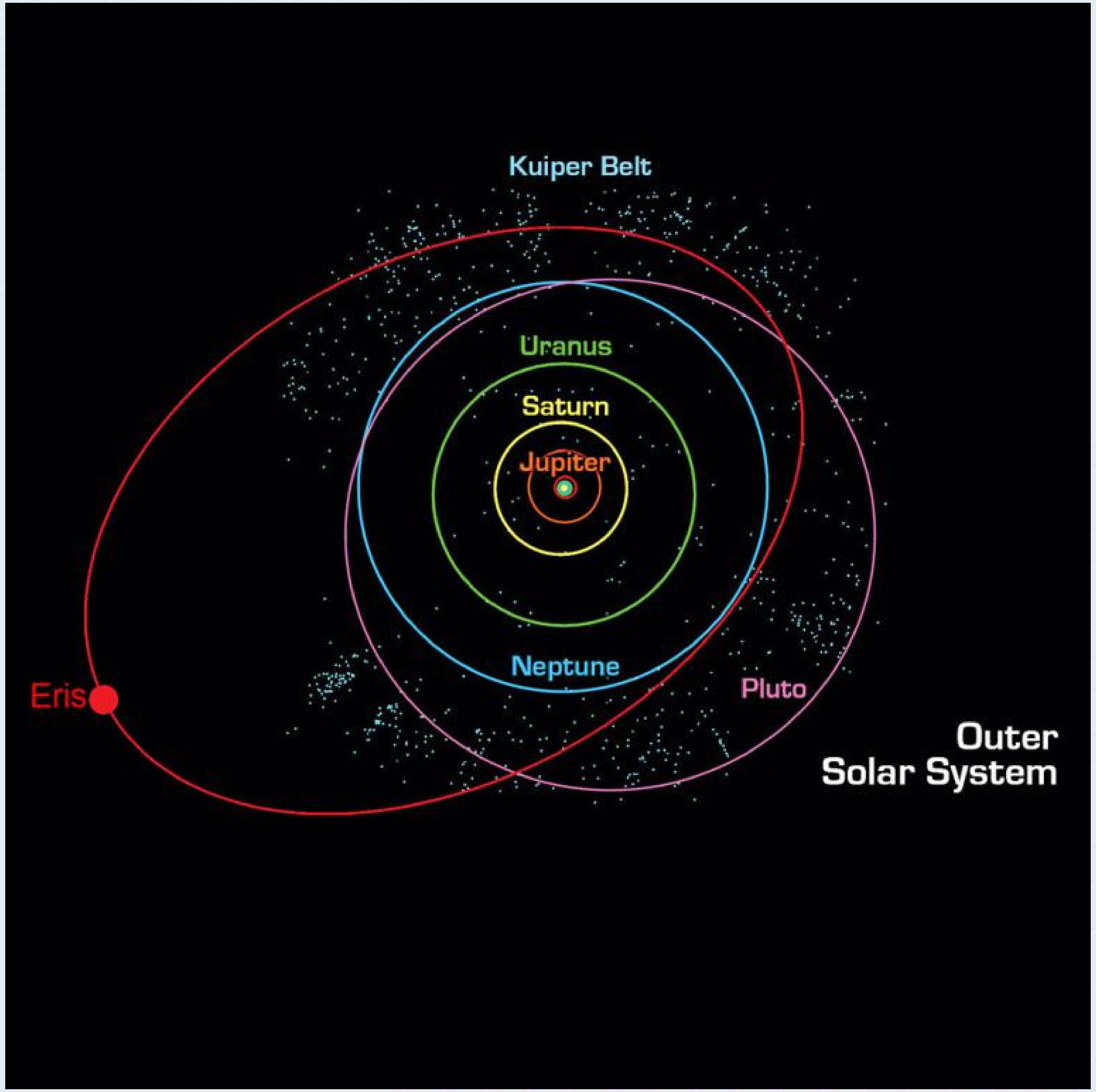


TESS in the Solar System: Kepler/K2 legacy

Kepler/K2 legacy:

12+ papers @ADS, many of them are led by us!

Kepler/K2 legacy:

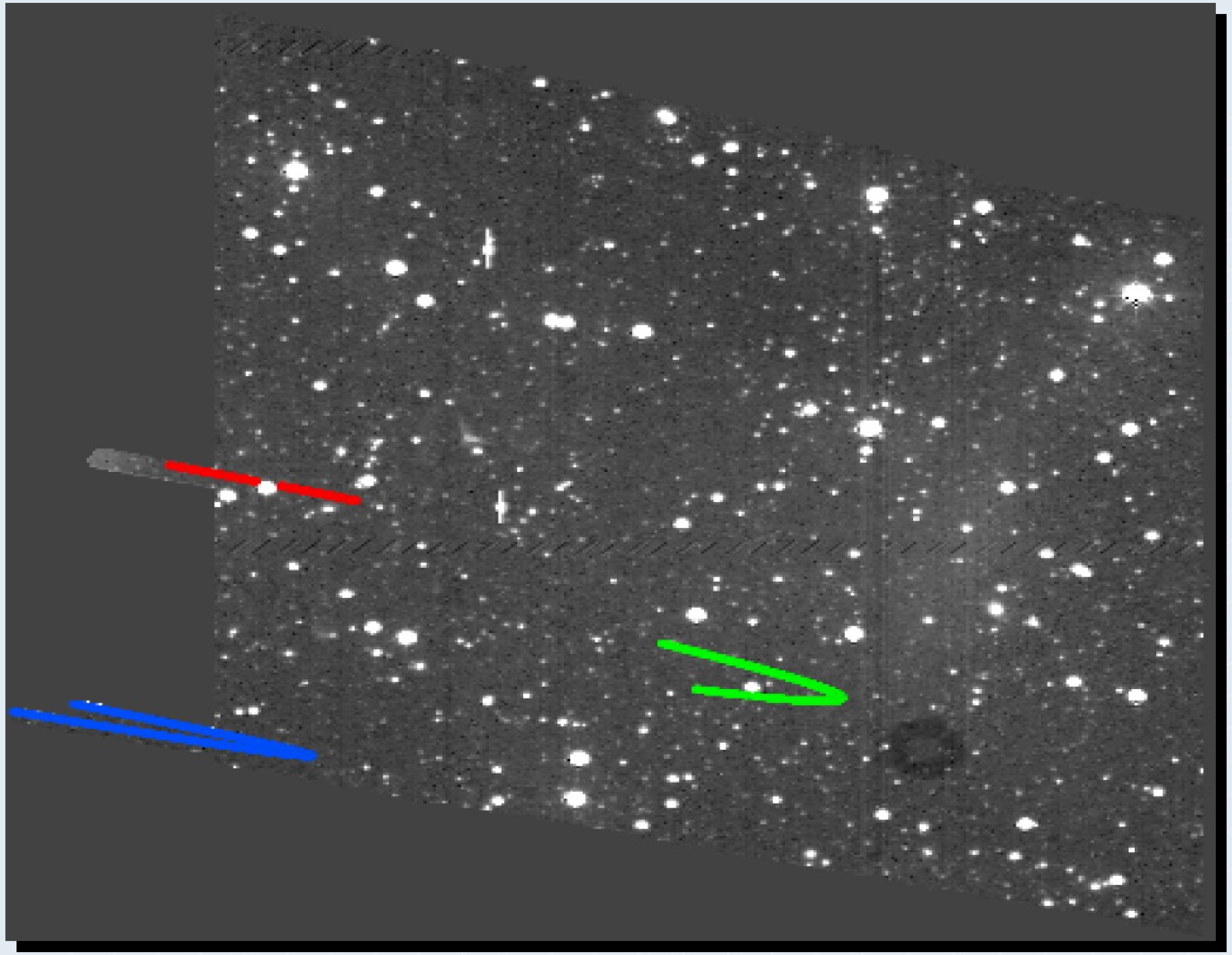
Some interesting papers + topics:

- Szabó, R. et al.: *Main-belt Asteroids in the K2 Engineering Field of View*
- Pál, A. et al.: *Pushing the Limits: K2 Observations of the Trans-Neptunian Objects 2002 GV31 and (278361) 2007 JJ43*
- Kiss, Cs. Et al.: *Nereid from space: rotation, size and shape analysis from K2, Herschel and Spitzer observations*
- Szabó, Gy. M. et al.: *The heart of the swarm: K2 photometry and rotational characteristics of 56 Jovian Trojan asteroids*
- Farkas-Takács, A. et al.: *Properties of the Irregular Satellite System around Uranus Inferred from K2, Herschel, and Spitzer Observations*
- Molnár, L. et al.: *Main-belt Asteroids in the K2 Uranus Field*

Kepler/K2 legacy:

Farkas-Takács, A. et al.: *Properties of the Irregular Satellite System around Uranus Inferred from K2, Herschel, and Spitzer Observations*

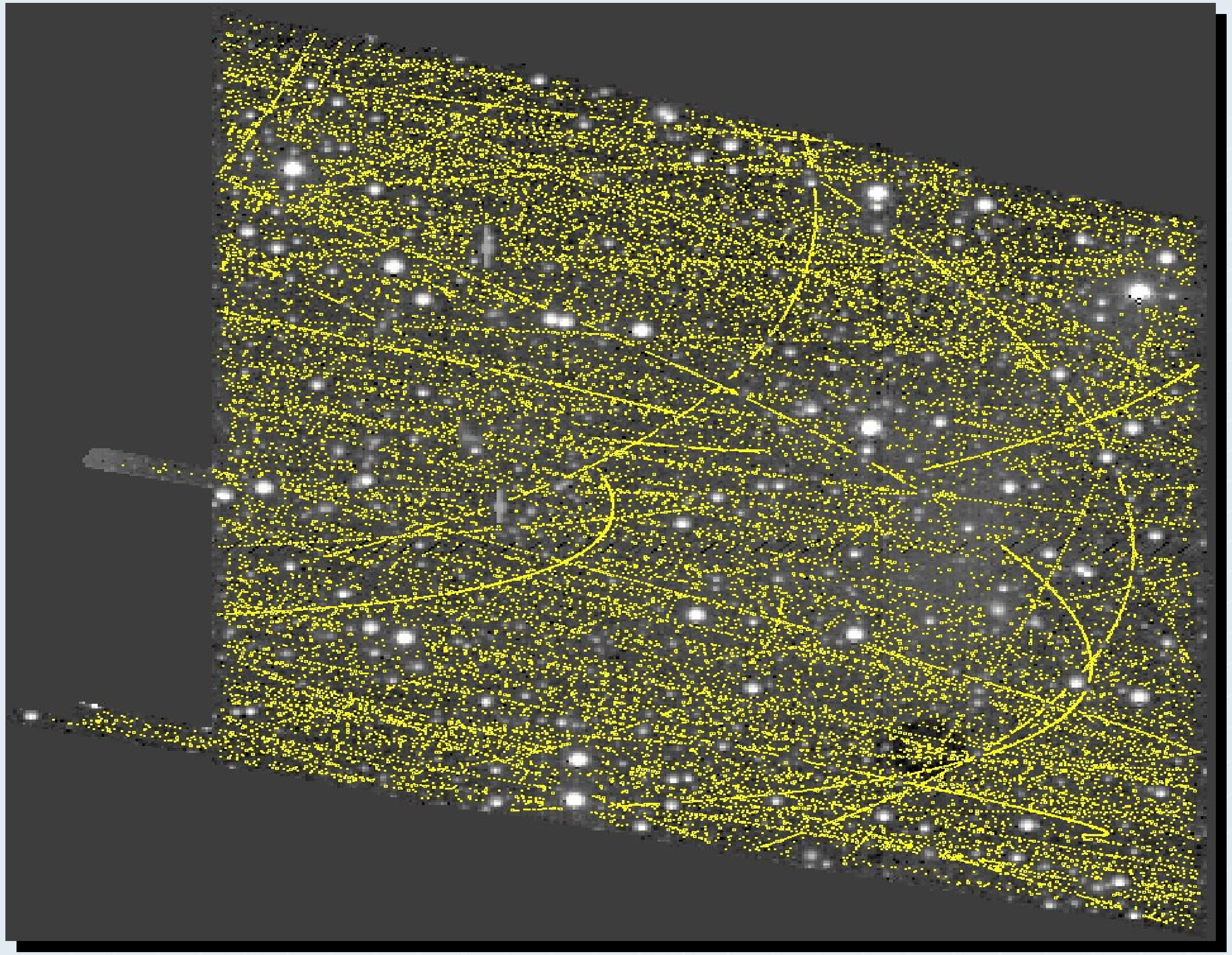
The tracks: Sycorax, Caliban, Setebos



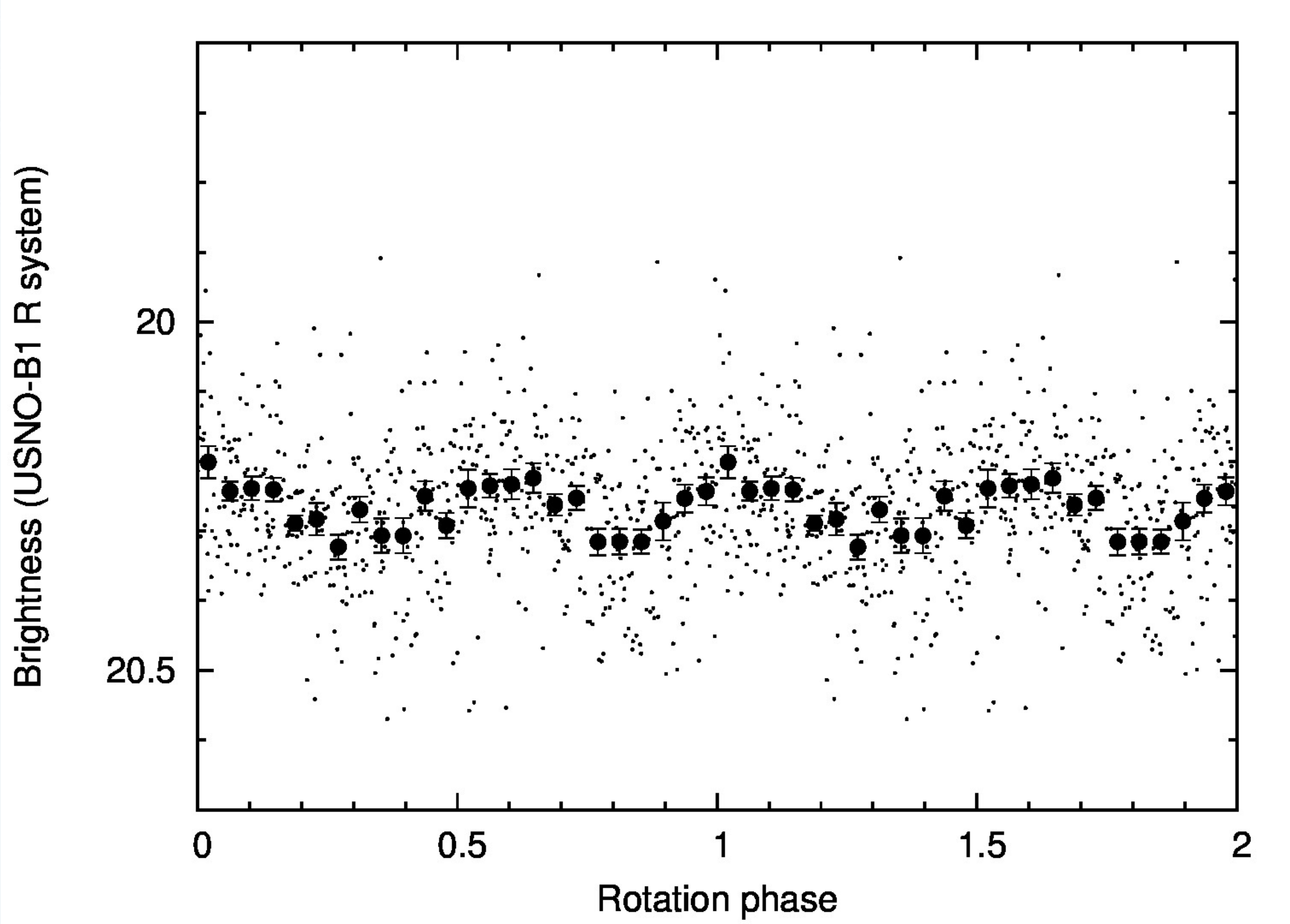
Kepler/K2 legacy:

Molnár, L. et al.: *Main-belt Asteroids in the K2 Uranus Field*

The tracks: yes!

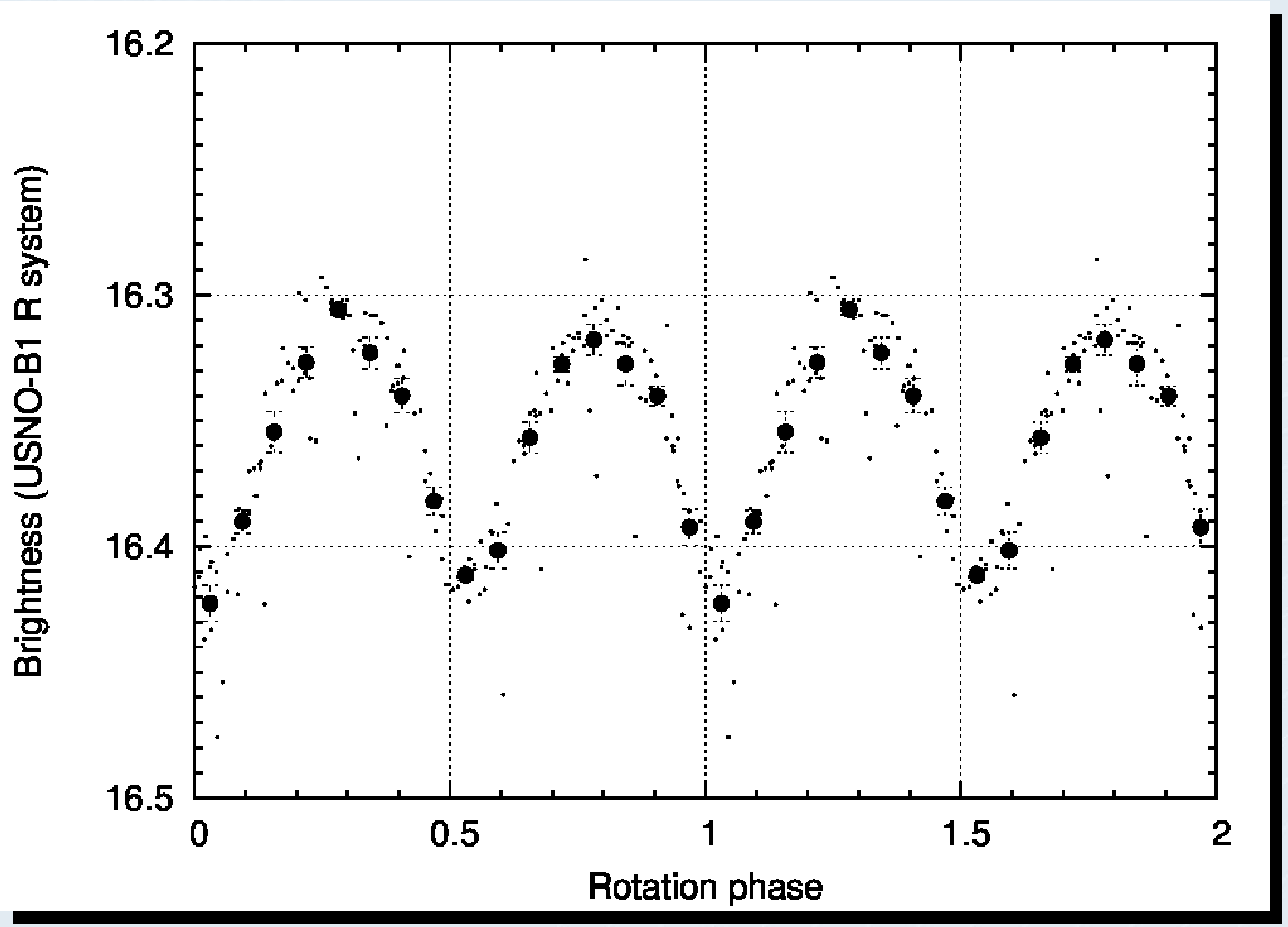


Kepler/K2 legacy:



The light curve of Sycorax (satellite of Uranus)

Kepler/K2 legacy:



The light curve of (1878) Hughes

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Small bodies in the Solar System

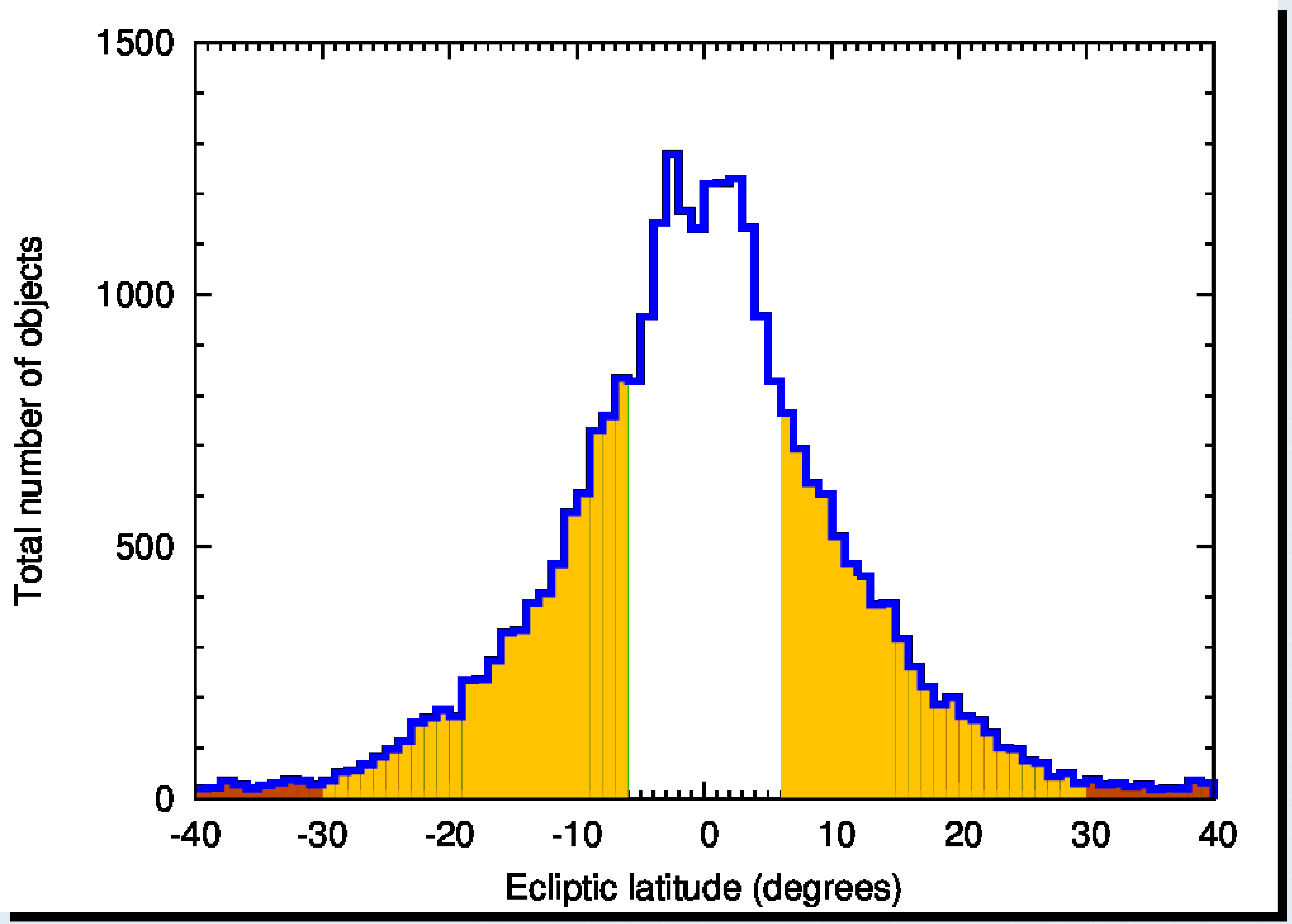
What kind of Solar System bodies are observed?

- **Planets? Not... really... Ecliptic plane is avoided by +/- 6 degrees**
- **Main belt asteroids!**
- **Jupiter Trojans!**
- **Centaurs and comets!**
- **Trans-Neptunian Objects!**
- **Zodiacal light(!)**

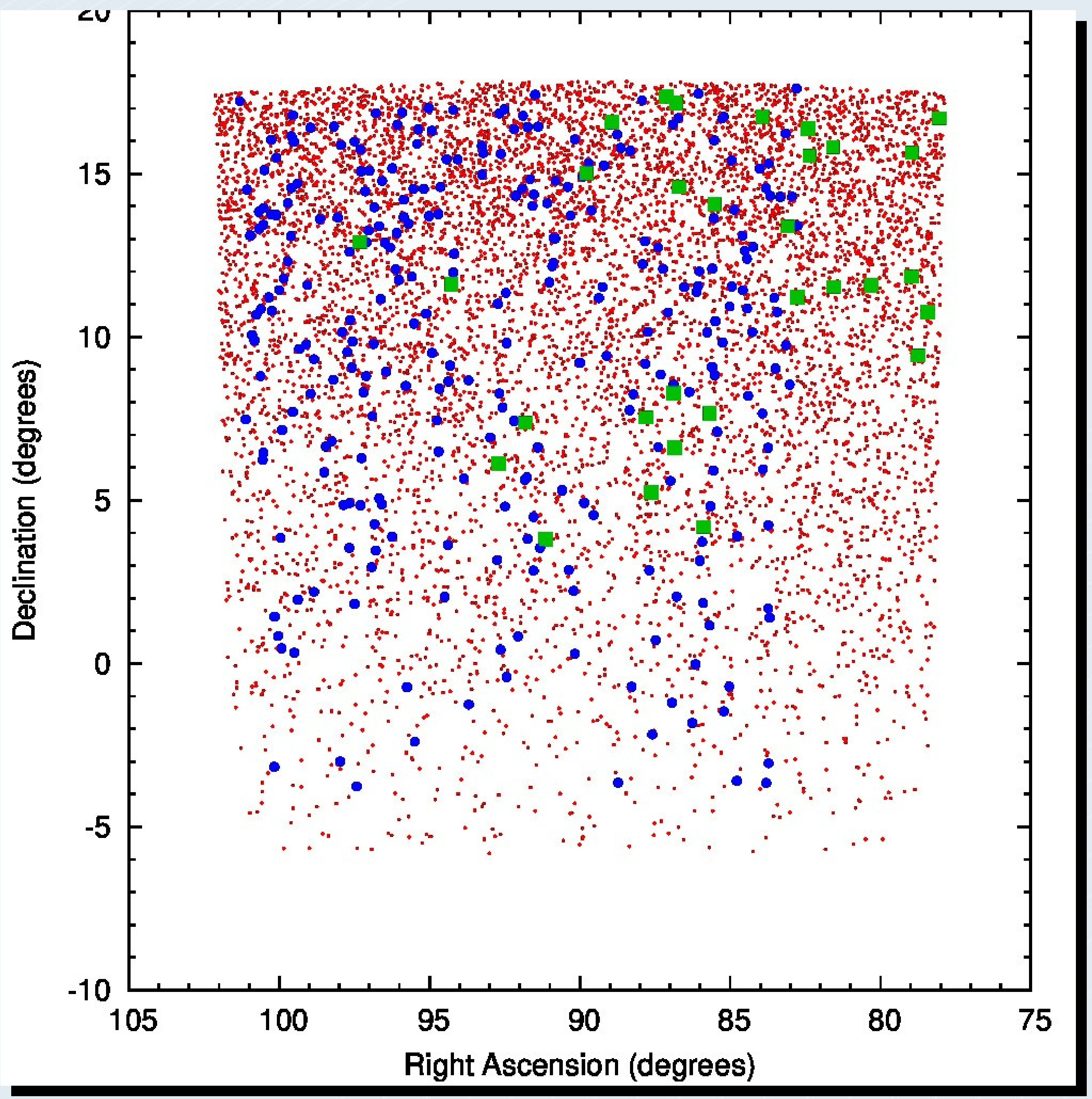
Because the characteristics scale height of these populations is significantly higher than 6 degrees…!

Now (in the primary mission): Camera #1 is our favourite one!

TESS in the Solar System: how does TESS work?



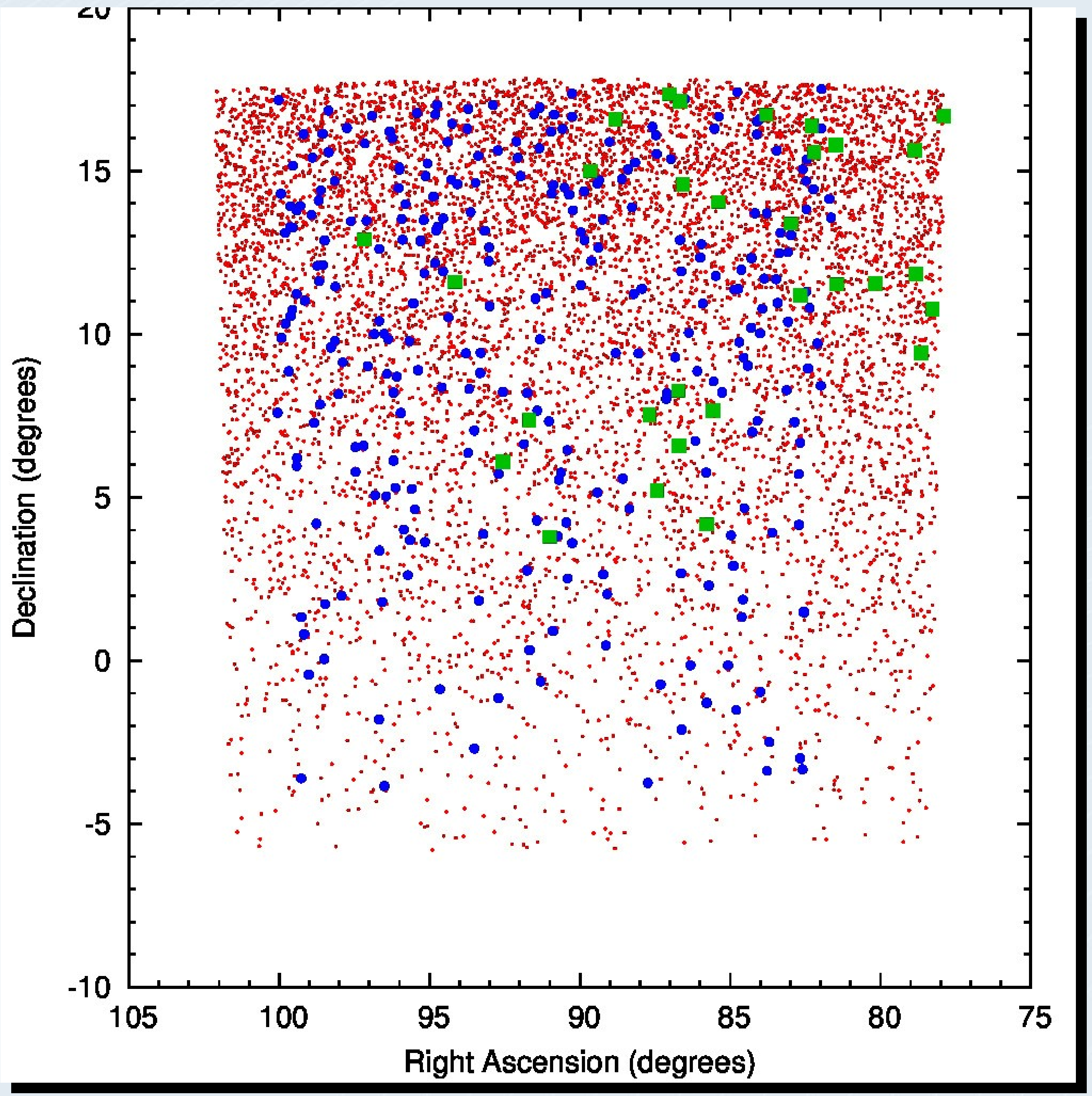
Sector ~6, Camera #1



Day #3

TESS in the Solar System: how does TESS work?

Sector ~6, Camera #1



Day #8

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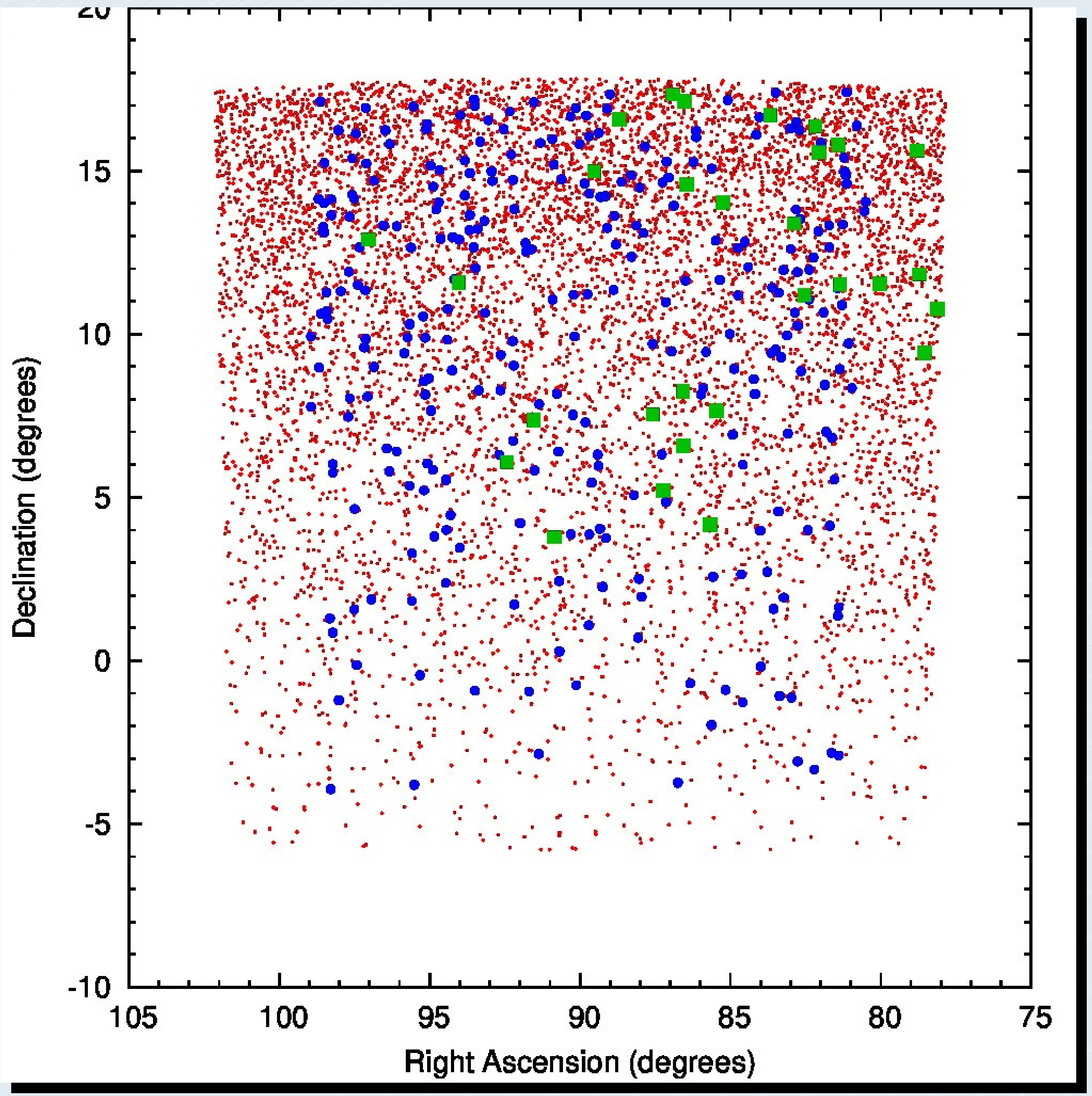
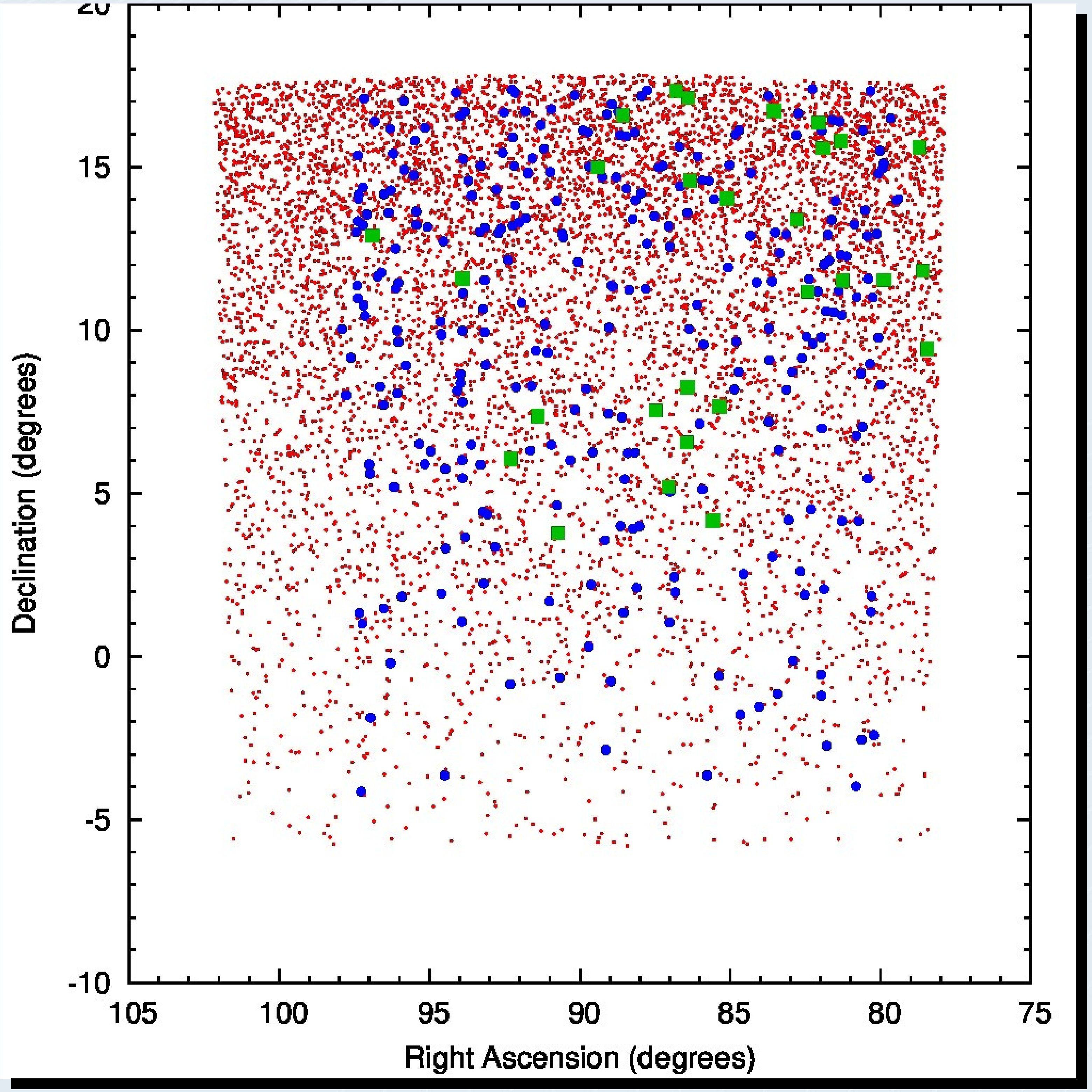
Sector ~6, Camera #1



Day #13

TESS in the Solar System: how does TESS work?

