Image Differencing and Solar System Science

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and the **Solar System Science Collaboration et al.**

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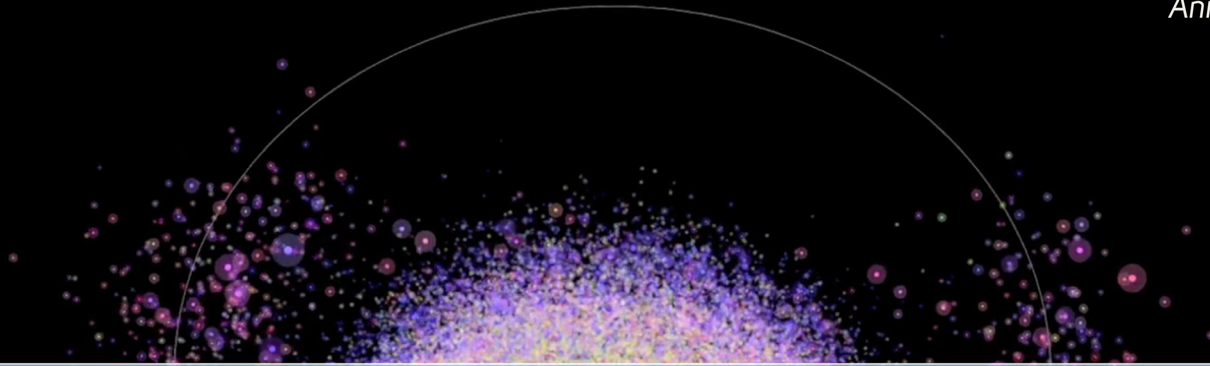
Solar System Science in 2020s

Animation: SDSS Asteroids
(Alex Parker, SwRI)



	Currently Known*	LSST Discoveries**	Typical number of observations+
Near Earth Objects (NEOs)	~20,000	200,000	(D>250m) 60
Main Belt Asteroids (MBAs)	~650,000	6,000,000	(D>500m) 200
Jupiter Trojans	~7000	280,000	(D>2km) 300
TransNeptunian Objects (TNOs) + Scattered Disk Objects (SDOs)	~3000	40,000	(D>200km) 450
Comets	~3000	10,000	?
Interstellar Objects (ISOs)	1	10	?

Estimates: Lynne Jones et al.

