Convolutional Neural Networks for Detecting Moving Objects in Wide-Field Surveys

Image credit: Caltech

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EPFL

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EPFL BRIDGE group

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- Elisabeth Rachith, PhD student
- Stephan Hellmich, postdoc
- Jean-Paul Kneib, PI

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Image credit: Bill Ross

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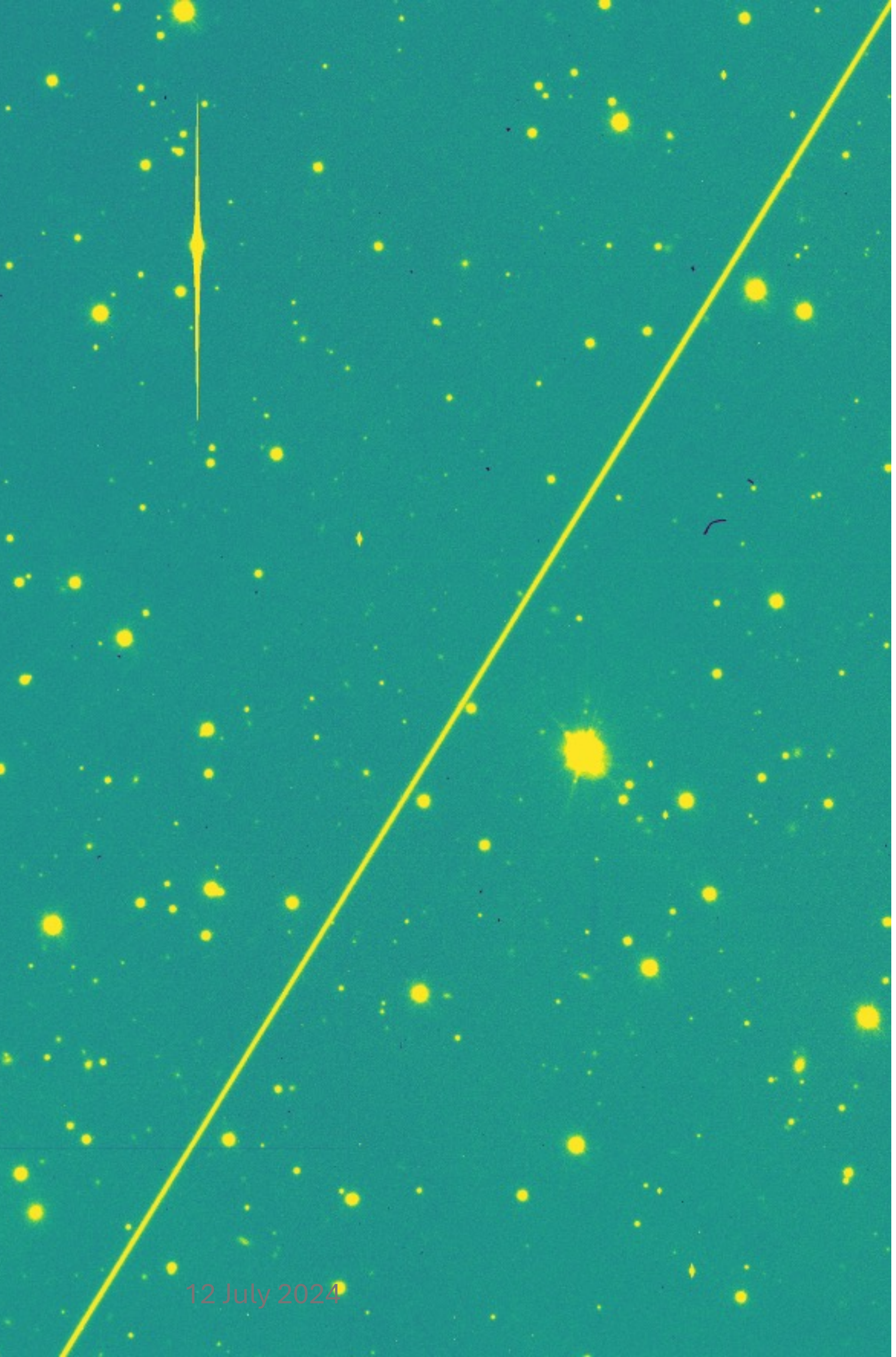
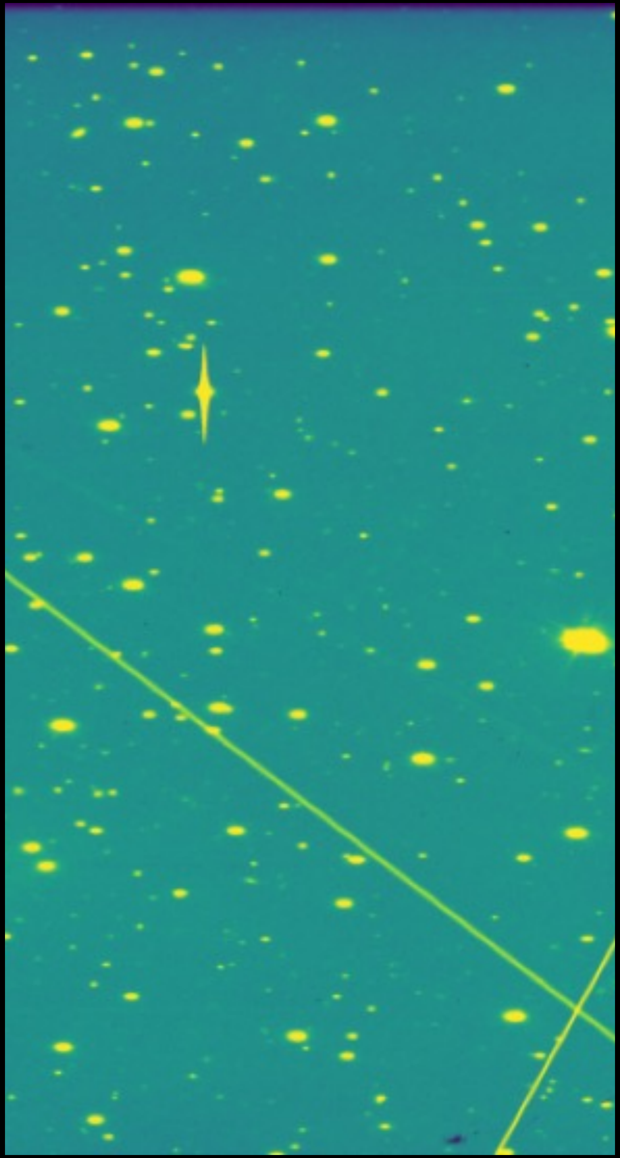


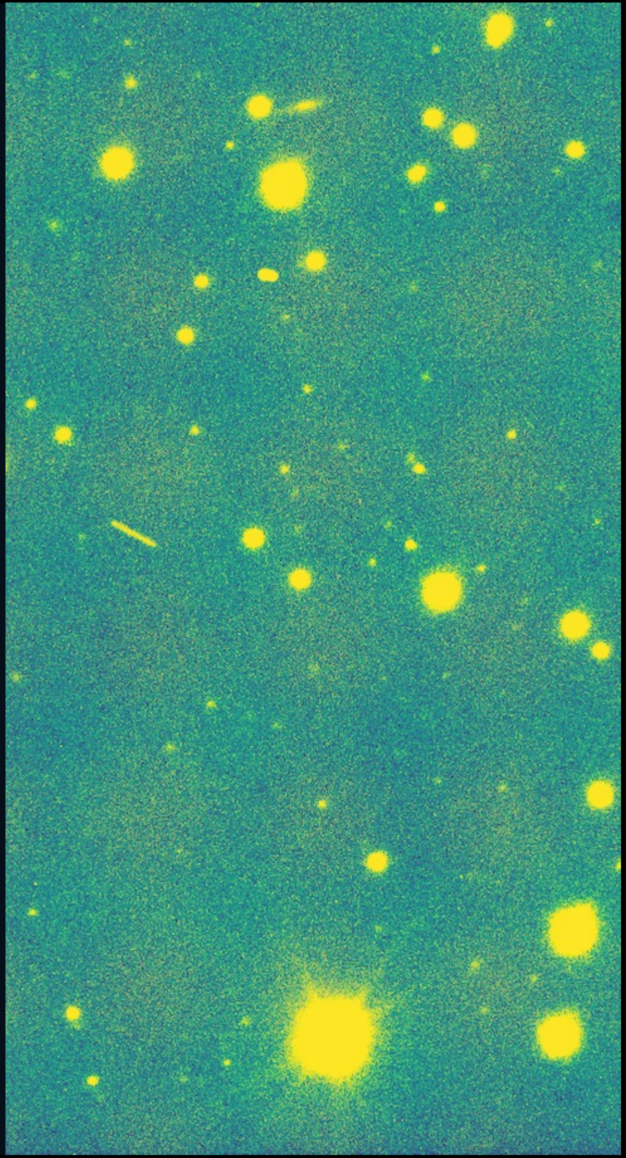
Moving objects in astronomical images

- Objects crossing the sky leave signature tracks in long-exposure astronomical images.
- These objects can be artificial (satellites and space debris) or natural (asteroids and comets).



Satellites and space debris

- moving faster (up to 0.5 deg/s)
- long tracks (cross the whole field)



Asteroids and comets

- moving slower (0.1-1 arcsec/s)
- short tracks (up to 200 pixels)