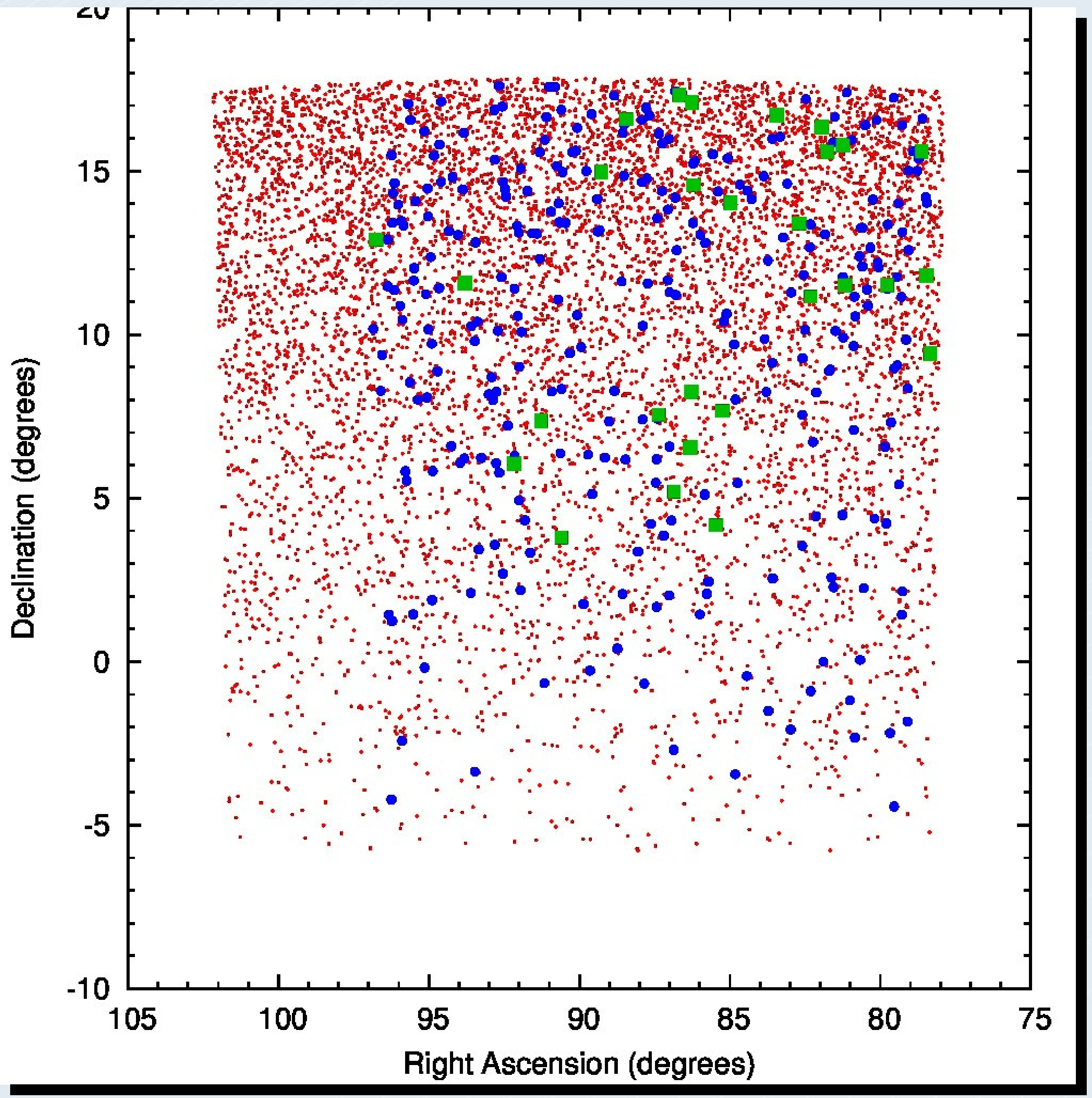
Sector ~6, Camera #1



Day #18

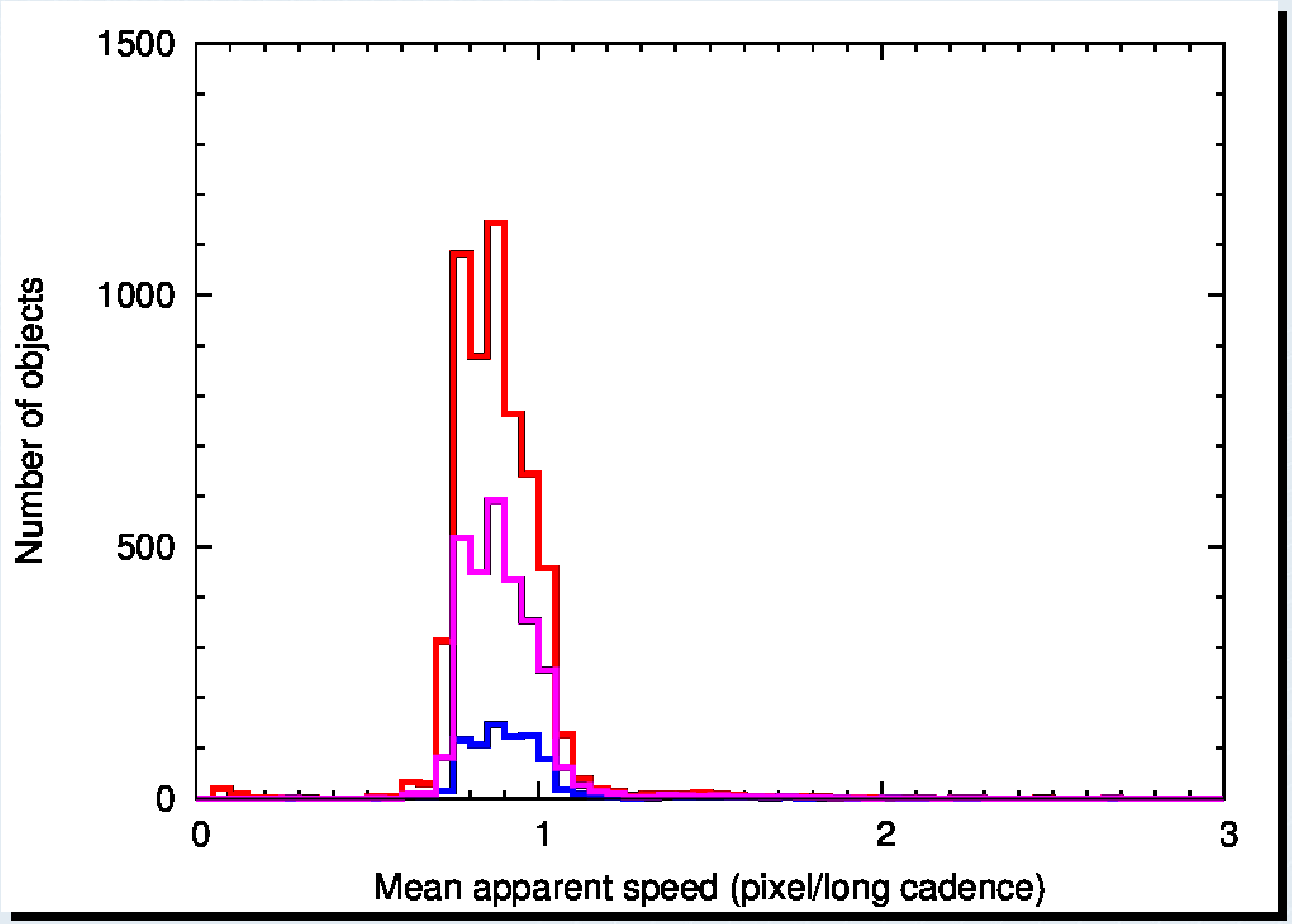
TESS in the Solar System: how does TESS work?

Sector ~6, Camera #1



Day #23

TESS in the Solar System: how does TESS work?



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Asteroid light curves

How can we obtain light curves?

- **Aperture photometry combined with differential photometry**
- **Apertures are not so elongated (see previous images and animations)**

What are the properties of these light curves in general?

- **Uninterrupted (besides those few ours at mid-sector when there is a data downlink period → TESS high gain antenna should point towards Earth, to the Deep Space Network antennas)**
- **Cadence: ½ hours (2-minute cadence would be too expensive…:/)**

Asteroid light curves

Why is it useful for us?

- Practically uninterrupted → nice Fourier spectra and window
- Nice Fourier window → unambiguous rotation period
- TESS observes towards the anti-Sun direction → one can measure the opposition surge → it makes constraints on the surface roughness
- Observations from multiple epochs → constraints on the spin axis orientation

How many light curves can we have?

- Hundreds or thousands for each sector!
- Due to the retrograde motion around opposition, a given asteroid won't be observed in the next sector.

Asteroid light curves – simulations

Background:

- Gaia DR2: see Rpmag vs. TESS magnitudes (passbands)
- Complete down to 20+ mag
- PSF size is: FWHM is around 1.6 pixels, let’s simulate this value.
- Pixel scale is known, it is around 170 pixels / degree.

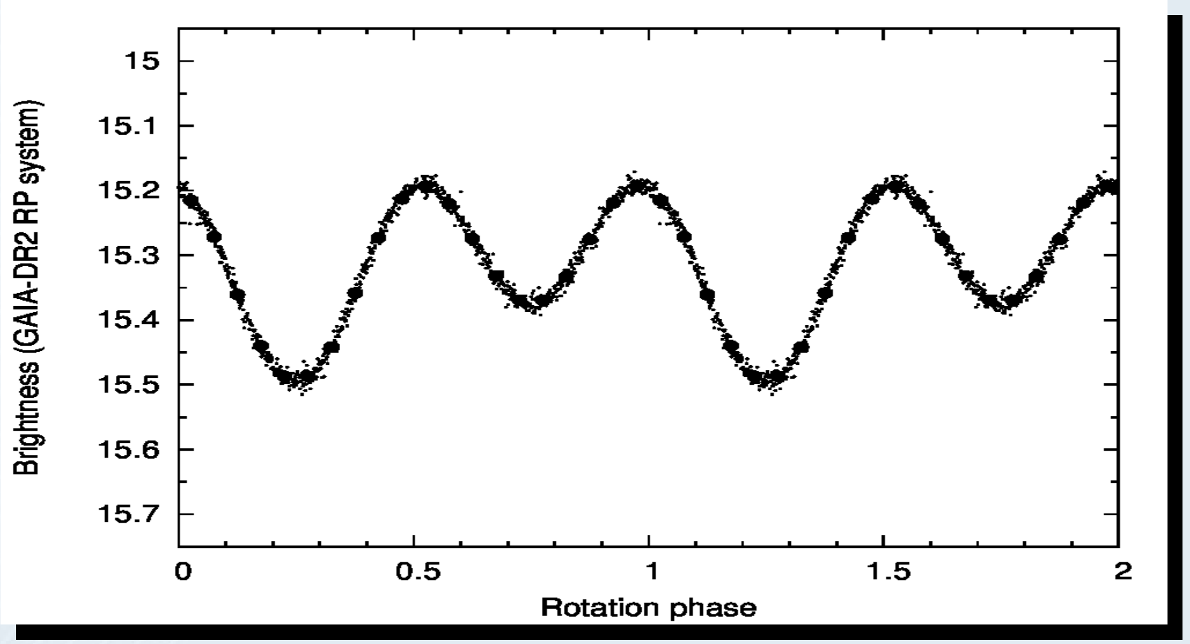
Foreground:

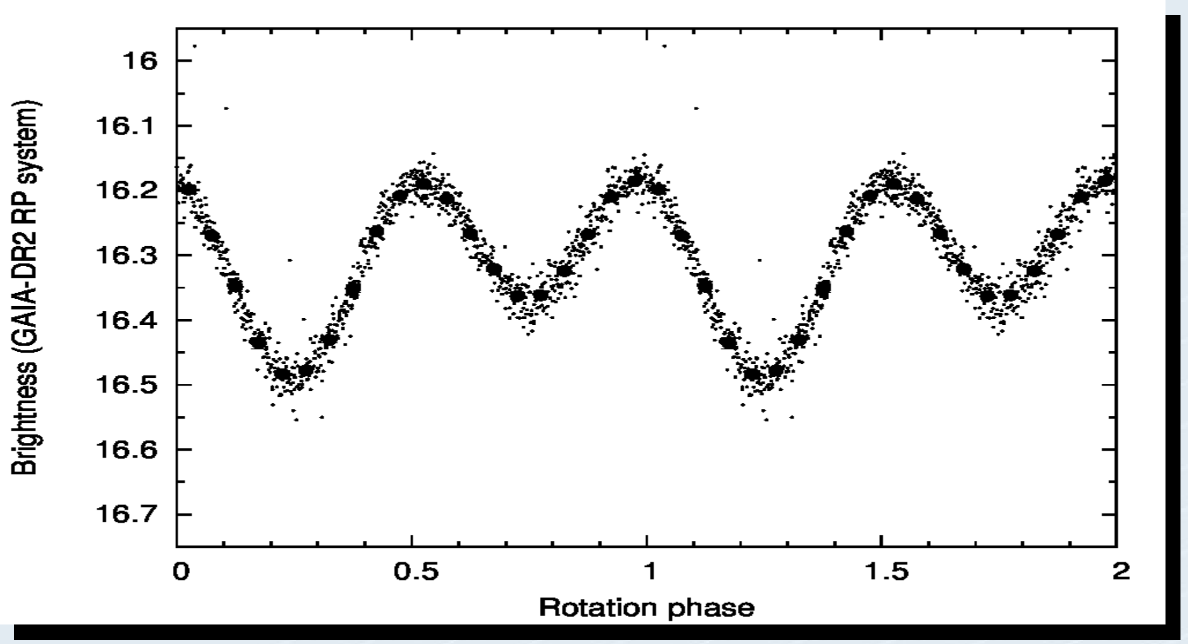
- Minor Planet Center: MPCORB.dat.gz (700k+ lines, one line per object)
- Apparent magnitude is computed from Hmag + distances

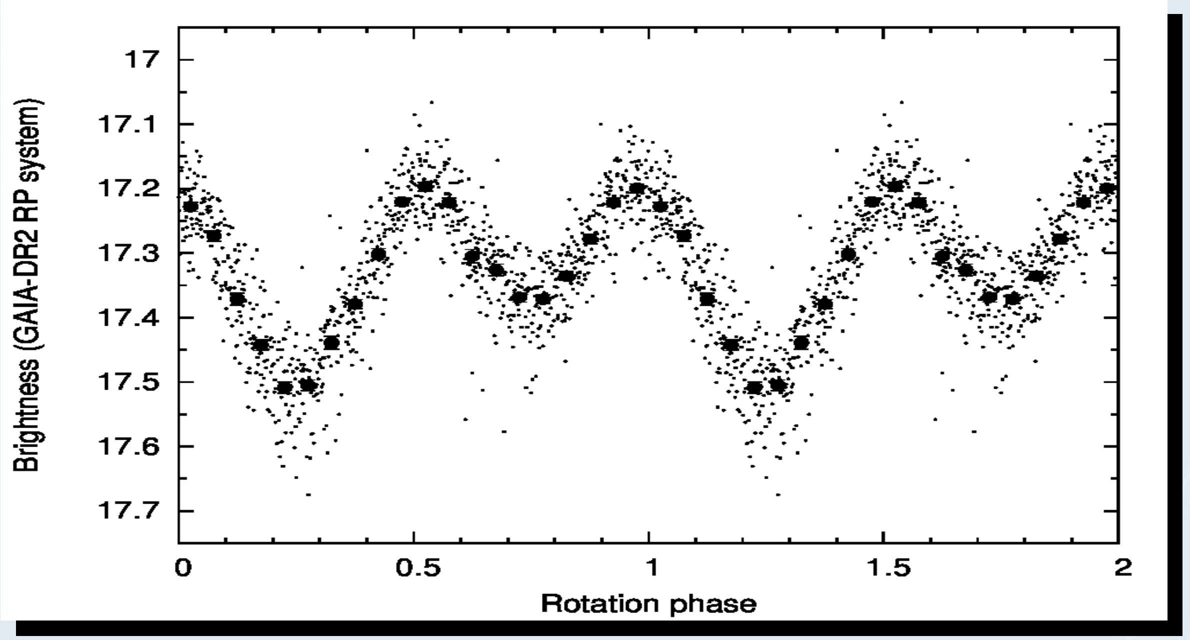
Noise:

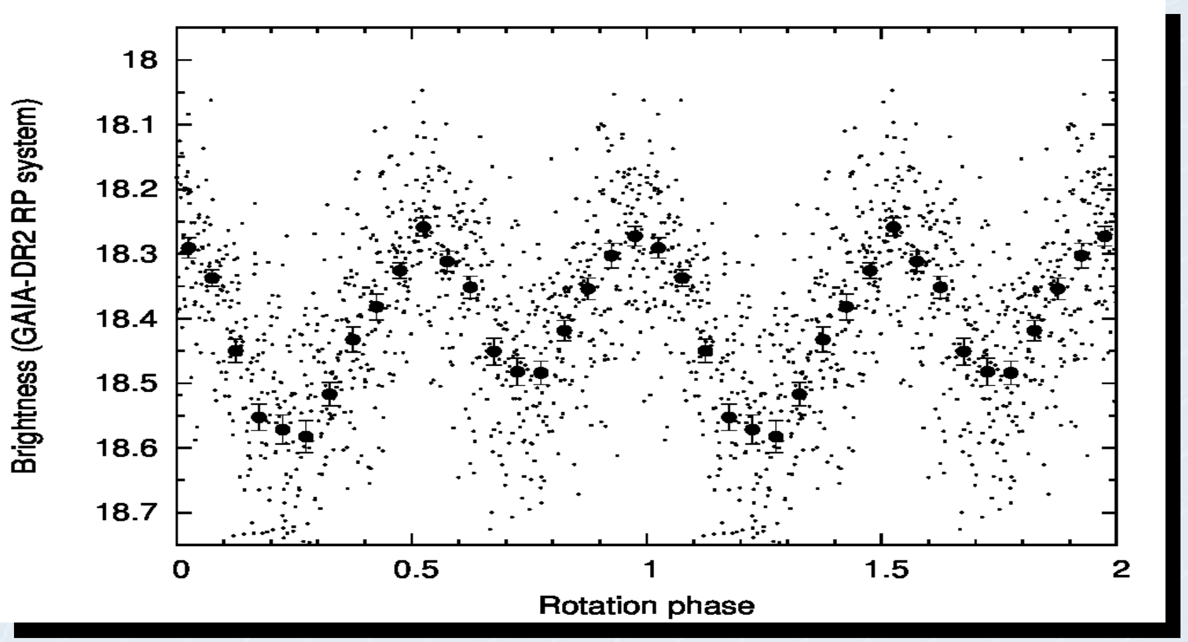
- Readout: 10 electrons / 2 seconds, 300 electrons per long cadence
- Shot noise: 18.3 mag object: 10000 electrons per long cadence

Asteroid light curves – high galactic latitudes

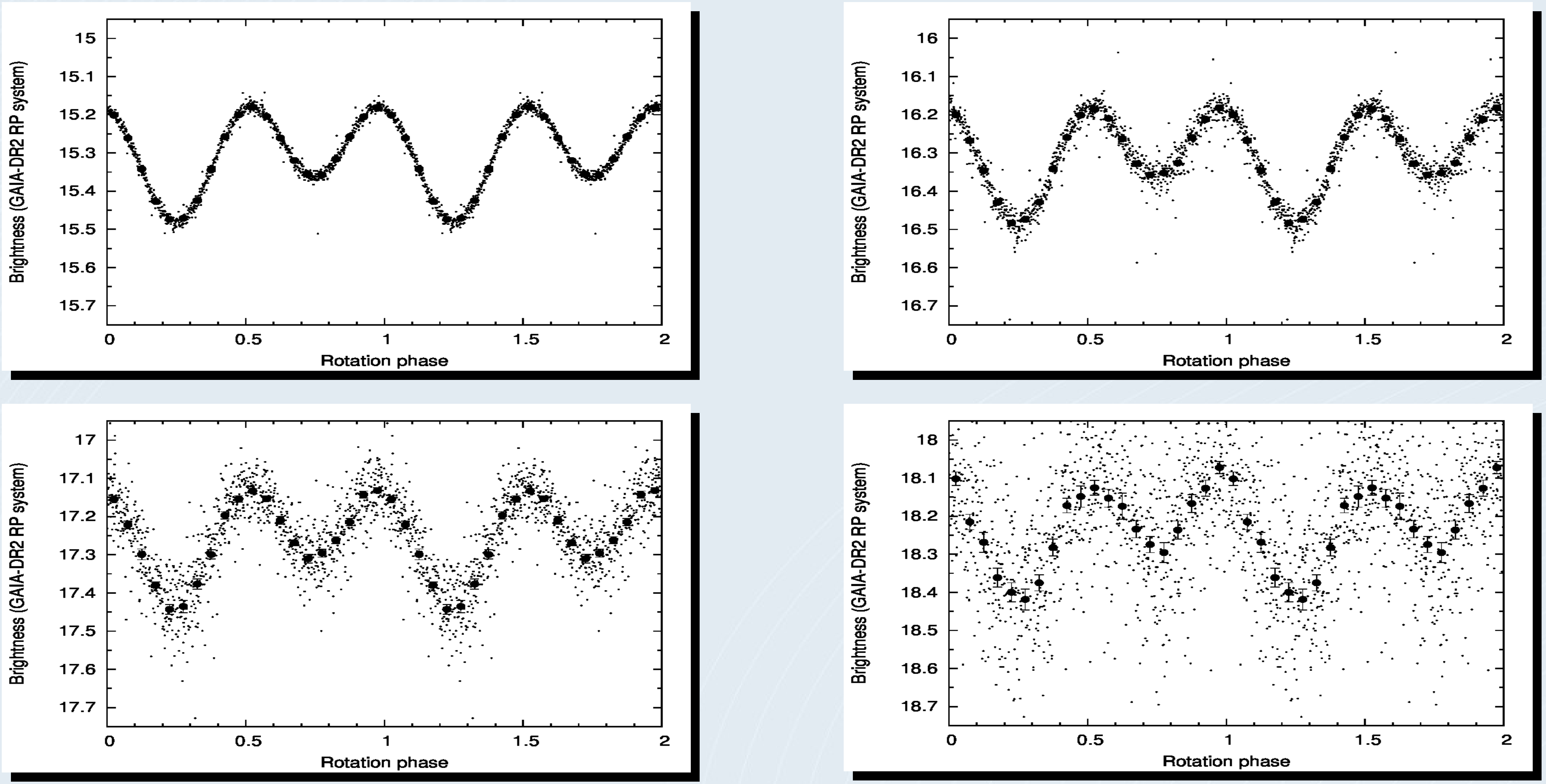




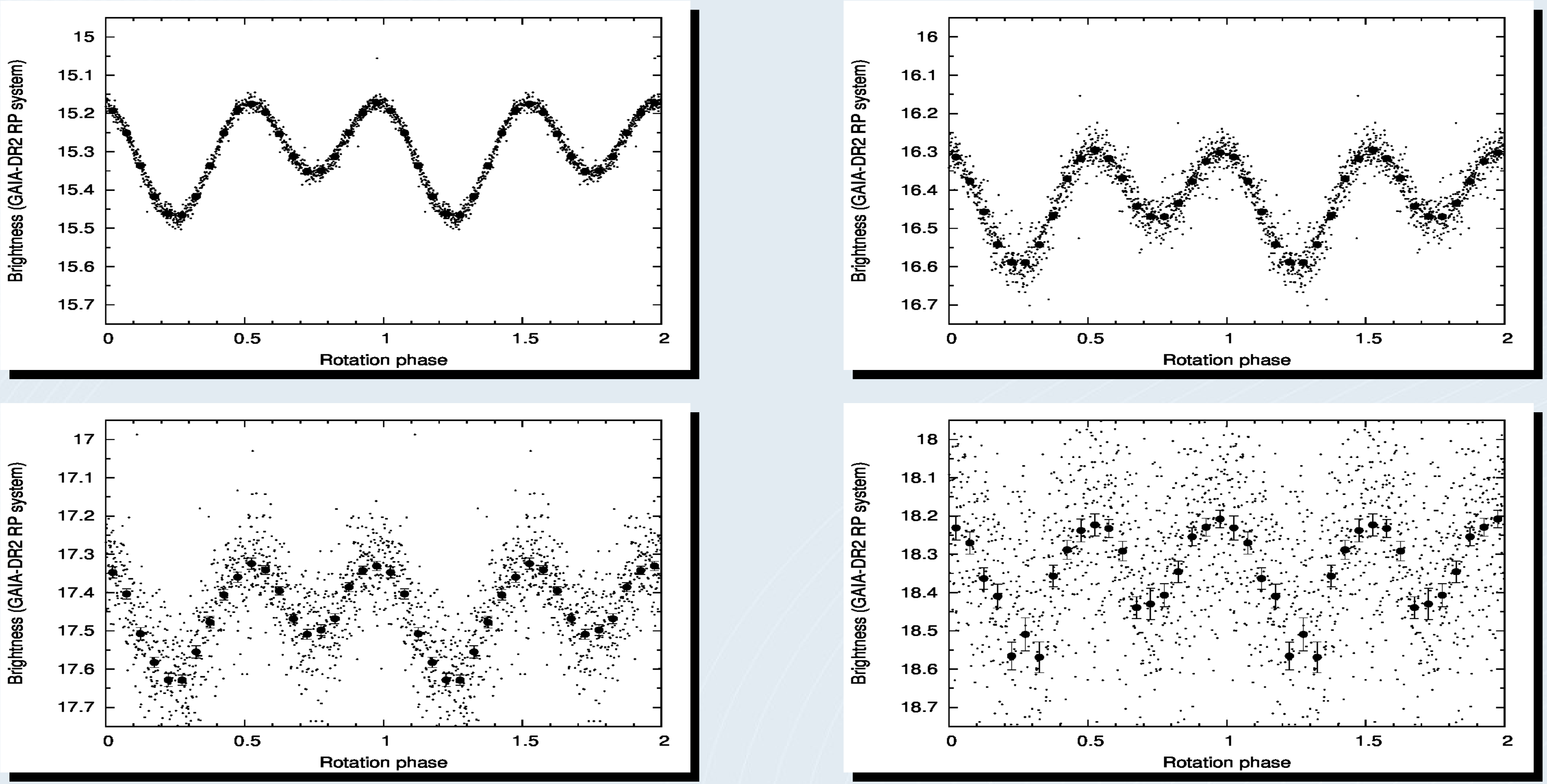




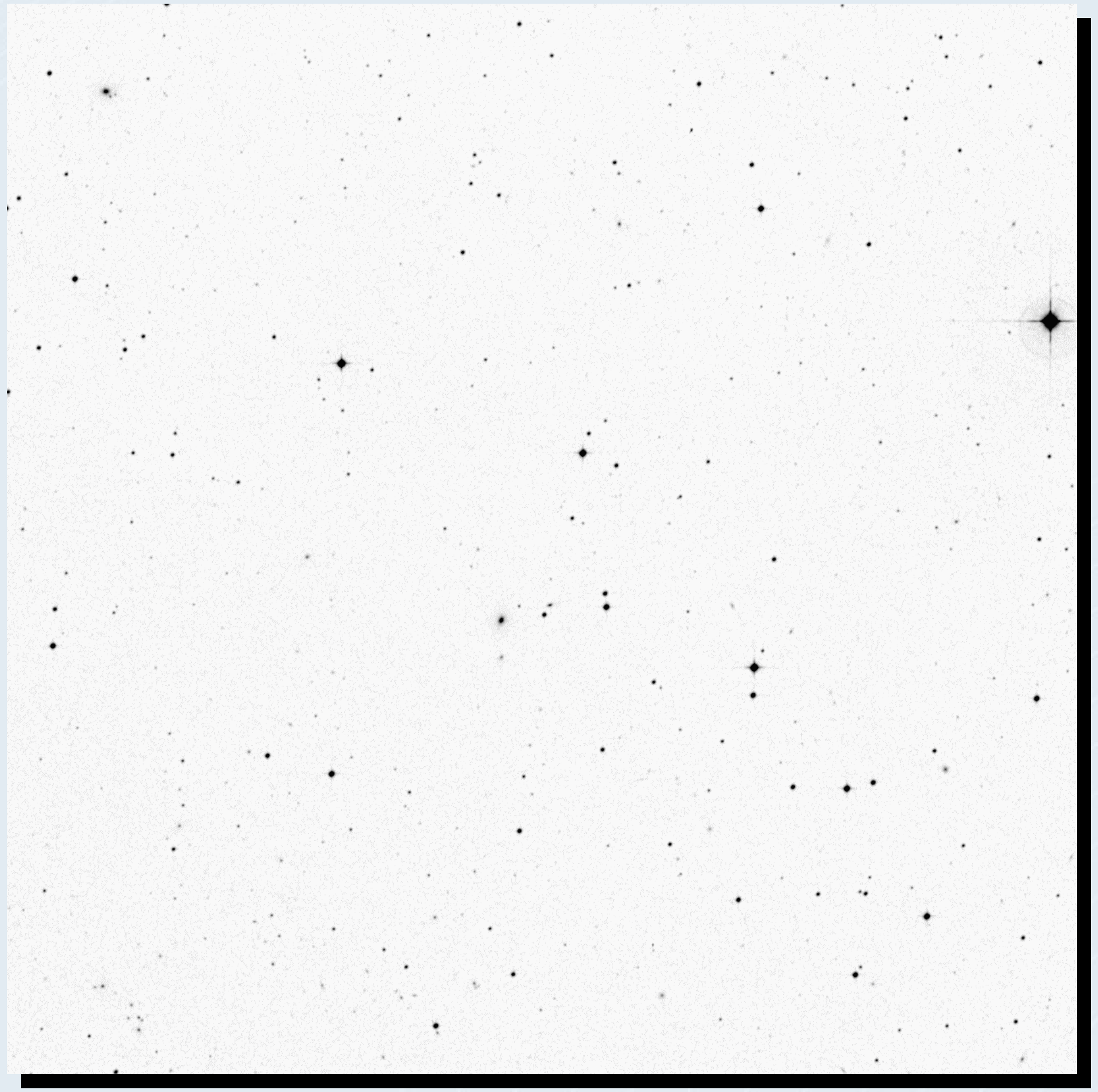
Asteroid light curves – mid galactic latitudes



Asteroid light curves – low galactic latitudes



Trans-Neptunian Objects: Eris – simulations



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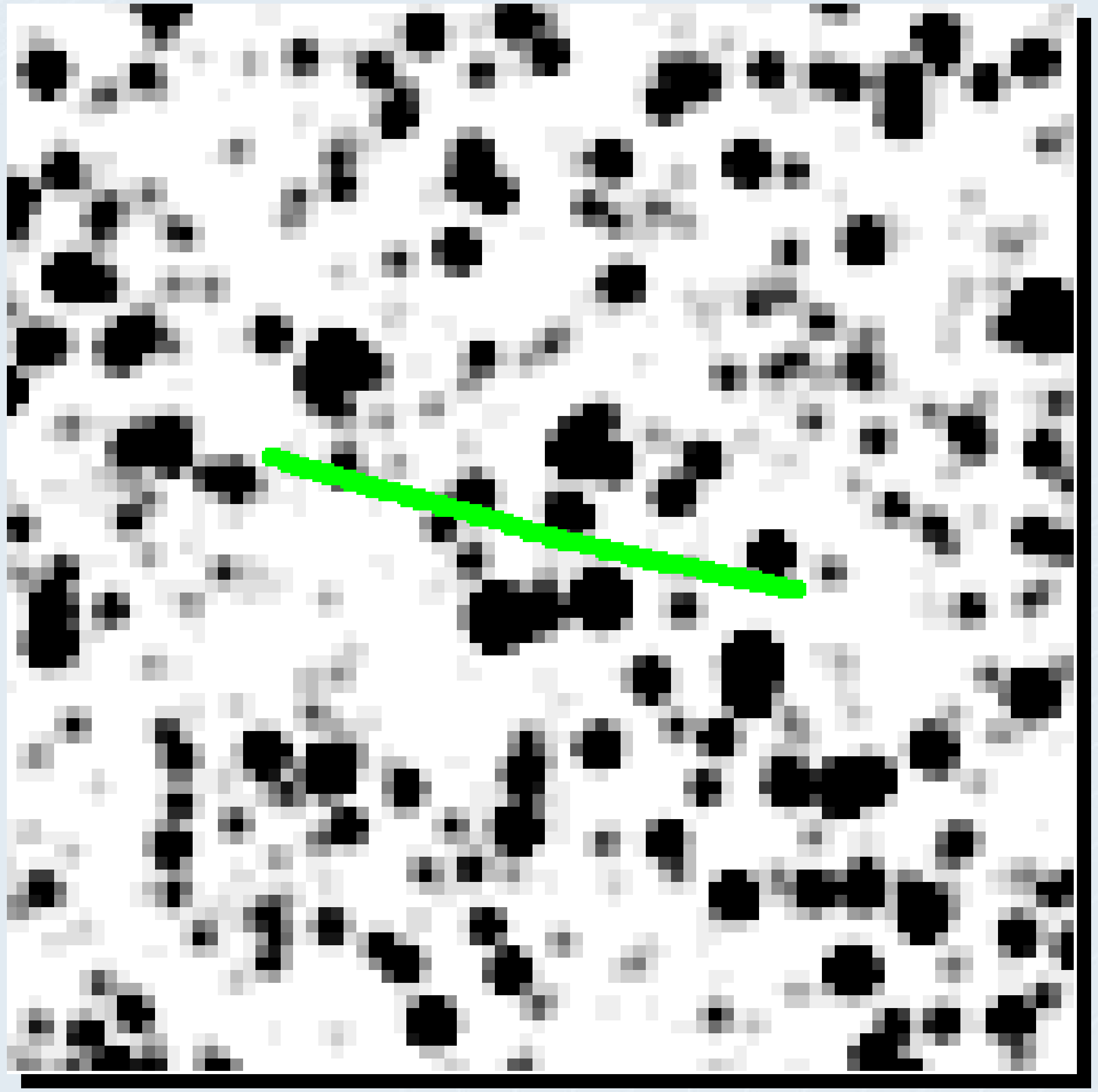

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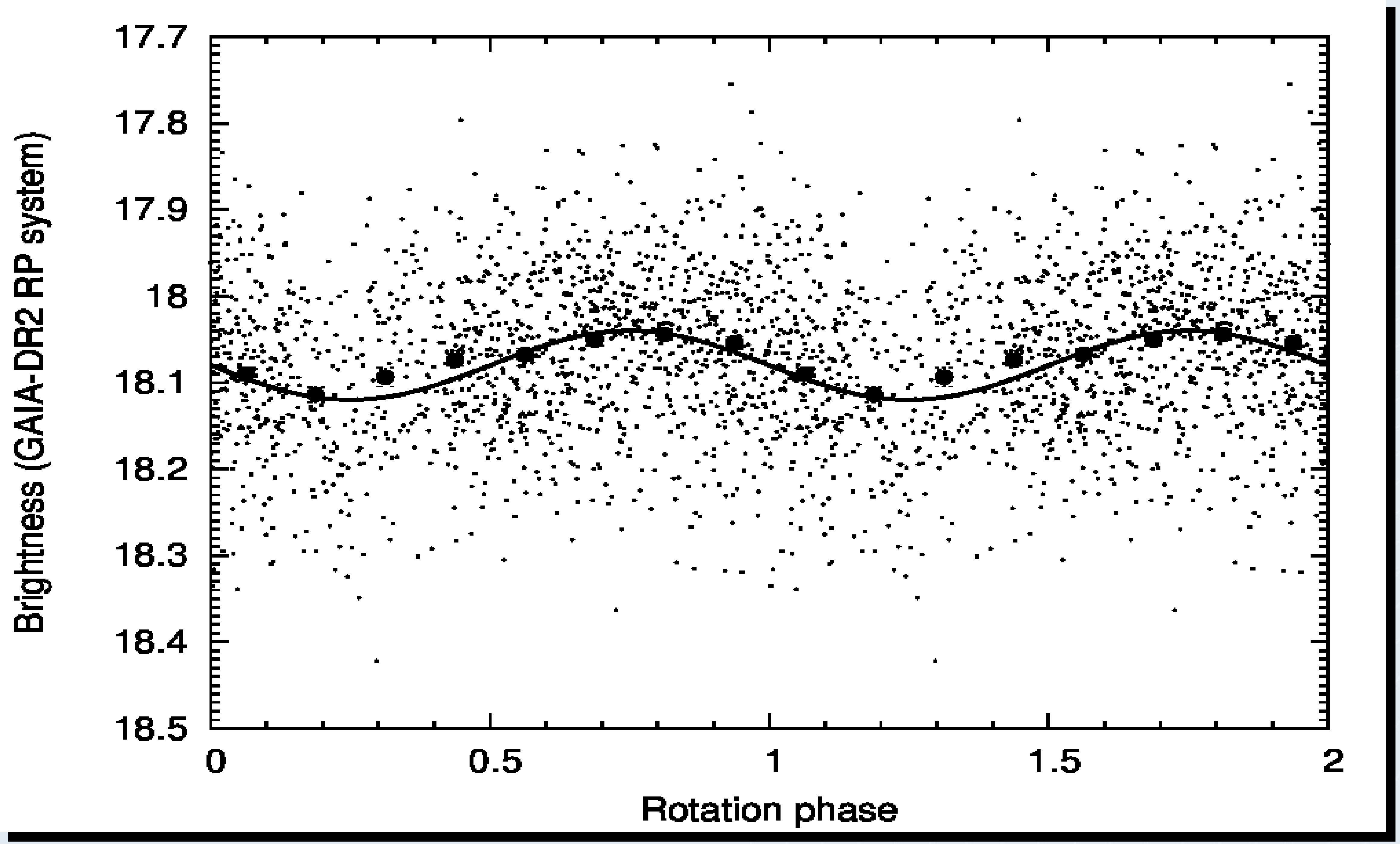

https://fitsh.net/

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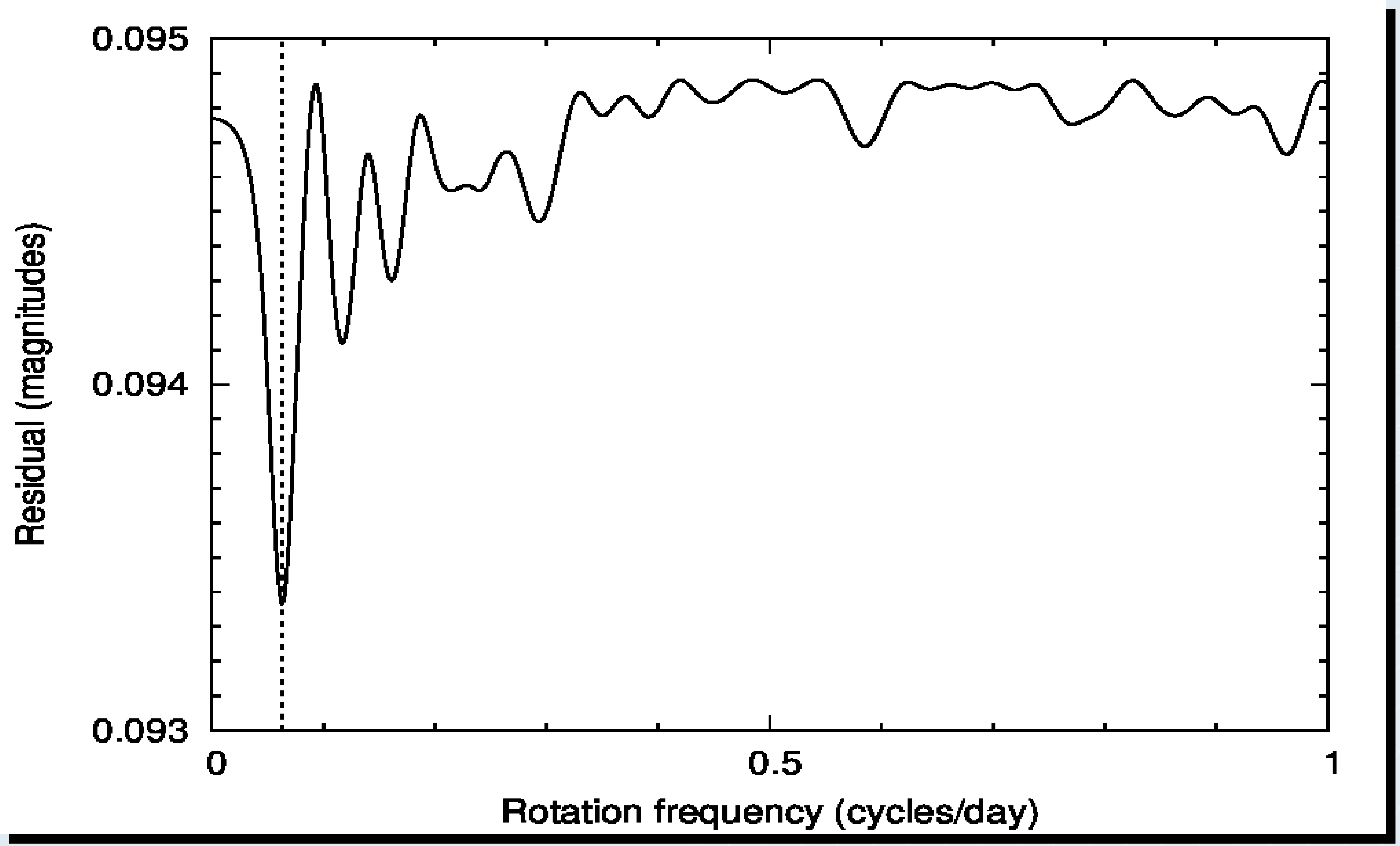


https://fitsh.net/

Asteroid families

What does “asteroid family” mean?