Selected Topics in Moving Objects and Image Differencing

> Streaks/Trails: Fast-moving asteroids

> Shift-and-stacking of DiffIms: Detecting faint KBOs

> Diffuse Moving Sources: Comets and Active Asteroids

1. Finding Fast Faint Moving Objects

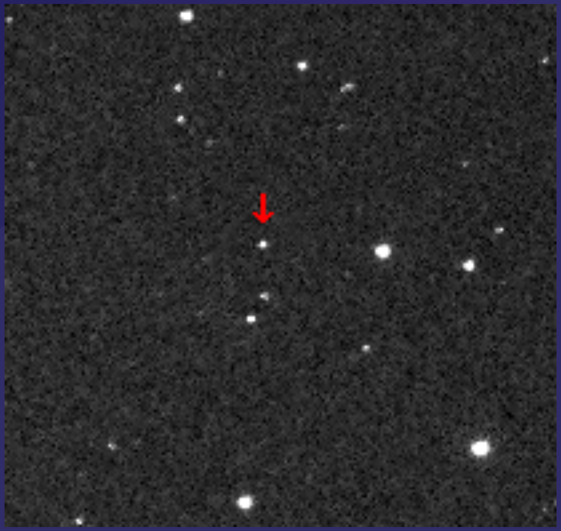
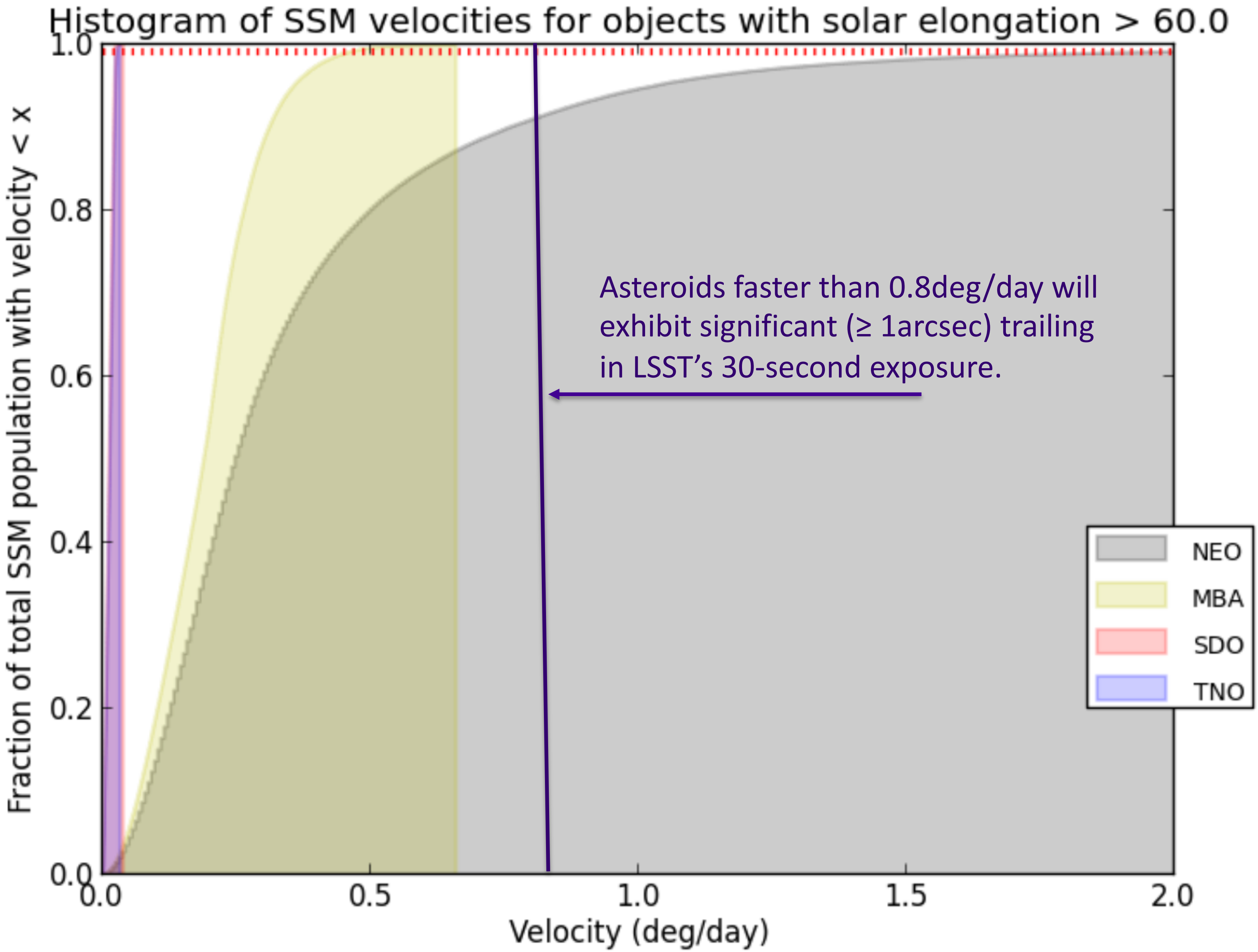
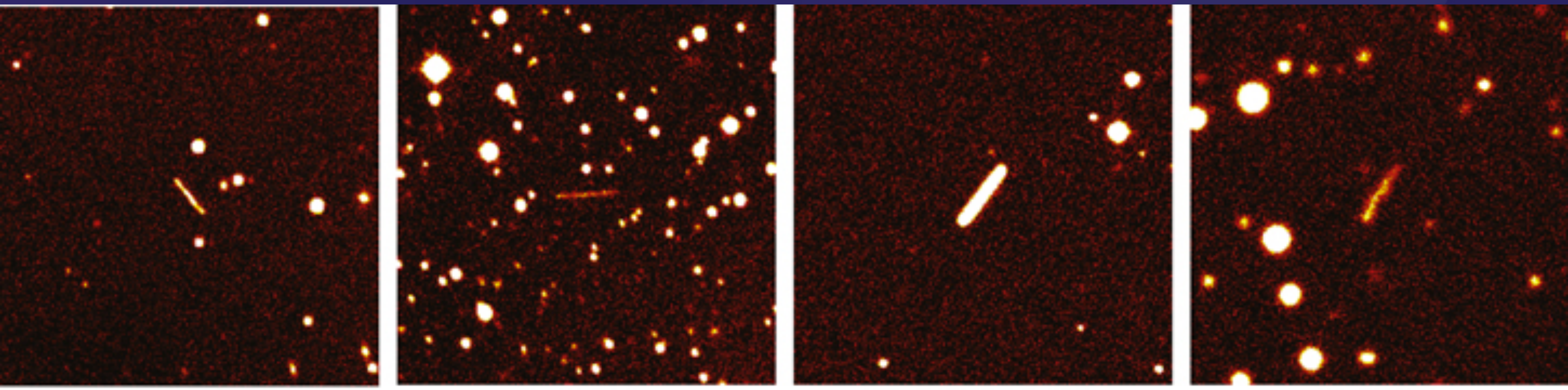


Image Credit: OAS - Osservatorio Astronomico Sormano


Histogram of SSM velocities for objects with solar elongation > 60.0
Fraction of total SSM population with velocity < x
Velocity (deg/day)
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.5
1.0
1.5
2.0
Asteroids faster than 0.8deg/day will exhibit significant (≥ 1arcsec) trailing in LSST's 30-second exposure.
NEO
MBA
SDO
TNO

Example: Trailed Asteroids in PTF

Waszczak et al. (2017)