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Asteroids and comets

Insights into the Solar System

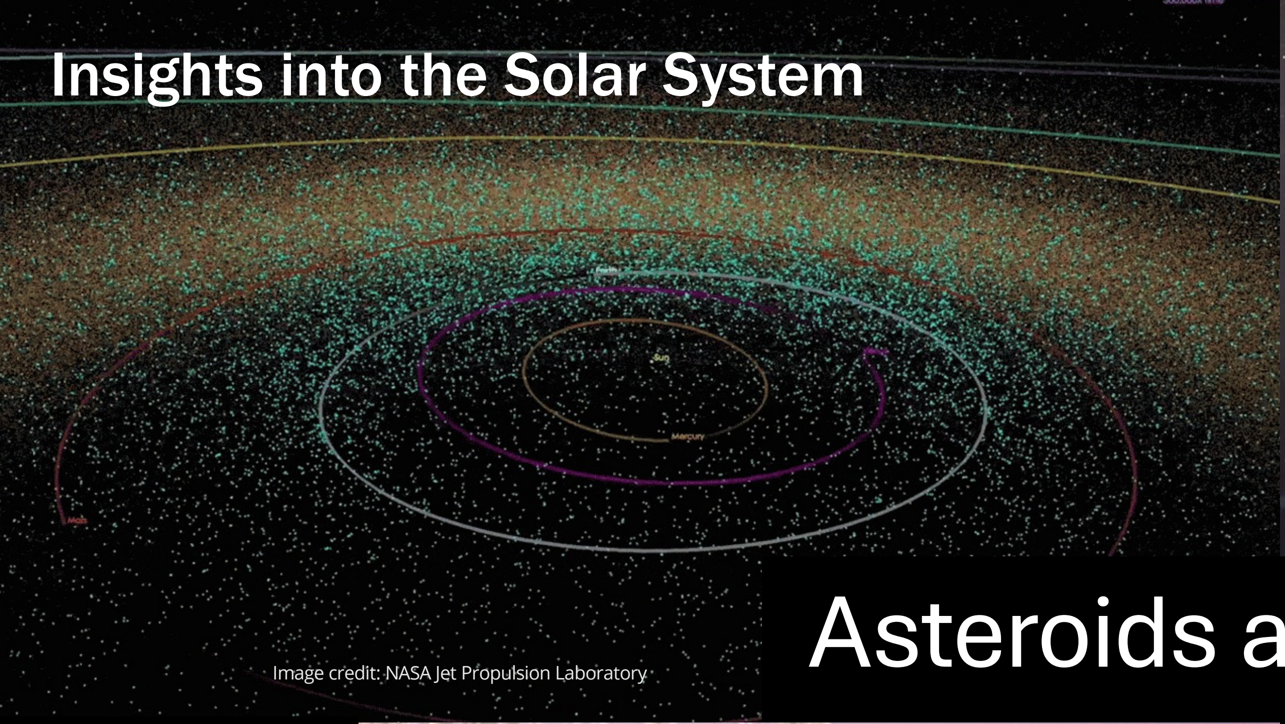


Image credit: NASA Jet Propulsion Laboratory

Threat to Earth

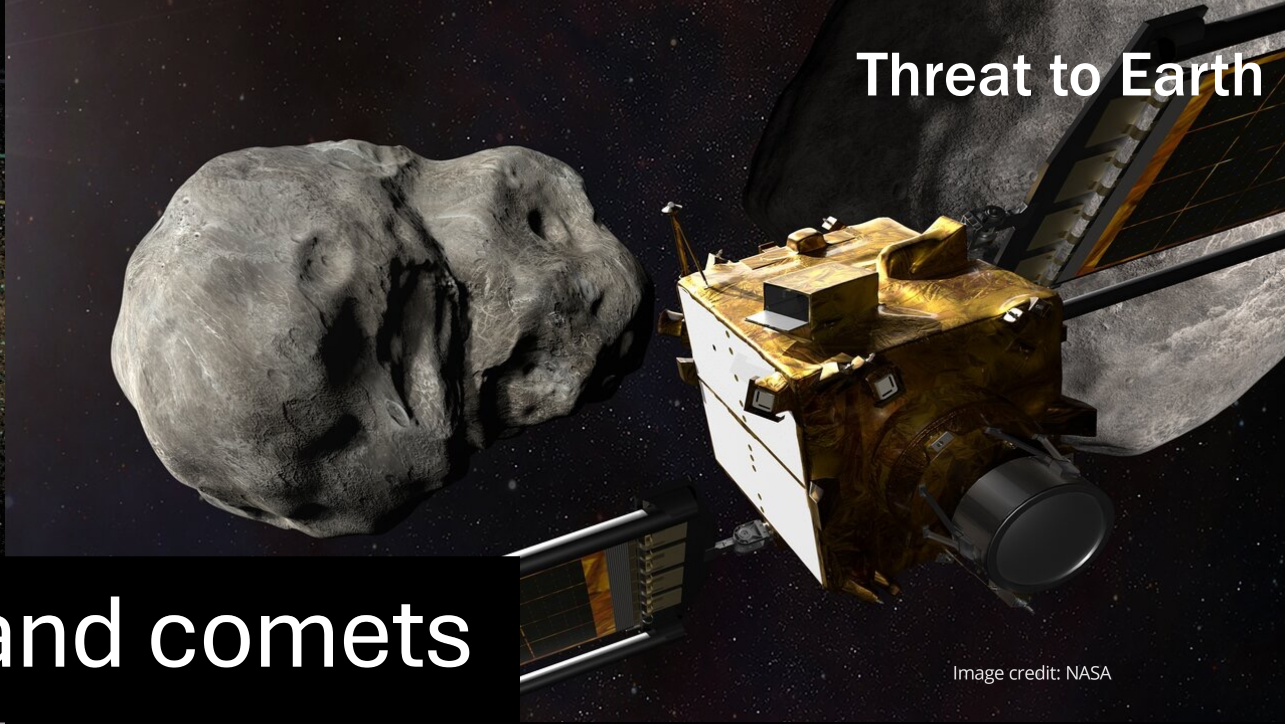


Image credit: NASA

Past events

Image credit: National Museum Scotland

Constant orbits

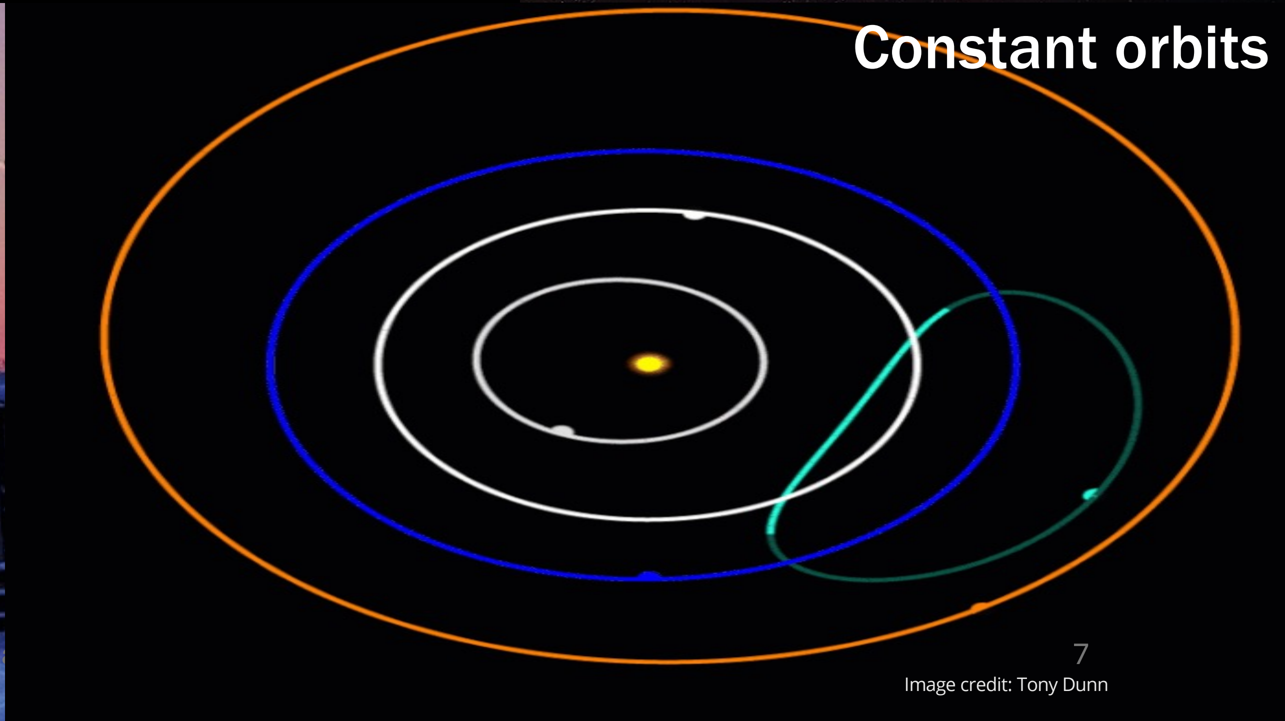
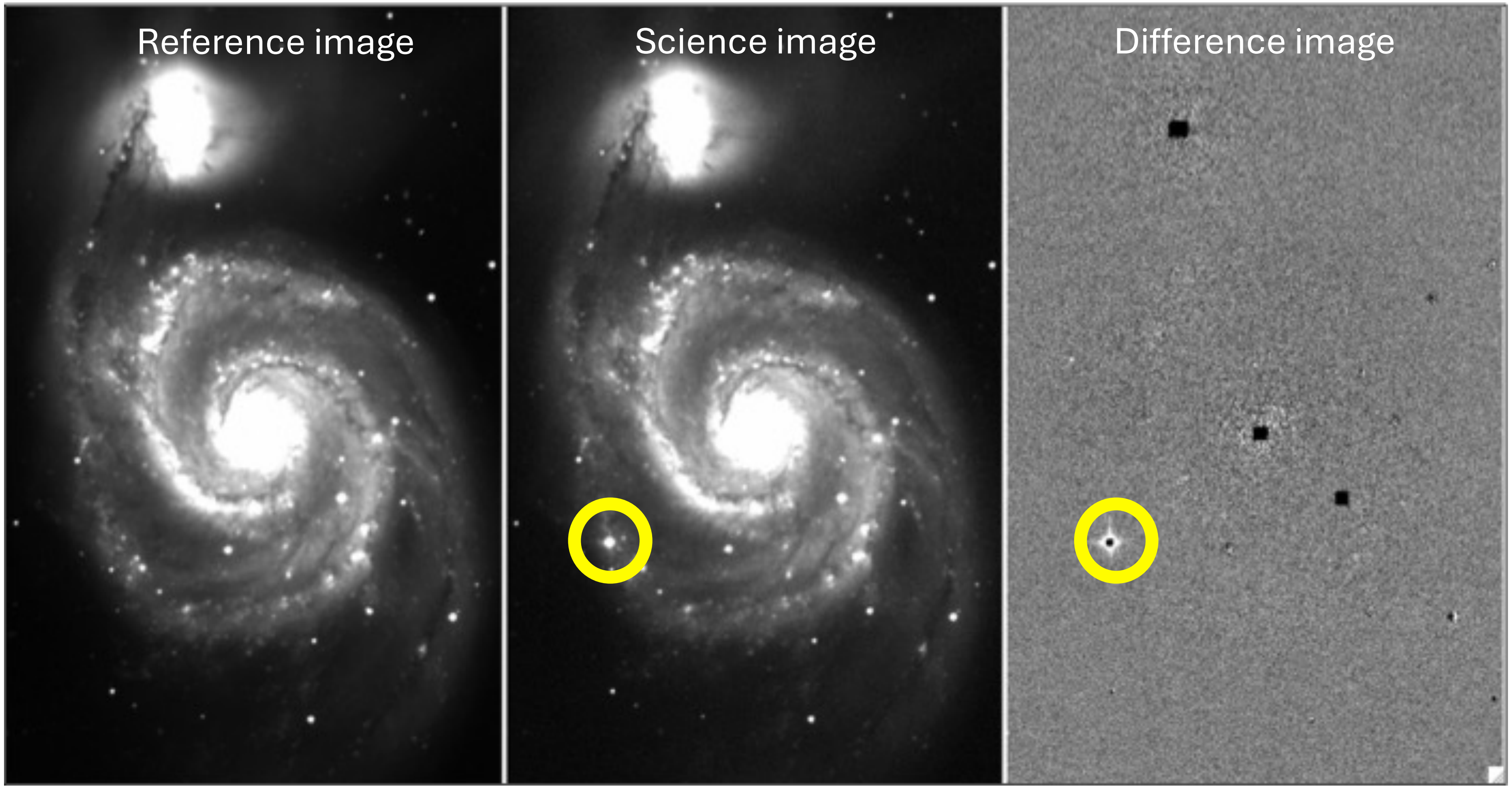


Image credit: Tony Dunn

Zwicky Transient Facility (ZTF)

- extremely large field of view (~47 square degrees)
- 30 s exposures
- difference images

Image credit: Caltech



Difference imaging in ZTF images, from Masci (2014).