- **(Mostly) a group of main belt objects with similar proper orbital elements.**

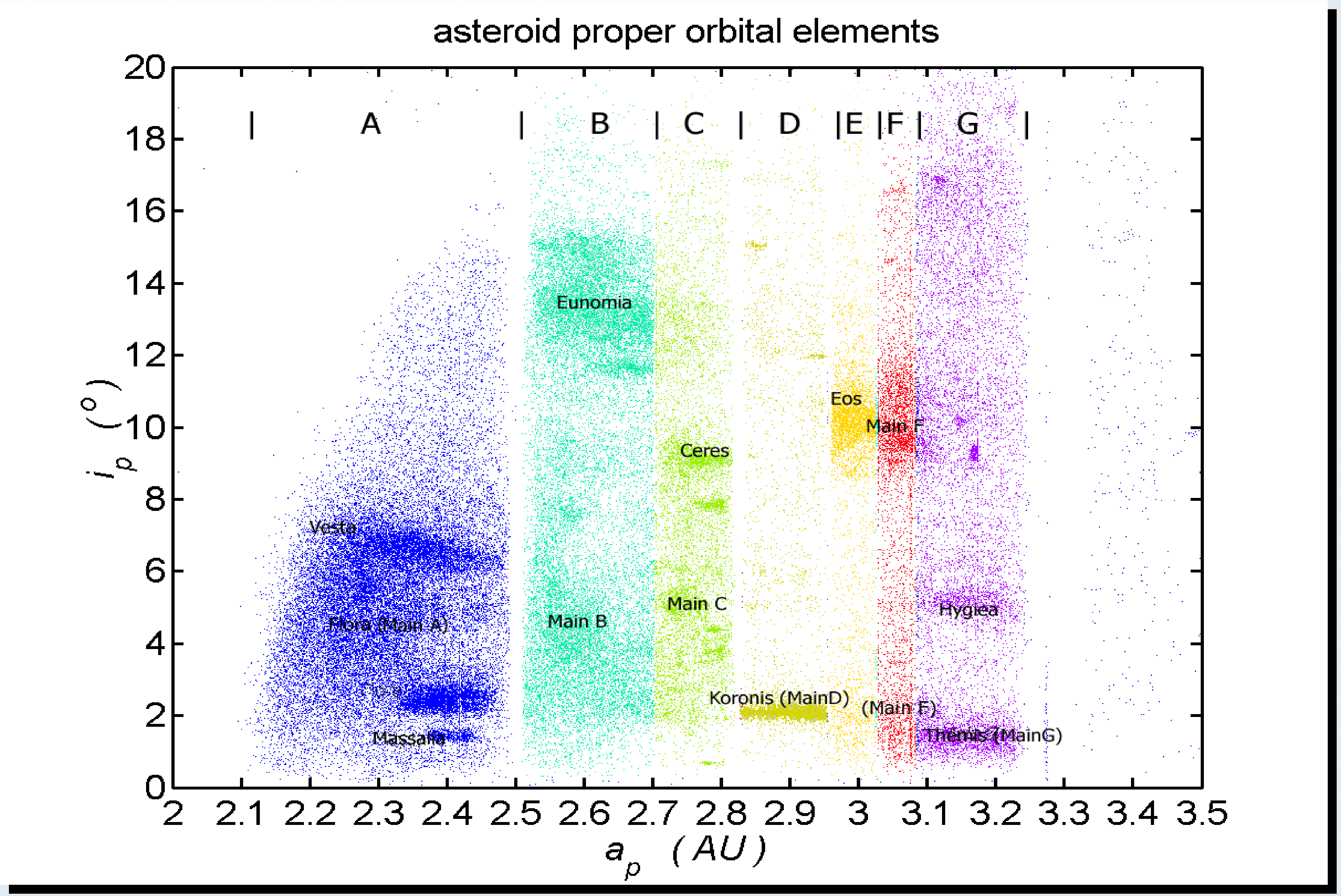
What does “proper orbital elements” mean?

- **Proper elements are constants of motion of an object in space that remain practically unchanged over an astronomically long timescale.**
- **Proper orbital elements can be: semimajor axis, eccentricity and inclination.**

Why is it useful for us?

- **The members of the families are thought to be fragments of past asteroid collisions → should have similar phsyical characteristics**

TESS in the Solar System: scientific questions & answers



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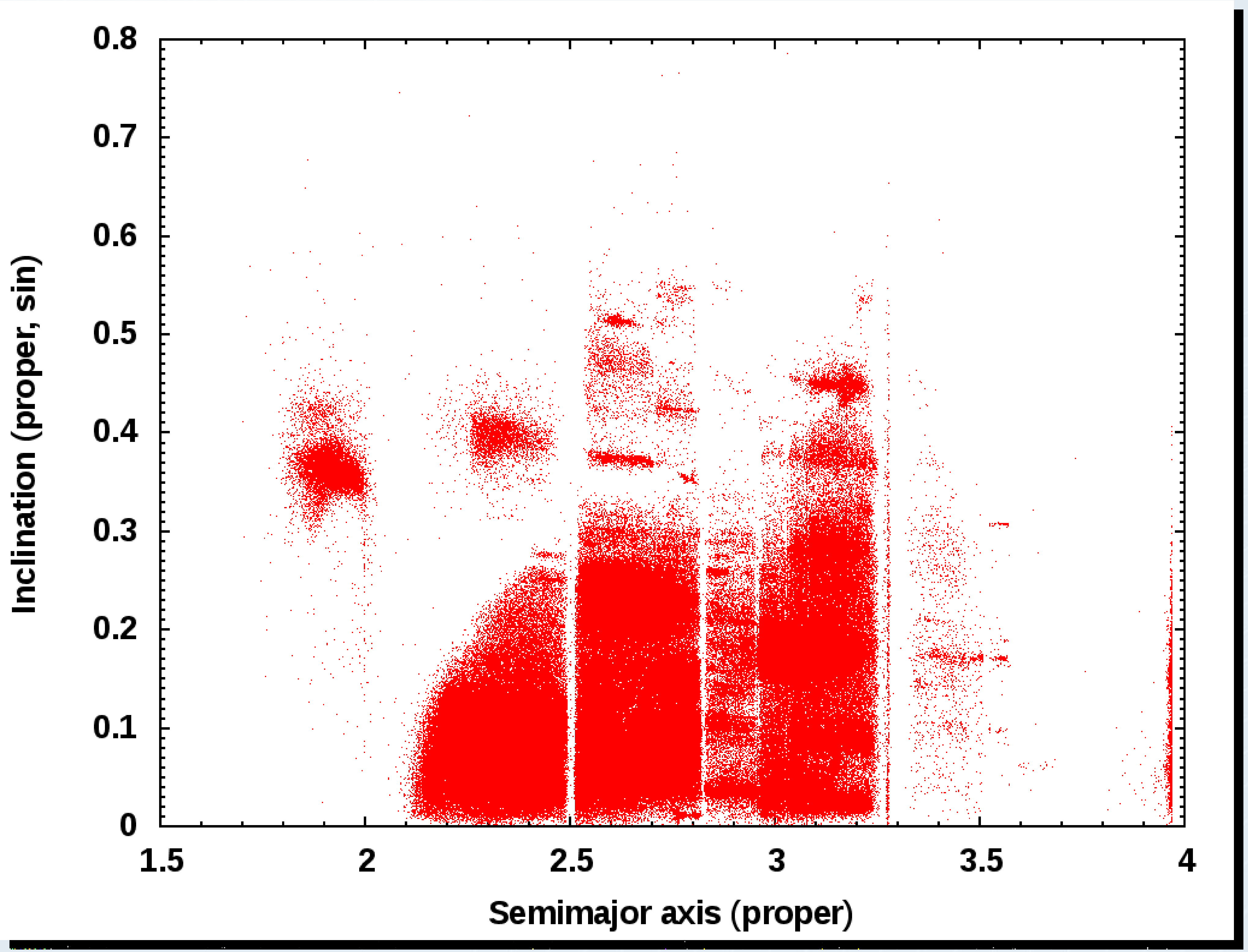

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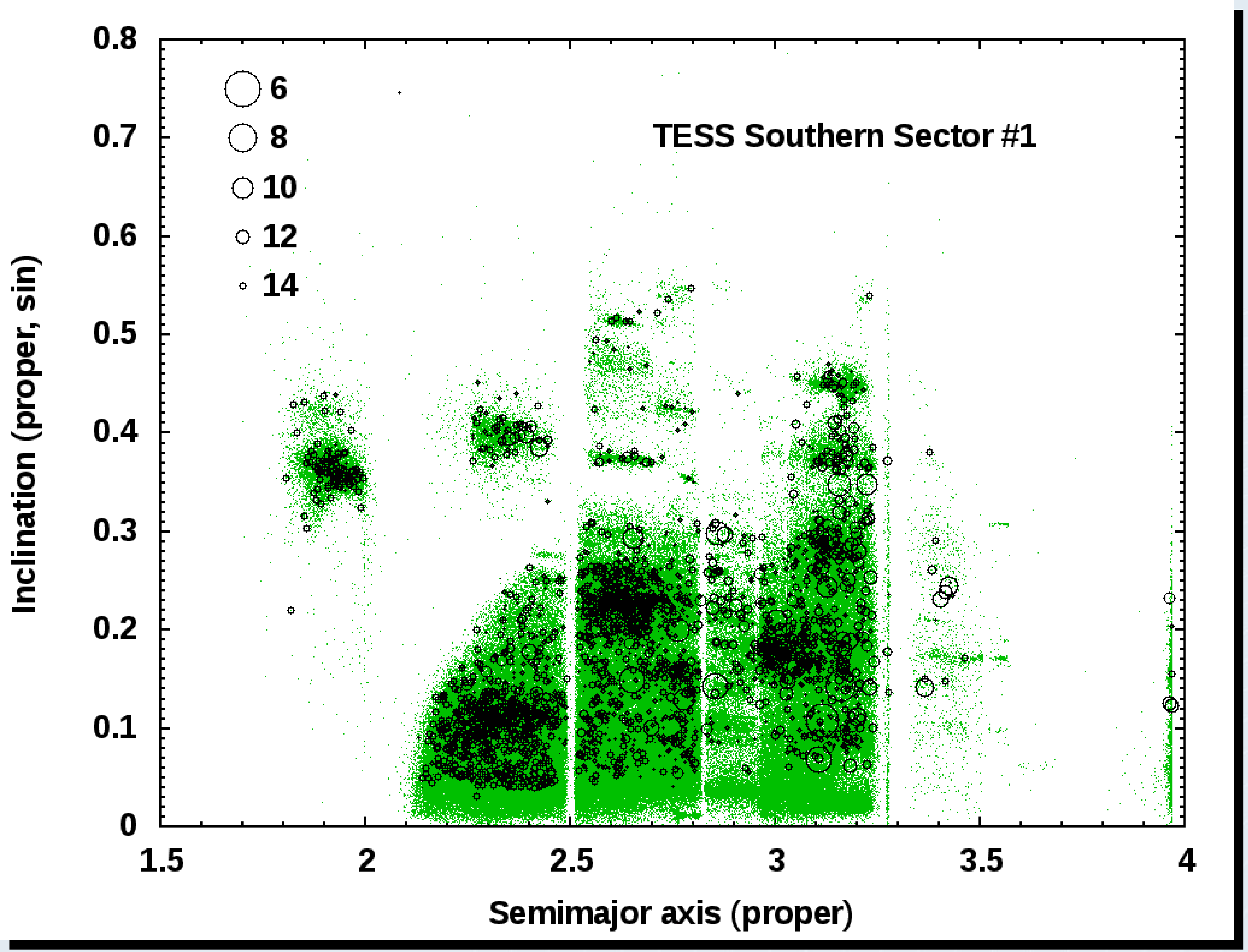

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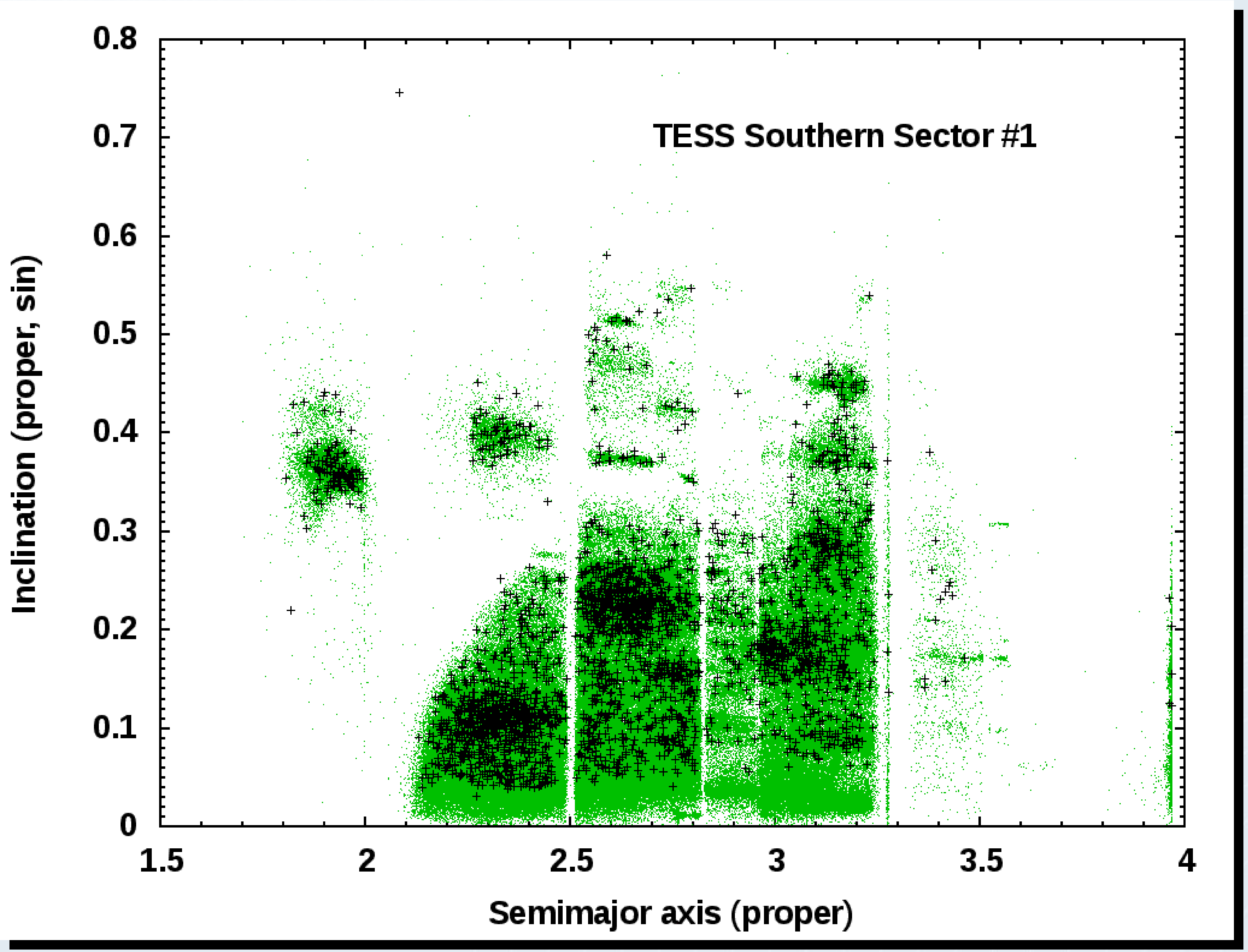

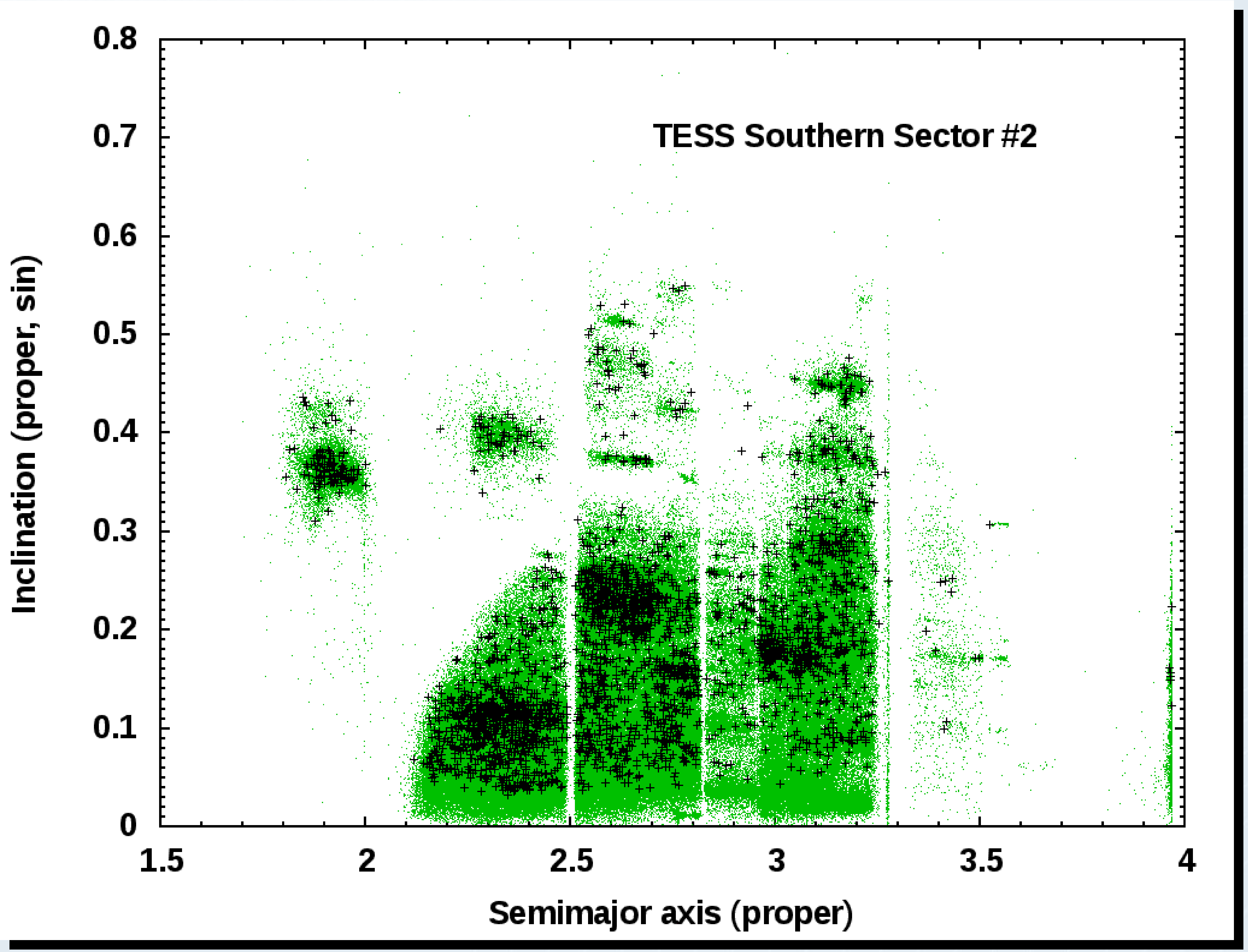
TESS Southern Sector #2
Inclination (proper, sin)
Semimajor axis (proper)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1.5
2
2.5
3
3.5
4

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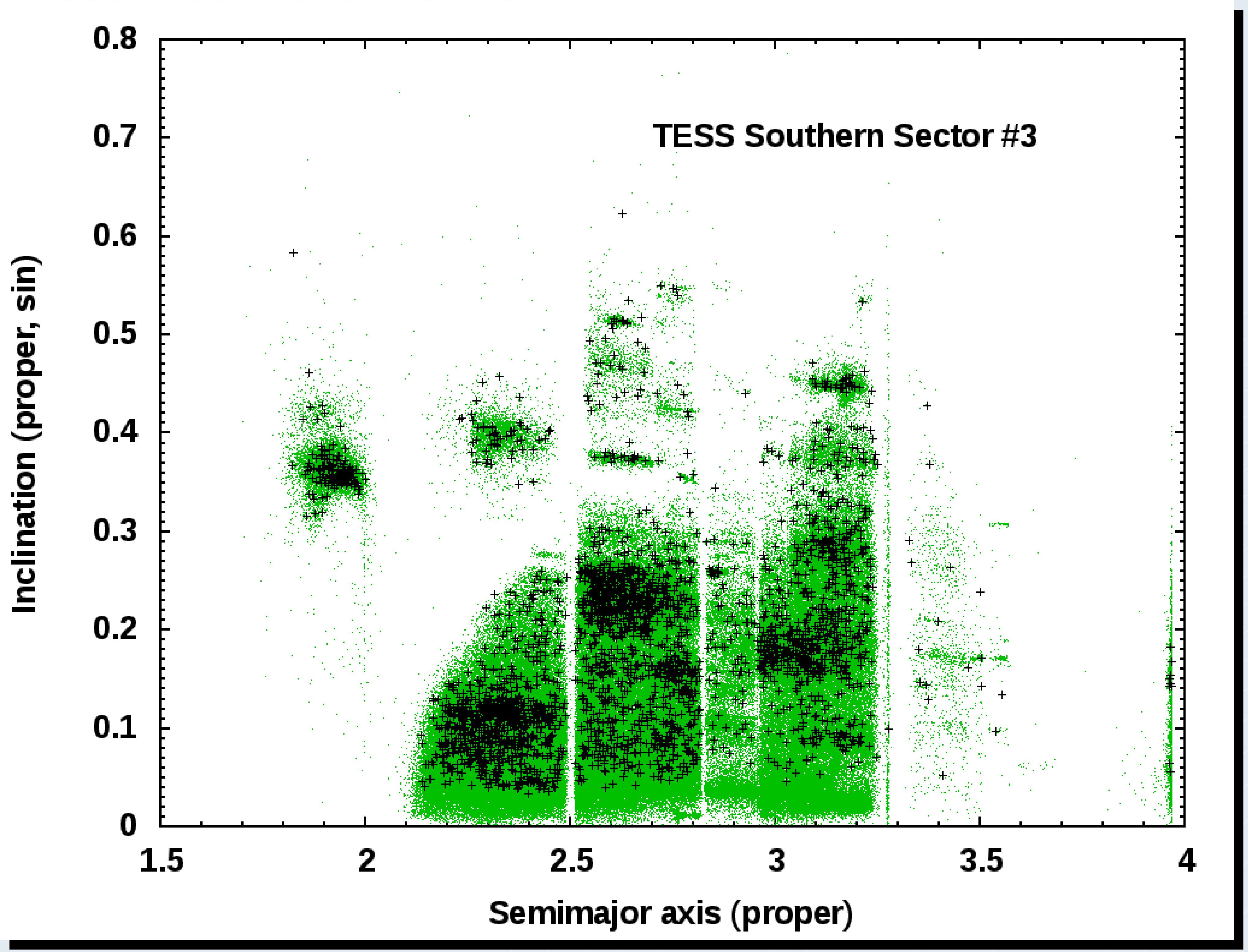

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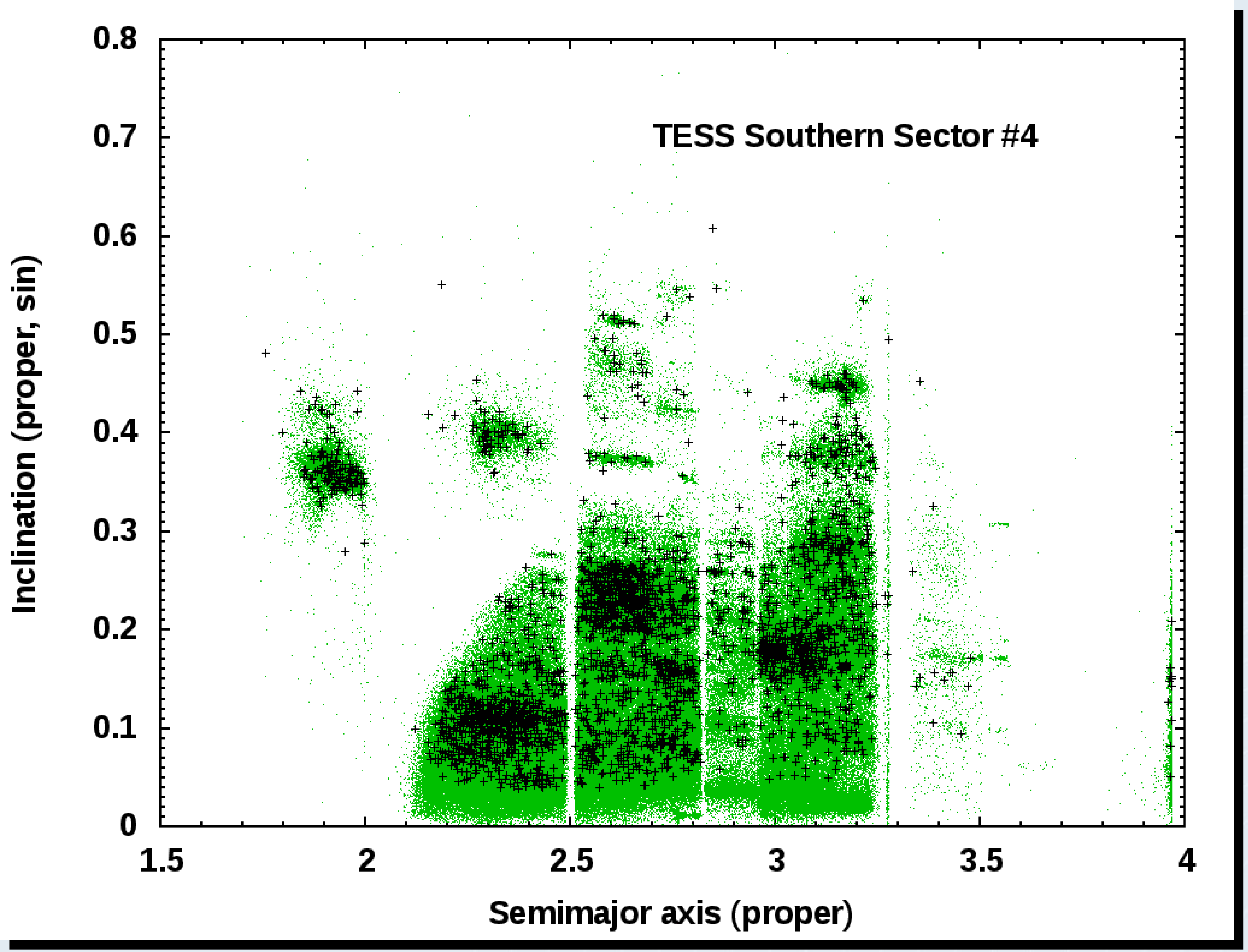

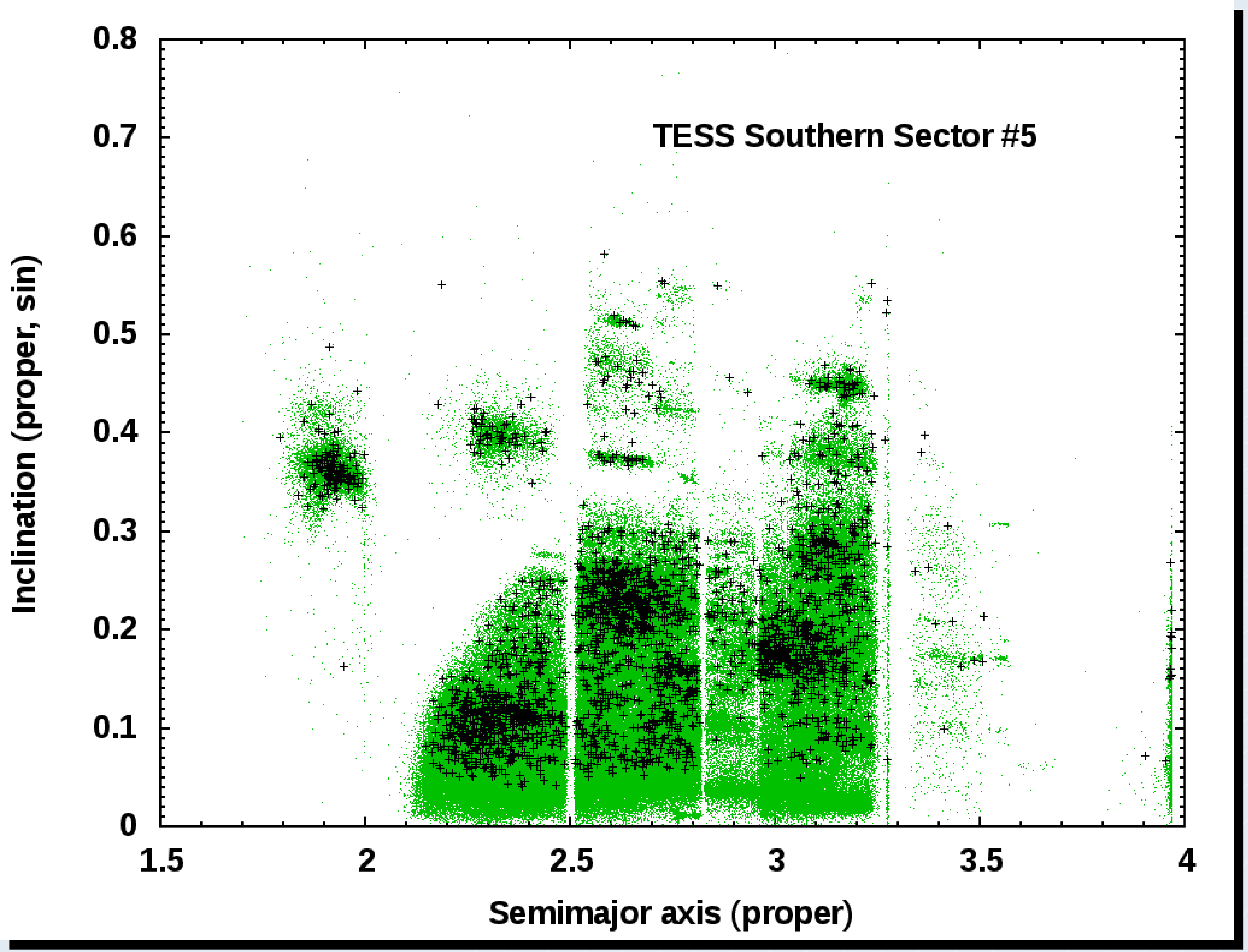
TESS Southern Sector #5
Inclination (proper, sin)
Semimajor axis (proper)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1.5
2
2.5
3
3.5
4

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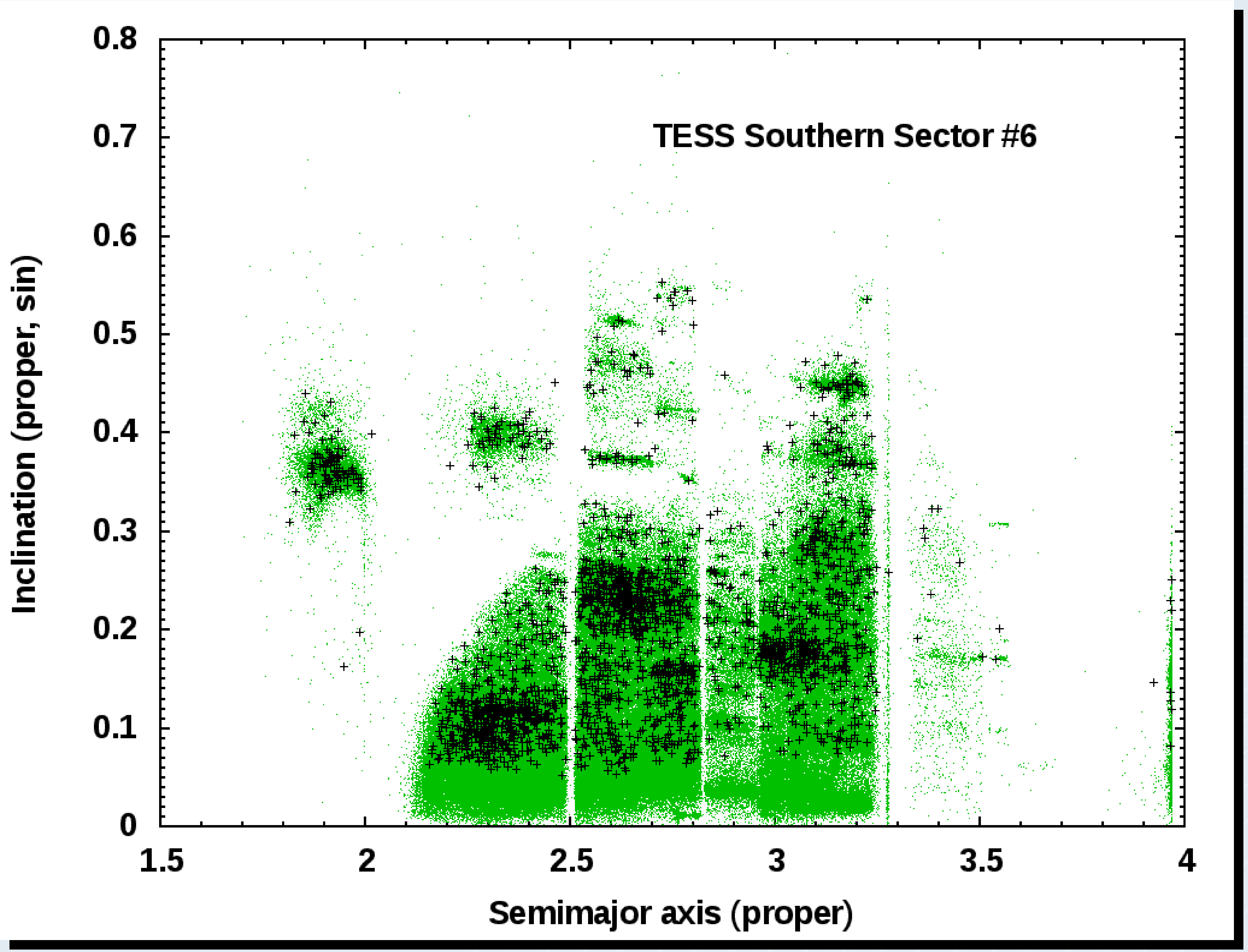