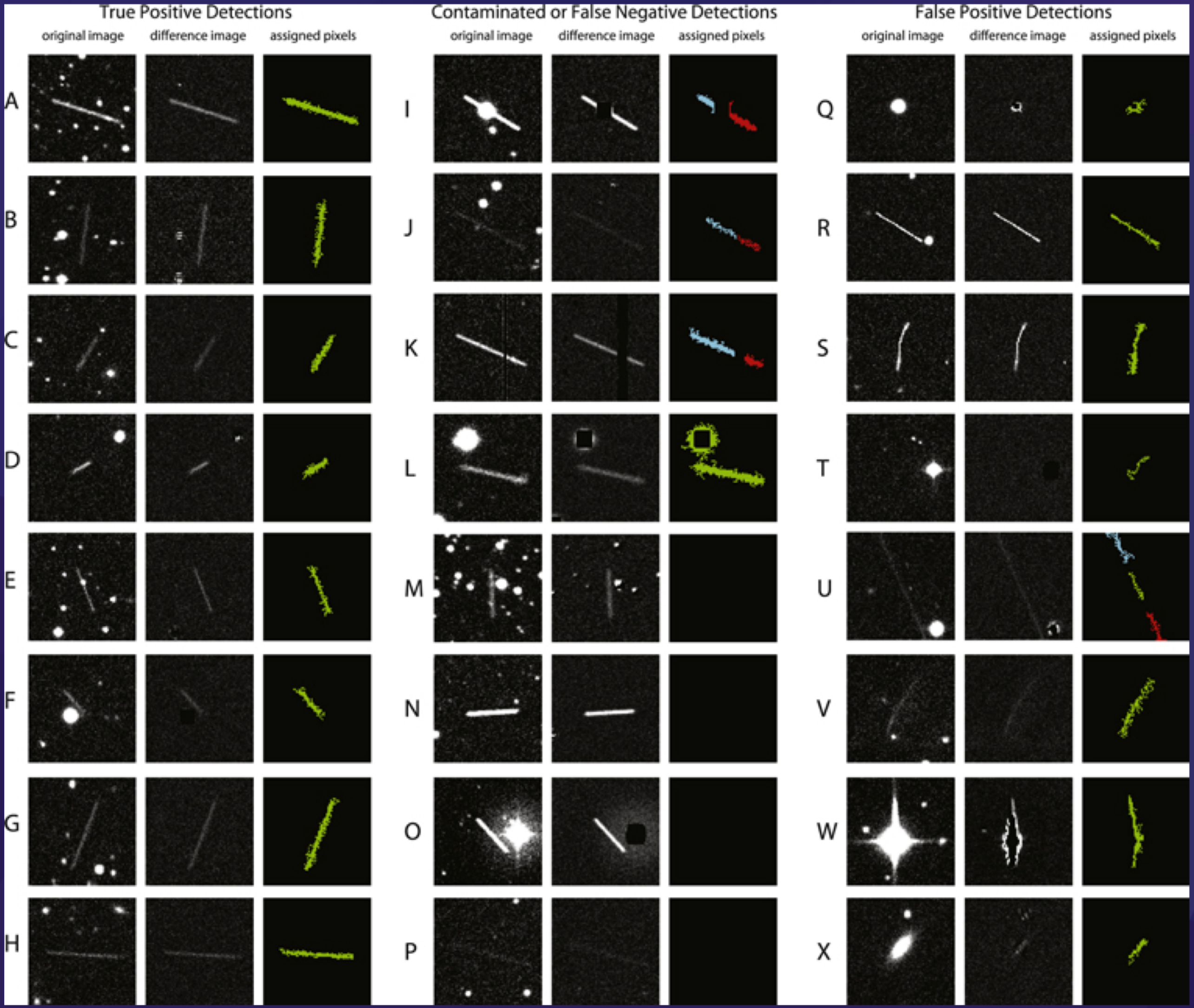
2009 HK73 V~17.5 length=24″ FWHM=2.1″ | 2010 UC7 V~18.5 length=32″ FWHM=2.6″ | (277475) 2005 WK4 V~14.3 length=34″ FWHM=2.4″ | 2013 SU24 V~16.6 length=36″ FWHM=5.0″

Detection of trailing allows for identification of a fast-moving asteroid from a single exposure.

Two back-to-back (~20 minutes) exposures allow for near-certain detection, direction of motion disambiguation.

=> Can react on NEO discoveries ASAP.

Detection and Contamination

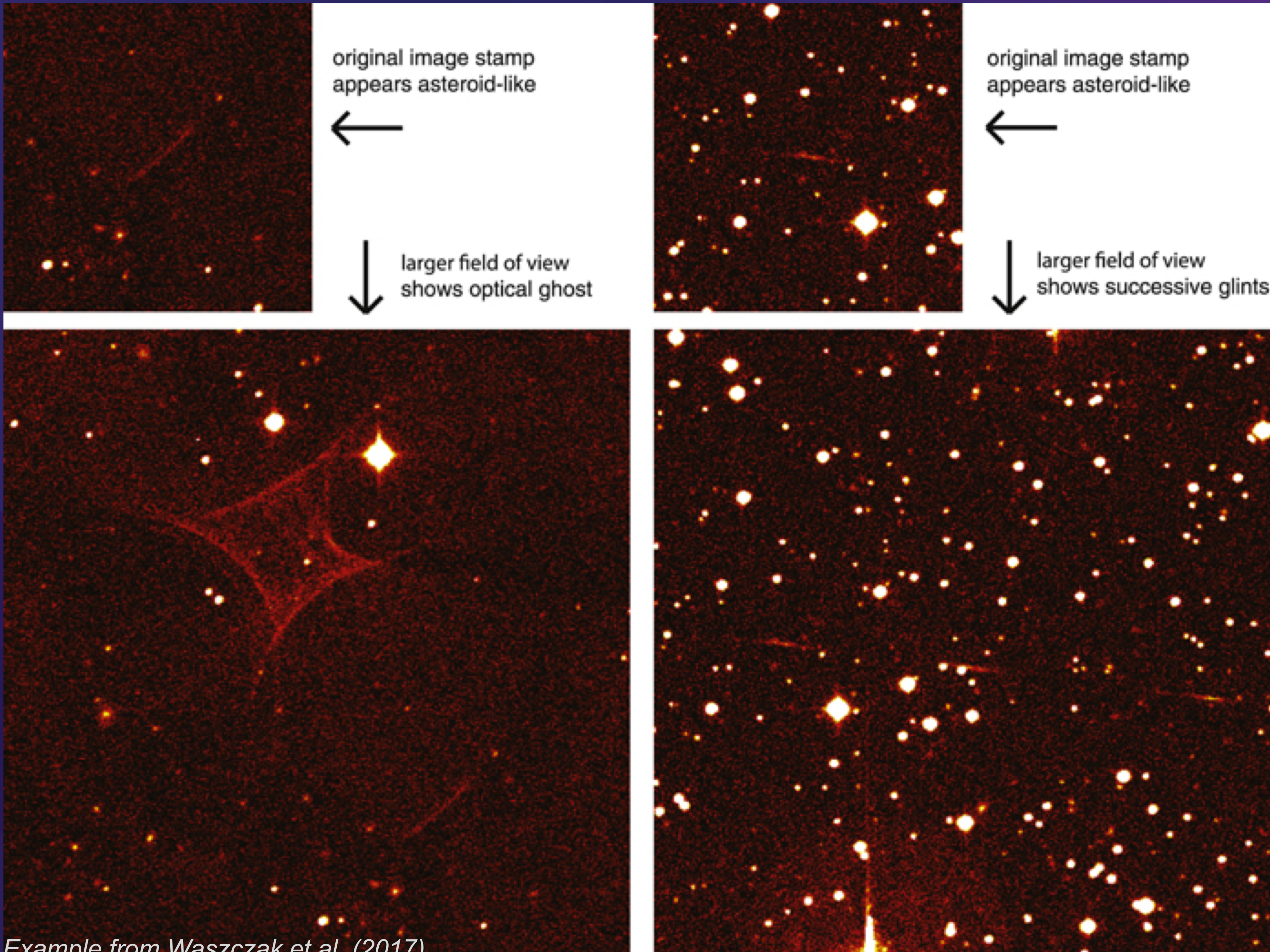


A number of algorithms for detection and characterization of trails.