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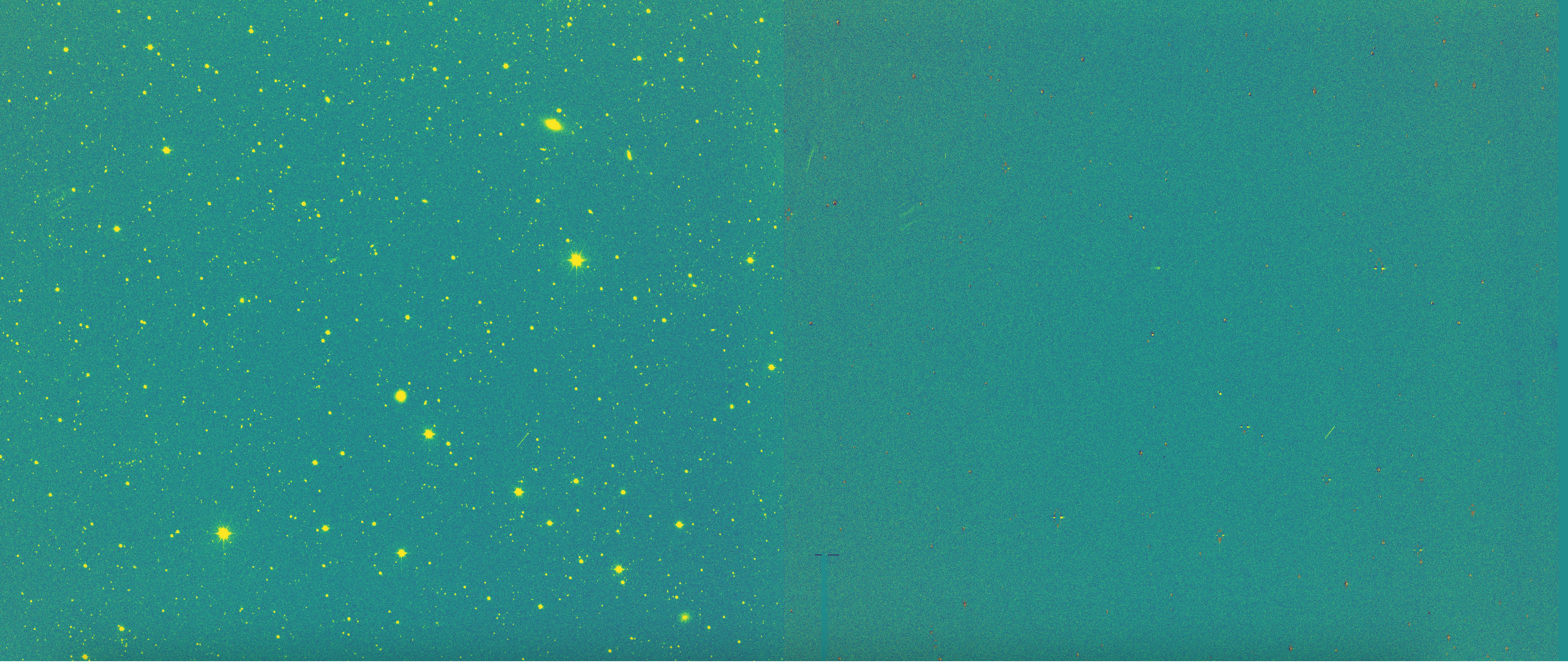

Difference imaging

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The work of the ZTF near-Earth object group

- More than 200 asteroids and comets discovered.

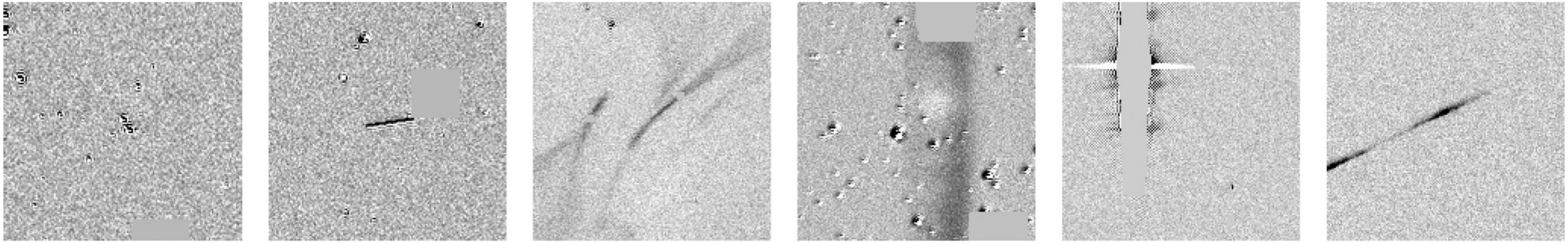
- The current pipeline consists of

— an automated streak-detection algorithm (~10^5 detections/night)

— a machine-learning classifier

— human scanners (≈10 detections/night)

False detections in the current pipeline



(a) Bad subtraction (b) Cosmic ray (c) “Dementor” (d) “Ghost” (e) Masked star (f) Satellite trail

Examples of false detections, from Duev et al.

Motivation

Can we make a pipeline that can

1. Find everything that the current algorithms are finding, while
2. Decreasing the rate of false detections, and even
3. Detect additional objects?

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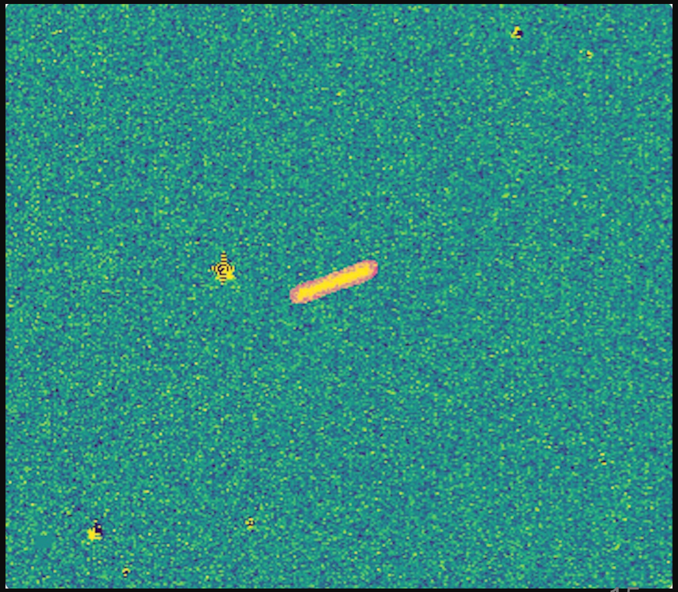
Image credit: Bill Ross

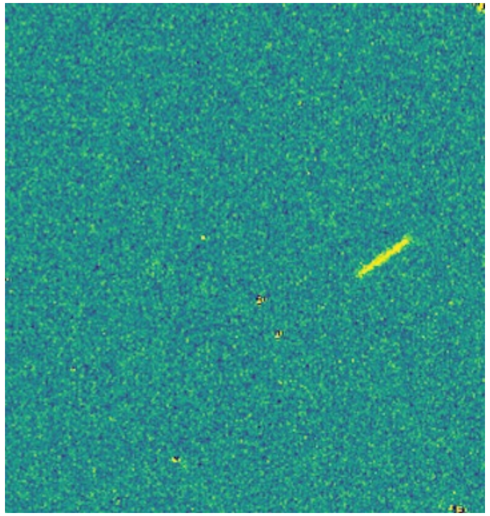
TOPO detection algorithm

TOPO-Loss for continuity-preserving crack detection using deep learning (Pantoja-Rosero et al., 2022)

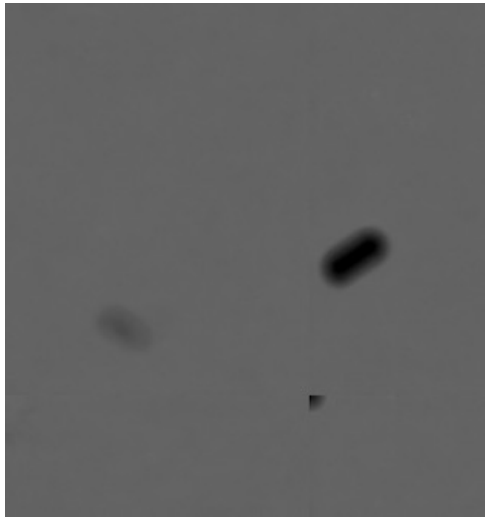
- convolutional neural network TernausNet (Iglovikov & Shvets, 2018)
- initially designed to identify cracks in buildings left by earthquakes
- re-trained for streak detection on astronomical images

Example of earthquake crack detection, from Pantoja-Rosero et al., 2022

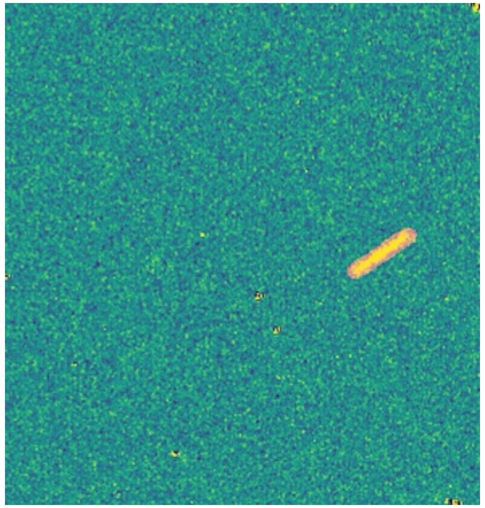




Original image



Detection heatmap



Overlayed detection

Input and output of TOPO

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Algorithm training

As a supervised-learning algorithm, TOPO was fed with 3 labelled datasets:

- real asteroids
- synthetic asteroids
- mix of both synthetic and real

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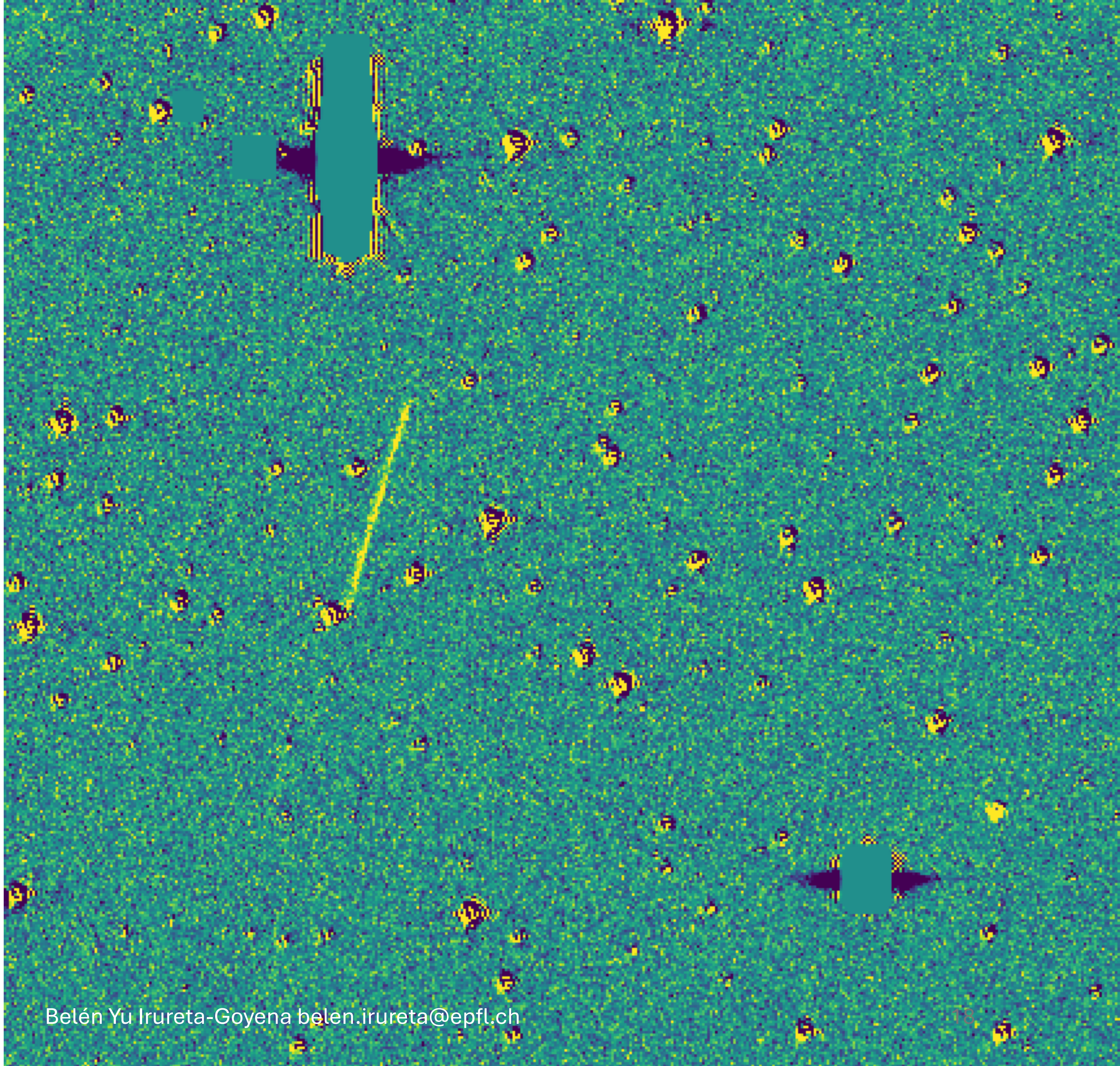
Real asteroids



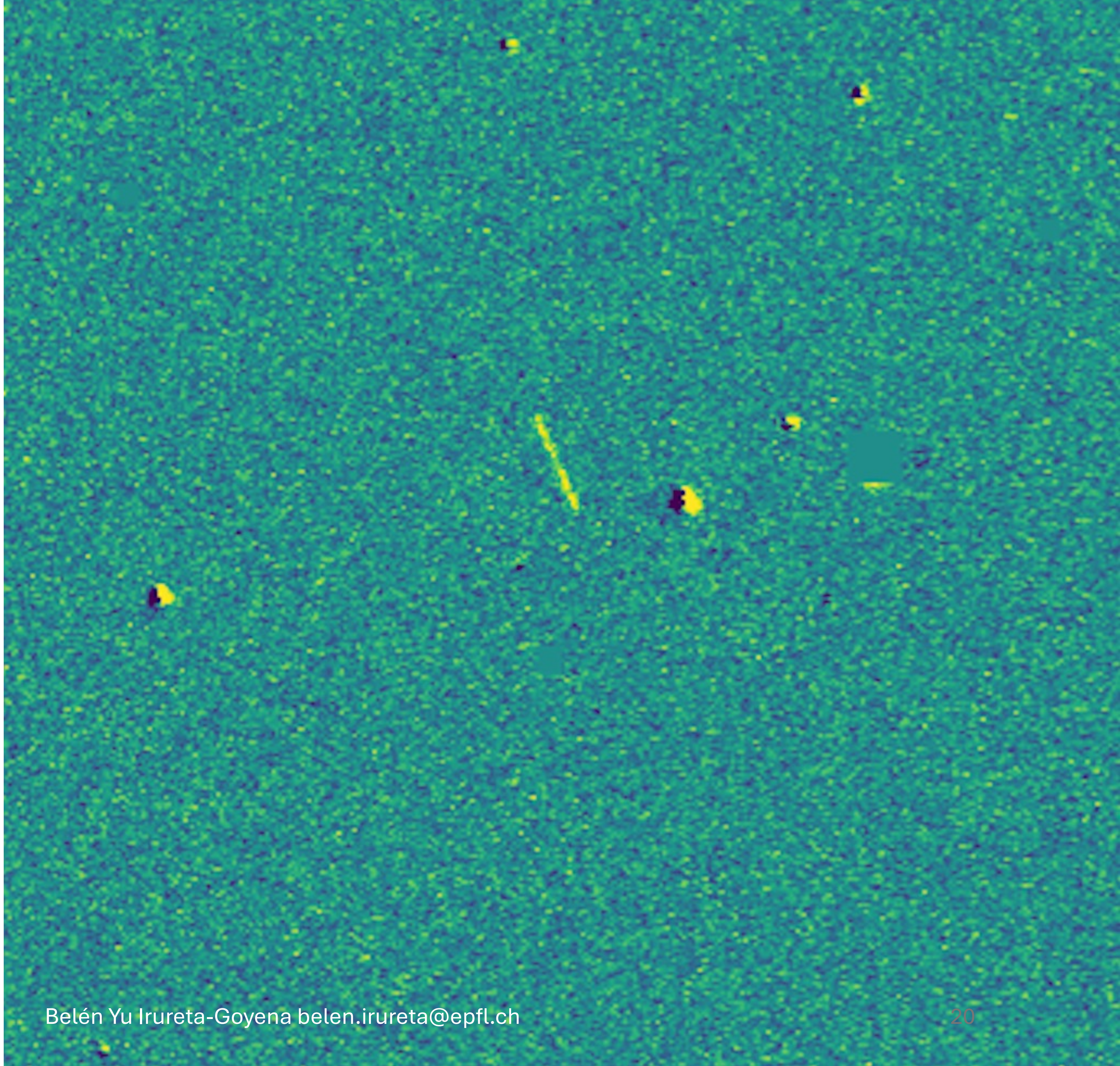
- 450 asteroids
- detected by the pipeline currently in operation
- confirmed by the Minor Planet Center

Synthetic asteroids

- We are not looking to reproduce the results of the current pipeline, but rather to complement it.
- By training with only detections of the current pipeline, we could be skewing our detections towards asteroids similar to those already found.
- Can we push the algorithm further by creating a new dataset?

Synthetic asteroids

- 20 000 asteroids
- magnitude and track length follow that of real asteroids
- injected streaks convolved with the PSF of each frame



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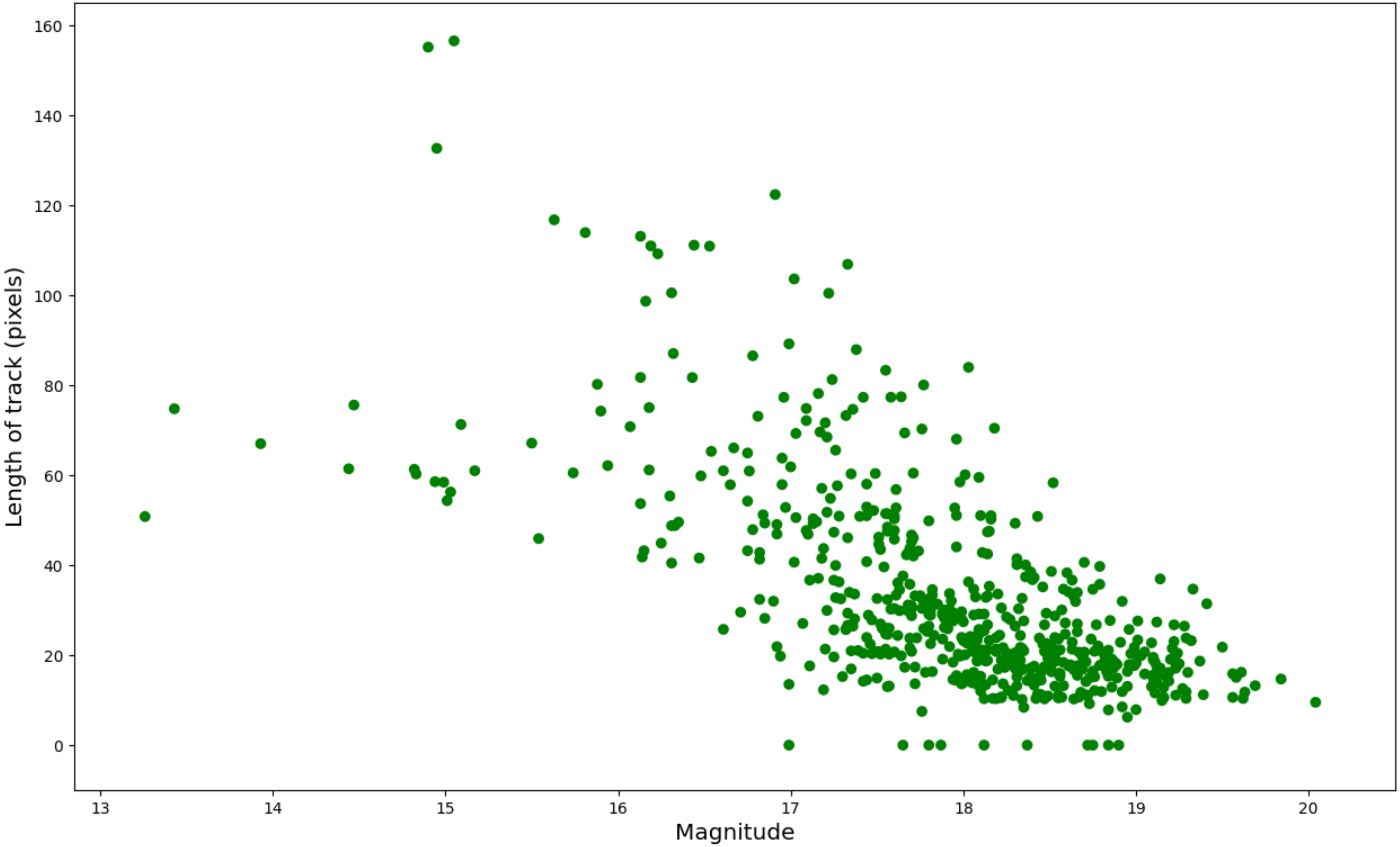
Distribution of the real asteroid population