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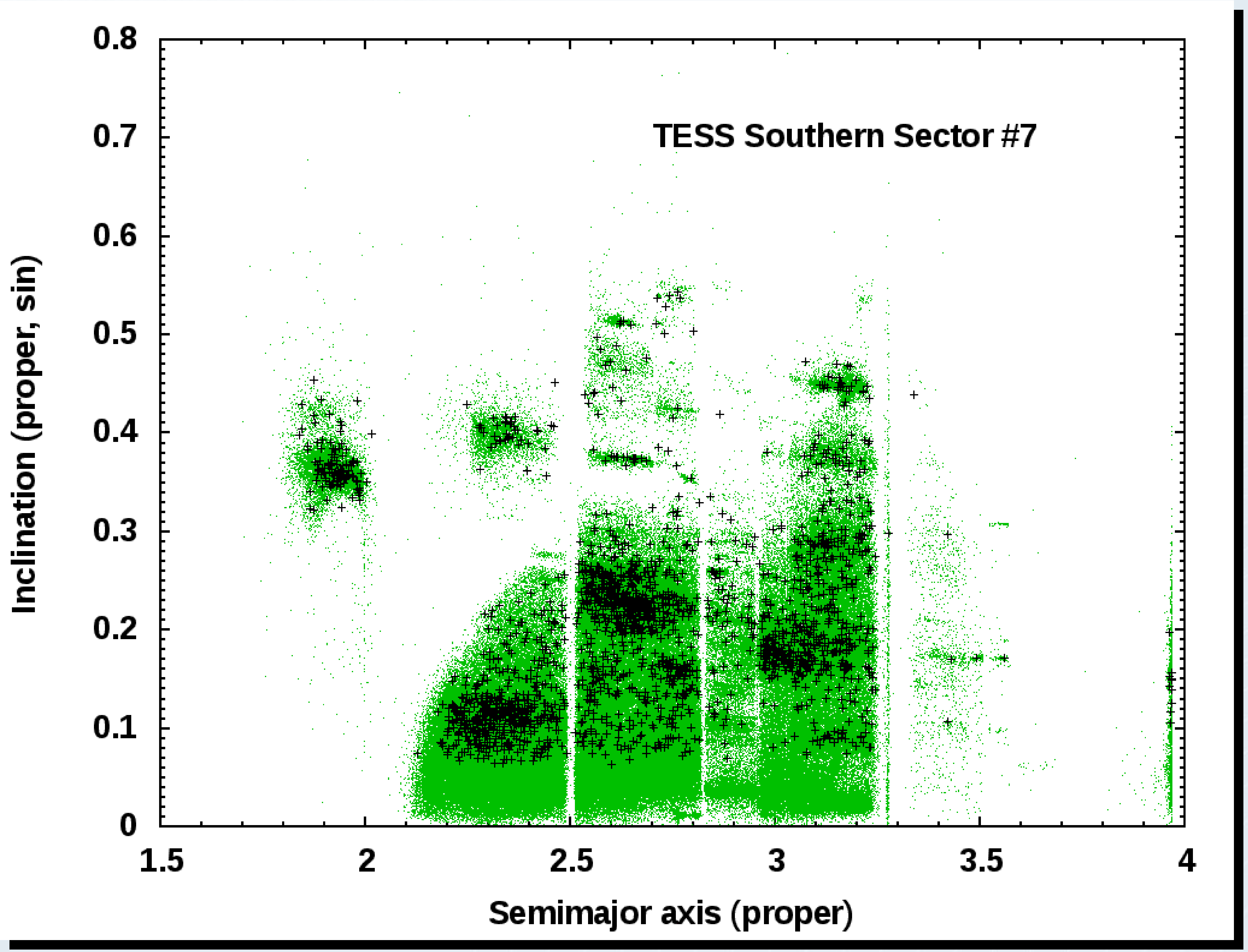

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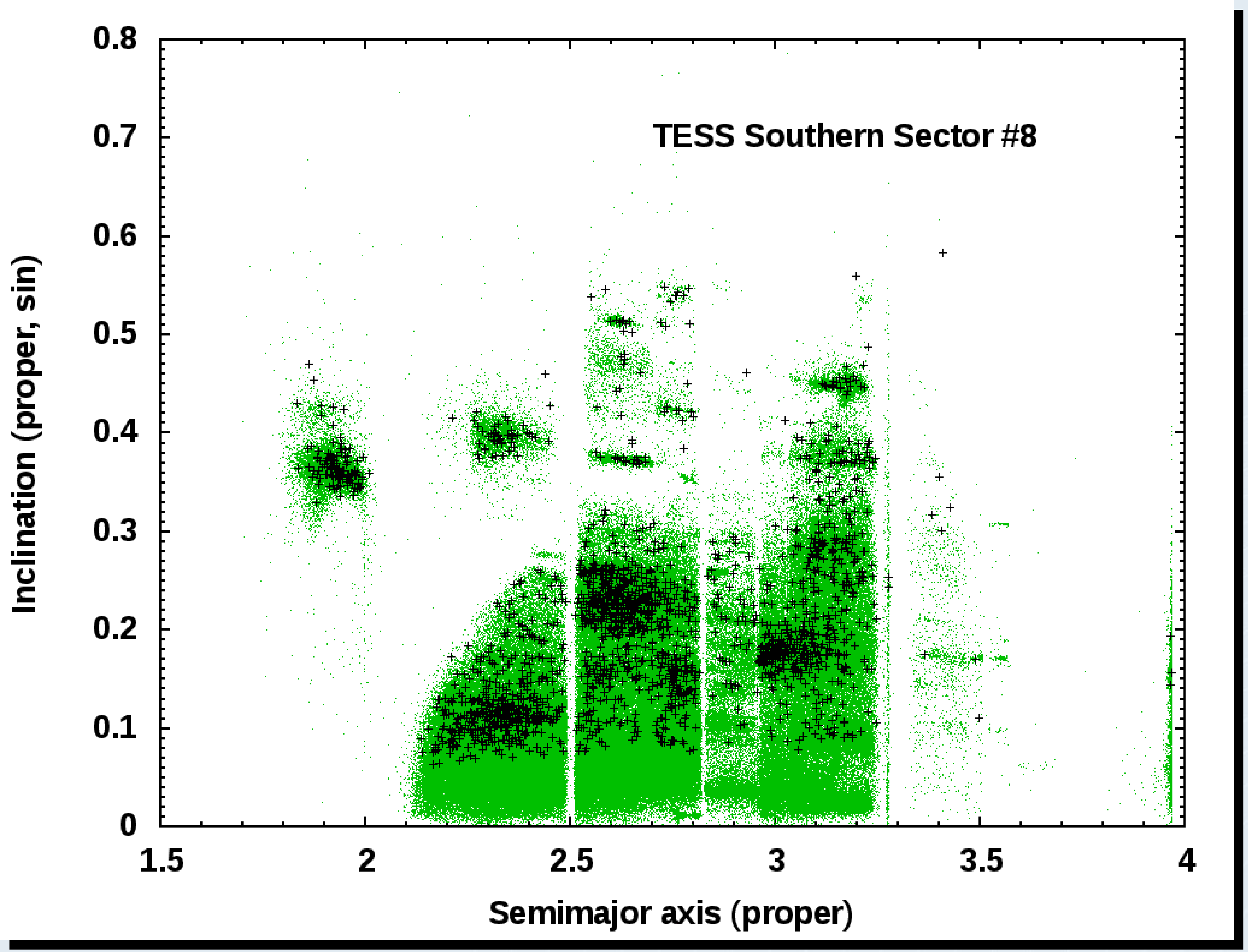

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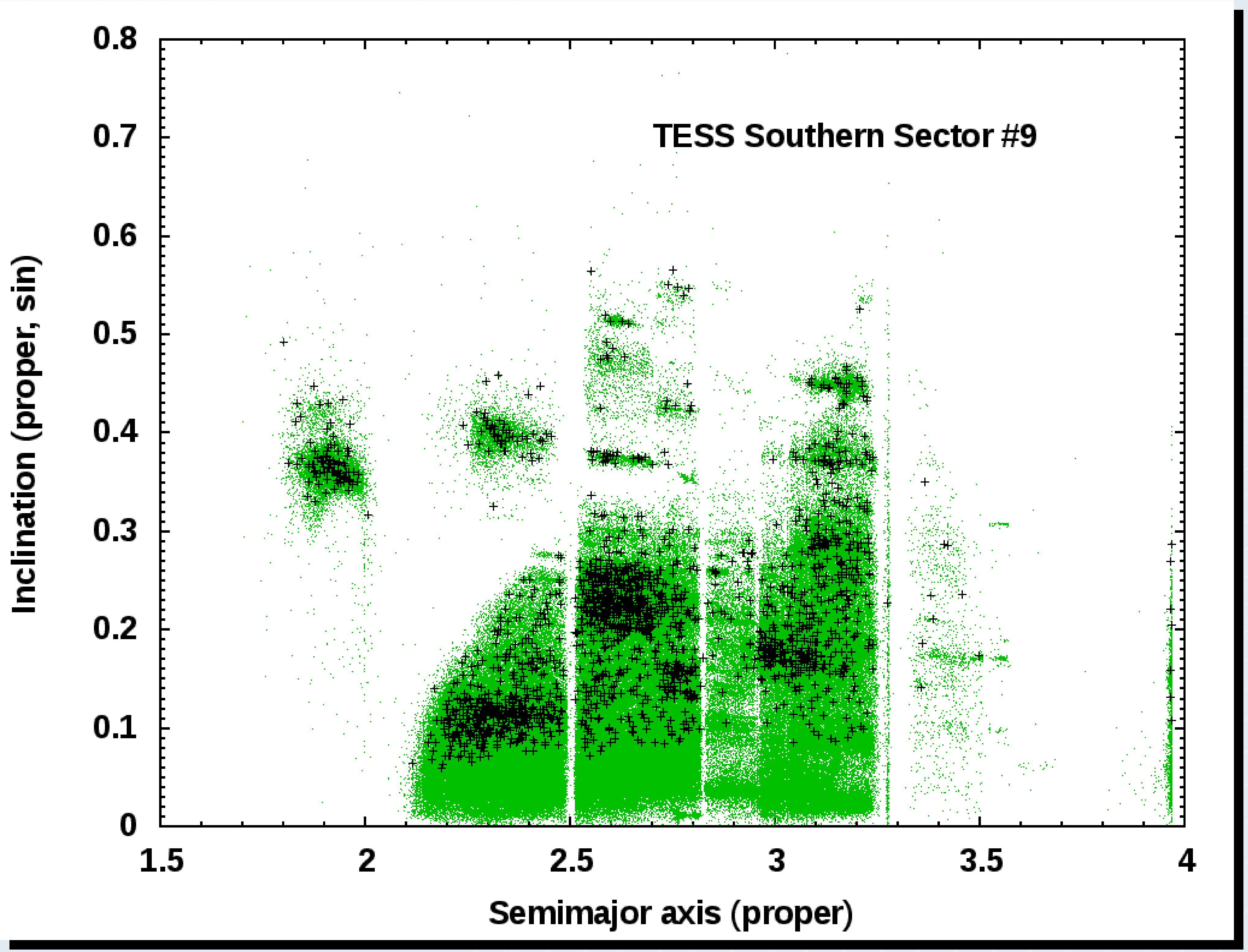

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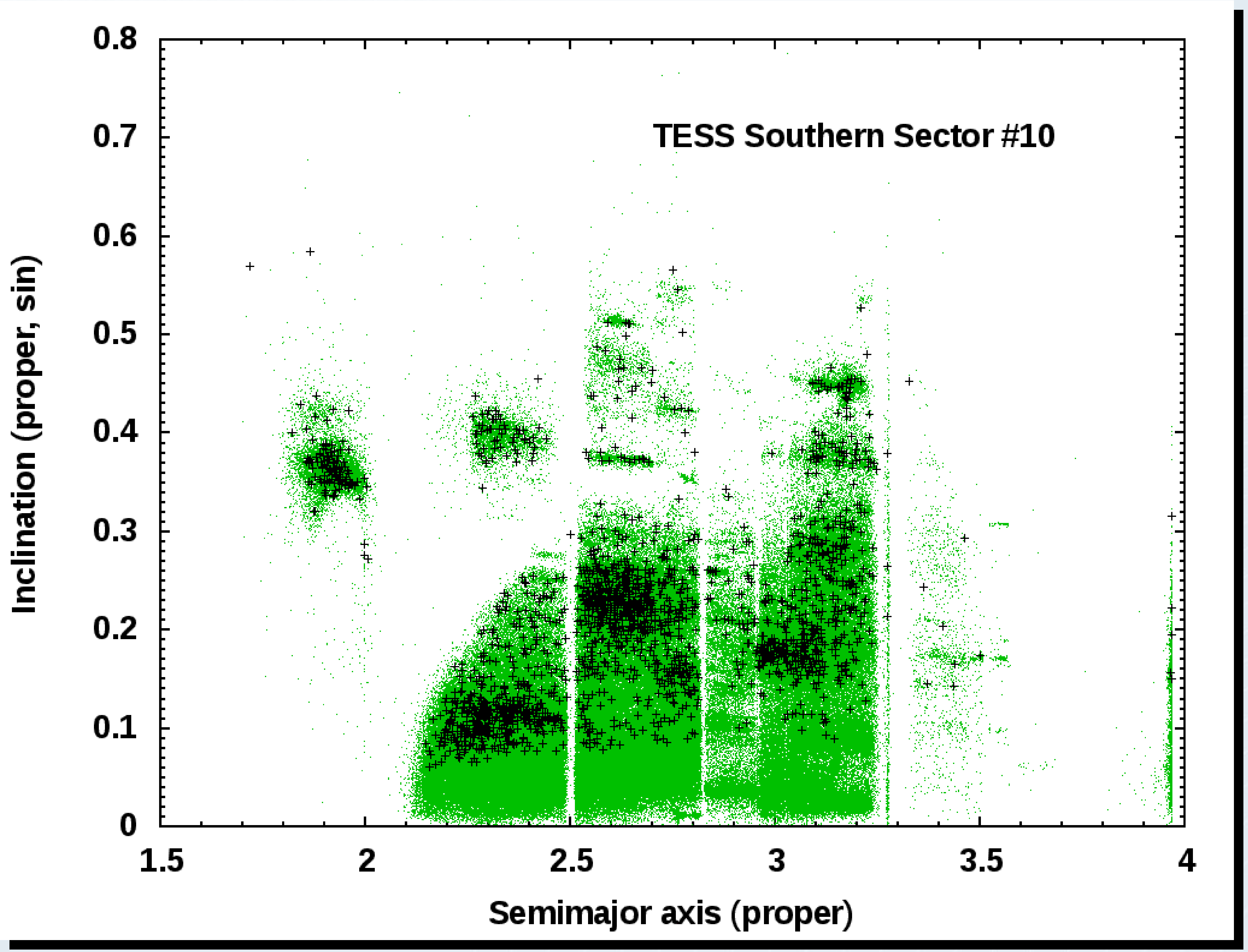

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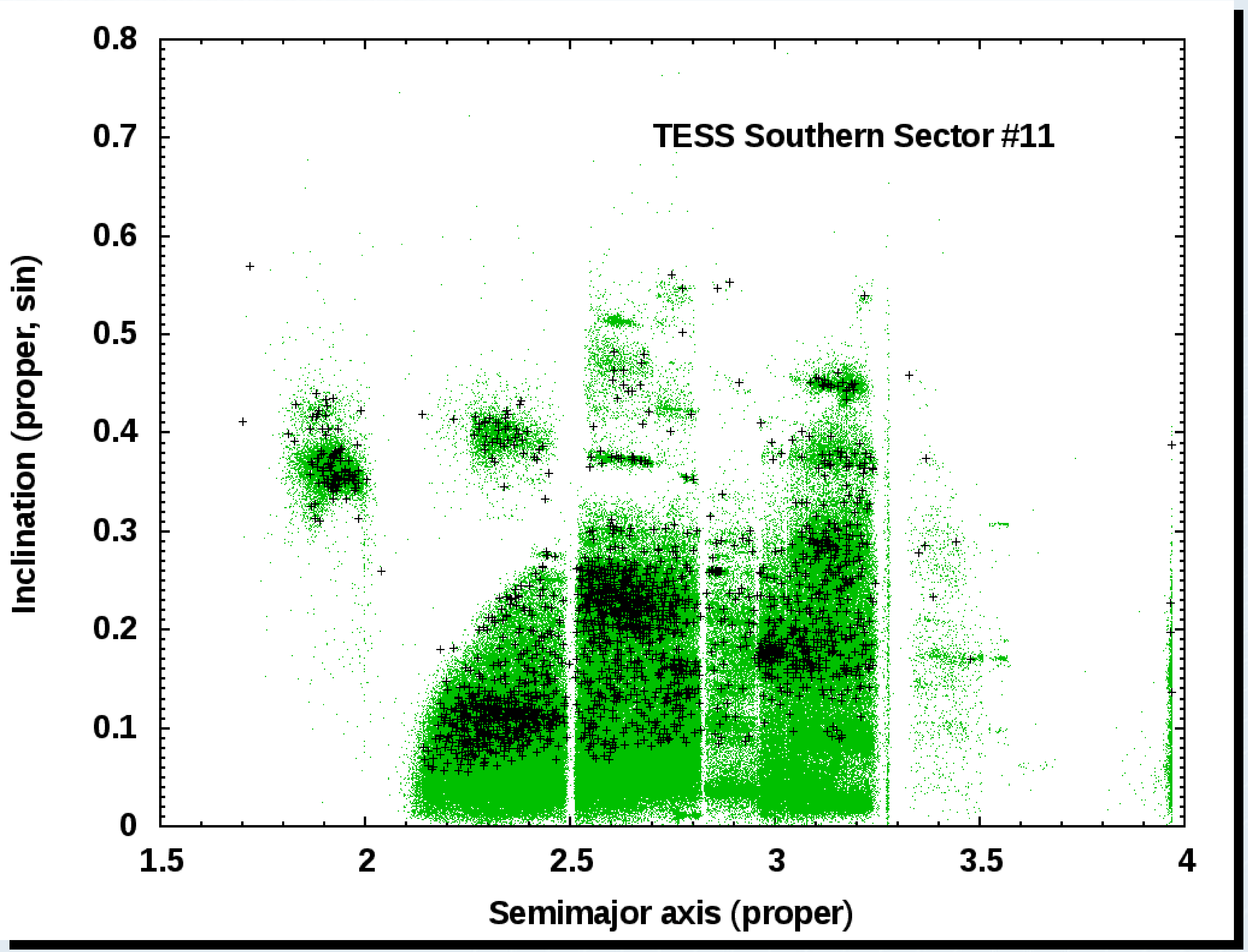

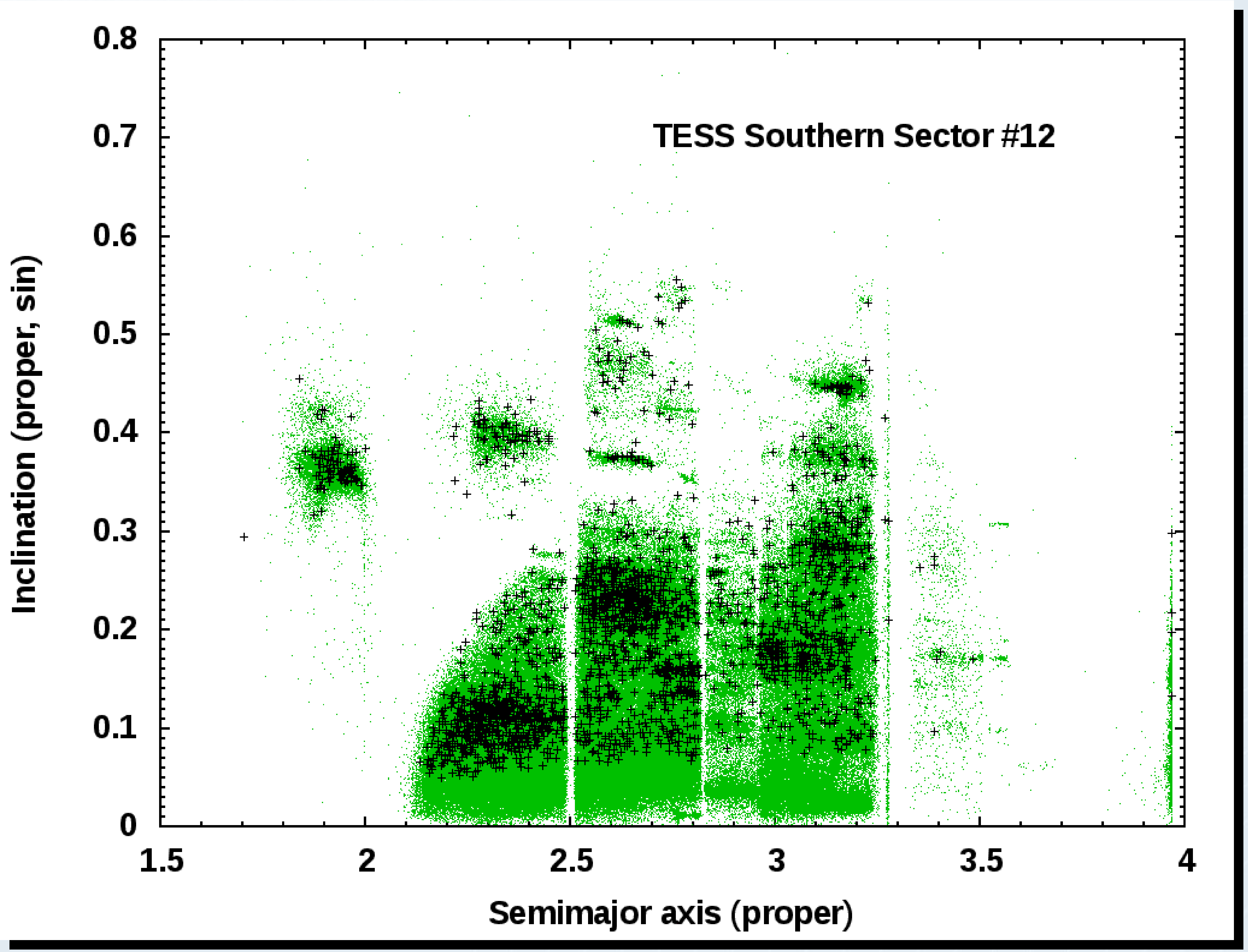
TESS Southern Sector #12
Inclination (proper, sin)
Semimajor axis (proper)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
1.5
2
2.5
3
3.5
4

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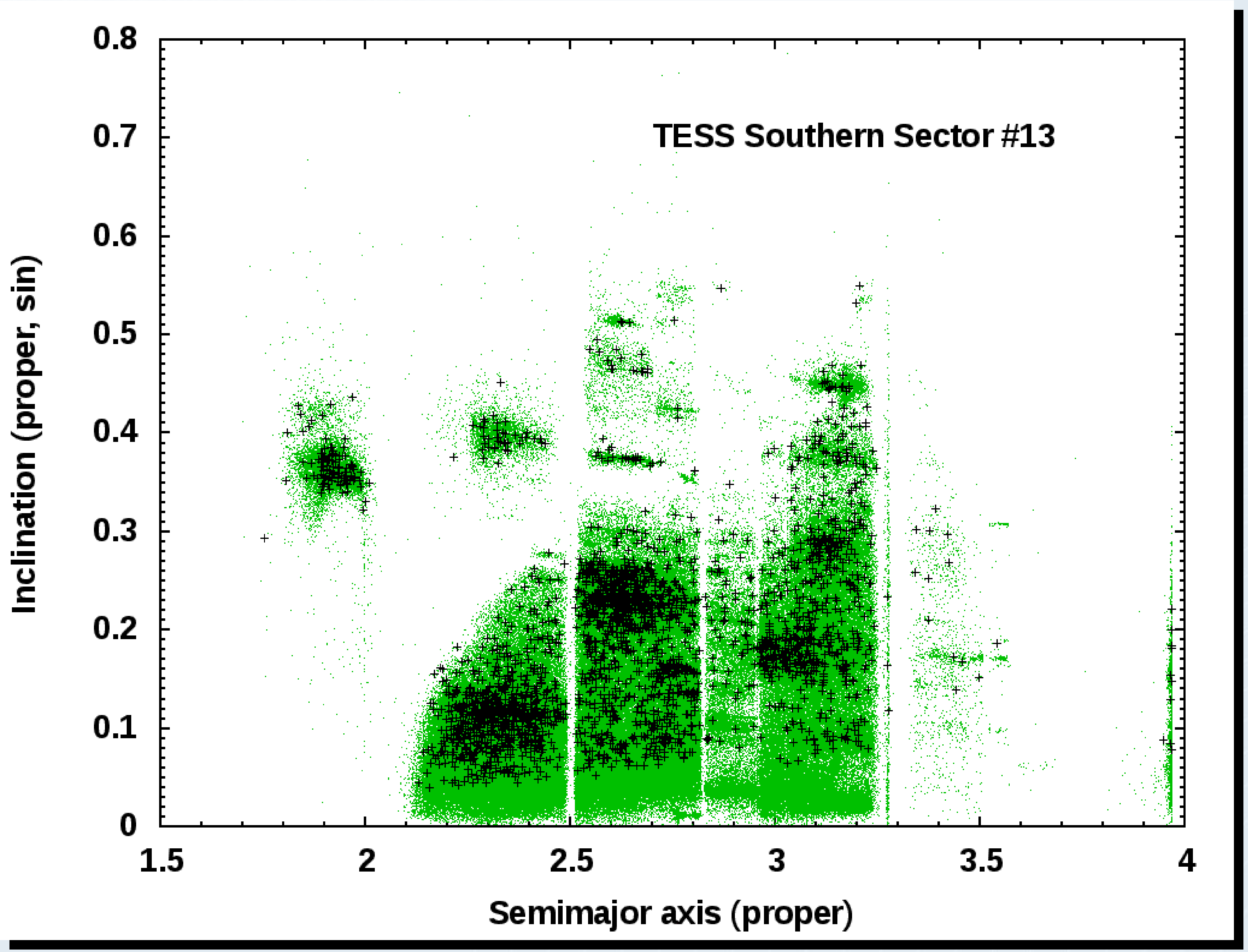

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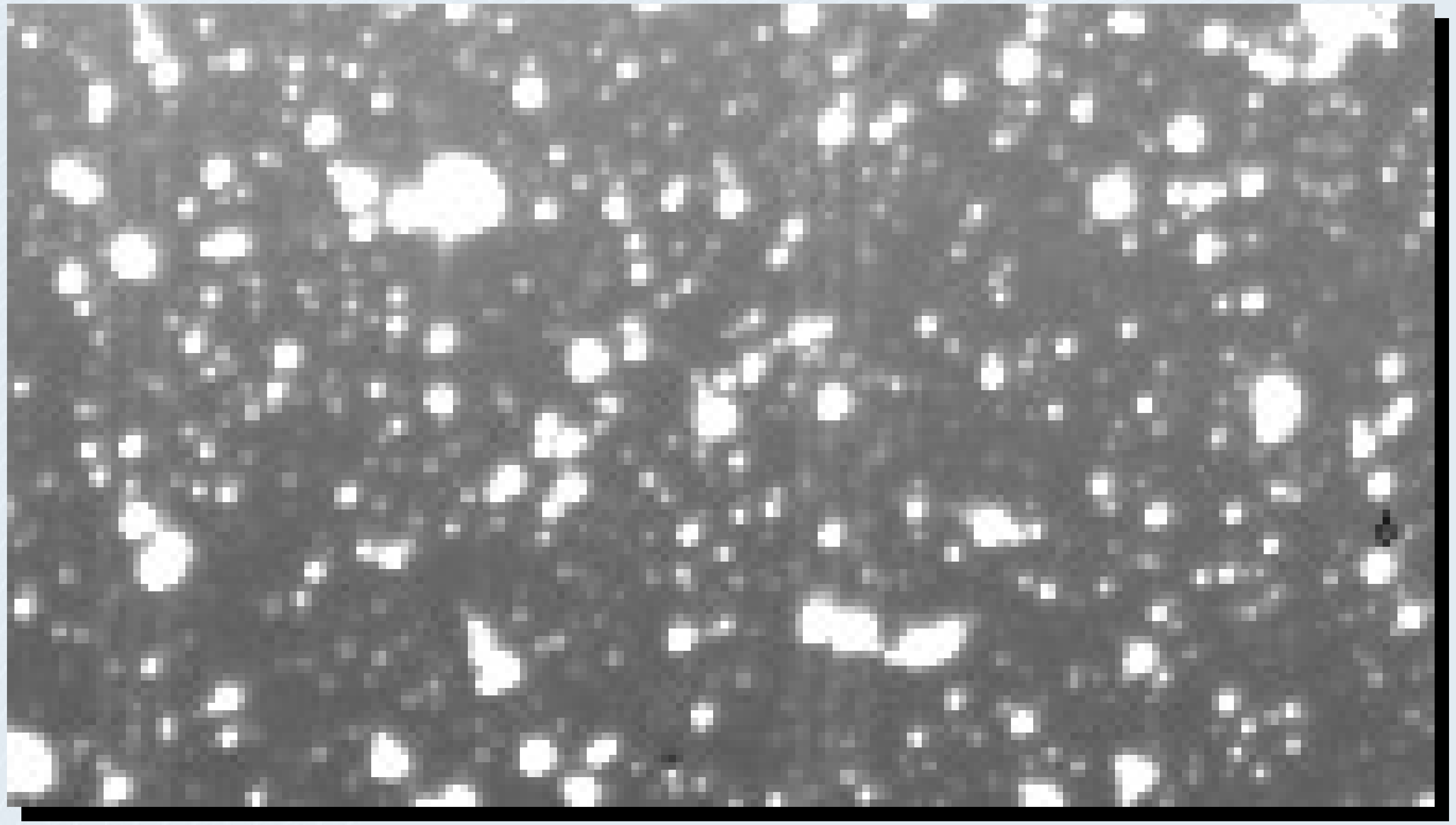
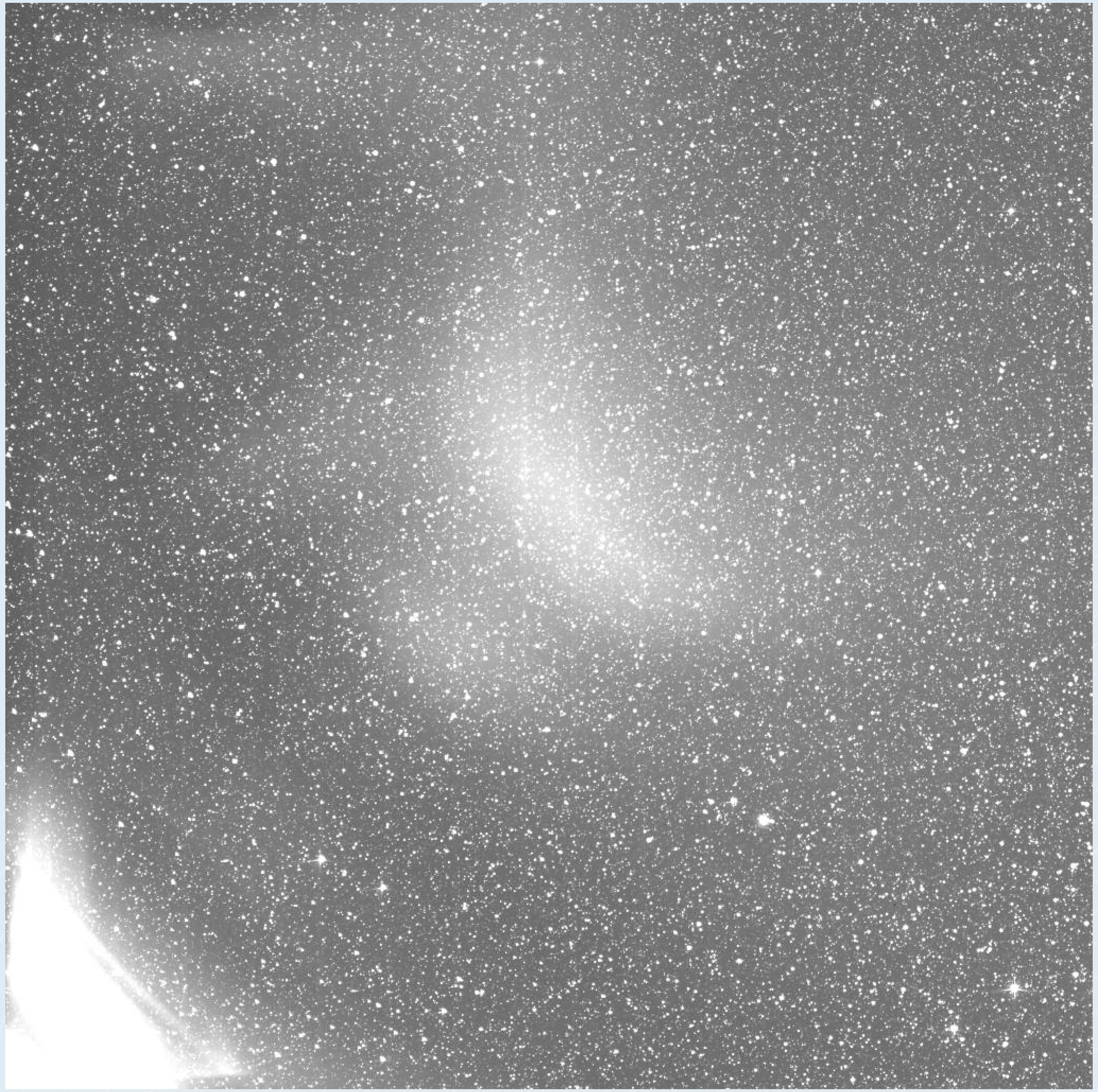
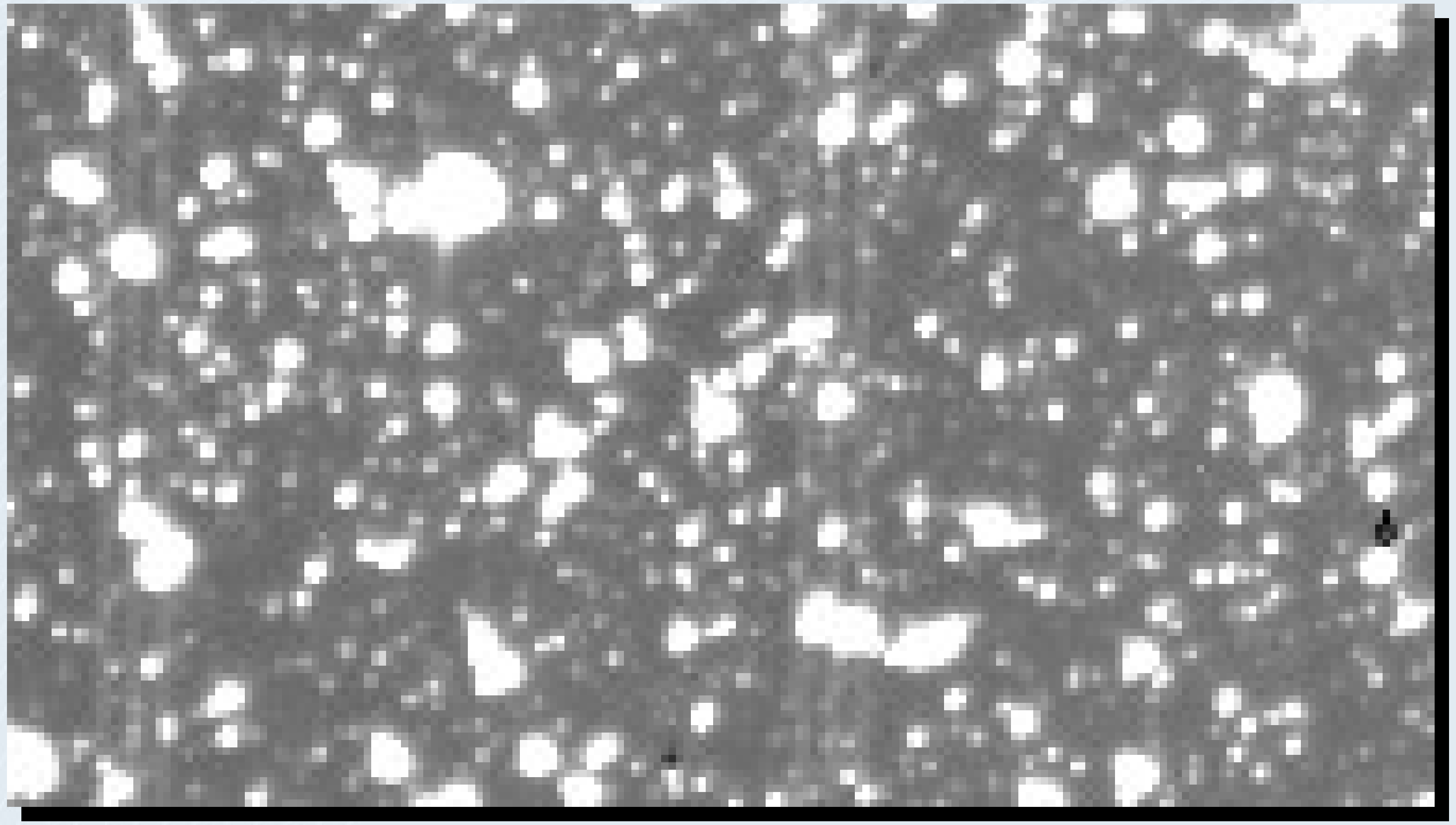
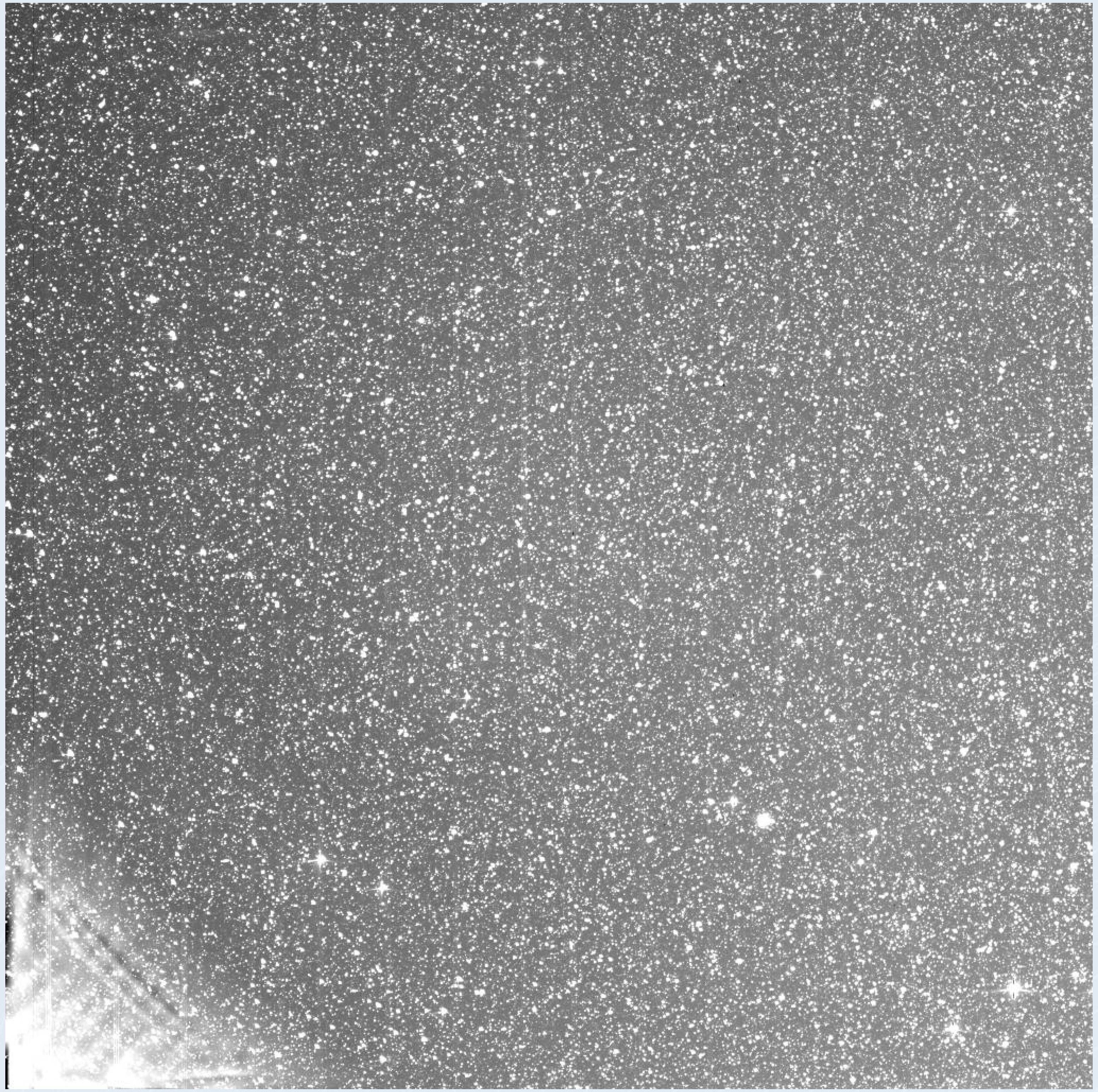