Usually thresholding followed by line-segment fits, or some variant of Hough/Radon transform.

All suffer from both false positives and negatives.

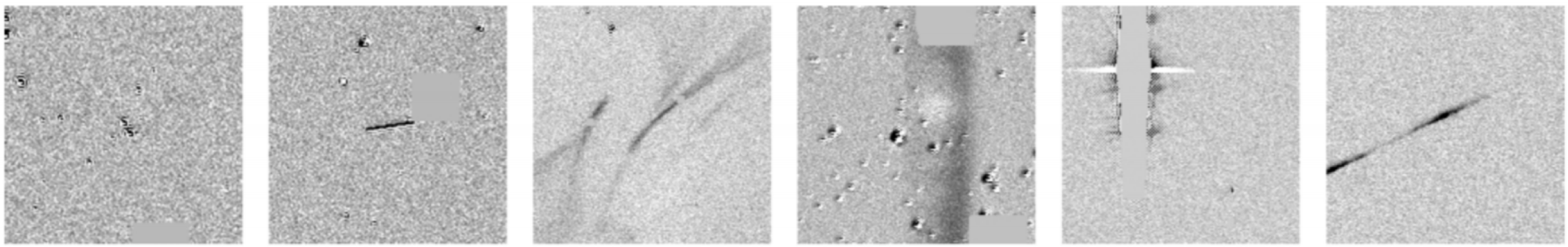
Waszczak et al. (2017)



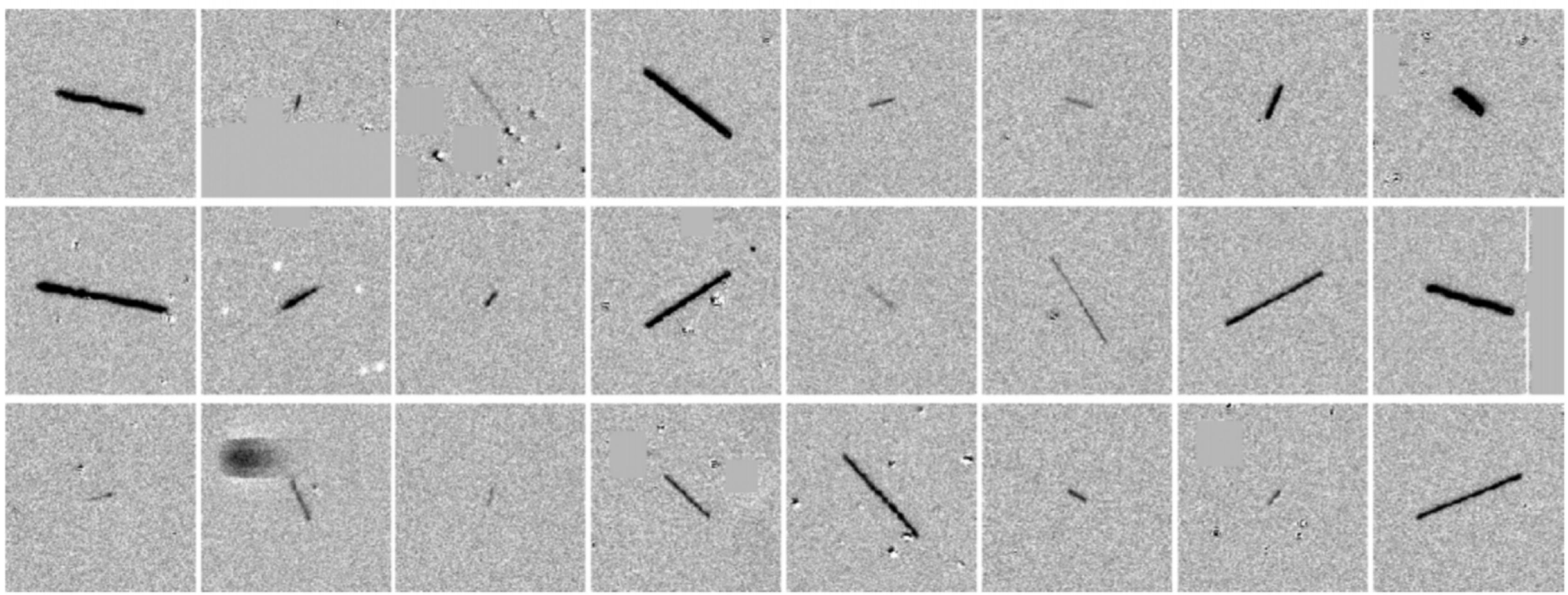
Example from Waszczak et al. (2017)

