Zwicky Transient Facility
Discovering NEOs, method 1: **ZMODE**

Palomar 48-inch

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Realtime processing at IPAC: image differencing

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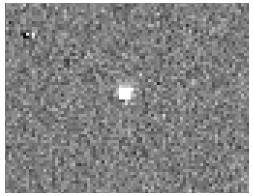
point-source transient extraction with machine-learned vetting to serve all science programs



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link sources into tracks using **ZMODE:** ZTF Moving Object Discovery Engine: <~ 4º/day

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preliminary orbit fit and threshold metrics

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cross-match to known objects and label

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QA metrics, image cutouts, reports

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human scanning

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- Objects moving at > 4º/day start to elongate and streak in 30s exposures, depending on seeing.
- Input: ~ 10^6 point-sources / night from three previous nights and executed at end of each night.
- Also executed separately on dedicated morning and evening obs. from Twilight Survey Program.
- Results submitted within ~ 2hrs of last observation
- Typically recover ~ 5-10k known objects/night.
- ~ 50 to 100 are unknown, potentially new objects.
- Having a very pure input stream of detections is key to maximizing track reliability.
- Sensitive to fainter, further, and slower objects.

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Discovering NEOs, method 2: **ZSTREAK**

- Min. angular velocity is constrained by shortest detectable streaks such that we don't become overwhelmed by artifacts (~ 3 PSF FWHMs)/30s.
- We detect ~ 10^5 *raw* streaks/night.
- Executed close to realtime, ~ 20 min following observation.
- Results submitted within ~ 1hr of observation.
- Typically report ~ few to several real streaking objects every night.
- Machine-learning vetting is a crucial component for reducing the false positive rate.

Palomar 48-inch

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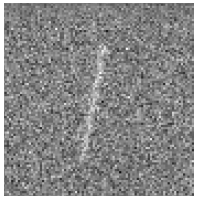
Realtime processing at IPAC: image differencing



streak detection: sensitive to faster and closer objects: >~ 6°/day

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streak PSF (x) line fitting: metadata

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machine-learned vetting & scoring by *DeepStreaks*: convolutional neural network that classifies image cutouts

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intra-night linking of streaks & orbit fit

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filter artificial objects

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human scanning

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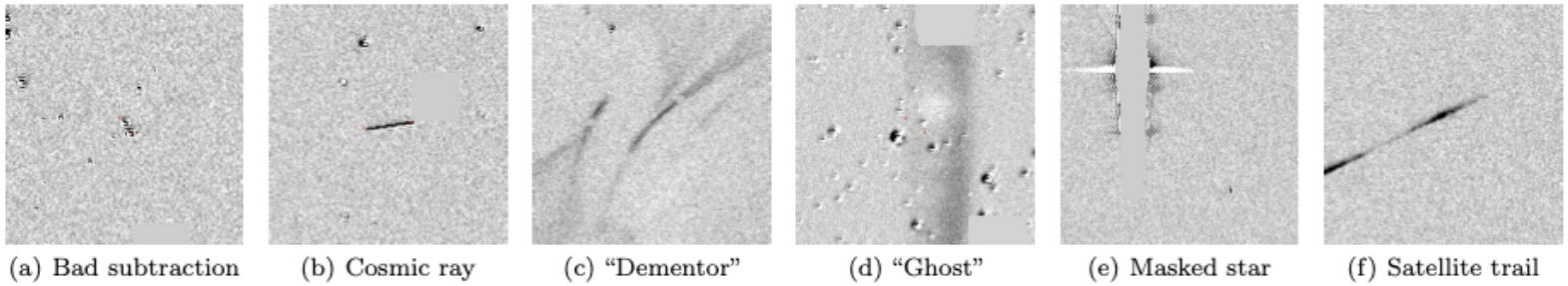
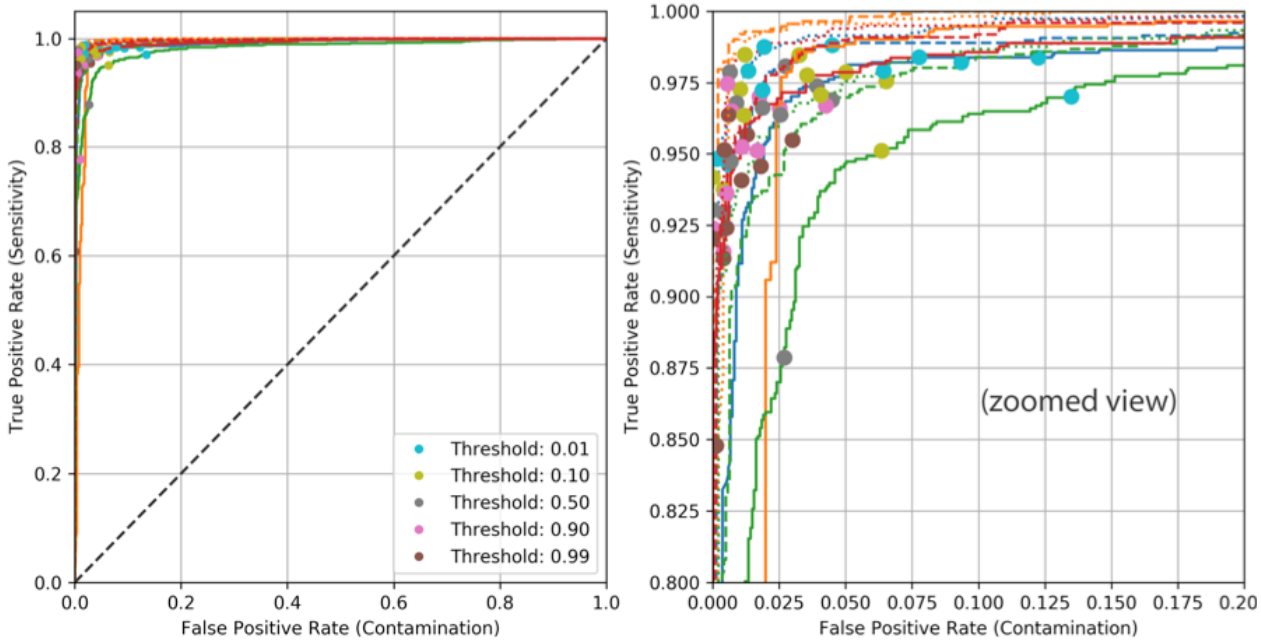
Performance of ZSTREAK machine-learned vetting (*DeepStreaks*)

- For details, see: Duev et al. 2019, MNRAS.
- Convolutional Neural Net based on deep-learning framework provided by *TensorFlow* Python library.
- For a False Positive Rate of ~ 1% (~ 99% reliability), have True Positive Rates (completeness) exceeding ~ 96% following automated classification.
- Sample of streaks classified as artifacts:



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



Back up

ZMODE:
ZTF's Moving Object Discovery Engine

- Novel algorithm implemented for the *intermediate* Palomar Transient Factory (2013 – 2017).
- Input: all difference image detections from previous four consecutive nights at most.
- Uses a two-step process to construct moving object tracks:
  1. Atomic building blocks: find triples of difference image detections ("stringlets") within min/max velocity cone centered on every detection by matching relative velocities.
  2. Bin the stringlet velocity vectors and merge all stringlets belonging to same object to build track.
- Includes optional iterative removal of MBAs to mitigate cross-track contamination.

For details, see Masci et al. 2019, PASP, vol. 131