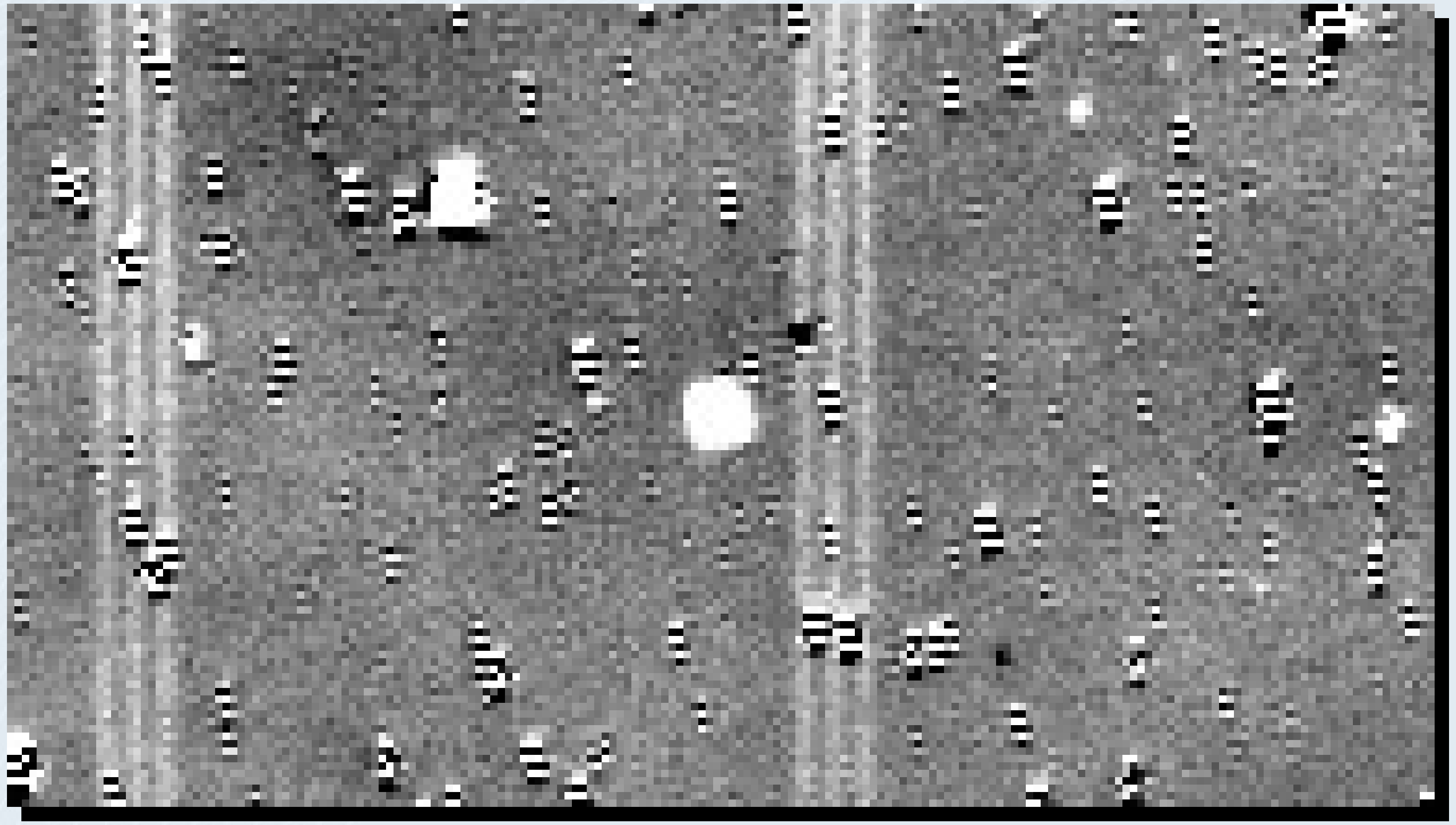
Original FFI

TESS in the Solar System: data processing





Backgrond variations are removed (stray light)



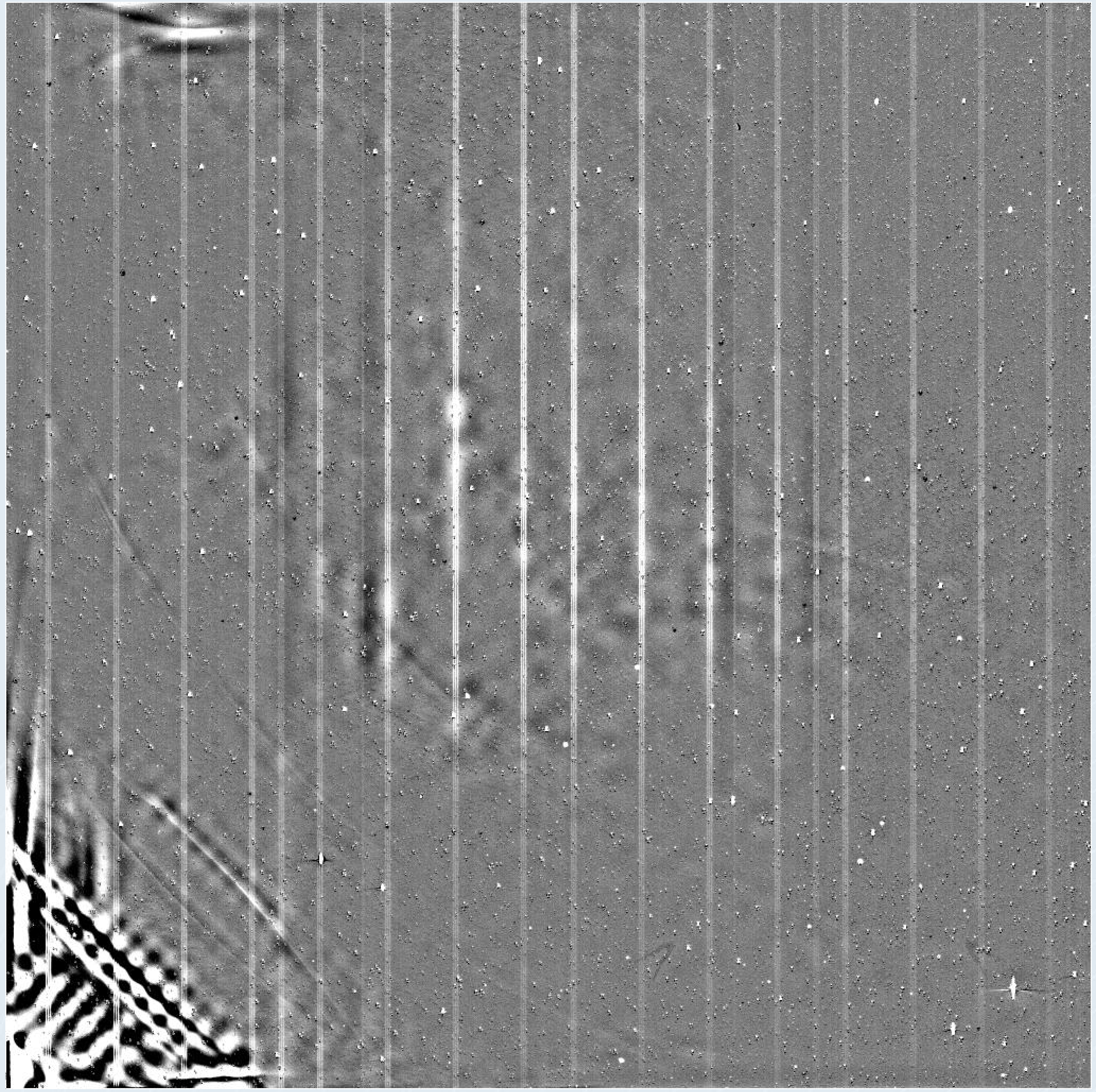
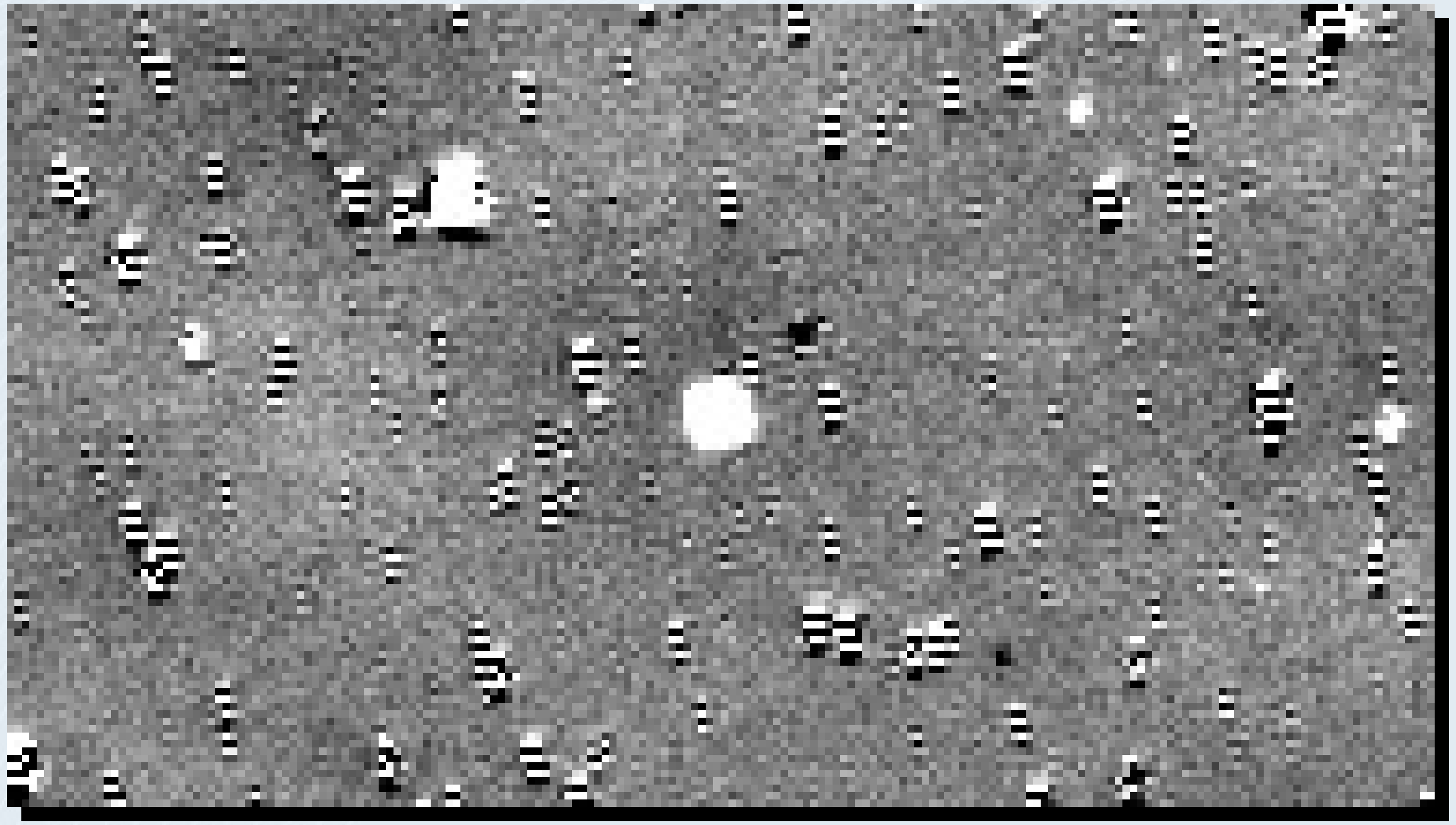
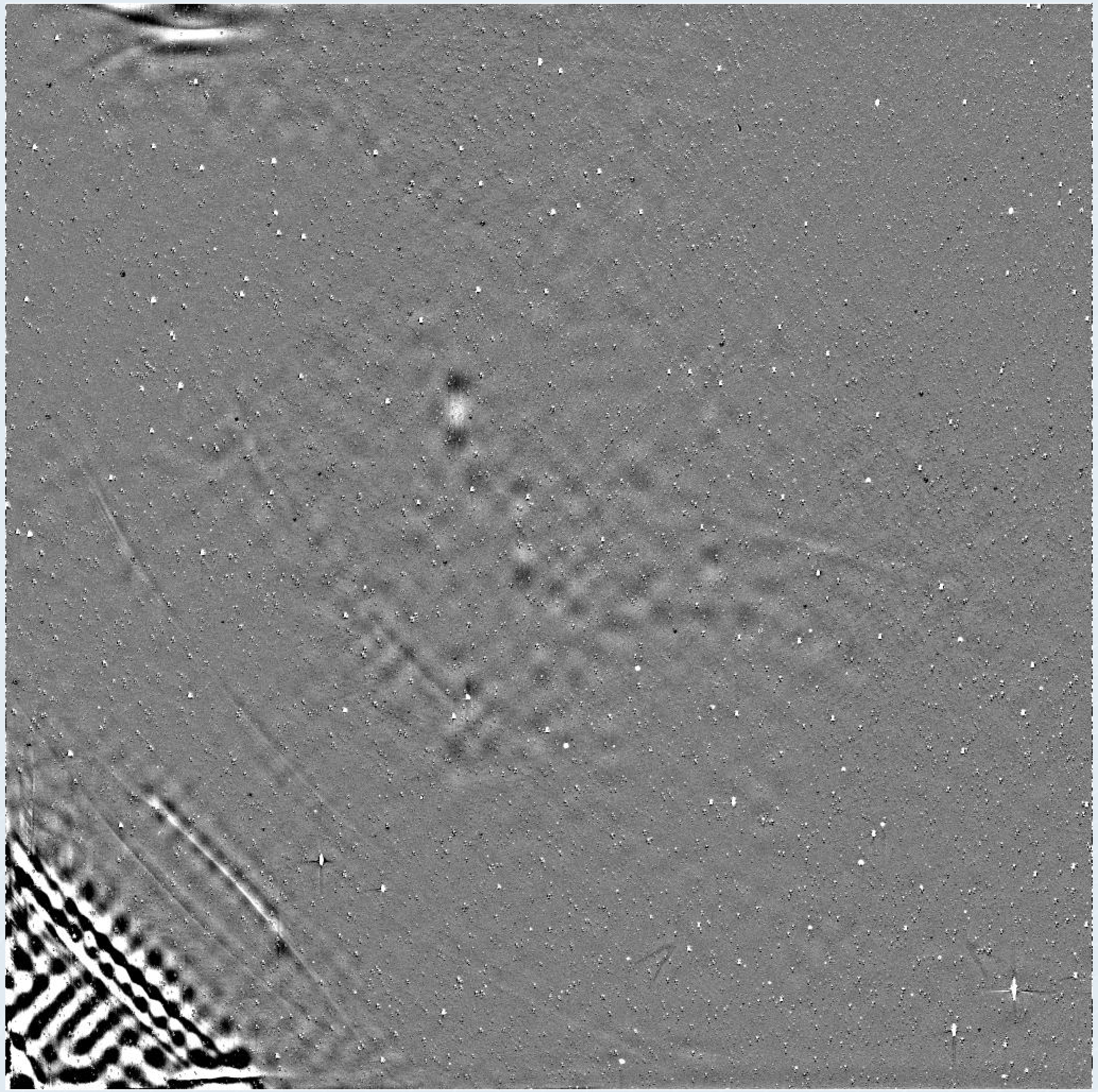
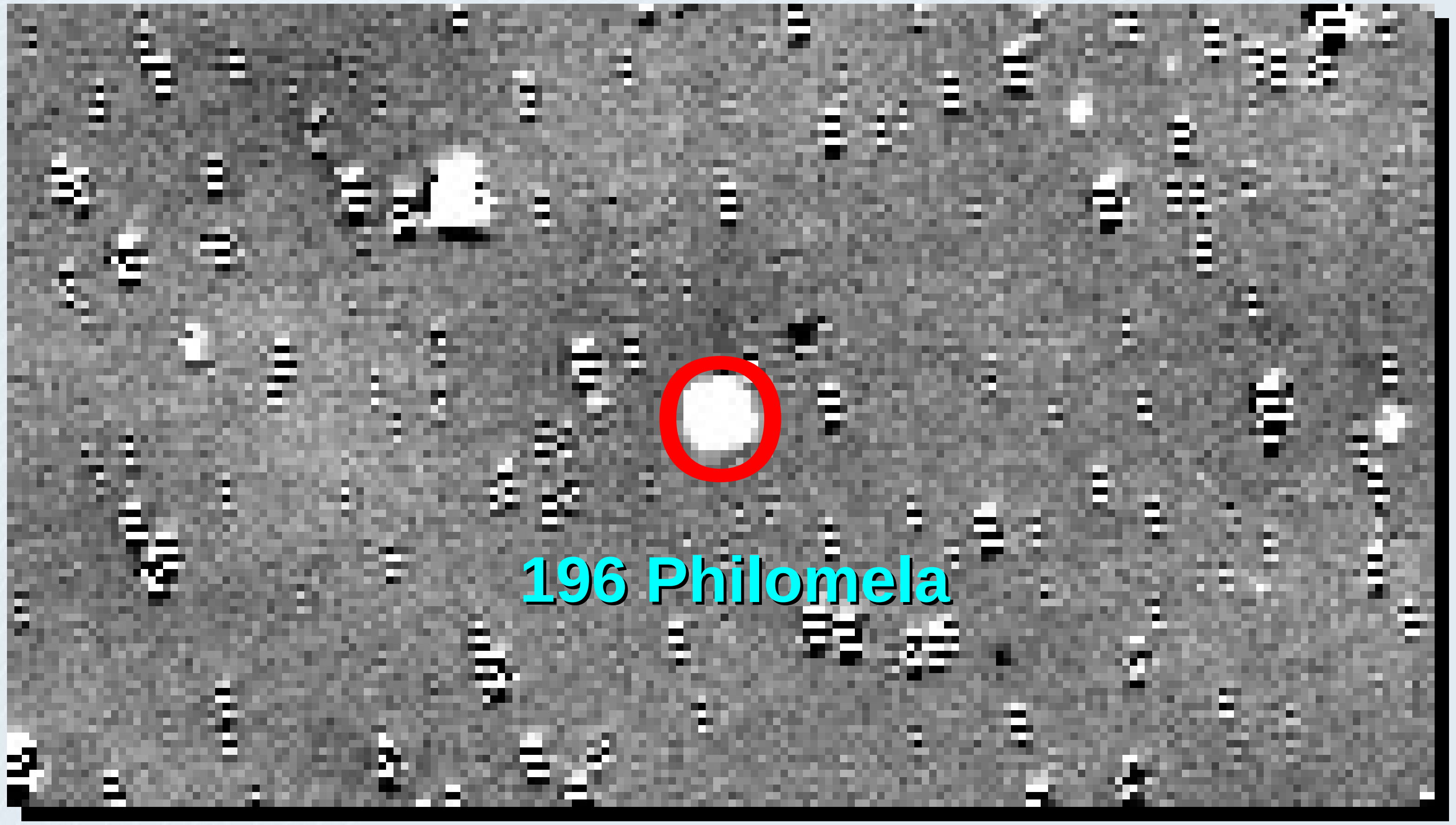


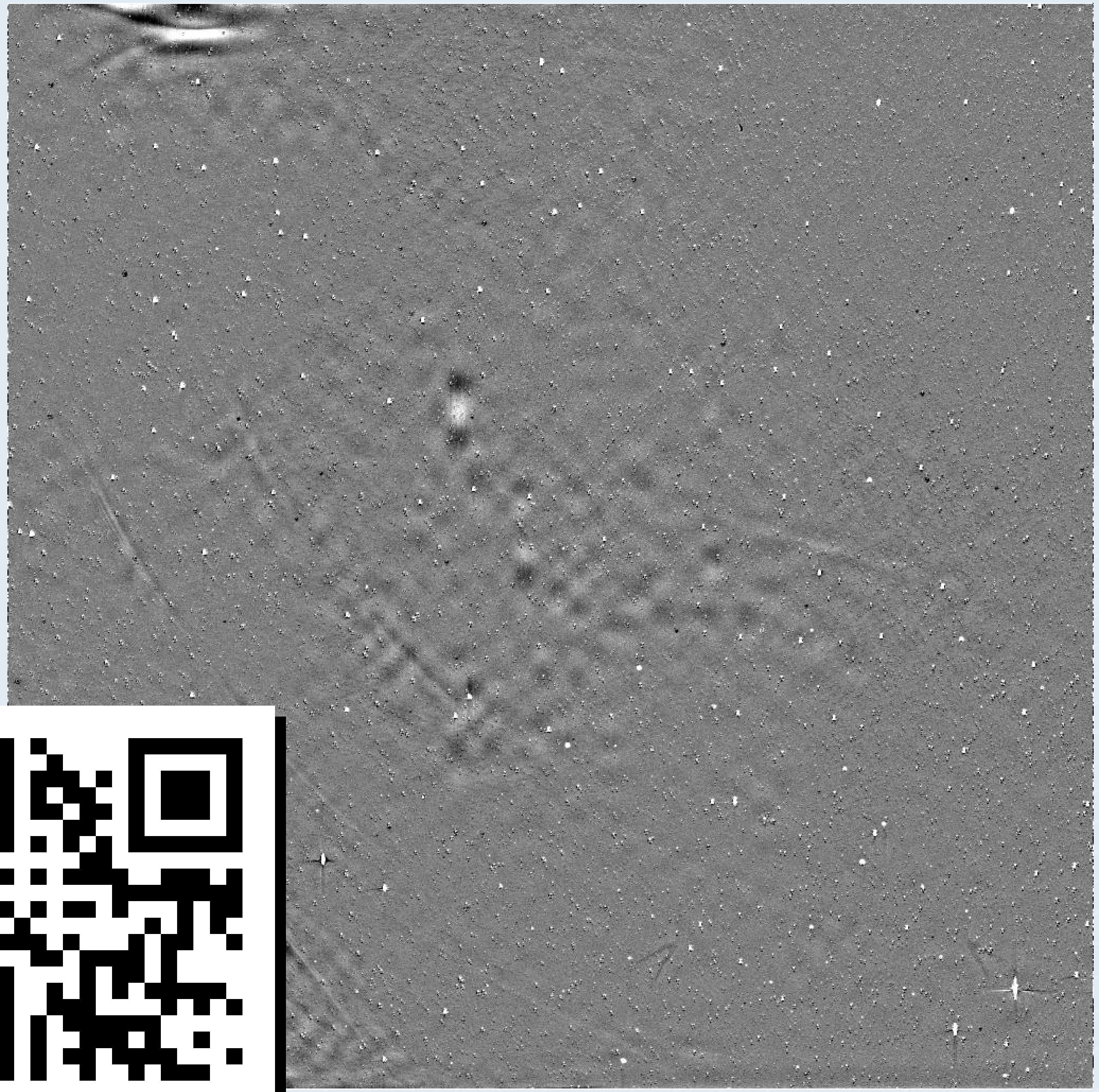
Image subtraction w/ convolution





Straps are removed





Source is identified!

https://fitsh.net/ =>

TESS in the Solar System

Outline of the next 22 ± 1 minutes:

- **Solar System**
- **Legacy of Kepler/K2 (in the context of Solar System studies)**
- **How does TESS work for Solar System objects?**
- **What are the interesting questions about the Solar System what can be answered by TESS?**
- **Some aspects of the data reduction: image subtraction, astrometry, stacking, and so on…!**
- **<u>Known objects: Some nice preliminary results and displays/exhibitions of light curves, detections</u>**
- **Here we show results related to known objects => next two talks: how can TESS be used to discover new ones?**

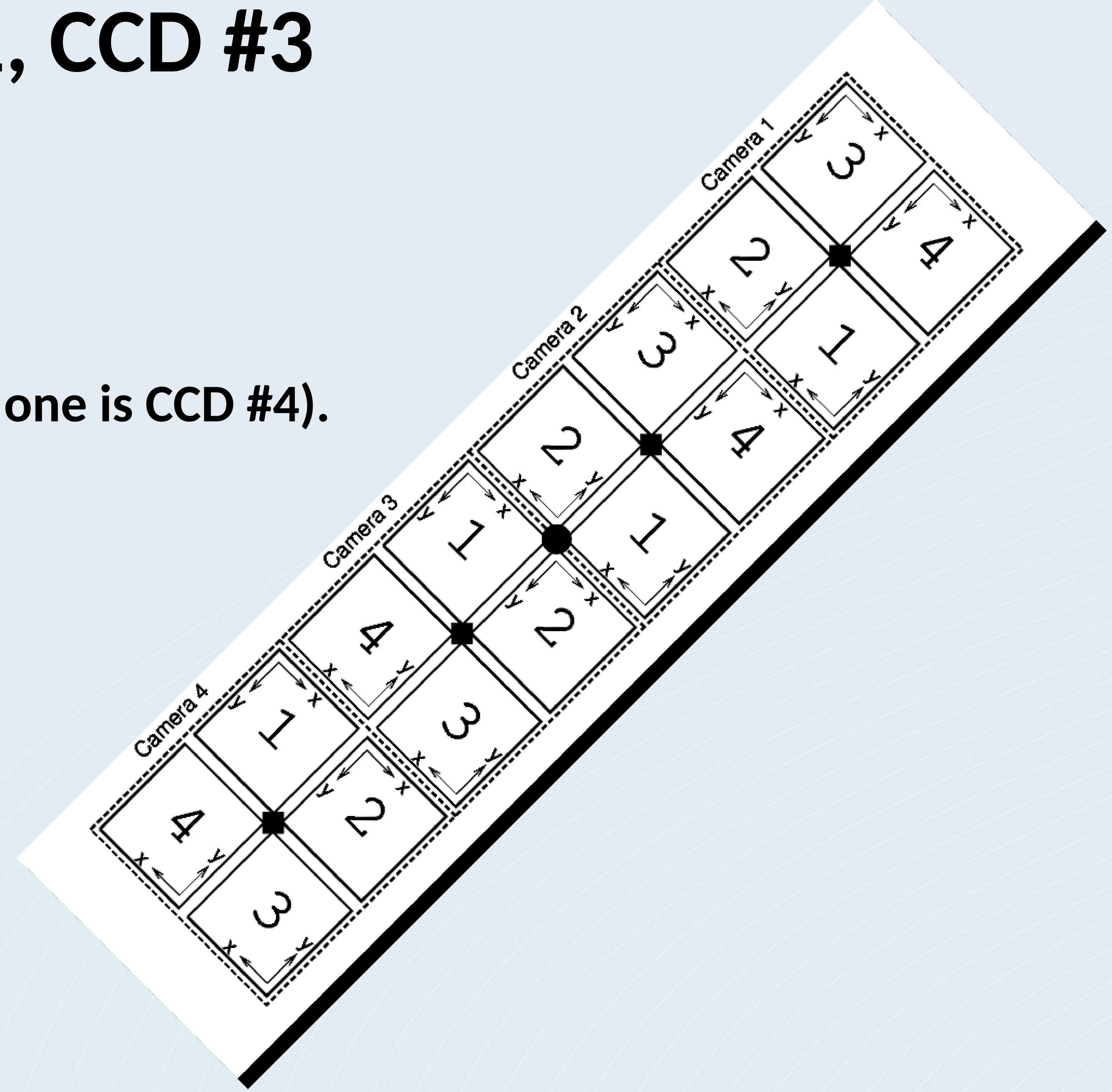
An example: Sector 1, Camera 1, CCD #3

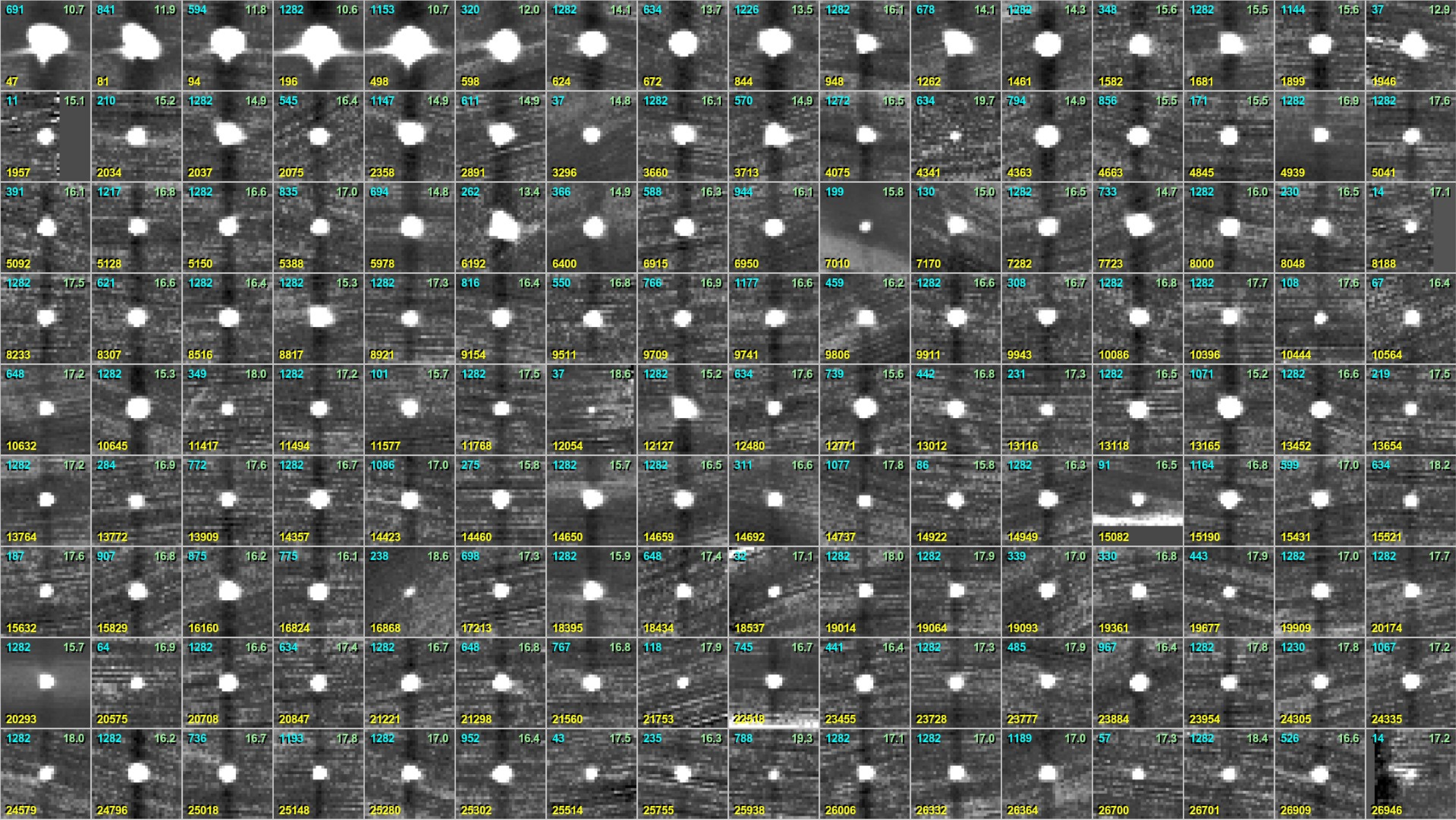
Observations:

- Between 2458325.32 … 2458353.15
- One of the closest CCD to the Ecliptic (the other one is CCD #4).
- Otherwise similar to any other sector…

Minor planets:

- 5129 objects crossed
- At least 4-sigma detection: 4650
- Light curves available: ~800-1000
- Astrometric offsets are also detected!