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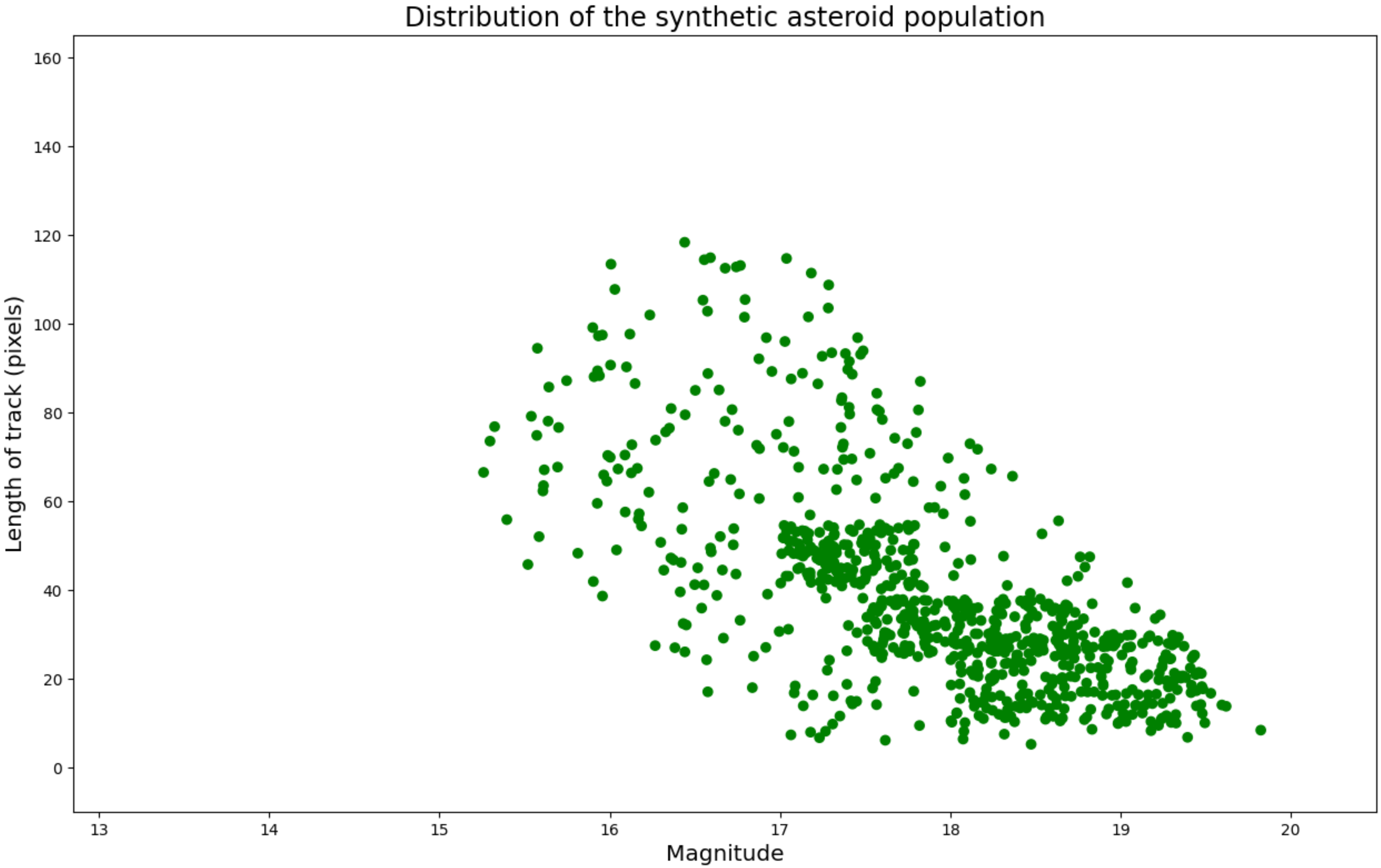

Distribution of the synthetic asteroid population
Length of track (pixels)
Magnitude
0
20
40
60
80
100
120
140
160
13
14
15
16
17
18
19
20

Testing the performance of TOPO

- The three models — (1) trained with real streaks, (2) trained with synthetic streaks and (3) trained with the mix — were applied to a test set.

- The test set comprised 115 real asteroid images that had not been ‘seen’ before by the algorithm.

- These detections had been reported by the current ZTF pipeline.

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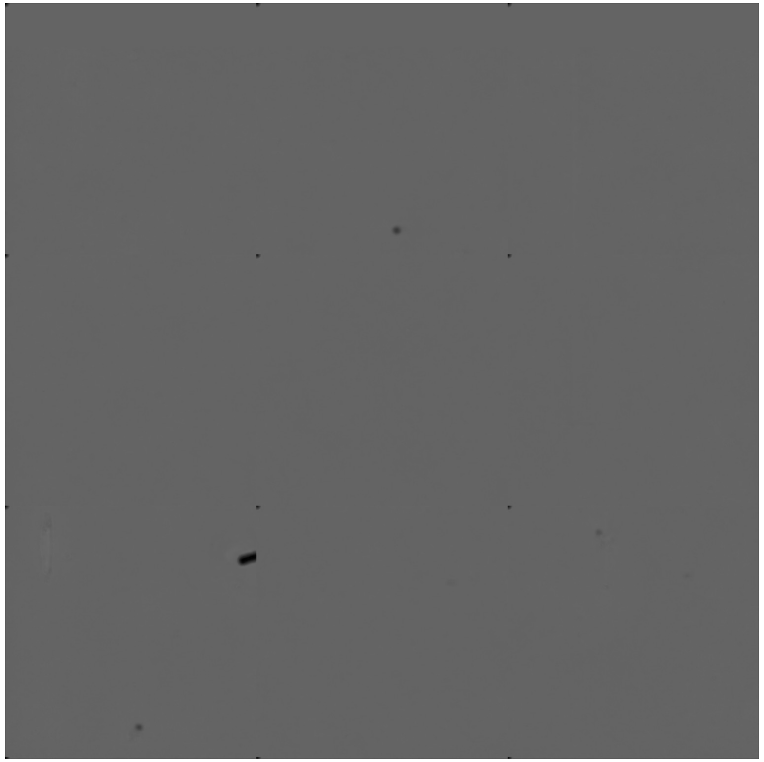
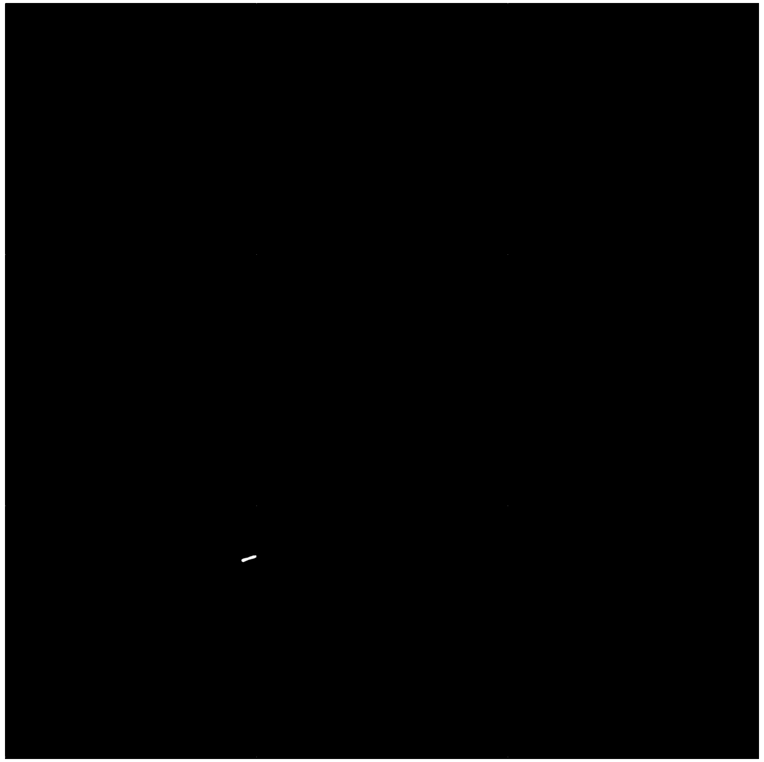
Image credit: Bill Ross