DeepStreaks: RB for Streaks

30k training examples; used Zwickyverse for labeling; trained on GPU



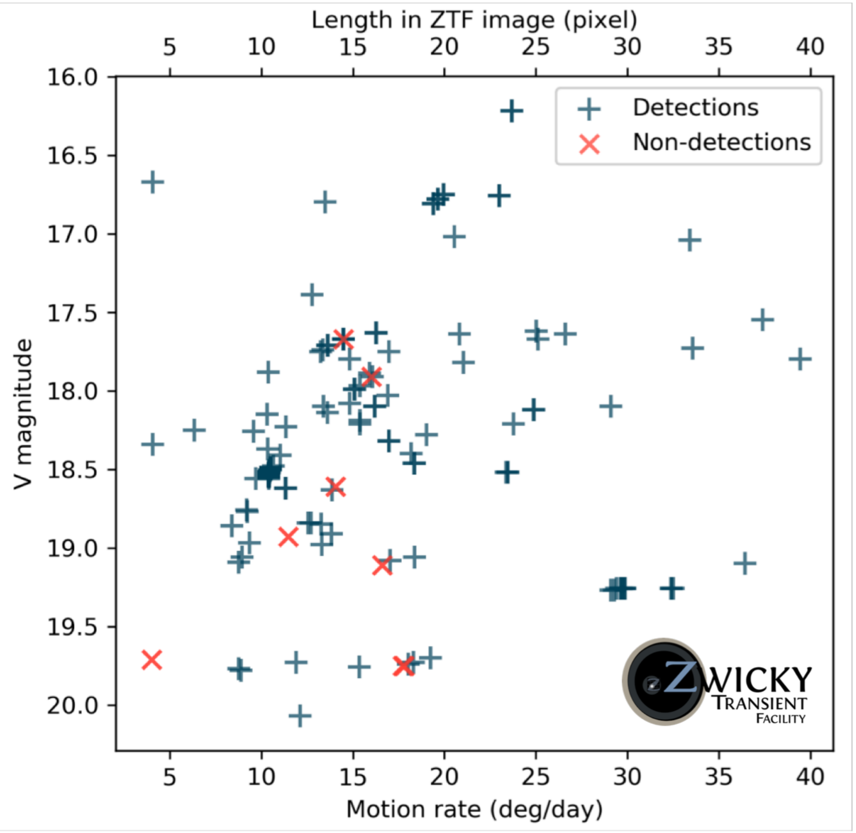
(a) Bad subtraction (b) Cosmic ray (c) "Dementor" (d) "Ghost" (e) Masked star (f) Satellite trail



http://www.astro.caltech.edu/ai19/talks/Duev.pdf

DeepStreaks: performance/results

- 96-98% true positive rate, depending on the night
  - Quantified by performance on test data sets and using known NEOs observed by ZTF
- Below 1% false positive rate, 50x-100x improvement over original RF classifier
  - Sanity check: 0% FPR on 8,000 random ImageNet images
- Near-real-time operations; below 10 min per day spent by human scanners vs ~hours with original RF classifier
- 60+ confirmed new NEAs
- Another 50+ "lost" due to insufficient follow-up



Completeness identifications using known NEOs observed by ZTF in October 2018 – January 2019. Out of 210 streaks from real NEOs detected by the ZTF Streak pipeline at IPAC, 202 (96%) are correctly classified.

Duev+ 2019 (MNRAS, arXiv: 1904.05920)

http://www.astro.caltech.edu/ai19/talks/Duev.pdf

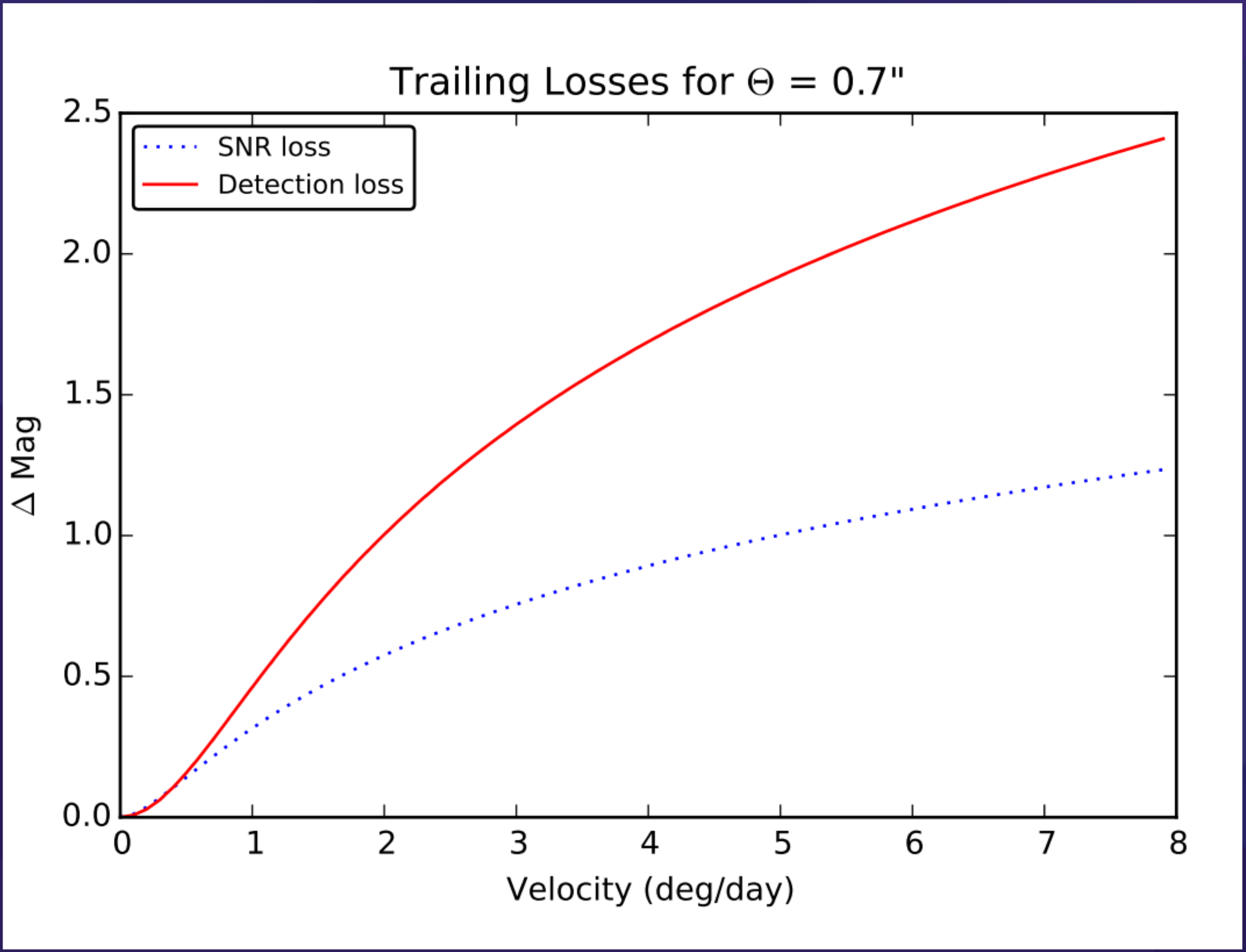
What Will LSST Do?