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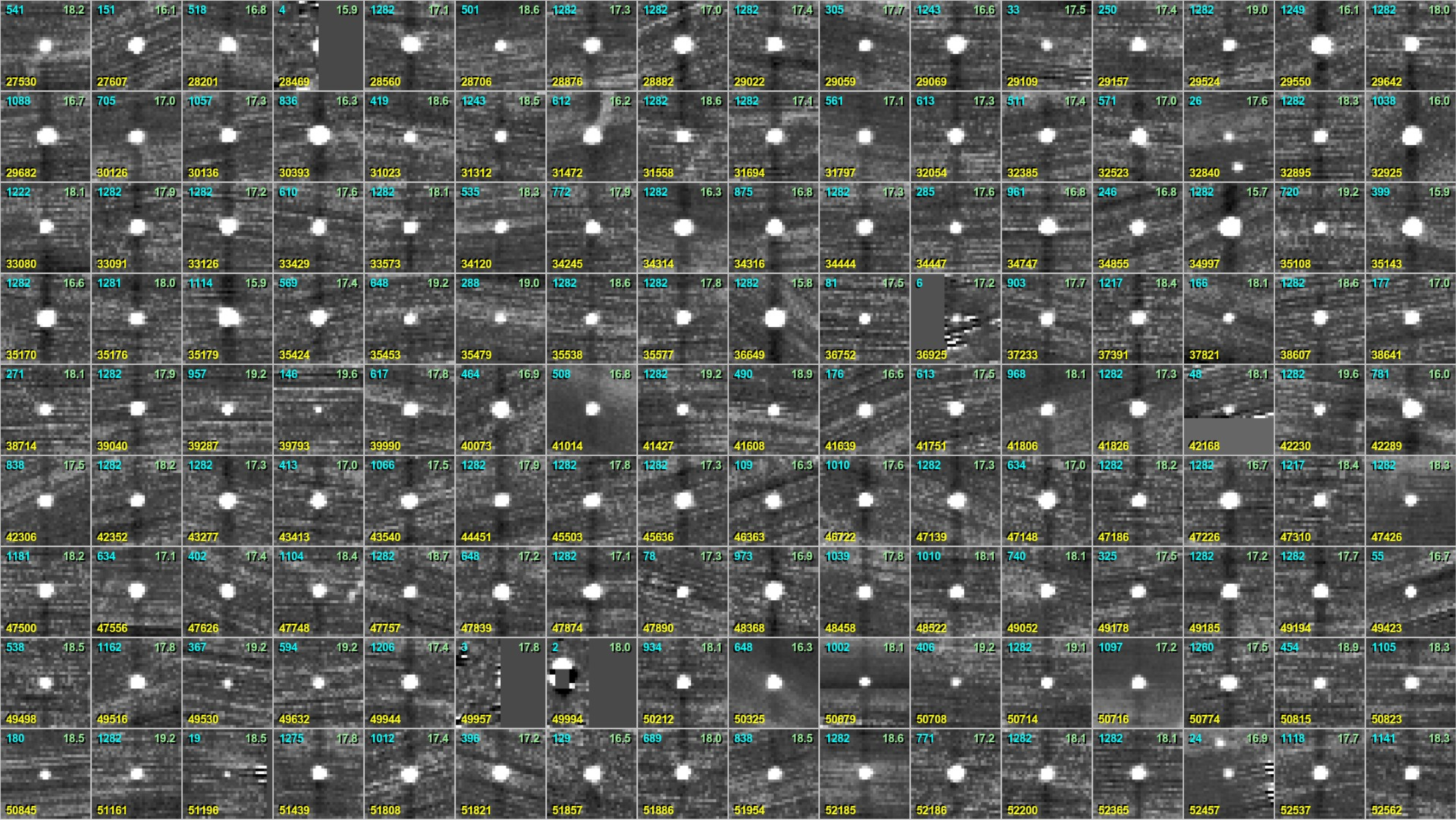
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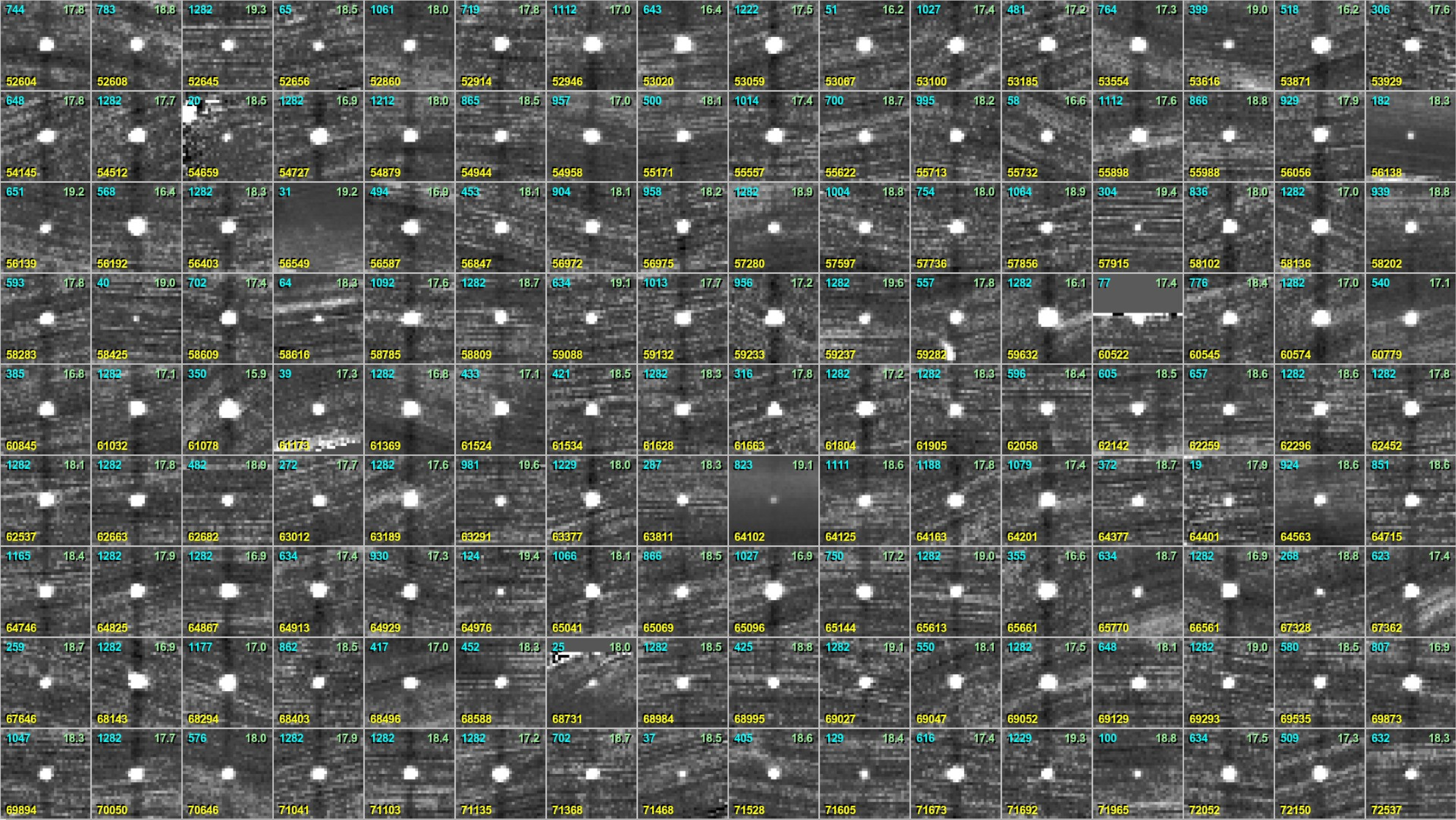
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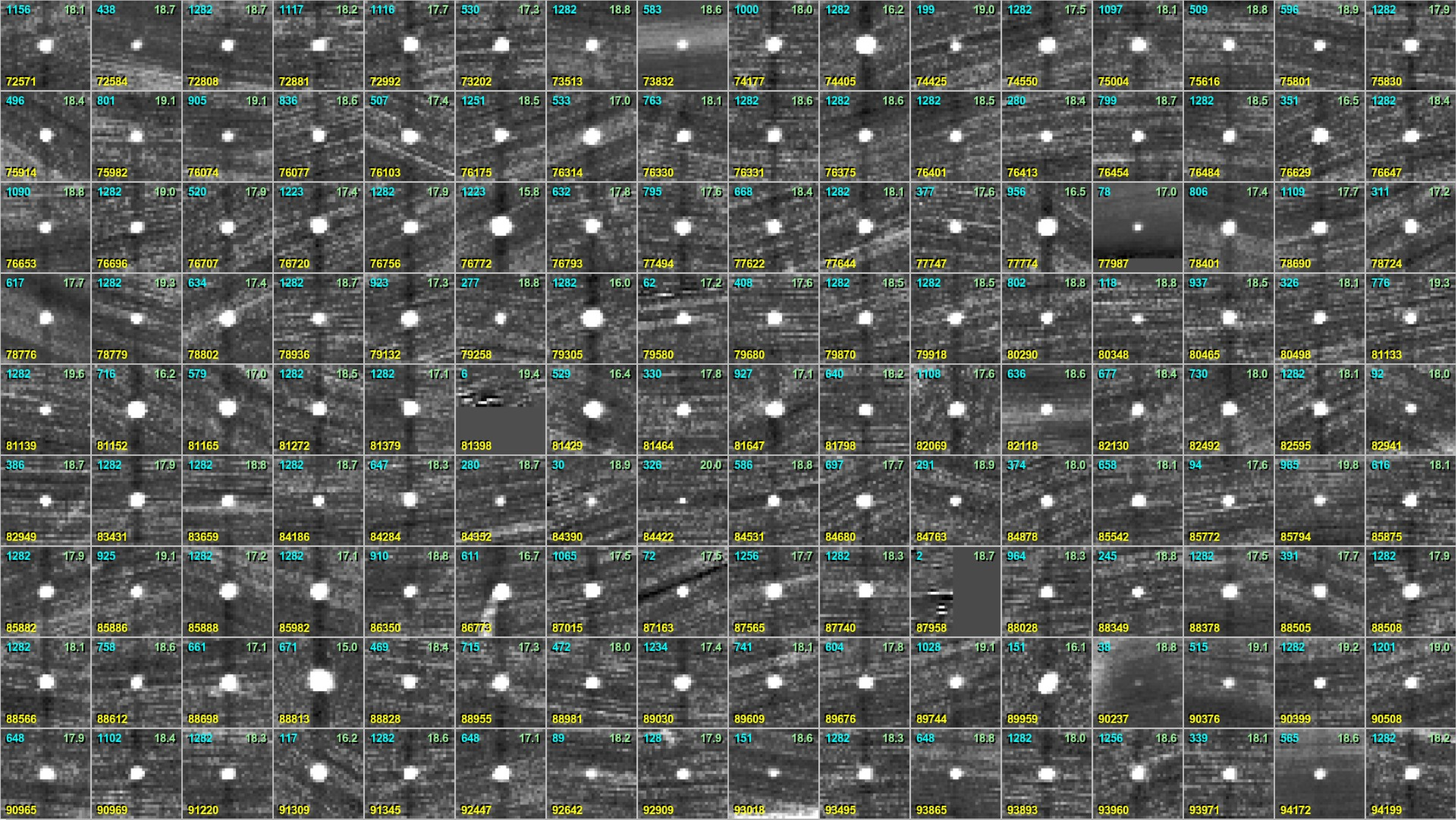
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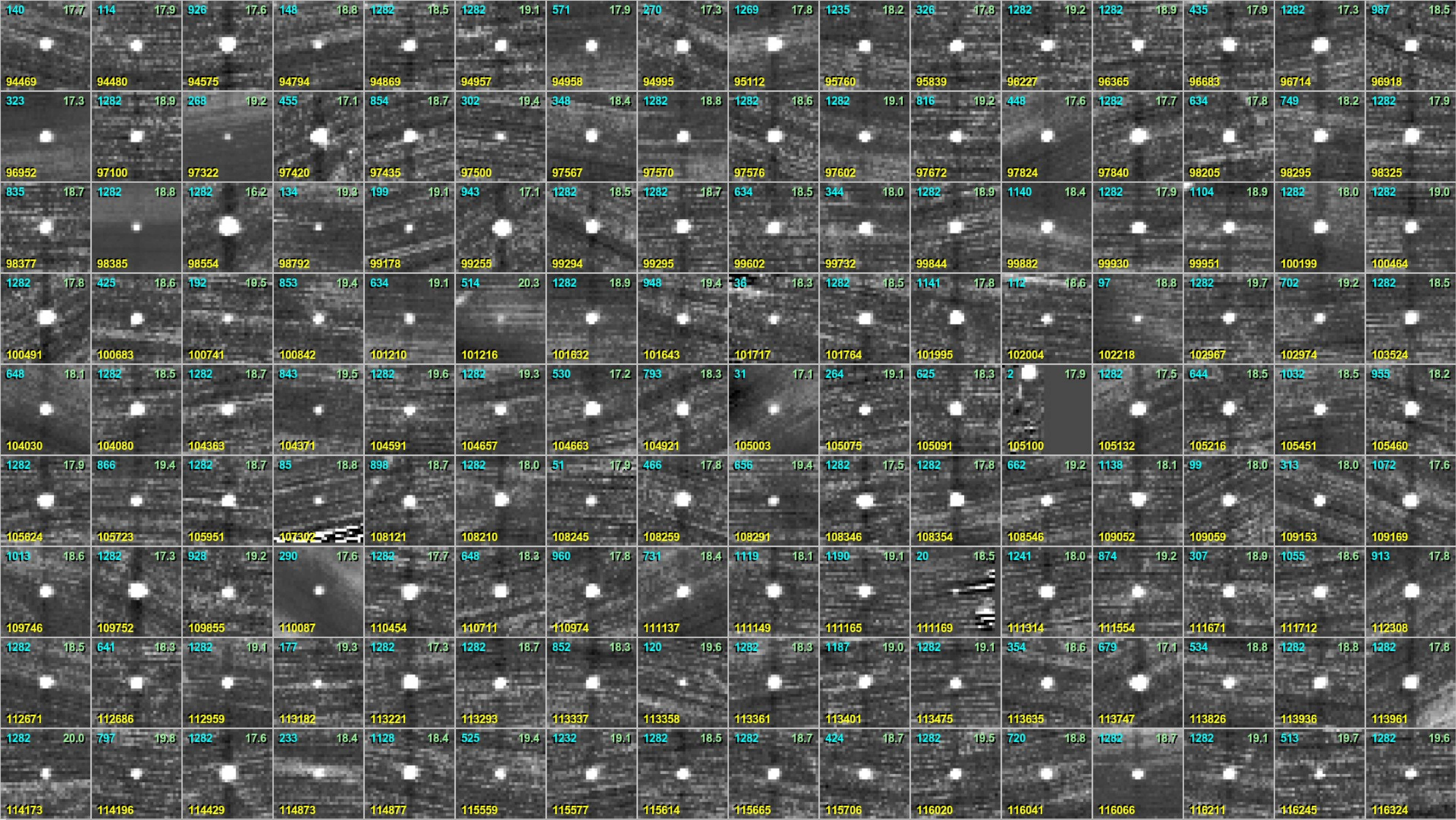
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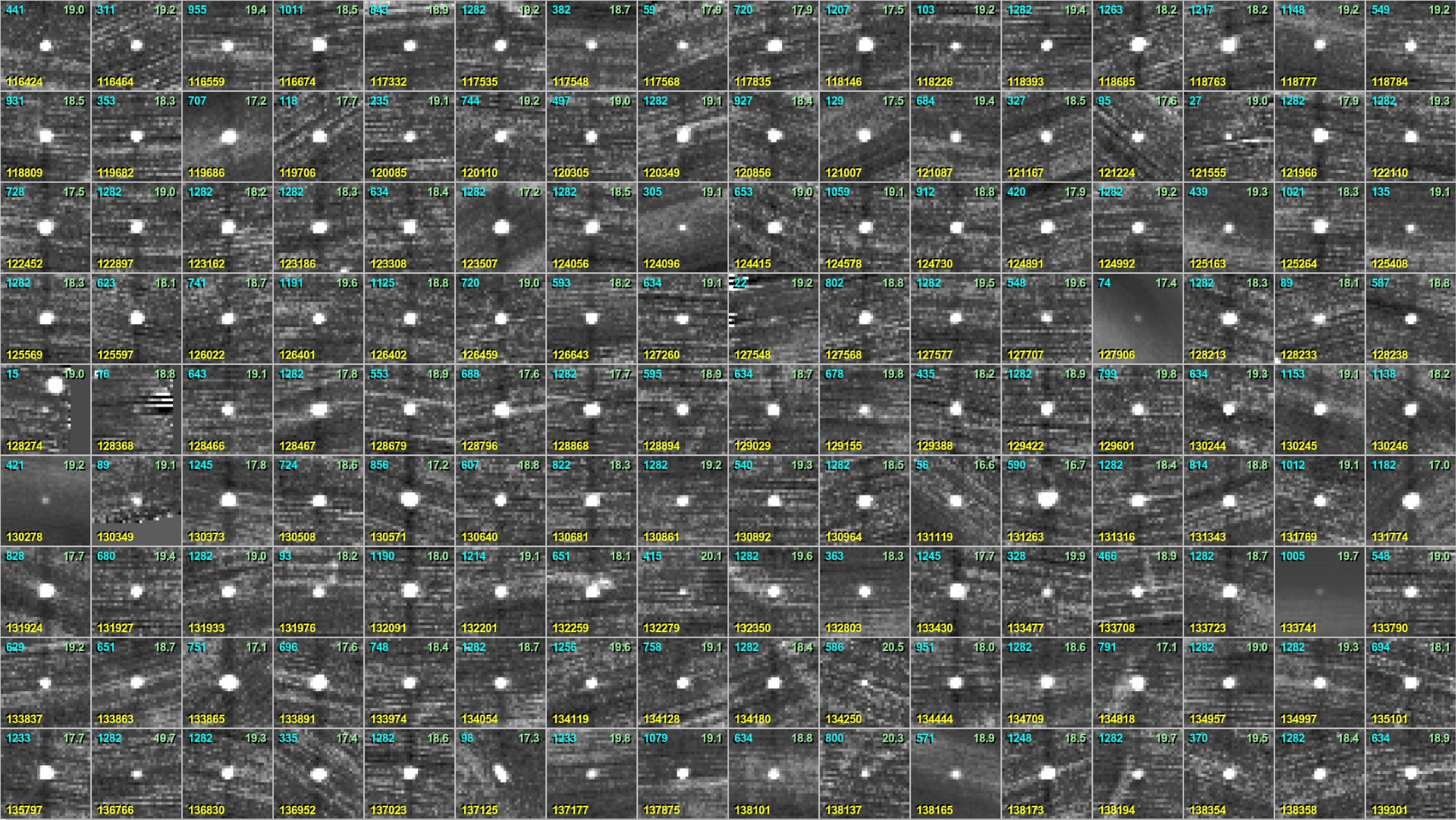

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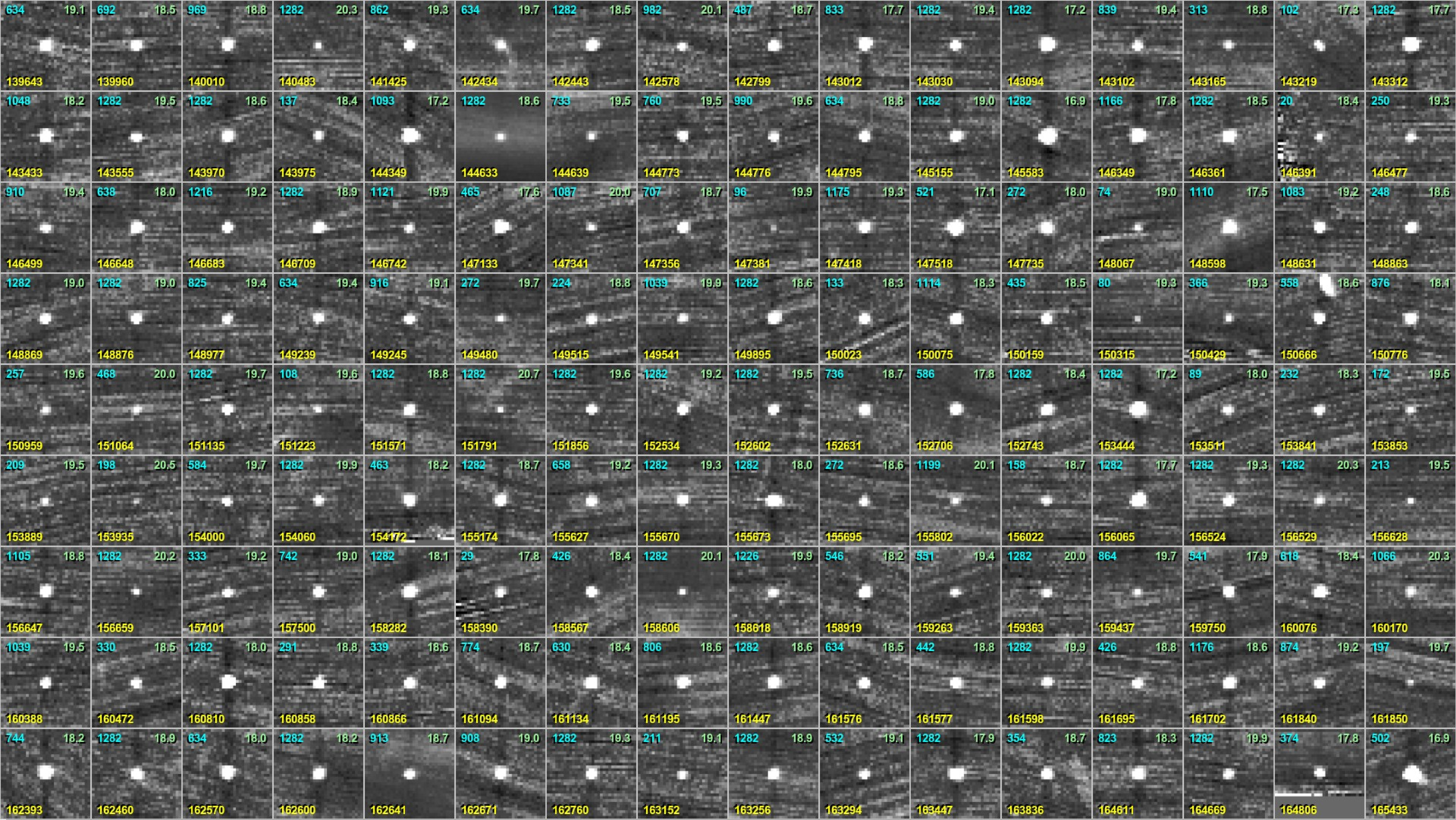

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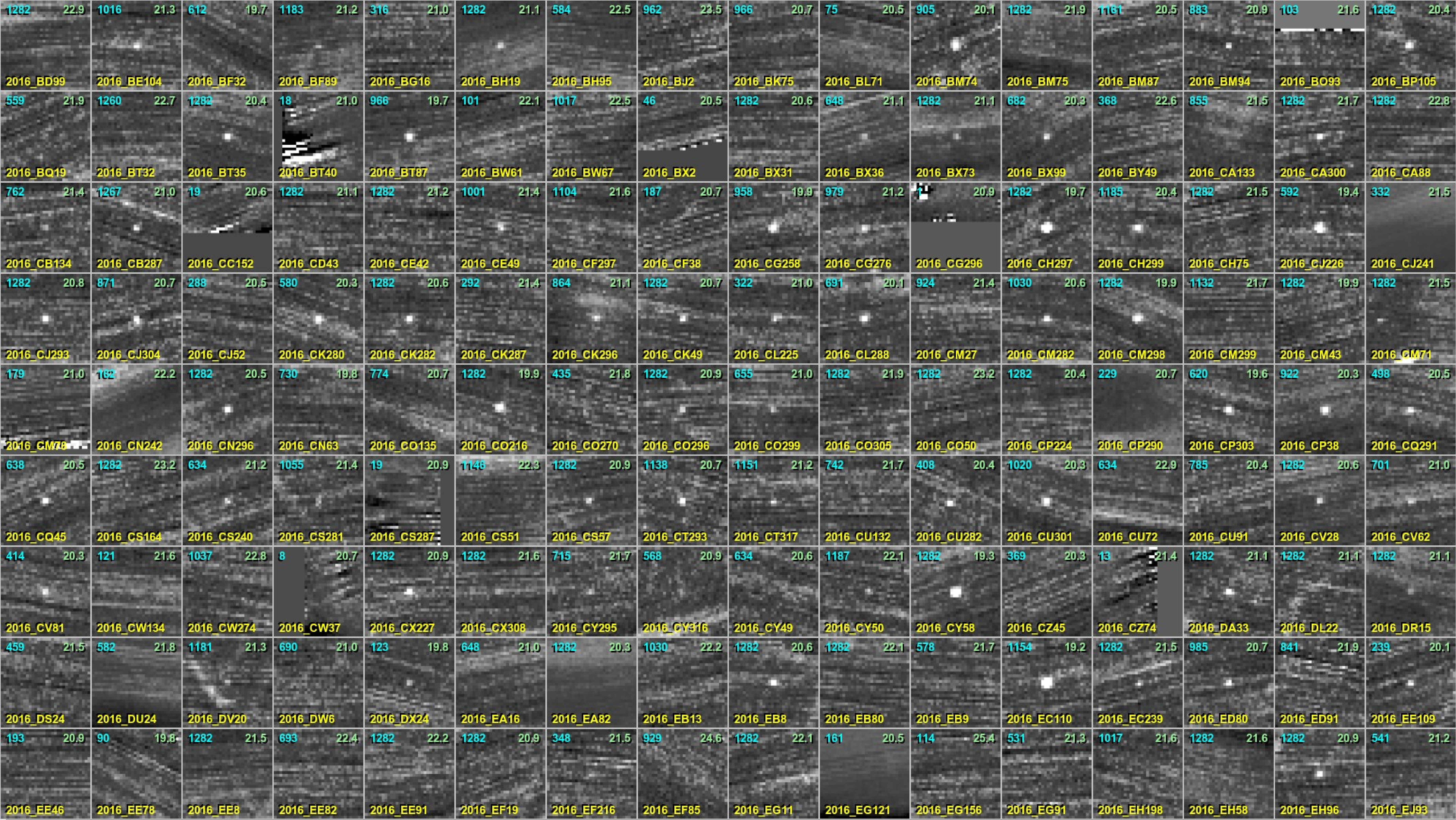
[26 slides skipped...]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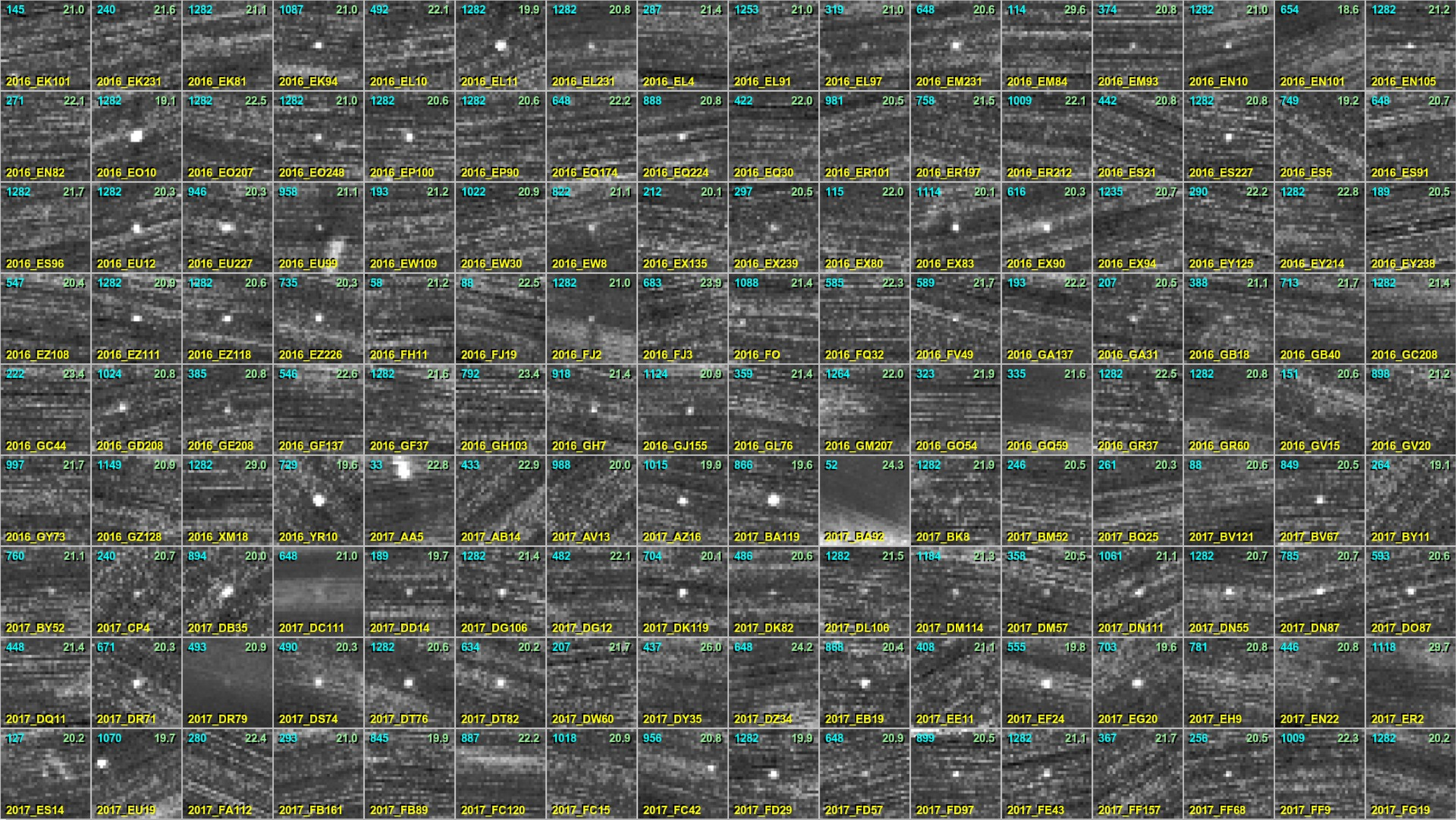
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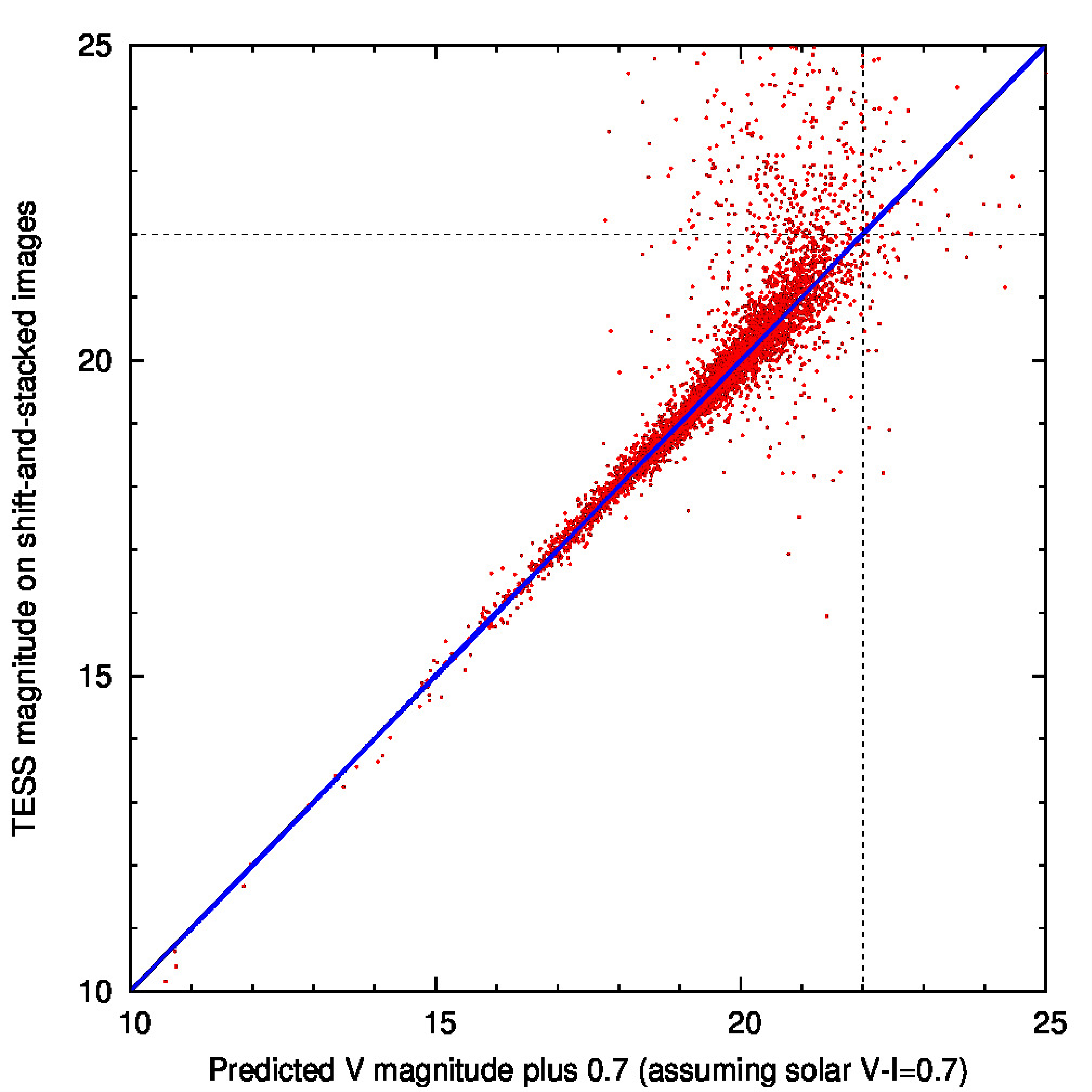
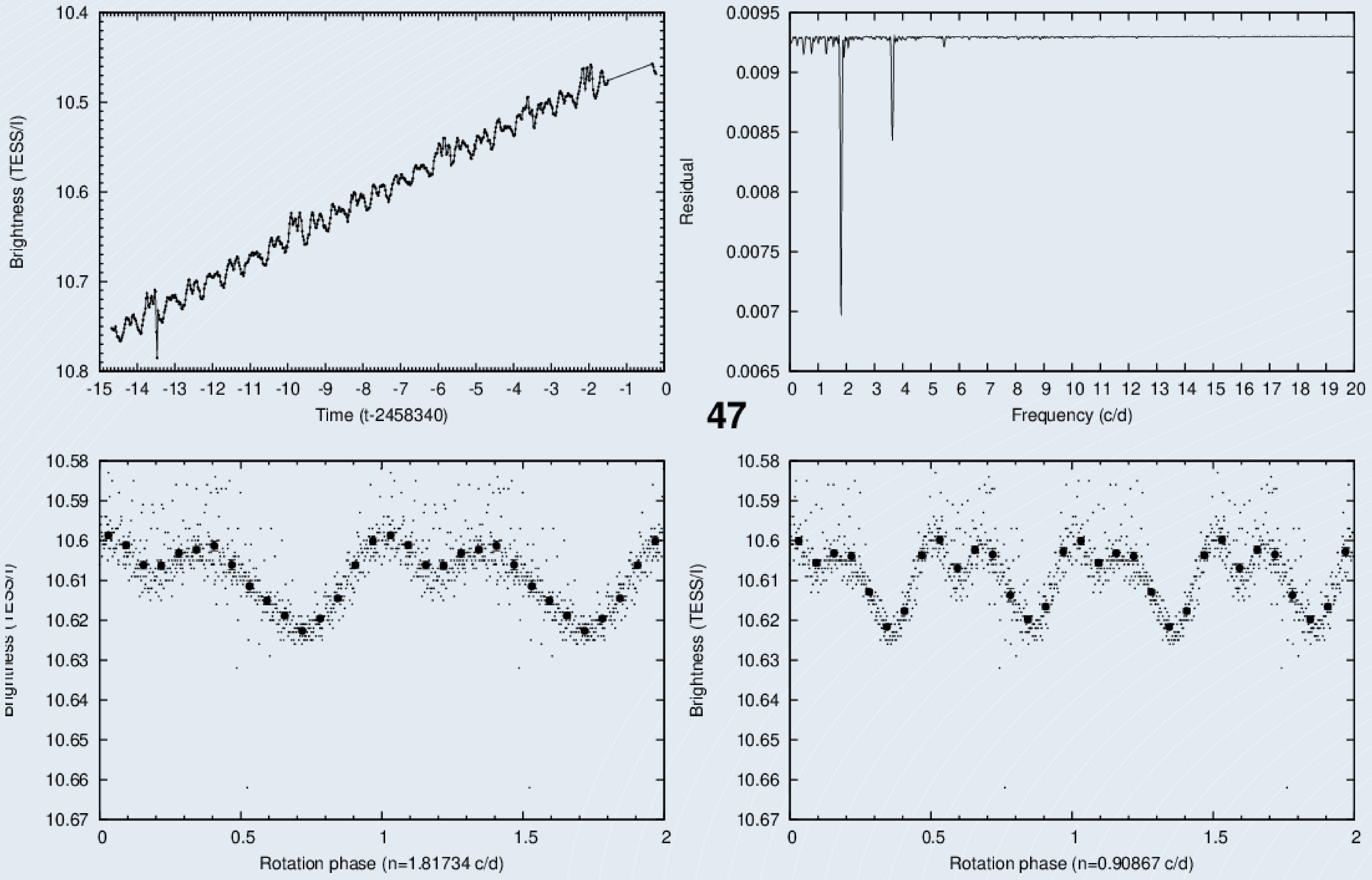
Detection completeness:

- **Sector 1** **=>**
- **Camera 1**
- **CCD 3**

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Time (t-2458340)
Residual
Frequency (c/d)
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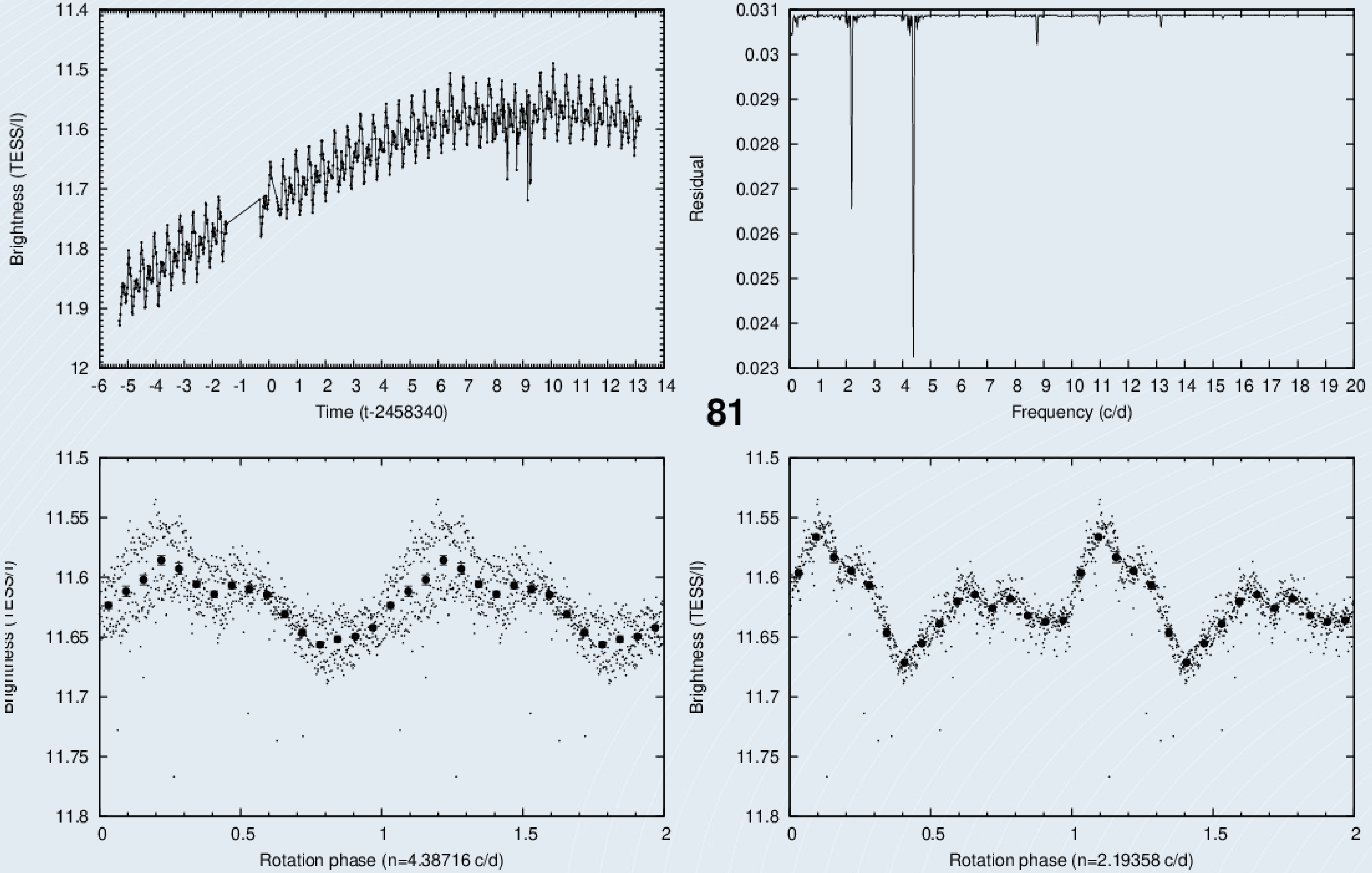
Rotation phase (n=1.81734 c/d)
Rotation phase (n=0.90867 c/d)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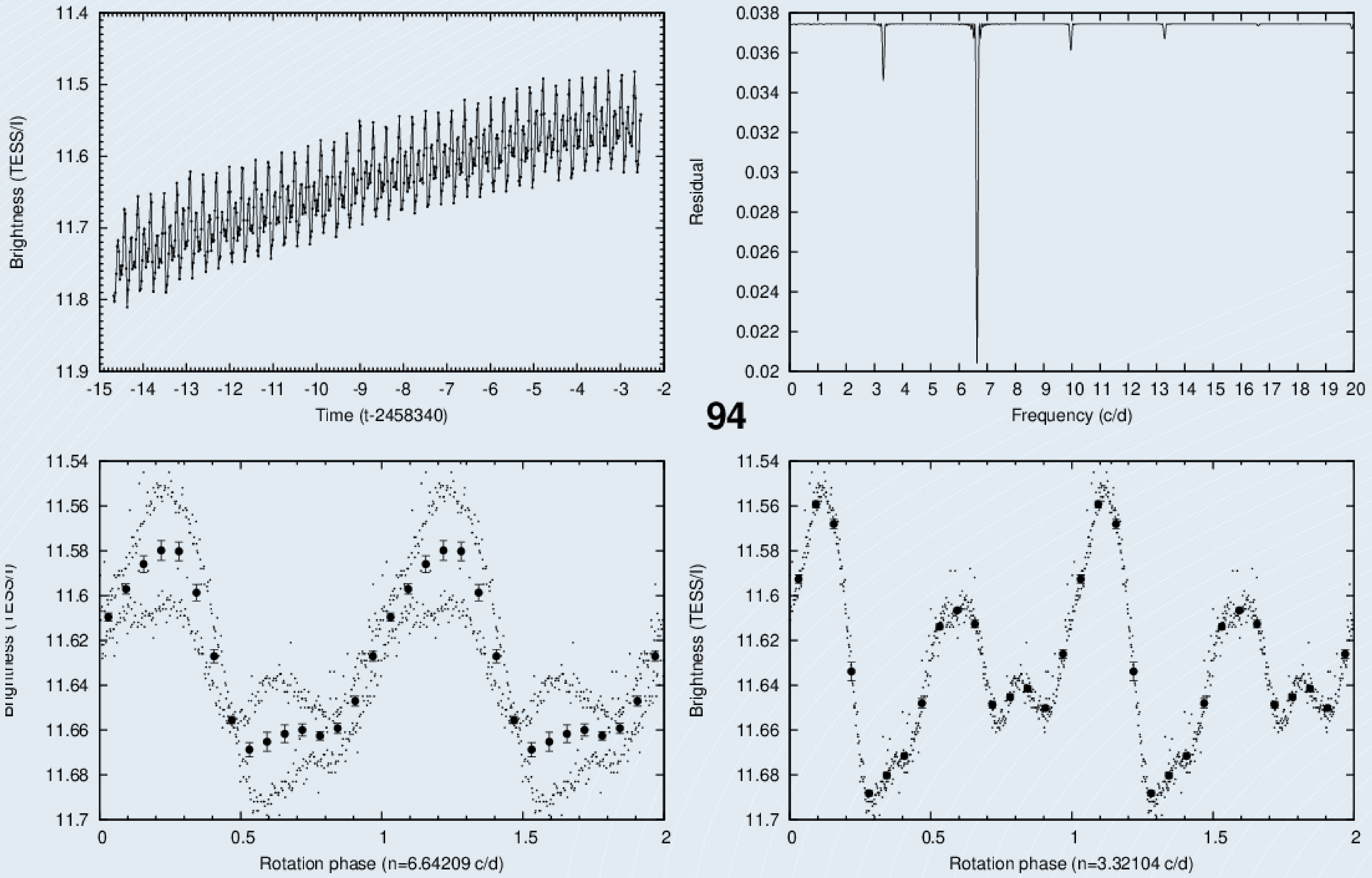

Brightness (TESS/I)
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11.5
11.6
11.7
11.8
11.9
-15 -14 -13 -12 -11 -10 -9 -8 -7 -6 -5 -4 -3 -2
Time (t-2458340)
Residual
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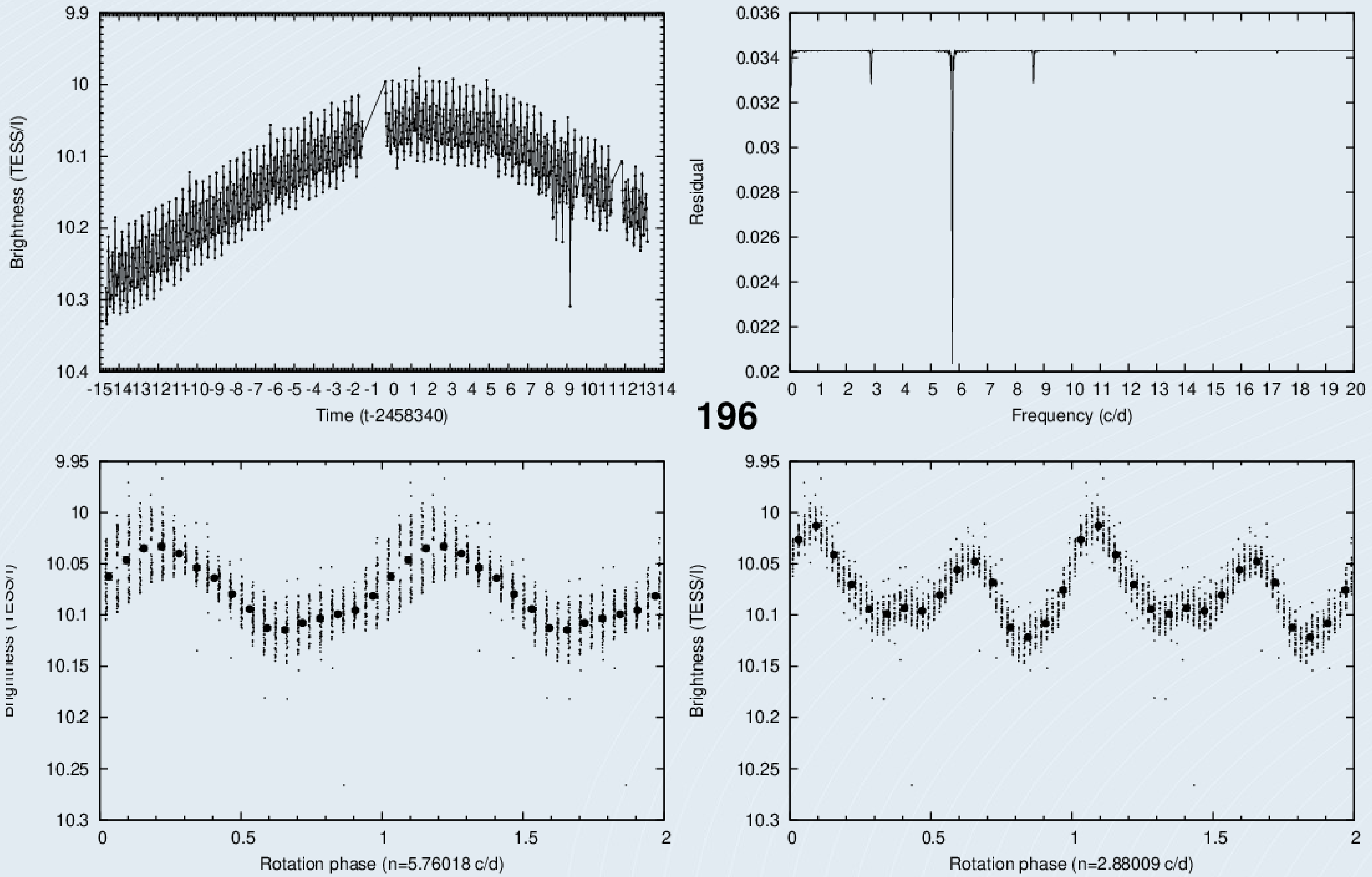
0.036
0.034
0.032
0.03
0.028
0.026
0.024
0.022
0.02
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Frequency (c/d)
94
11.54
11.56
11.58
11.6
11.62
11.64
11.66
11.68
11.7
0 0.5 1 1.5 2
Rotation phase (n=6.64209 c/d)
Brightness (TESS/I)
0 0.5 1 1.5 2
Rotation phase (n=3.32104 c/d)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Residual
Frequency (c/d)
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Brightness (TESS/I)
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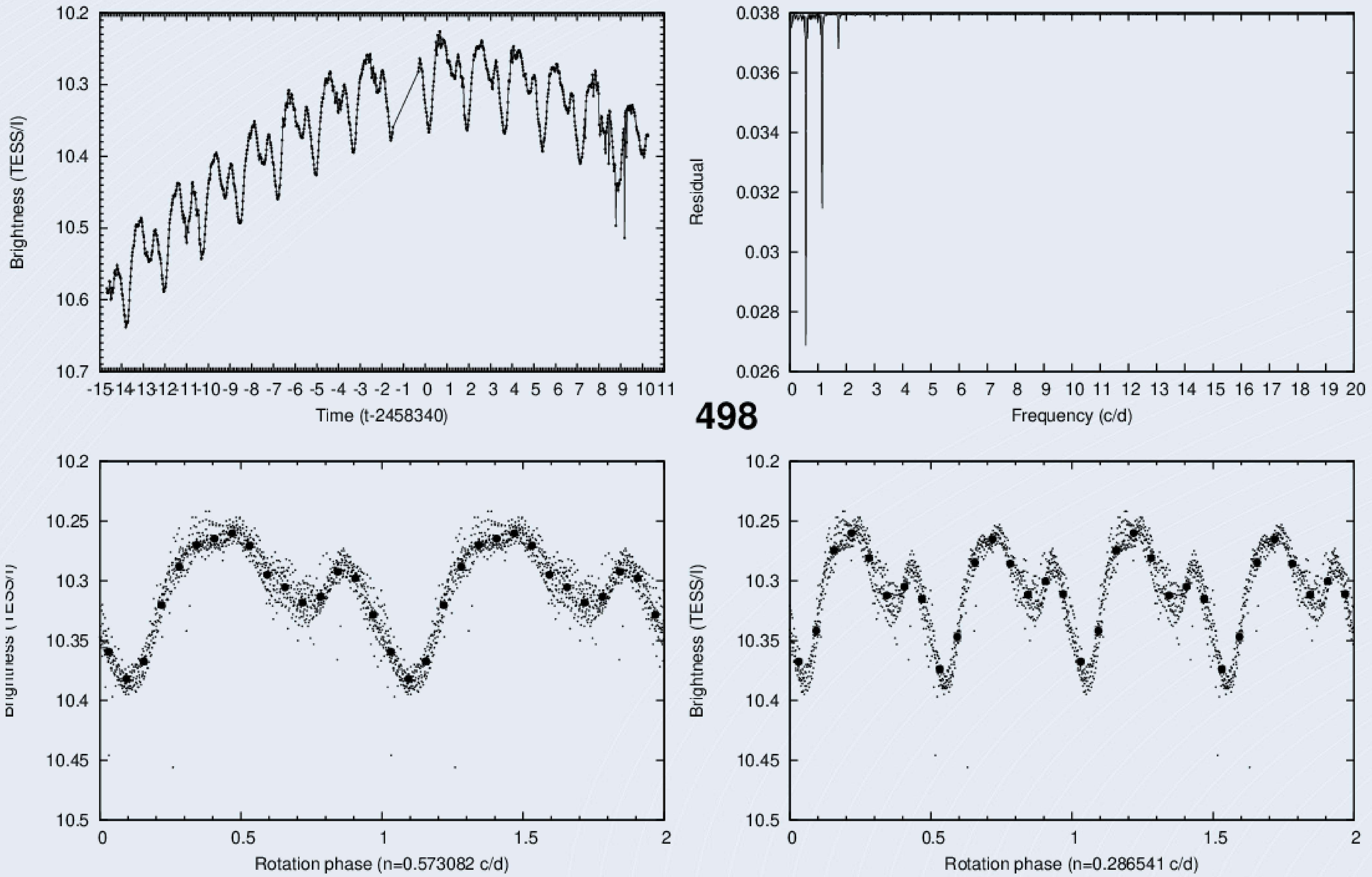
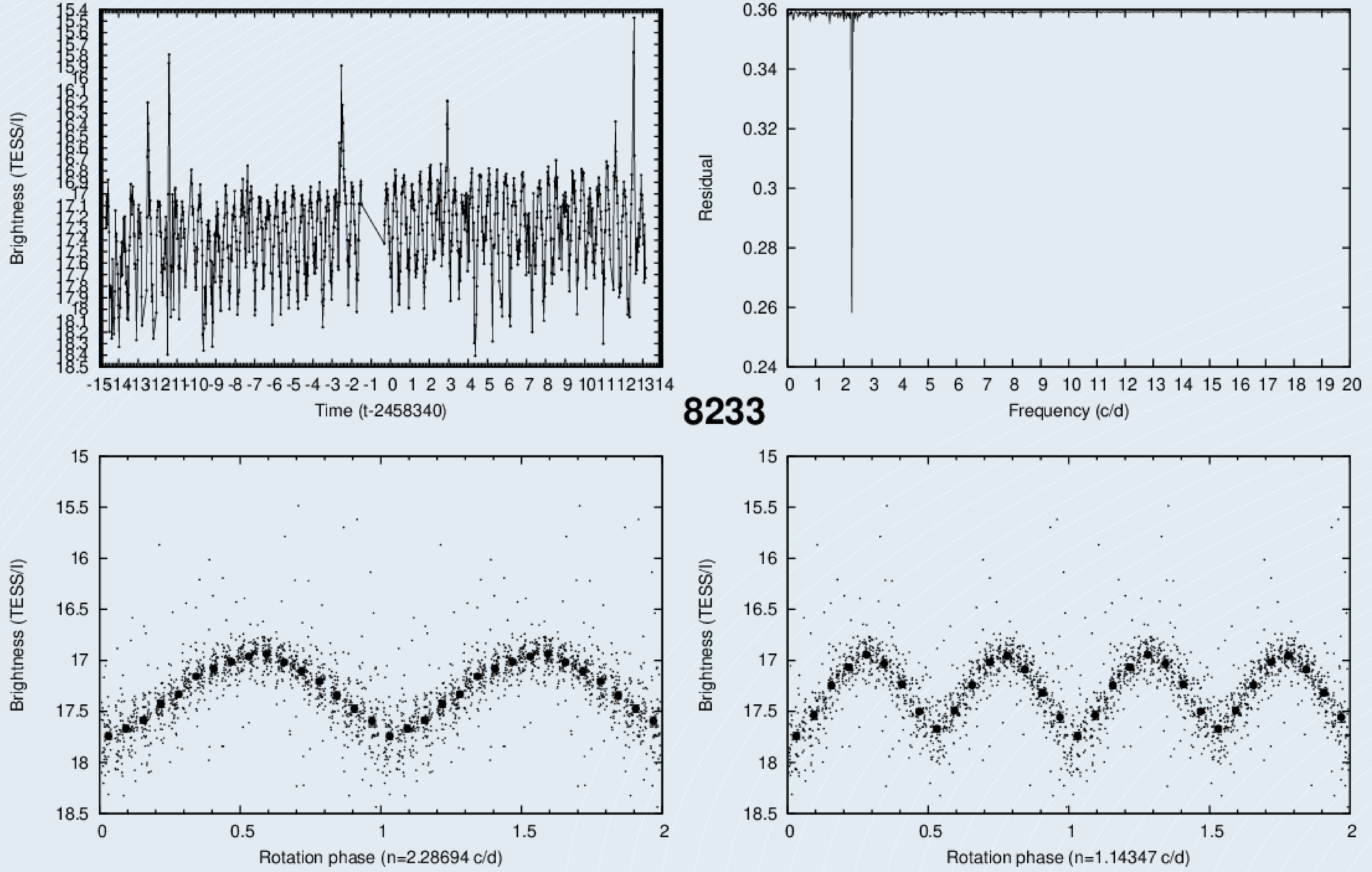
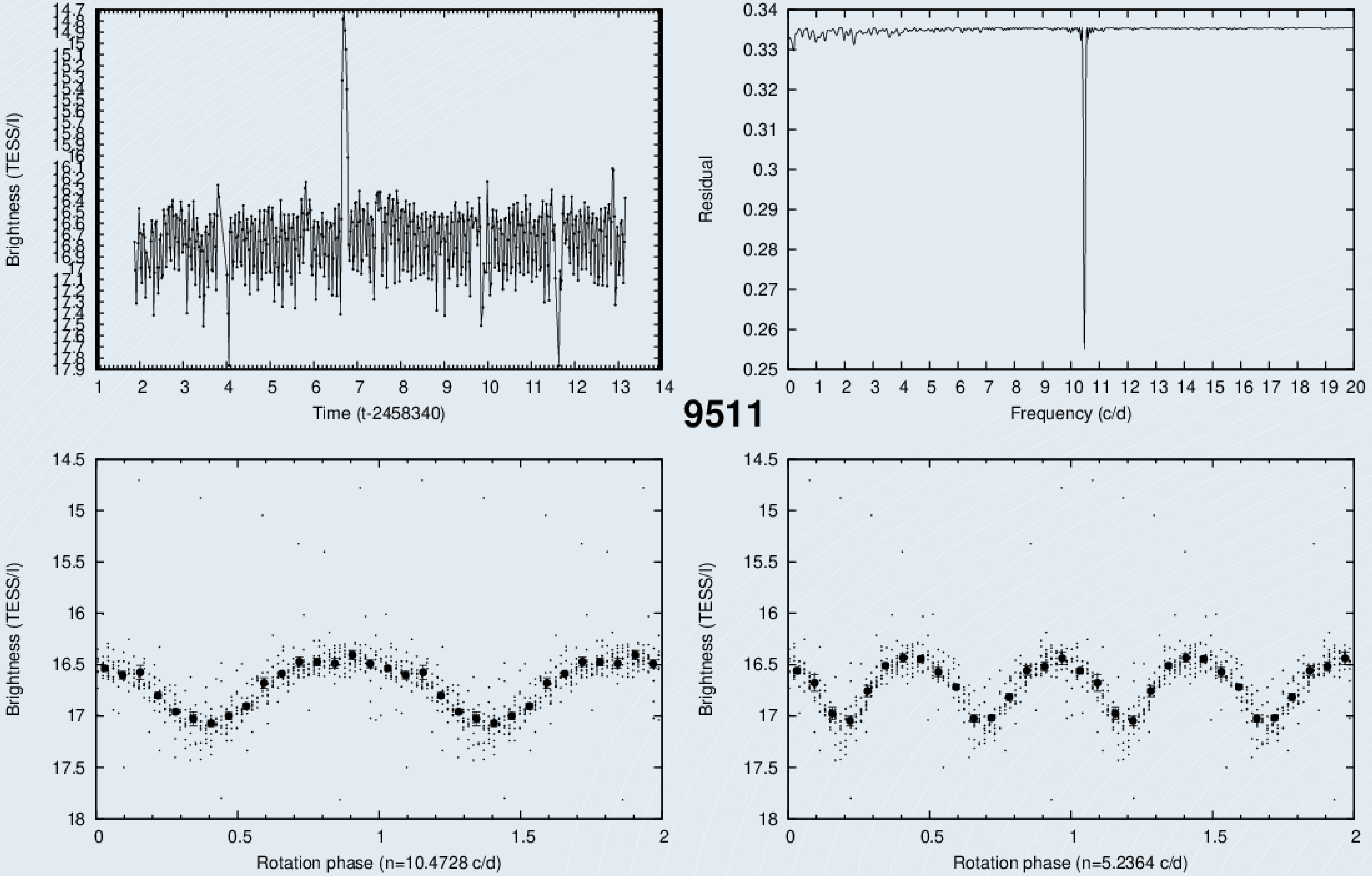
Brightness (TESS/I)
Rotation phase (n=2.88009 c/d)



Brightness (TESS/I)
Time (t-2458340)
Residual
Frequency (c/d)
Rotation phase (n=0.573082 c/d)
Rotation phase (n=0.286541 c/d)

498


8233
Brightness (TESS/I)
Time (t-2458340)
Residual
Frequency (c/d)
Brightness (TESS/I)
Rotation phase (n=2.28694 c/d)
Brightness (TESS/I)
Rotation phase (n=1.14347 c/d)



Brightness (TESS/I)
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Residual
Frequency (c/d)
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Brightness (TESS/I)
Rotation phase (n=10.4728 c/d)
Brightness (TESS/I)
Rotation phase (n=5.2364 c/d)

47 Aglaja – occultation, see Millis et al.

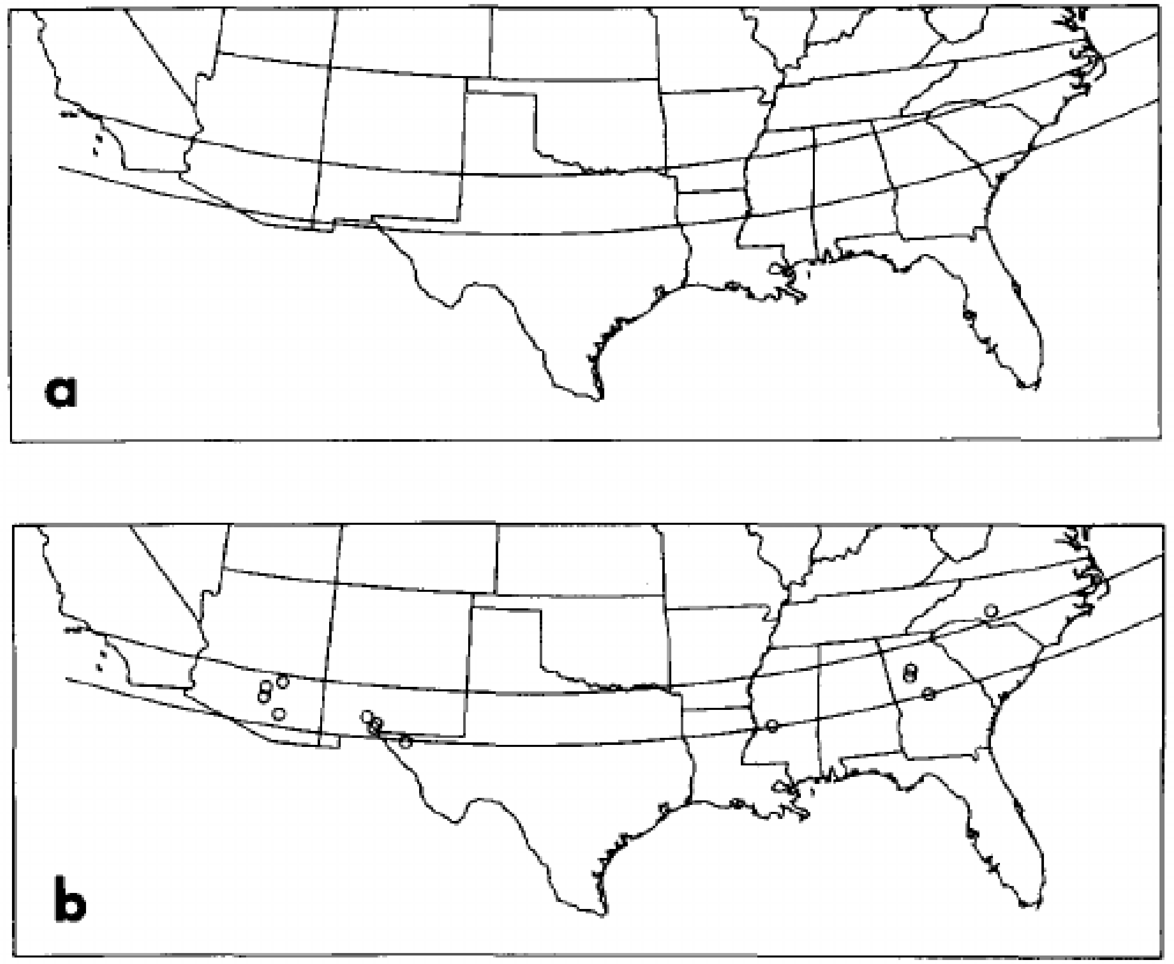


FIG. 1. (a) The predicted ground track of the 16 September 1984 occultation of SAO 146599 by 47 Aglaja. This track is based on four plates taken with the 18-in. Lowell astrograph on 12, 13, and 14 September. (b) The occultation track derived from observations of the occultation. Open circles mark the locations of the sites listed in Table I.

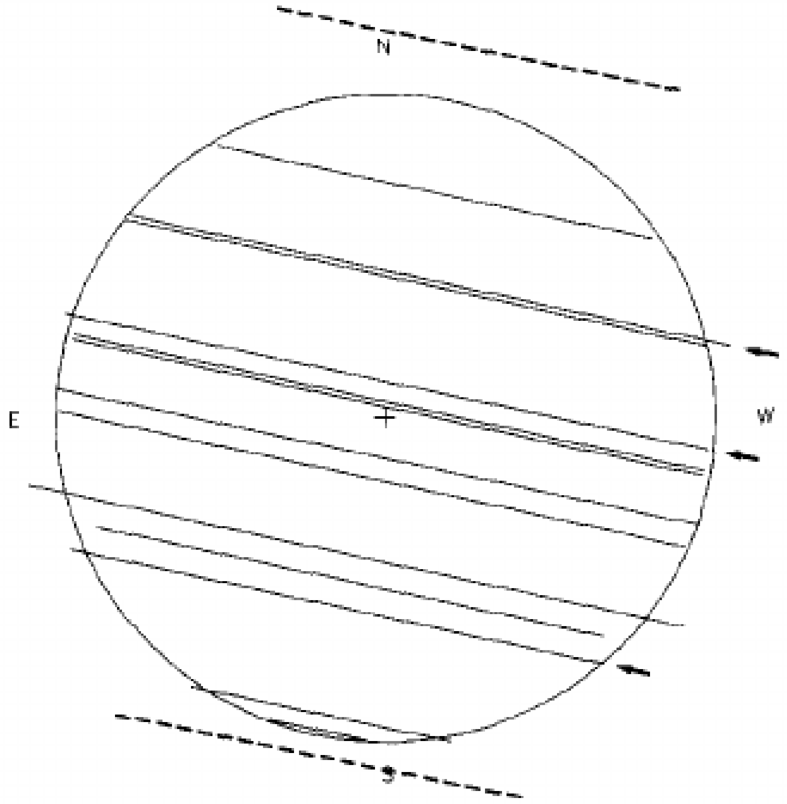
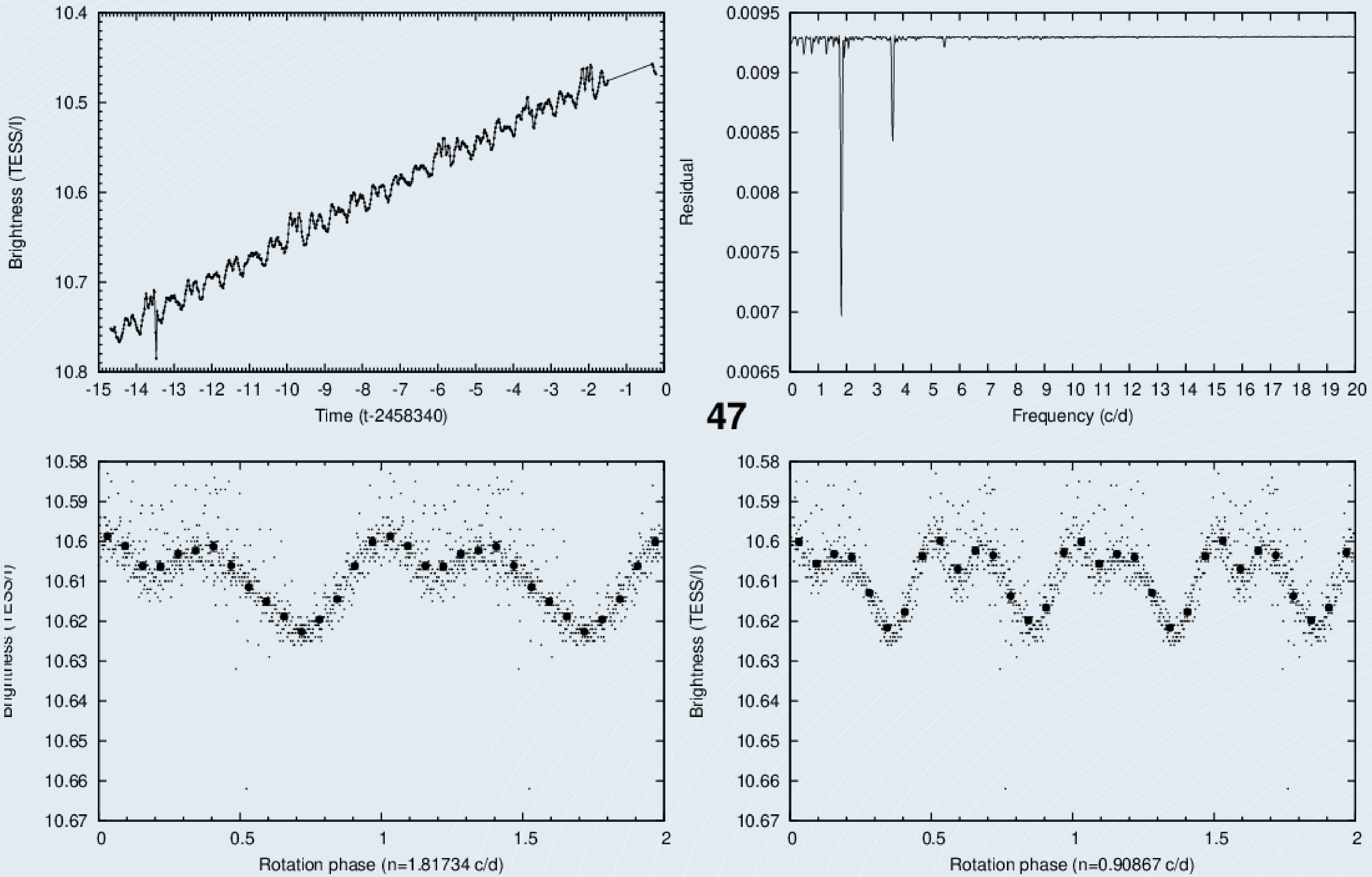


FIG. 2. A circular limb profile fitted by least squares to the observed chords across Aglaja. Arrows indicate chords derived from photoelectric or video observations; all others are based on visual timings of the occultation. The dashed lines denote constraints placed on the least-squares solution by negative observations from sites near, but outside, the ground track. From top to bottom of the figure, sites are in the same order in which they are listed in Table I.

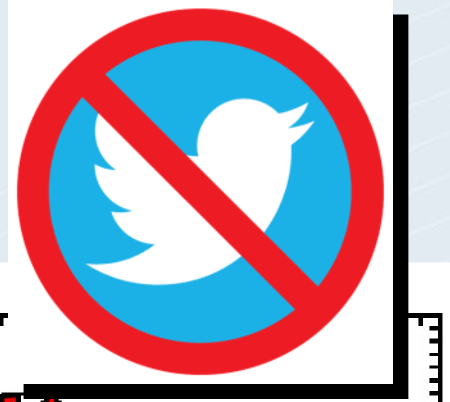
47 Aglaja

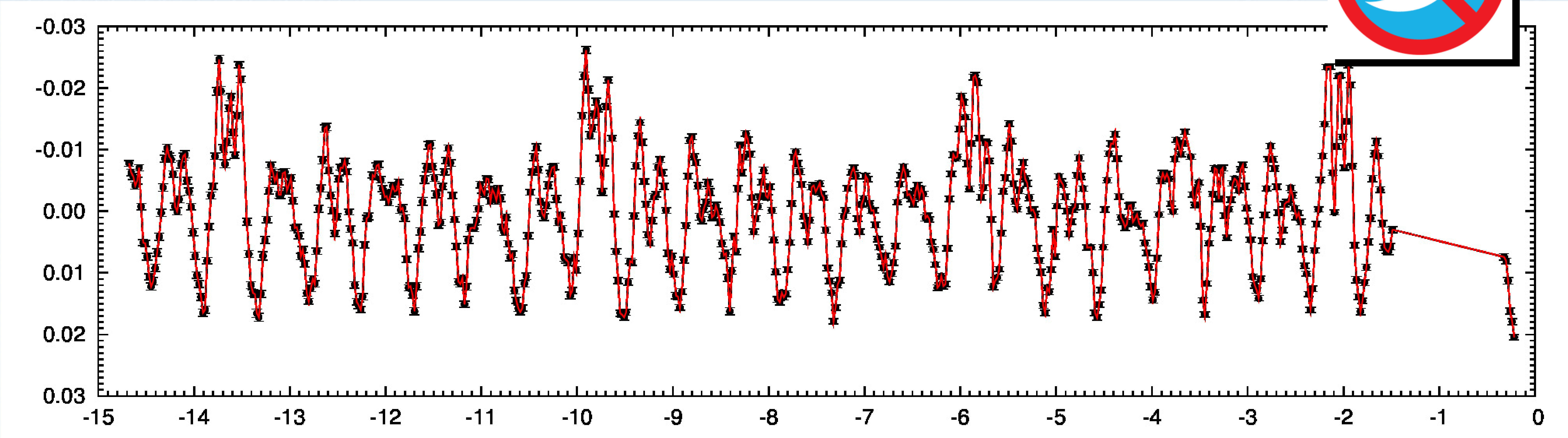


Brightness (TESS/I)
Time (t-2458340)
Residual
Frequency (c/d)
47
Rotation phase (n=1.81734 c/d)
Rotation phase (n=0.90867 c/d)

47 Aglaja – not-so-pleriminary lightcurve

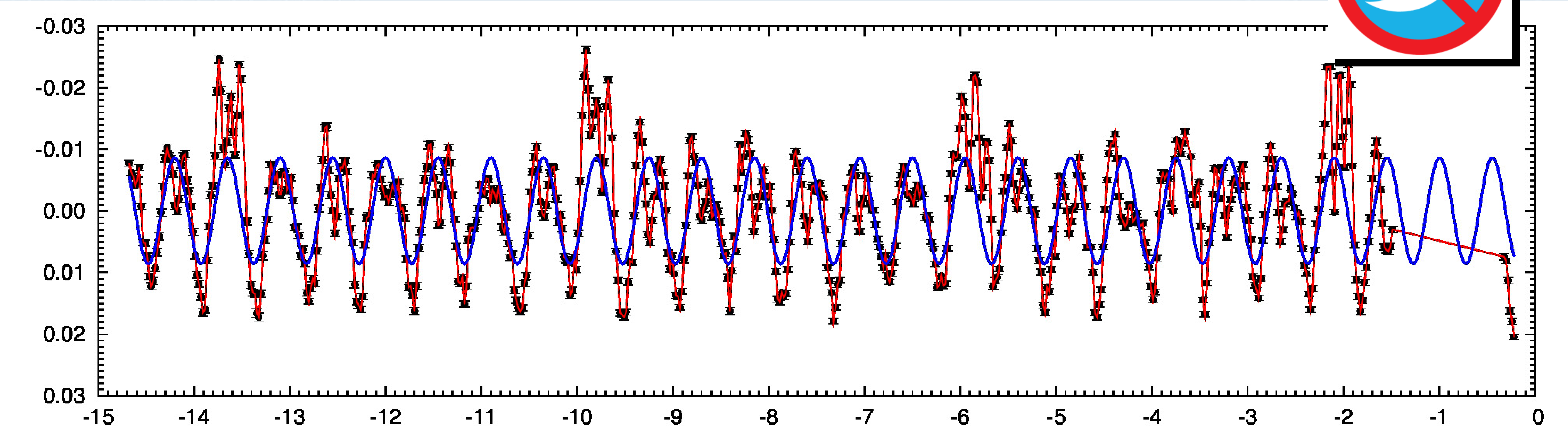
- Small light curve amplitude and rotation frequency confirmed
- However: double-peaked solution, w/ every 7th peak is brighter





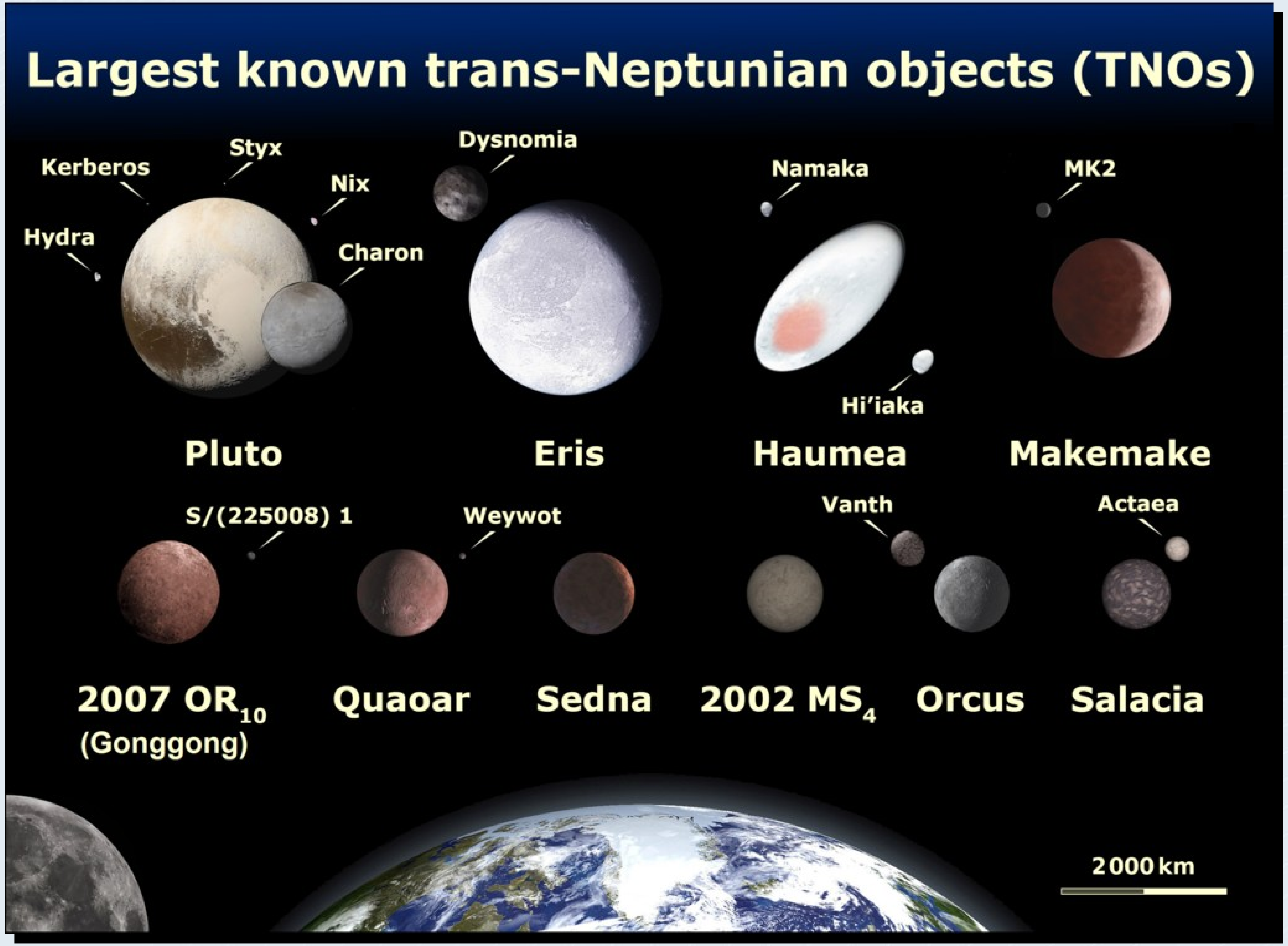
47 Aglaja – not-so-pleriminary lightcurve

- it can be the largest (and nearly spherical!) tumbling asteroid in the Main Belt
- what do we see? Irregular shape or structures on the surface?