Detection thresholding

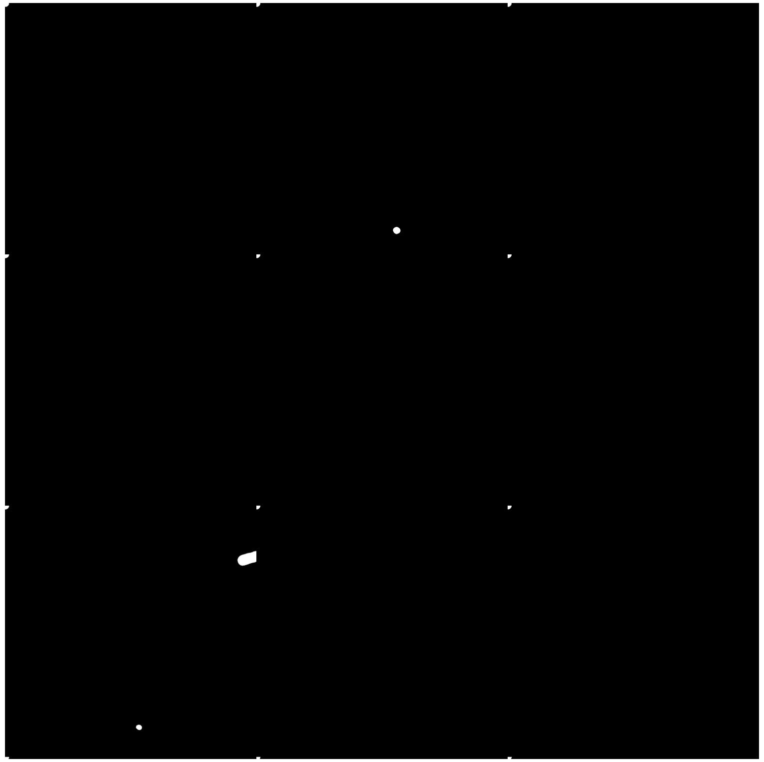
Detection heatmap

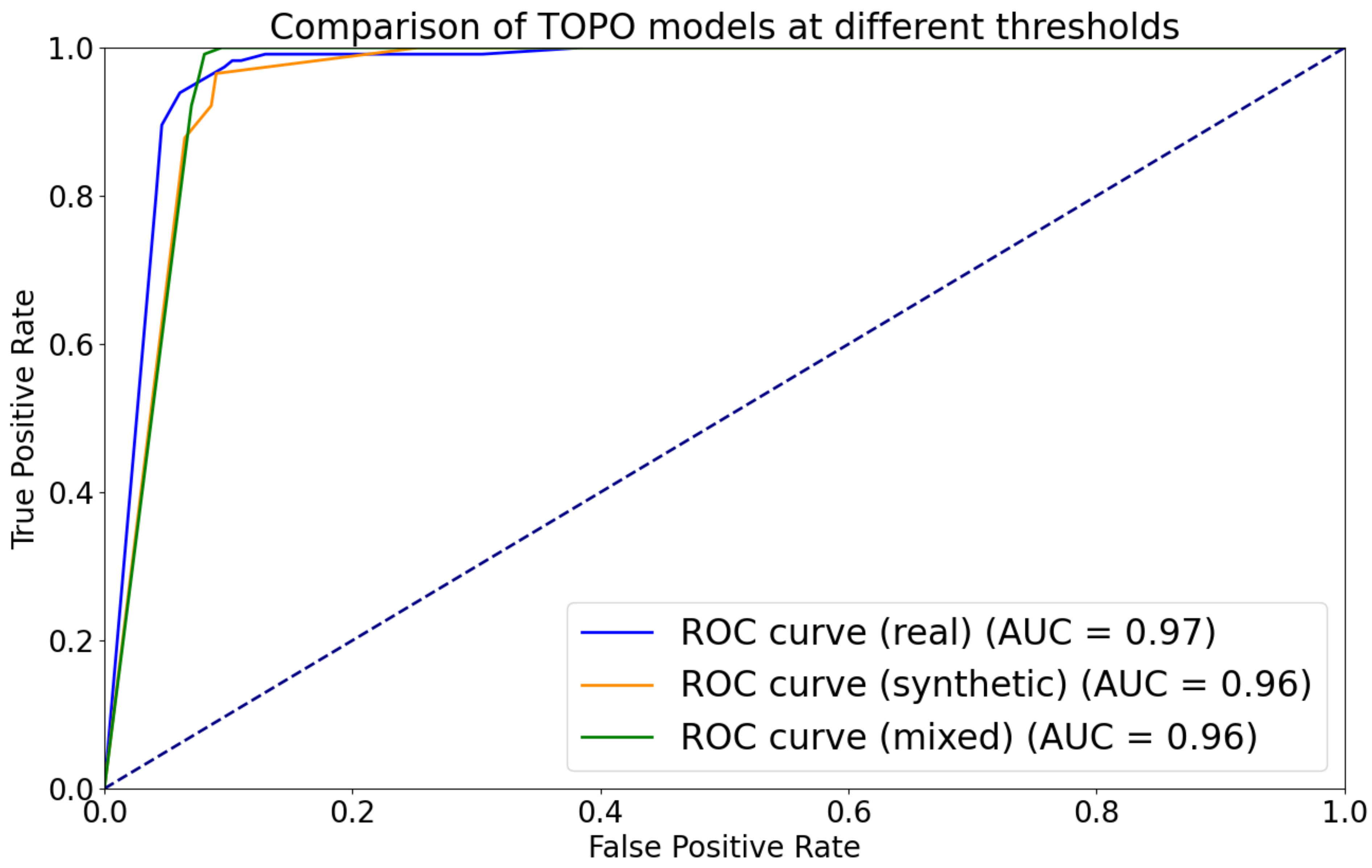


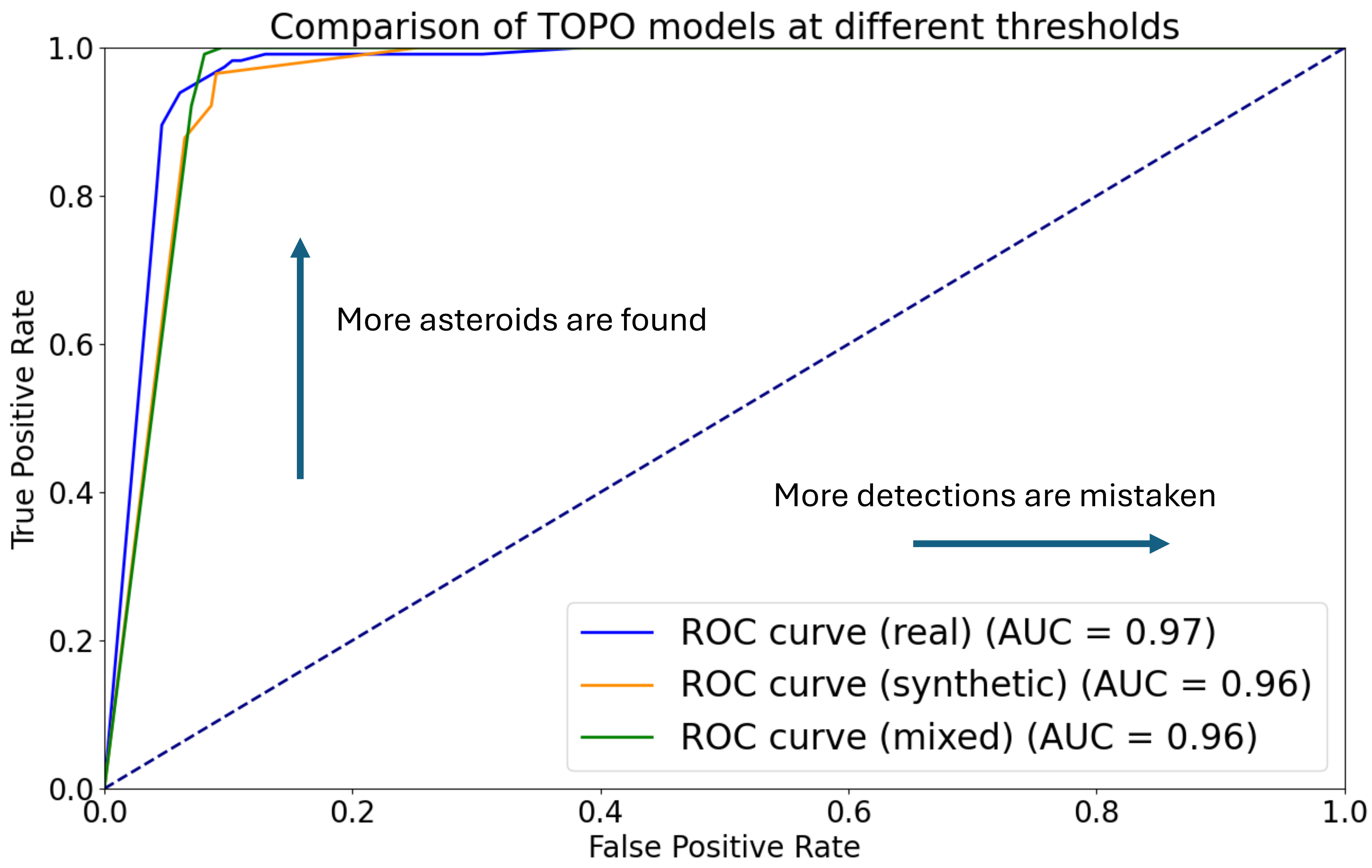
Threshold 1

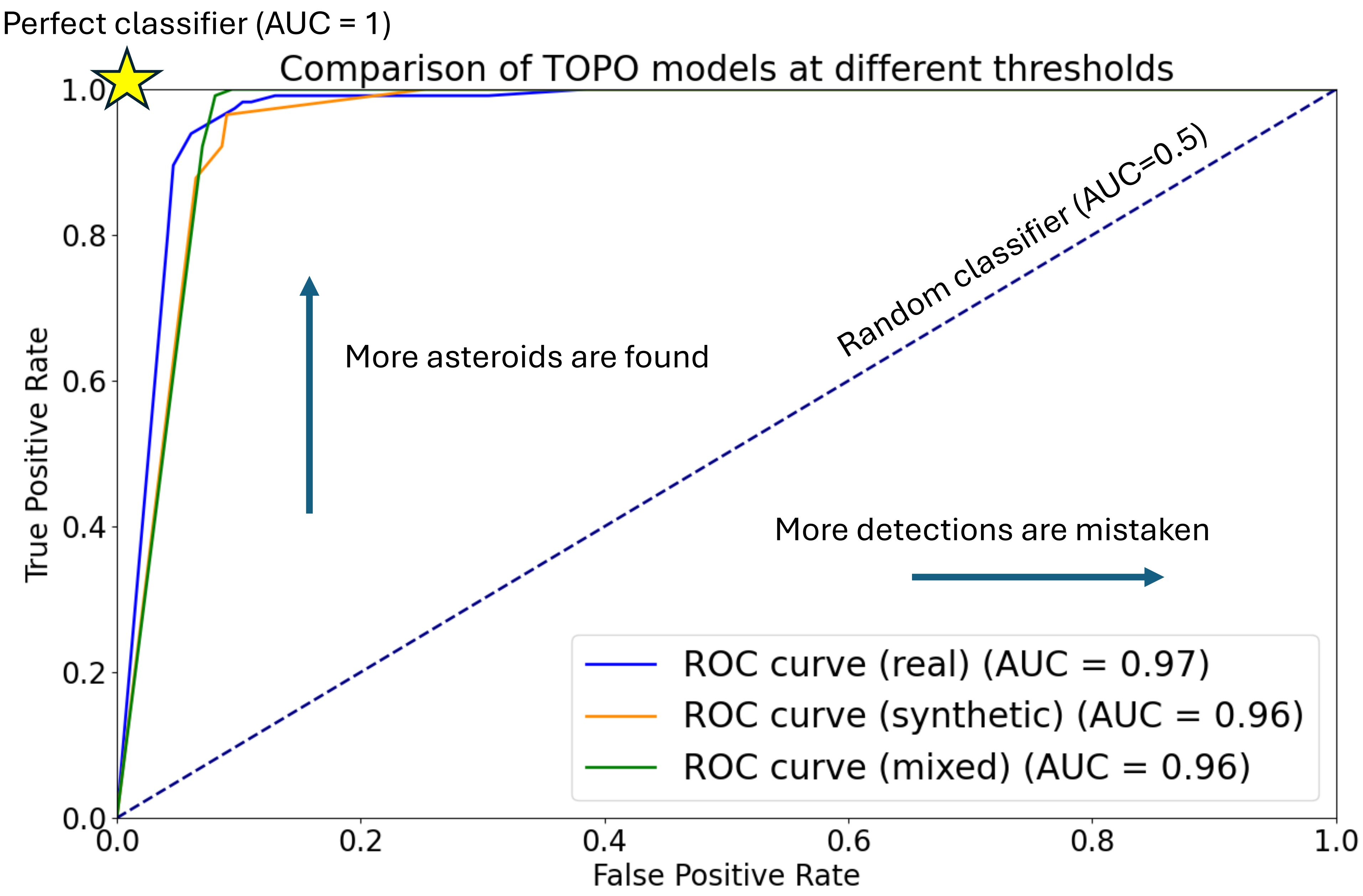


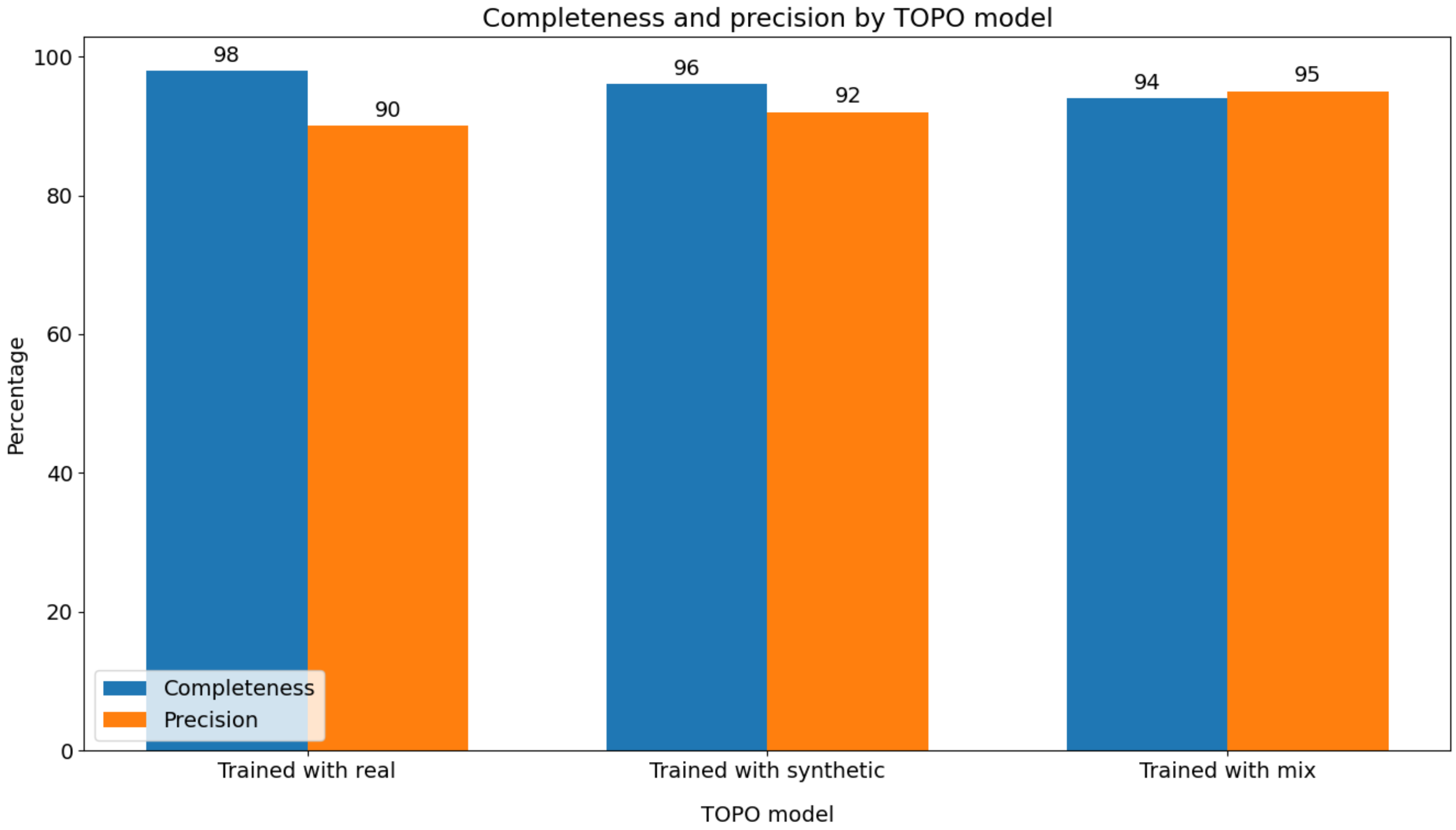
Threshold 2




Comparison of TOPO models at different thresholds
True Positive Rate
False Positive Rate
0.0
0.2
0.4
0.6
0.8
1.0
ROC curve (real) (AUC = 0.97)
ROC curve (synthetic) (AUC = 0.96)
ROC curve (mixed) (AUC = 0.96)


Comparison of TOPO models at different thresholds
1.0
0.8
0.6
0.4
0.2
0.0
True Positive Rate
0.0
0.2
0.4
0.6
0.8
1.0
False Positive Rate
More asteroids are found
More detections are mistaken
ROC curve (real) (AUC = 0.97)