> For every (>5σ PSF SNR) detected source on a difference image, LSST will perform a trailed model (TM) fit.
  – Fit a line segment convolved with the PSF

> Performing simple cuts on goodness of (say) TM vs. PSF model fits may be sufficient to extract a set of trailed object candidates

> ML classifiers revisit re-detection coincidence will further purify the sample

We can do better with optimal detection



LSST sensitivity for very fast moving objects drops as their rate of motion increases.

This is partly unavoidable (SNR is lower due to increased background), but it's largely due to the way LSST detects sources (using a PSF matched filter).

Jones et al. (2018)

OPTIMAL AND EFFICIENT STREAK DETECTION IN ASTRONOMICAL IMAGES

GUY NIR[1], BARAK ZACKAY[2], AND ERAN O. OFEK[1]

Draft version October 9, 2018

ABSTRACT

Identification of linear features (streaks) in astronomical images is important for several reasons, including: detecting fast-moving near-Earth asteroids; detecting or flagging faint satellites streaks; and flagging or removing diffraction spikes, pixel bleeding, line-like cosmic rays and bad-pixel features. Here we discuss an efficient and optimal algorithm for the detection of such streaks. The optimal method to detect streaks in astronomical images is by cross-correlating the image with a template of a line broadened by the point spread function of the system. To do so efficiently, the cross-correlation of the streak position and angle is performed using the Radon transform, which is the integral of pixel values along all possible lines through an image. A fast version of the Radon transform exists, which we here extend to efficiently detect arbitrarily short lines. While the brute force Radon transform requires $\mathcal{O}(N^3)$ operations for a $N \times N$ image, the fast Radon transform has a complexity of $\mathcal{O}(N^2 \log(N))$. We apply this method to simulated images, recovering the theoretical signal-to-noise ratio, and to real images, finding long streaks of low-Earth-orbit satellites and shorter streaks of Global Positioning System satellites. We detect streaks that are barely visible to the eye, out of hundreds of images, without a-priori knowledge of the streaks' positions or angles. We provide implementation of this algorithm in Python and MATLAB.

2. Finding Slow Faint Moving Objects

Coadding an Image of a Moving Source Increases the SNR

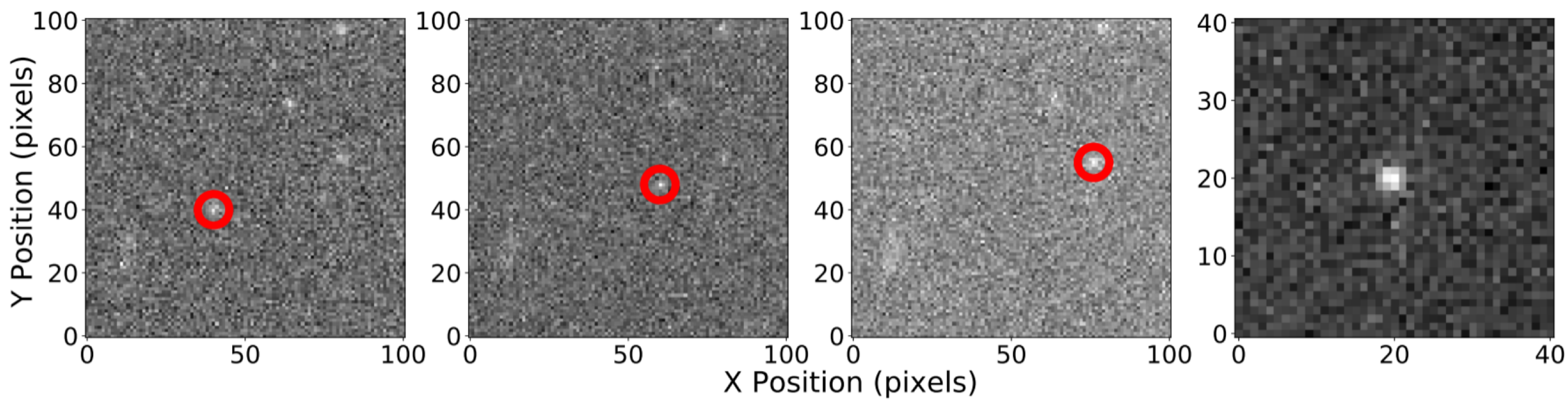


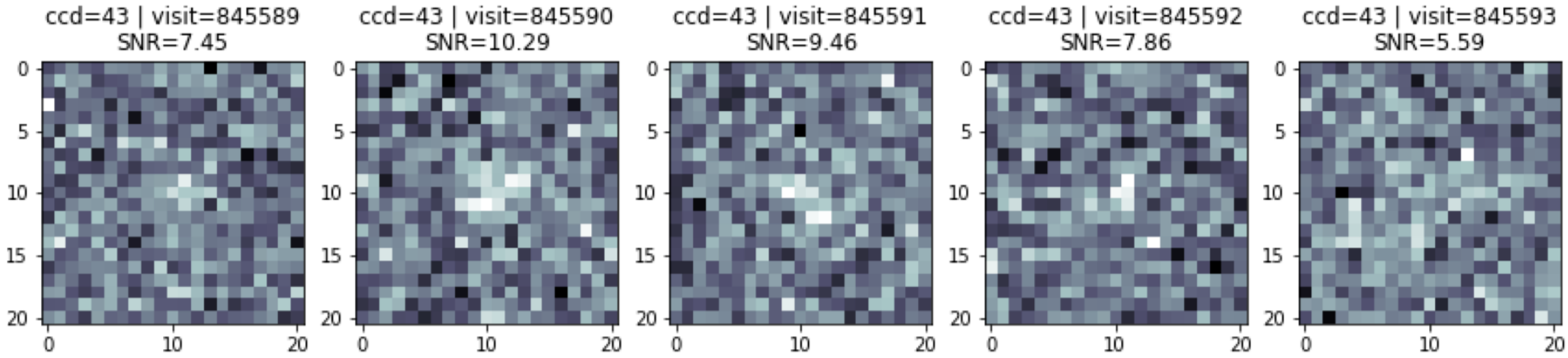
Figure 1. Shifting and stacking of individual images along the asteroid's trajectory creates a single point source in the stacked image.