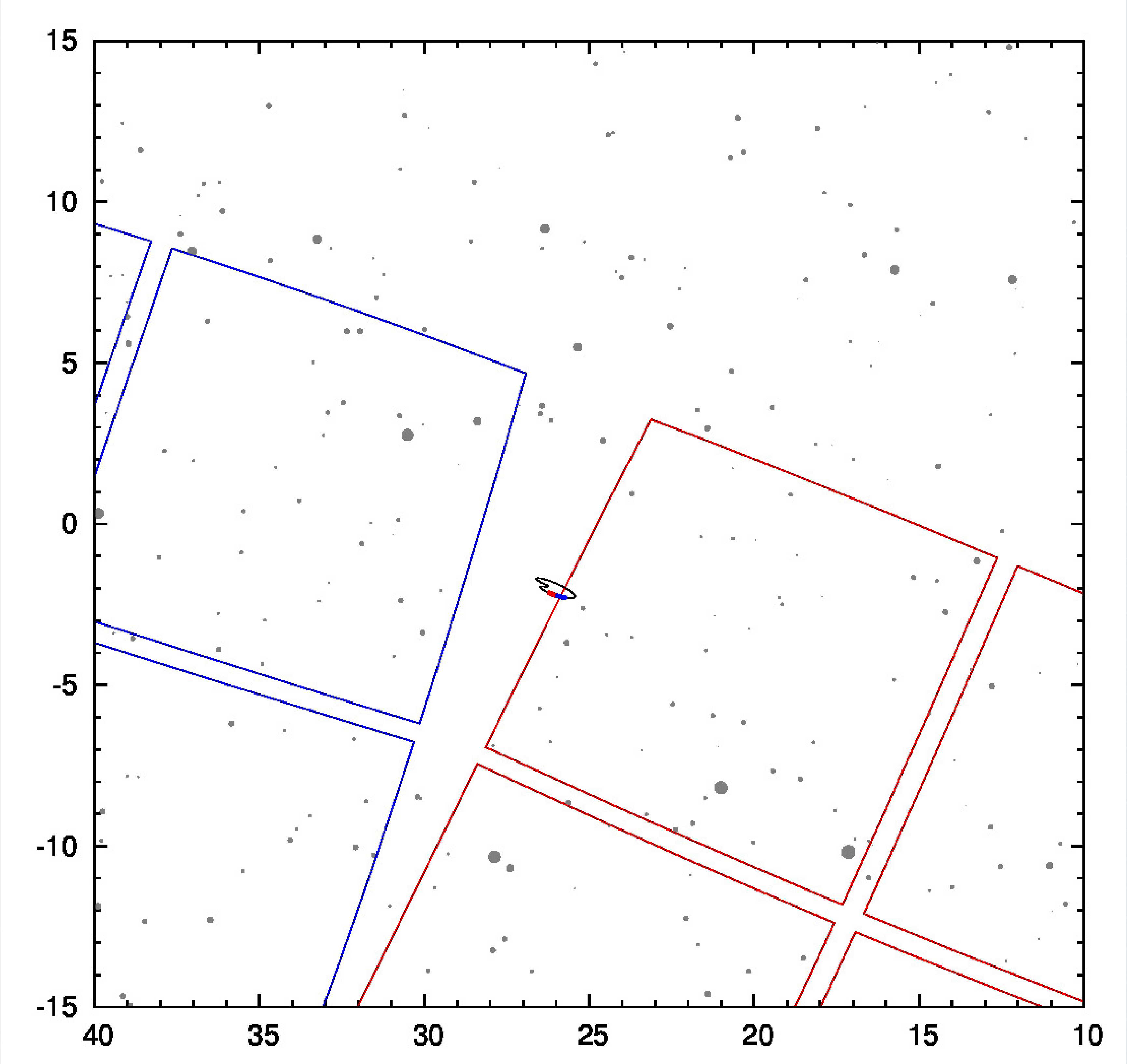


Kuiper-belt objects:

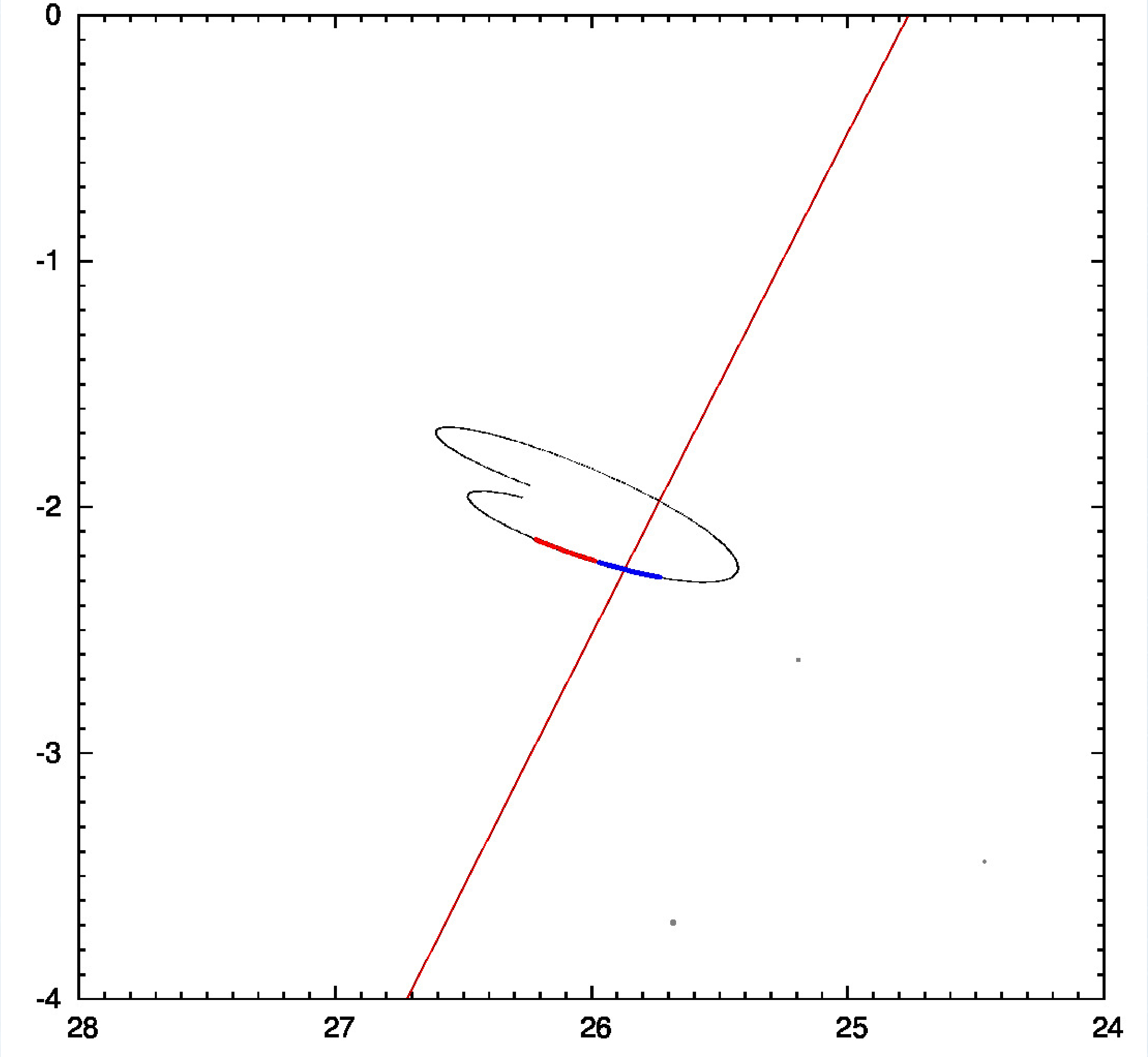
Eris & Orcus



Eris... unfurtunately b/w Sectors #3 and #4

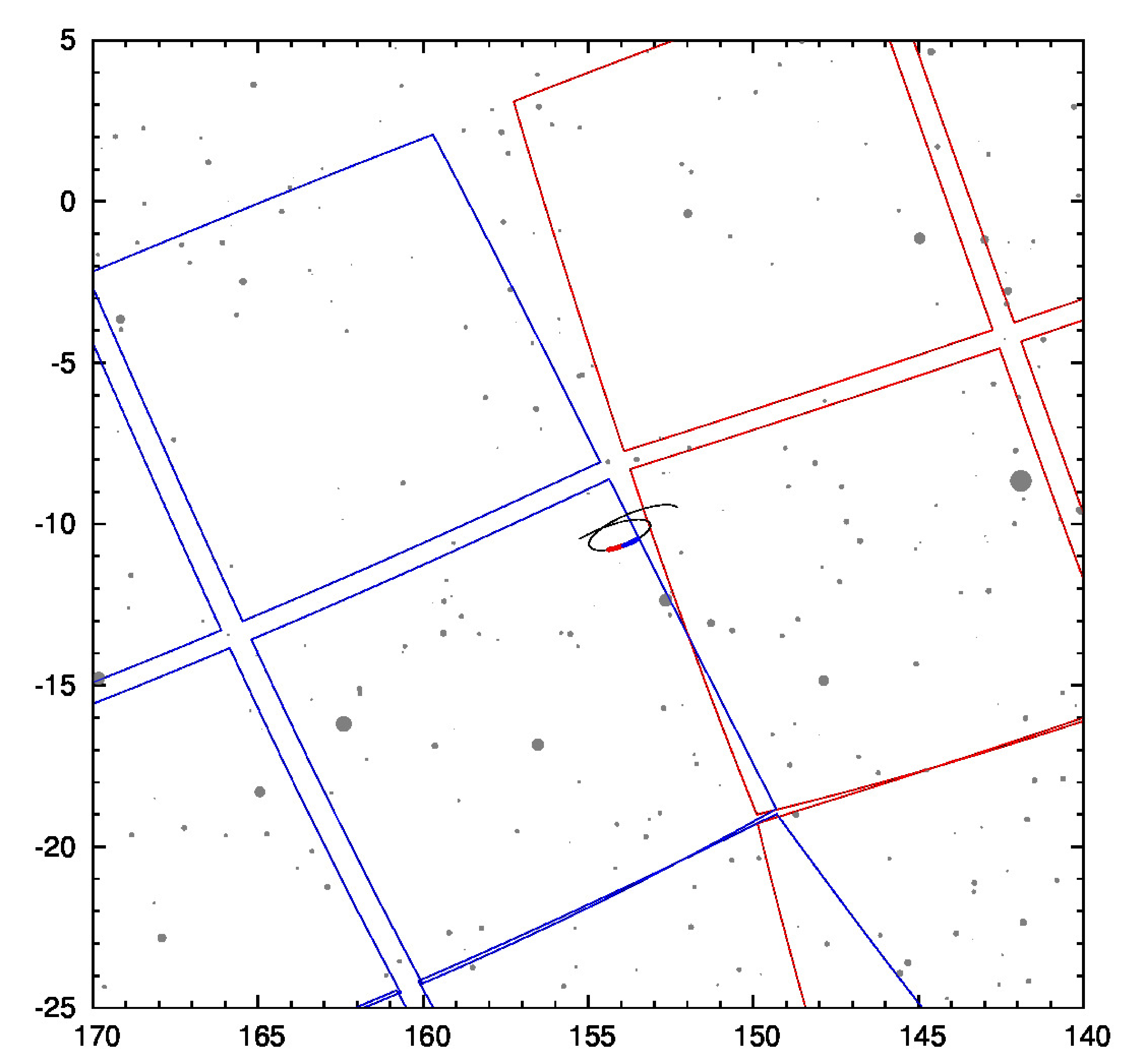


Eris… unfurtunately b/w Sectors #3 and #4



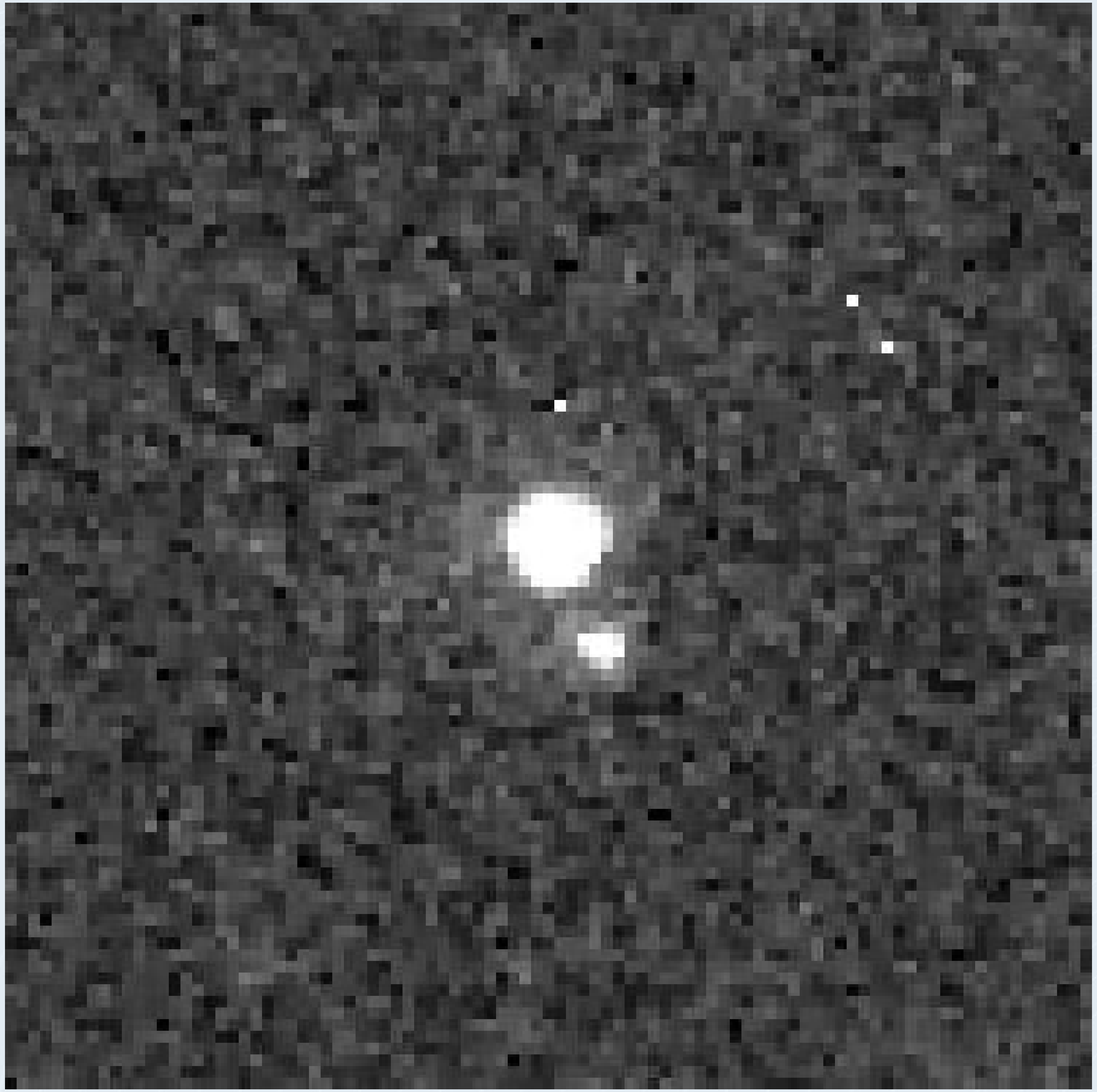
Orcus: Sector 9!

- Has a moon: Vanth
- Unknown rotational period (at least, ambiguous)
- Realatively bright (V=19.3 at opposition => TESS: ~18.6)



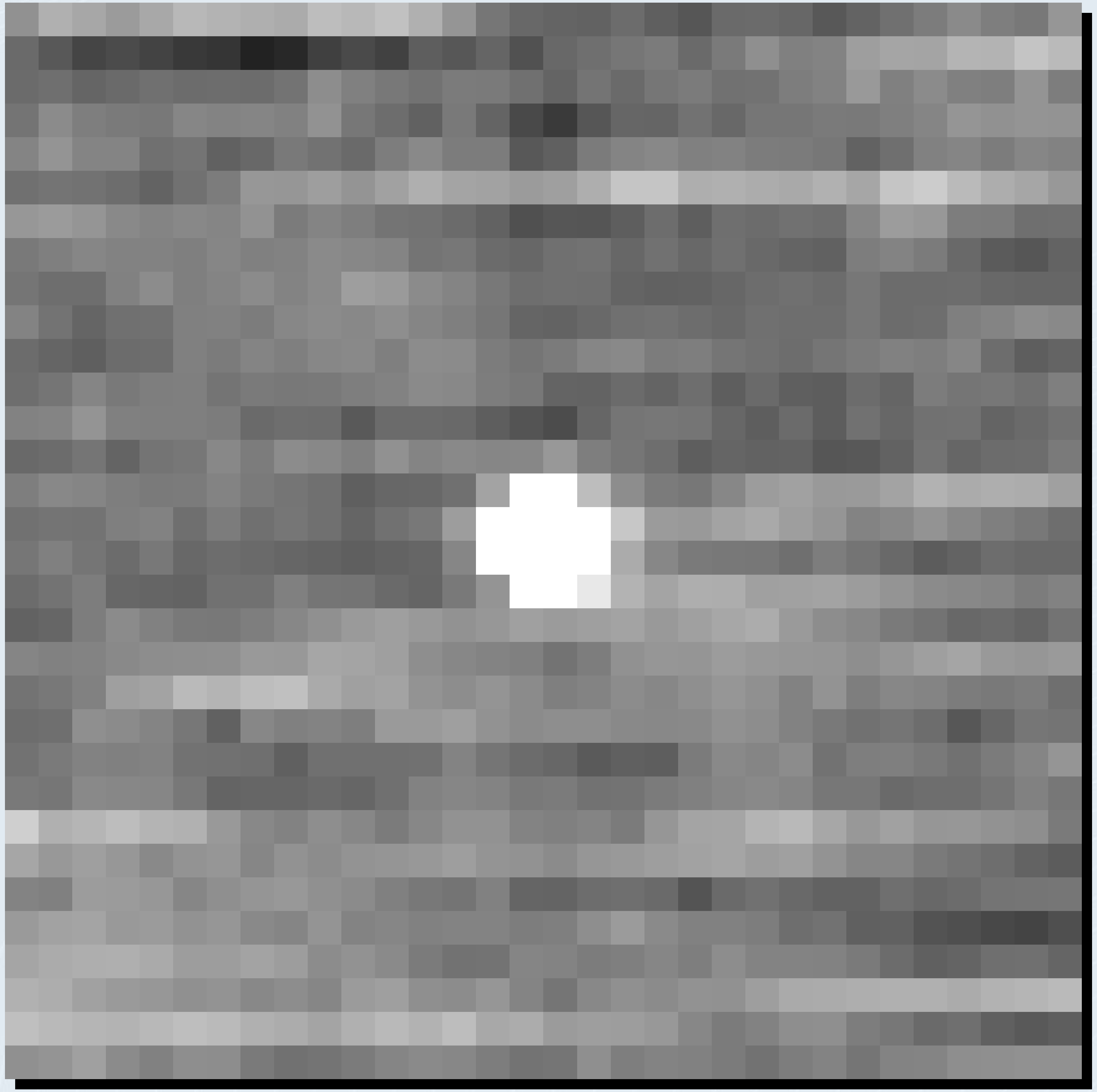
Orcus: Sector 9!

- Has a moon: Vanth
- Unknown rotational period (at least, ambiguous)
- Realatively bright (V=19.3 at opposition => TESS: ~18.6)
- An HST image, covering 4”x4”:



Orcus: Sector 9!

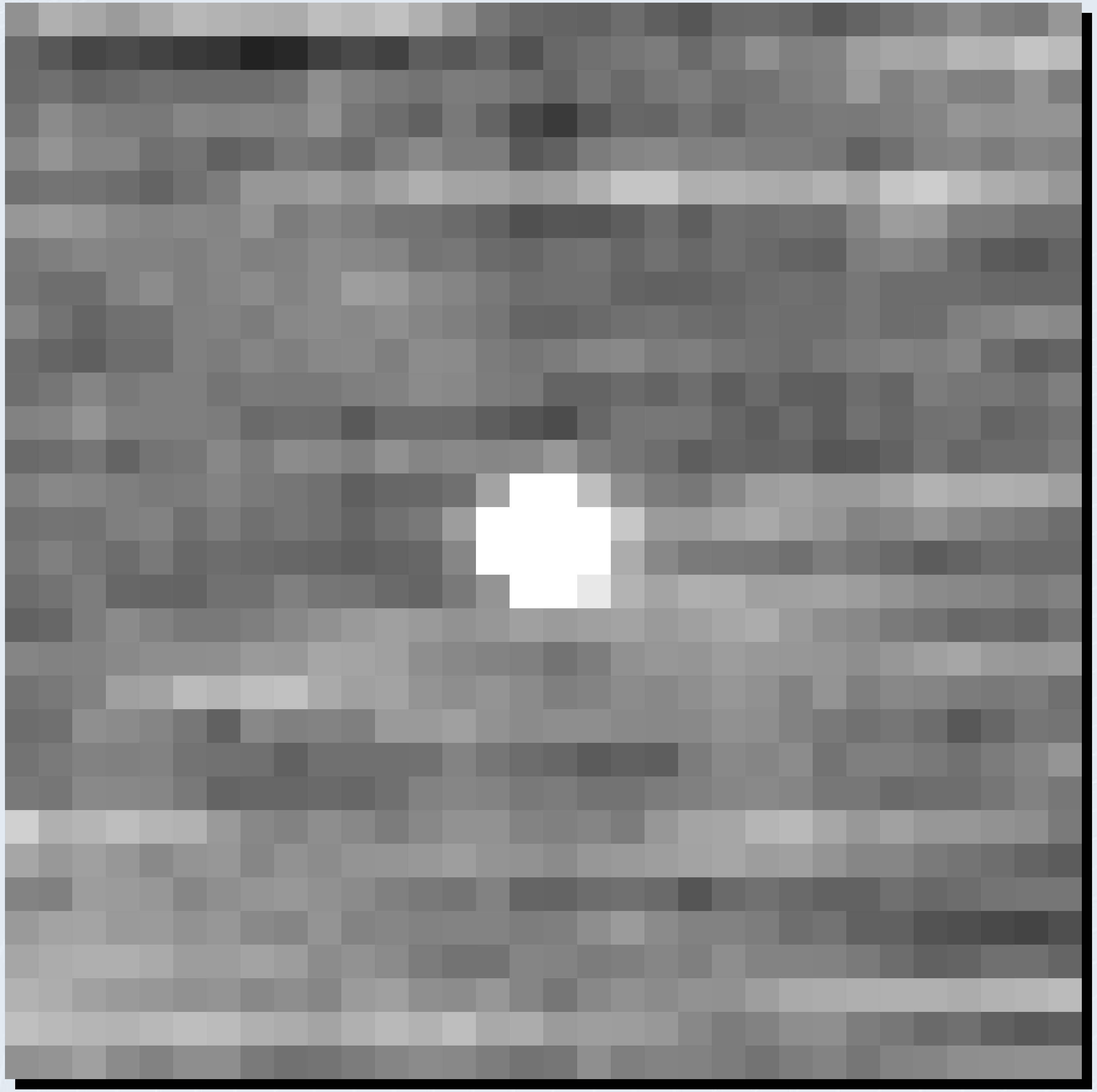
- Has a moon: Vanth
- Unknown rotational period (at least, ambiguous)
- Realatively bright (V=19.3 at opposition => TESS: ~18.6)
- TESS image, 680” x 680”:



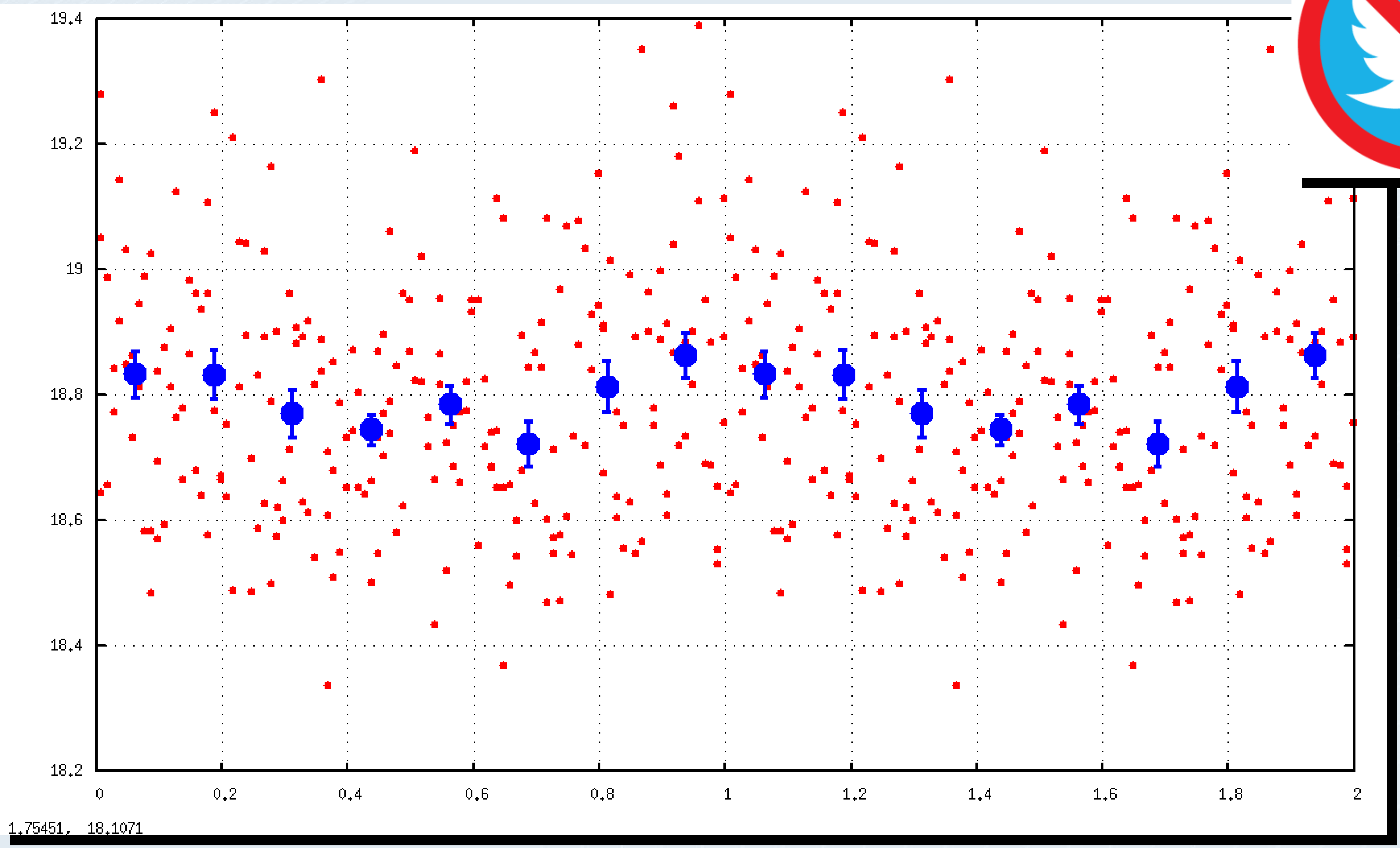
Orcus: Sector 9!

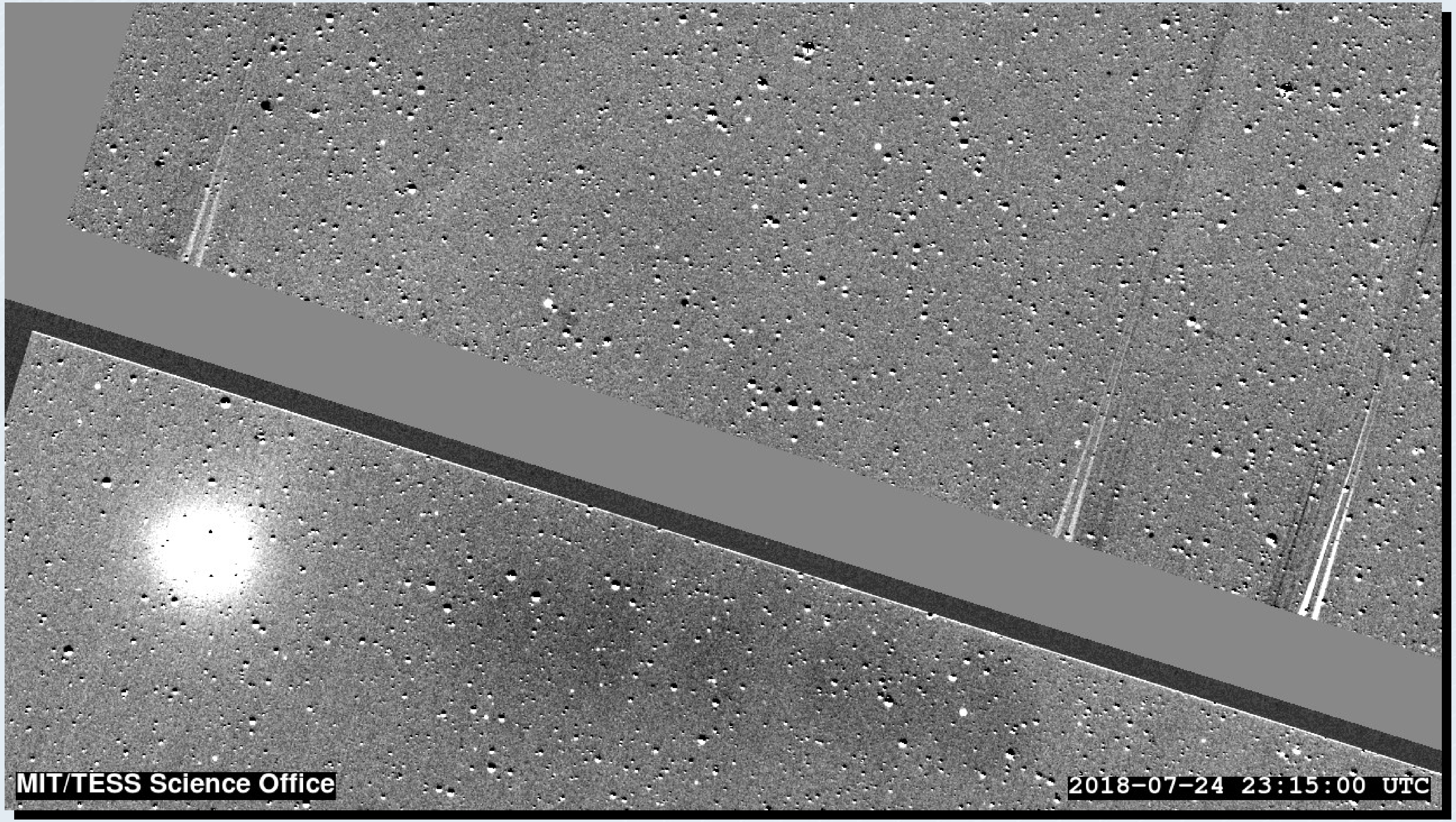
- Has a moon: Vanth
- Unknown rotational period (at least, ambiguous)
- Realatively bright (V=19.3 at opposition => TESS: ~18.6)
- TESS image, 680” x 680”:

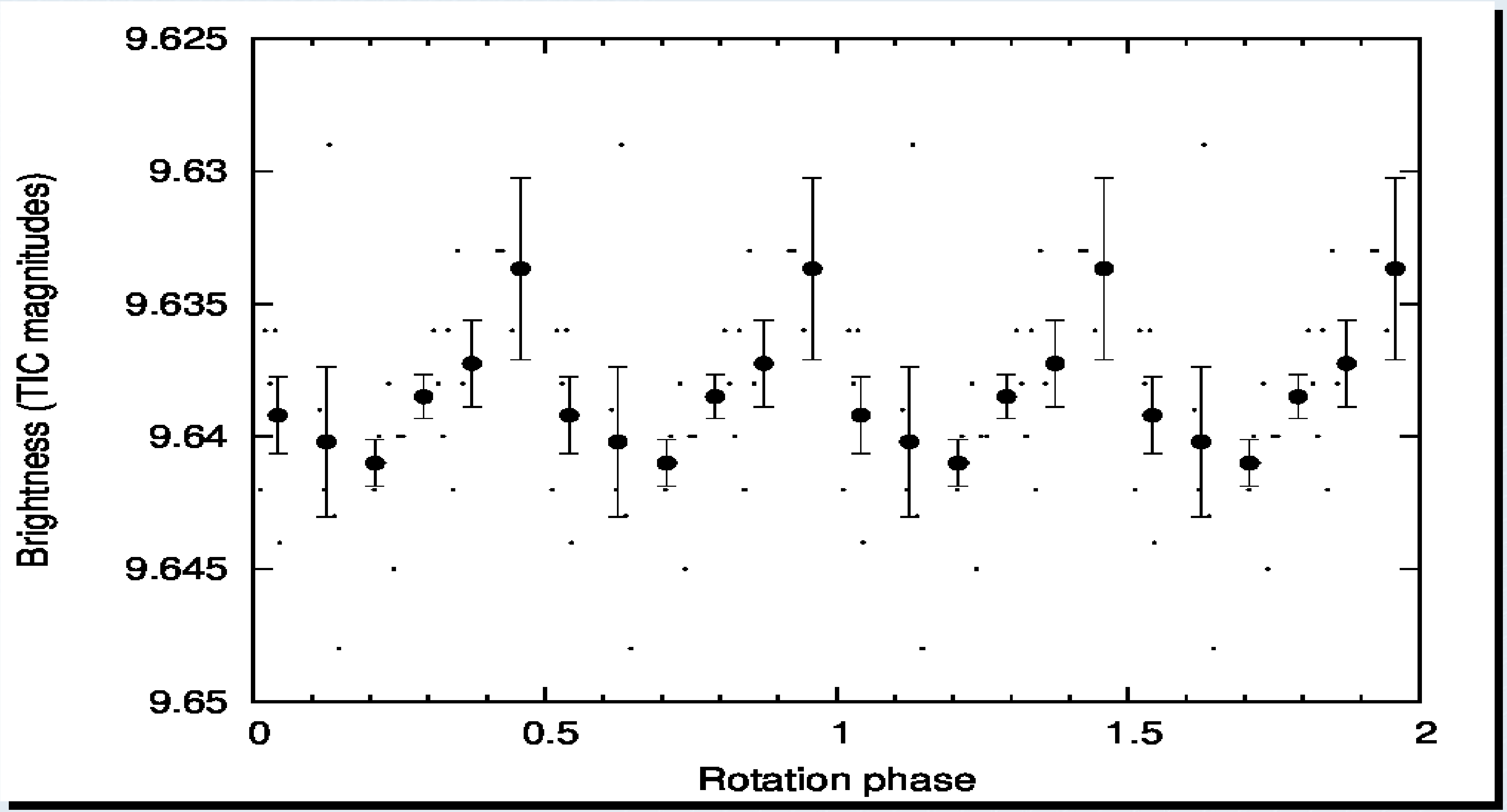
The HST image!



Orcus: Sector 9: preliminary light curve




MIT/TESS Science Office
2018-07-24 23:15:00 UTC


9.625
9.63
9.635
9.64
9.645
9.65
Brightness (TIC magnitudes)
0
0.5
1
1.5
2
Rotation phase

– Thank you! –