ROC curve (synthetic) (AUC = 0.96)
ROC curve (mixed) (AUC = 0.96)

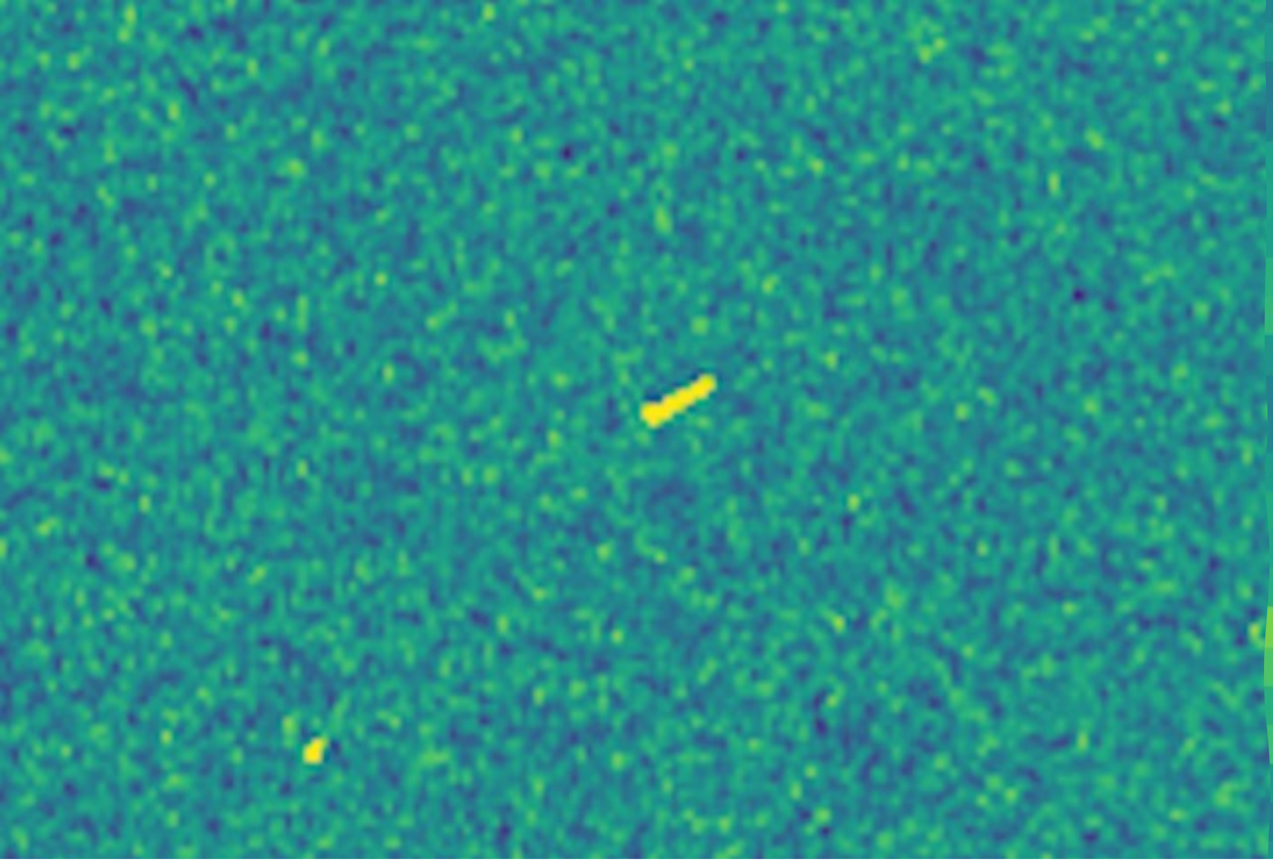

Perfect classifier (AUC = 1)
Comparison of TOPO models at different thresholds
True Positive Rate
0.0
0.2
0.4
0.6
0.8
1.0
False Positive Rate
0.0
0.2
0.4
0.6
0.8
1.0
More asteroids are found
More detections are mistaken
Random classifier (AUC=0.5)
ROC curve (real) (AUC = 0.97)
ROC curve (synthetic) (AUC = 0.96)
ROC curve (mixed) (AUC = 0.96)

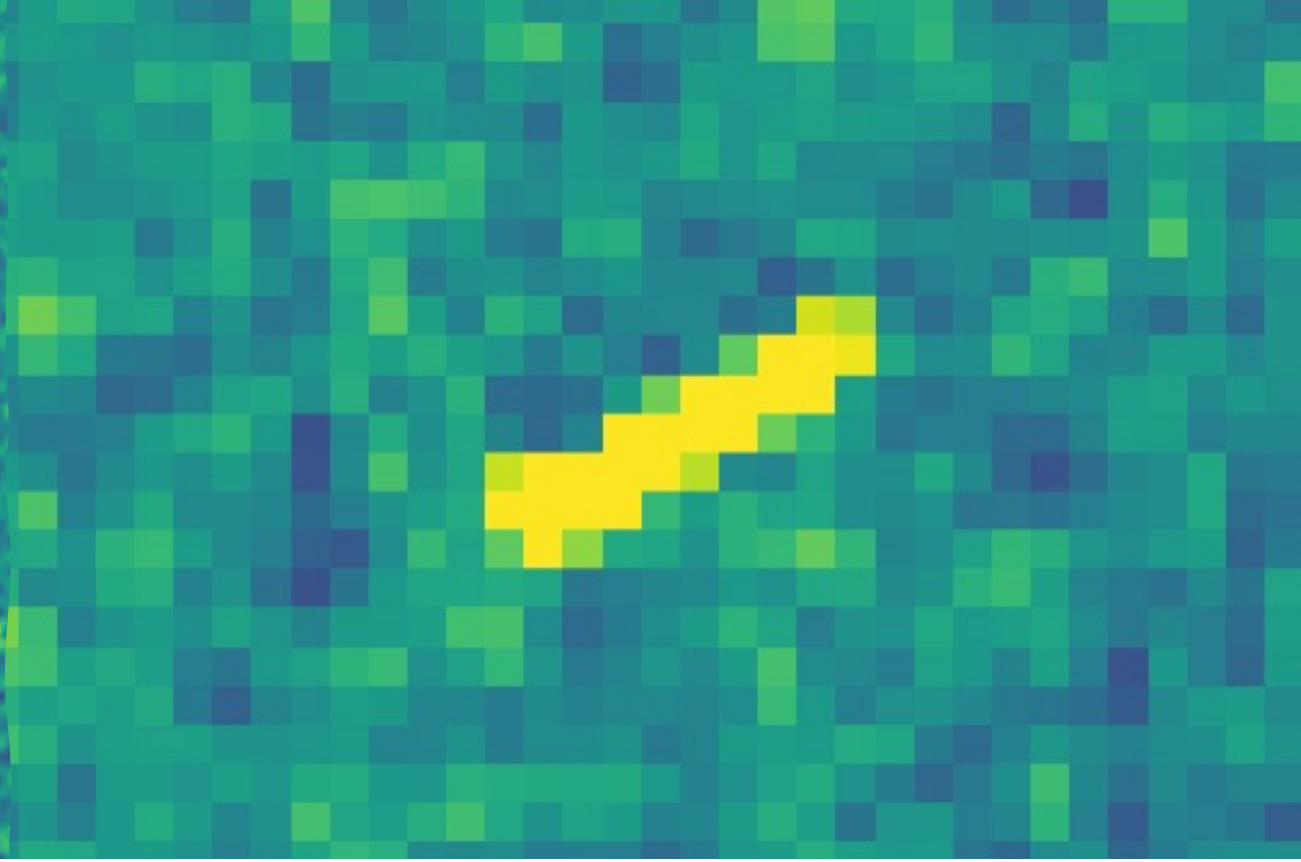

Completeness and precision by TOPO model
100
80
60
40
20
0
Percentage
98
90
96
92
94
95
Completeness
Precision
Trained with real
Trained with synthetic
Trained with mix
TOPO model

Which model performed best?