Whidden et al. (2019)

Large Synoptic Survey Telescope

Detecting Faint Objects

What to do when objects aren't even detected in a single image?



Visualization by Hayden Smotherman, from Deep Ecliptic Exploration Program (DEEP) data (DECam)

When the exact location of an object is unknown, all plausible orbits need to be examined.
Fortunately, distant objects move slowly, and linearly (on ~week timescales).

DiRAC

Exploring plausible trajectories

Run over all plausible motion vectors.

This is incredibly parallel (and vectorizable) -> GPUs are well suited for evaluation.

For example, this is implemented in KBMOD:

https://github.com/dirac-institute/kbmod

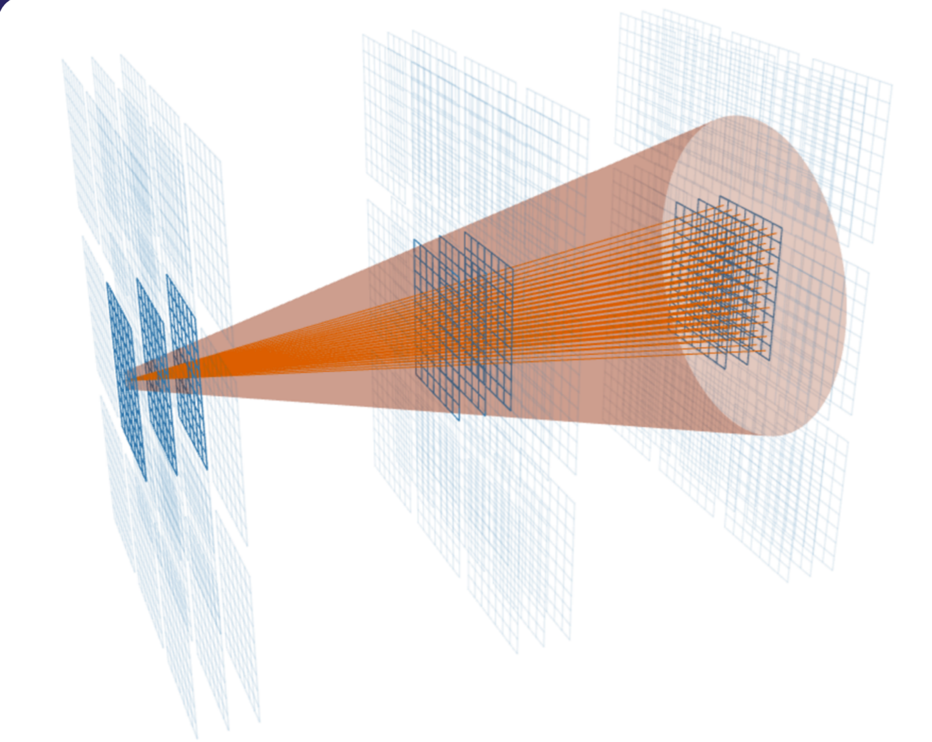
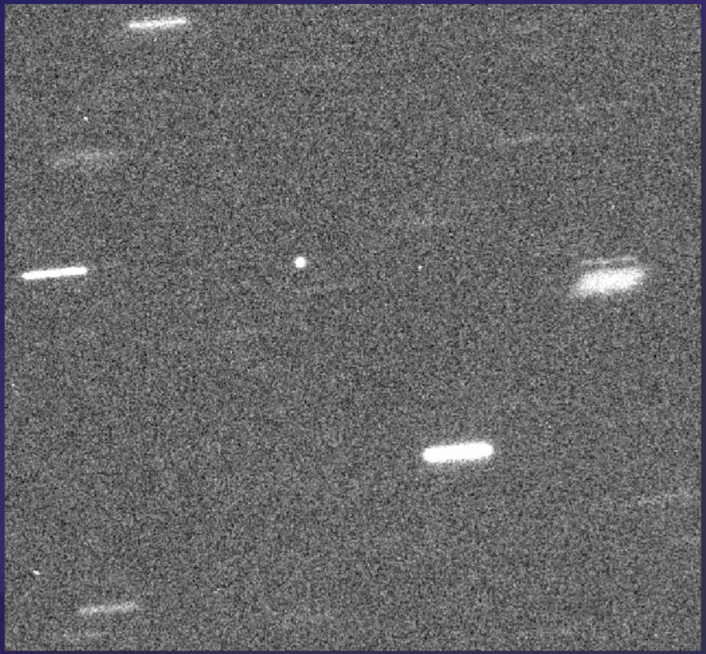


Figure 2. Visualization of the many trajectories that must be searched in order to cover a defined velocity and angle range over a stack of images of the same field taken at different times.