- The model trained only with synthetic asteroids performed as well when finding real asteroids as the model trained with real asteroids.

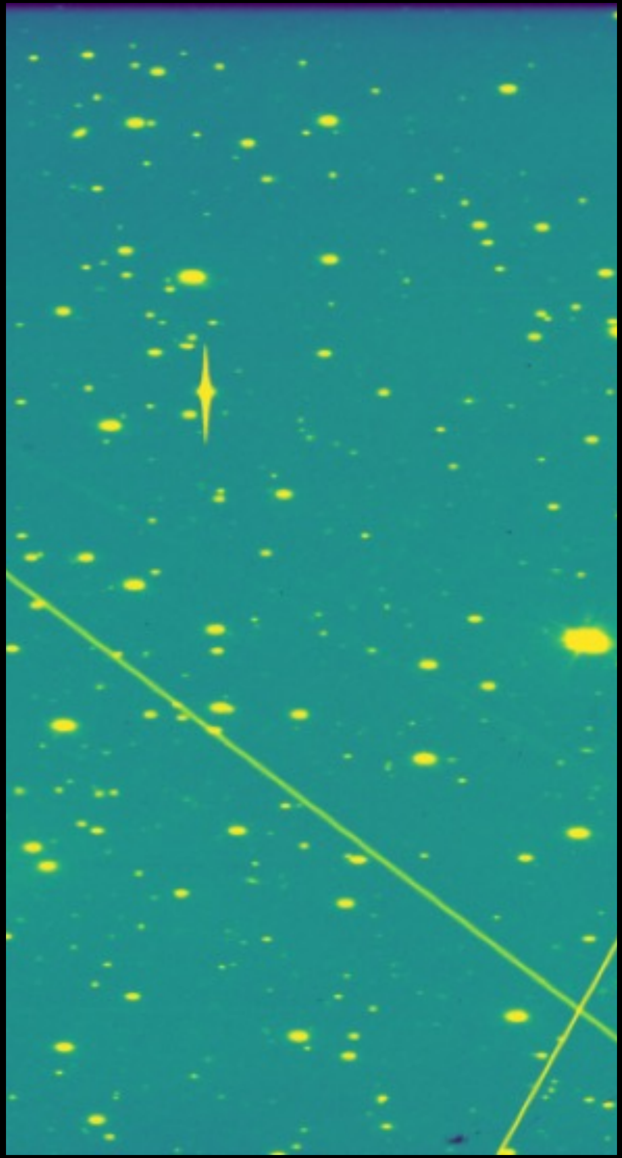
- This implies that the synthetic asteroids are realistic and can be used to enlarge the training set, which is currently small.





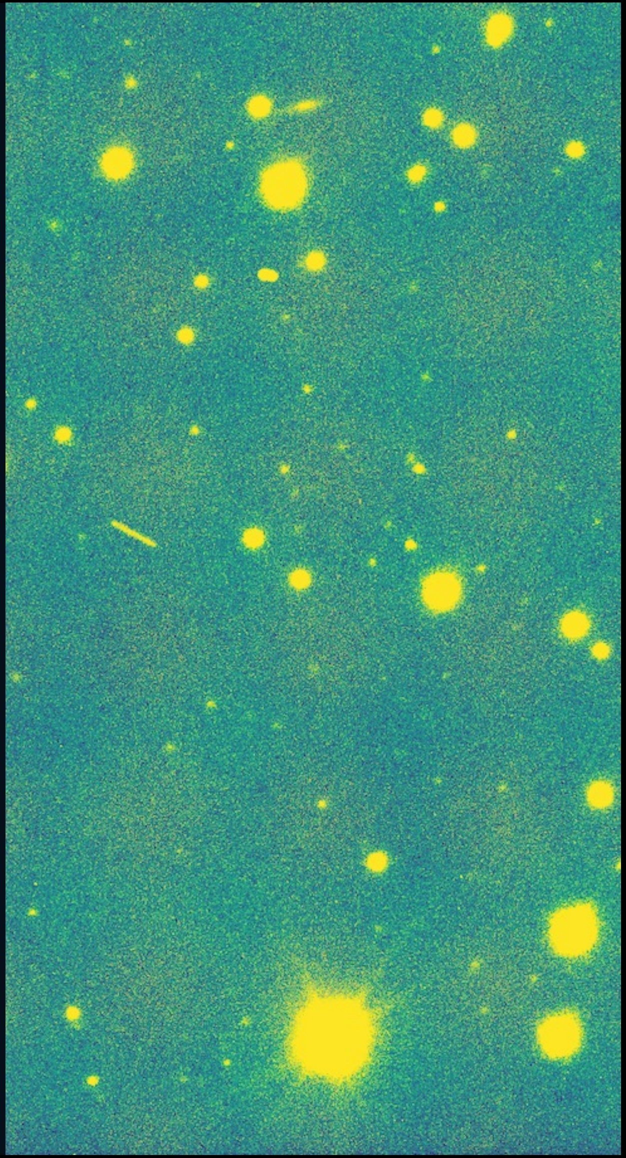
Were there any new candidates found?

- In addition to the known asteroids in the images, some potential object candidates were found.
- A larger test set needed to determine whether adding the synthetic asteroids leads to finding new objects.



Satellites and space debris

- moving faster (up to 0.5 deg/s)
- long tracks (cross the whole field)



Asteroids and comets

- moving slower (0.1-1 arcsec/s)
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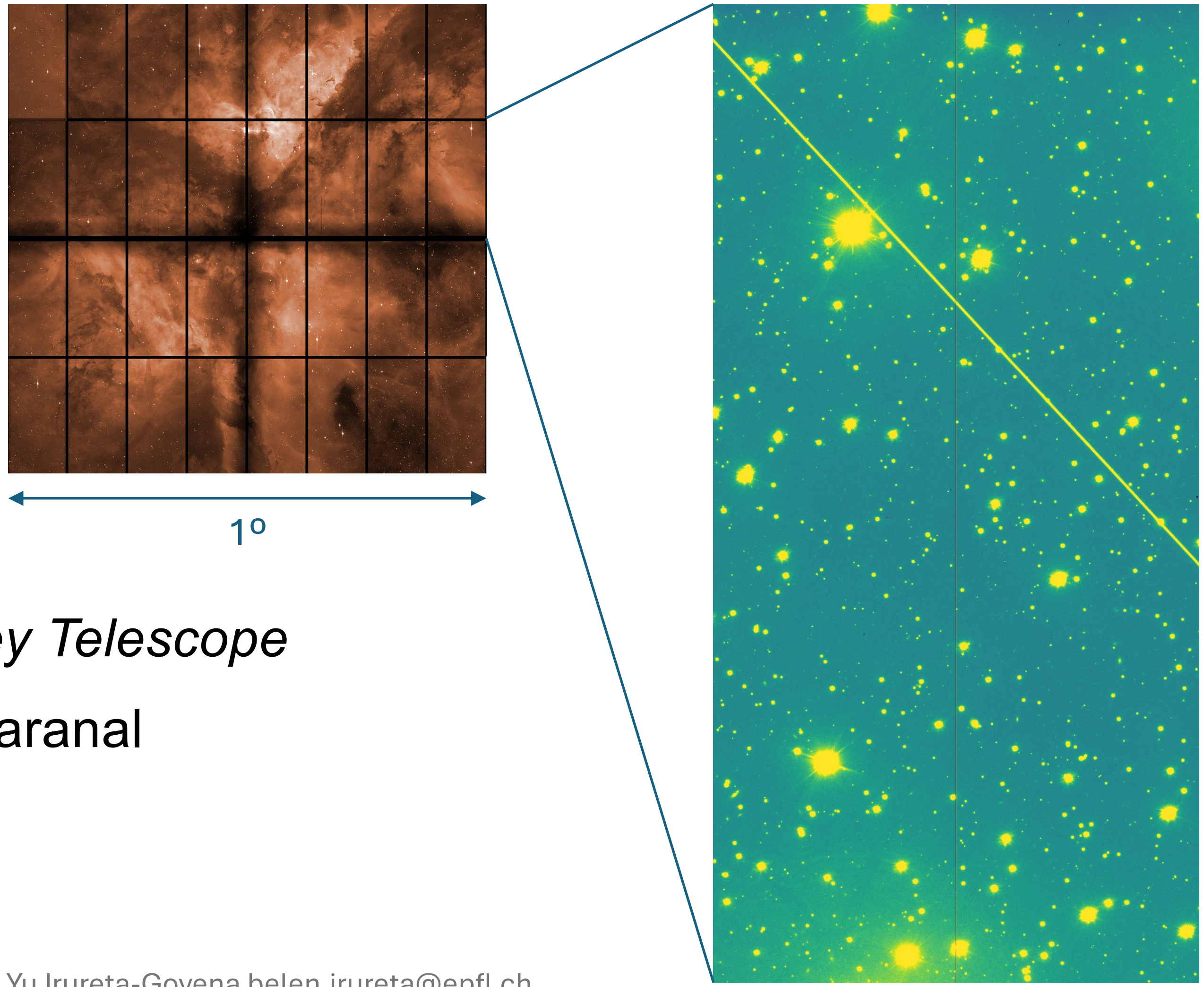
Detecting satellites and space debris



OmegaCAM *ESO VLT Survey Telescope*

- 2.6 m telescope on Cerro Paranal

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Detecting satellites and space debris

- Based on **HT-LCNN** by Lin *et al. (2020)*.
- OmegaCAM dataset of 6176 individual images.
- Manual annotation of streaks and addition of artificial ones.

→ 97.4% average precision on the validation dataset (594 images).

Ground Truth	True Positives	False Positives	False Negatives
1221	1193	71	28

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Image credit: Bill Ross

Outlook

- On the test set, the new algorithm has recovered as many asteroids as the current pipeline, with much higher precision than the first stage of the ZTF pipeline (line-detection algorithm).

- It should be applied to live data to ensure a fair comparison with the two subsequent stages of the pipeline (machine learning and human scanners).

- These tools could be applied to not only the ZTF data, but also to other wide-field surveys. So far, they have been successful on VST images (Irureta-Goyena, 2024, in prep.), and will be applied to Euclid images.

Thanks!

- In case you have any further questions, please contact me at belen.irureta@epfl.ch.
- I will be graduating at the end of 2025 and looking for postdoc opportunities, please get in touch if interested!