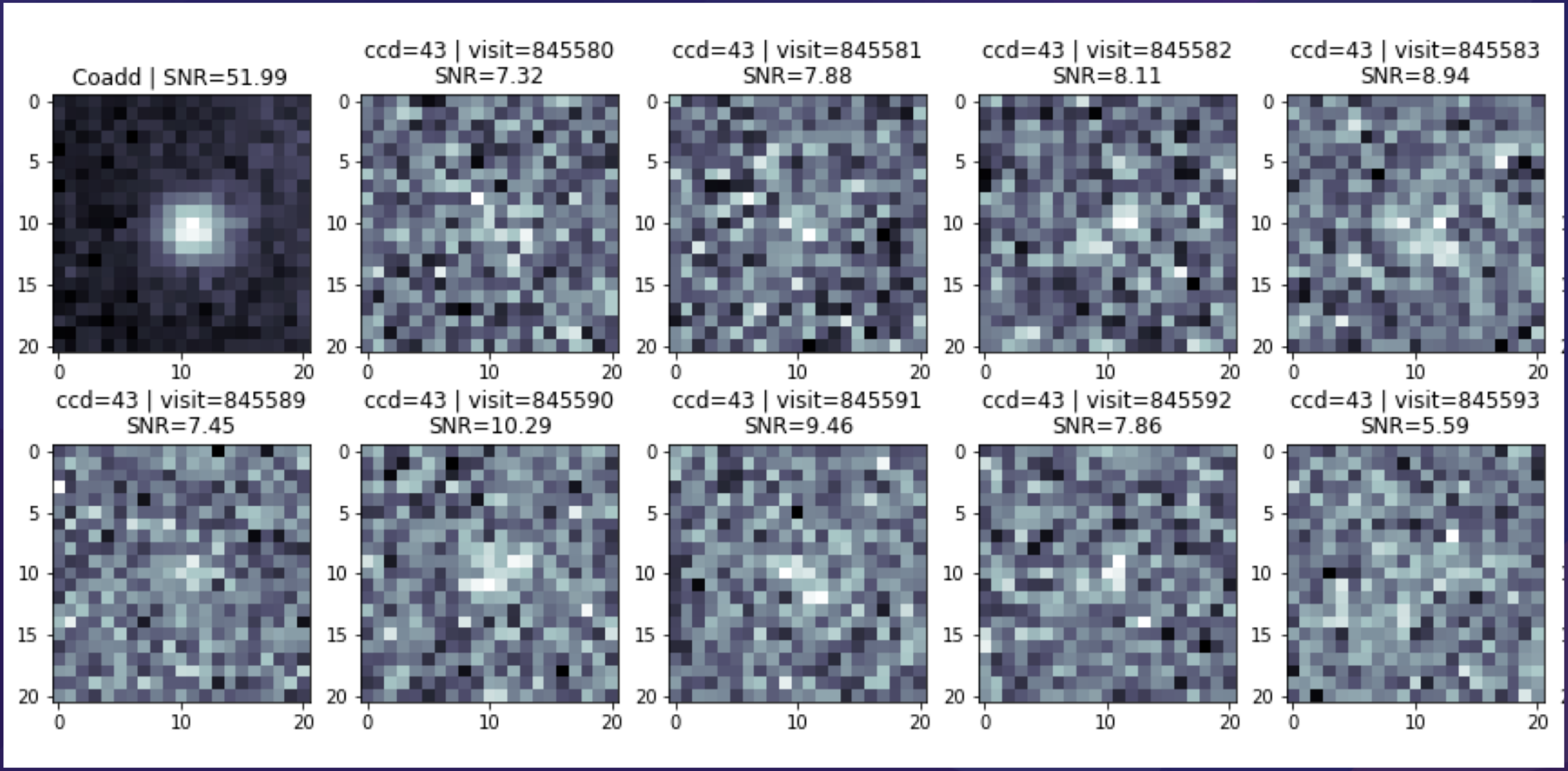
Whidden et al. (2019)

Image differencing: Cleaning up the Background



http://www.cfht.hawaii.edu/en/news/UM2019/presentations/session8-wainscoat.pdf

Example of shift-and-stack with Deep Ecliptic Exploration Project data



https://deepsurvey.org (coming soon…)

Large Synoptic Survey Telescope

Opportunity: Let's do this over the entire LSST footprint!

Opportunities:

> **4-8x more KBOs (!!)**

> **5x larger discovery volume for Planet X**

Challenges to resolve:

- Scales quadratically with time span and linearly with the number of images
- Bunching up ~10 observations in a ~10 day period would enable shift-and-stack runs.

- Even so, O(10) Petaflop-months of GPU power to process all of LSST (equiv to running on ~O(1000) V100 GPUs)

Enabling Deep All-Sky Searches of Outer Solar System Objects

Mario Jurić, R. Lynne Jones, J. Bryce Kalmbach, Peter Whidden, Dino Bektešević, Hayden Smotherman, Joachim Moeyens, Andrew J. Connolly, Wesley Fraser, David Gerdes, Megan E. Schwamb, David Trilling, and Michael Mommert

November 30, 2018

Abstract

A foundational goal of the Large Synoptic Survey Telescope (LSST) is to map the Solar System small body populations that provide key windows into understanding of its formation and evolution (Ivezić et al., 2008; LSST Science Collaboration et al., 2009). This is especially true of the populations of the Outer Solar System – objects at the orbit of Neptune $r > 30$ AU and beyond.

In this whitepaper, we propose a minimal change to the LSST cadence that can greatly enhance LSST's ability to discover faint distant Solar System objects across the entire *wide-fast-deep* (WFD) survey area. Specifically, we propose that the WFD cadence be constrained so as to deliver least one sequence of $\gtrsim 10$ visits per year taken in a ~ 10 day period in any combination of g, r, and i bands. Combined with advanced shift-and-stack algorithms (e.g. Whidden et al., 2018) this modification would enable a nearly complete census of the outer Solar System to ~ 25.5 magnitude, yielding $4-8$x more KBO discoveries than with single-epoch baseline, and enabling rapid identification and follow-up of unusual distant Solar System objects in $\gtrsim 5$x greater volume of space.

These increases would enhance the science cases discussed in Schwamb et al. 2018 whitepaper, including probing Neptune's past migration history as well as discovering hypothesized planet(s) beyond the orbit of Neptune (or at least placing significant constraints on their existence).

Juric et al (2019)

DiRAC

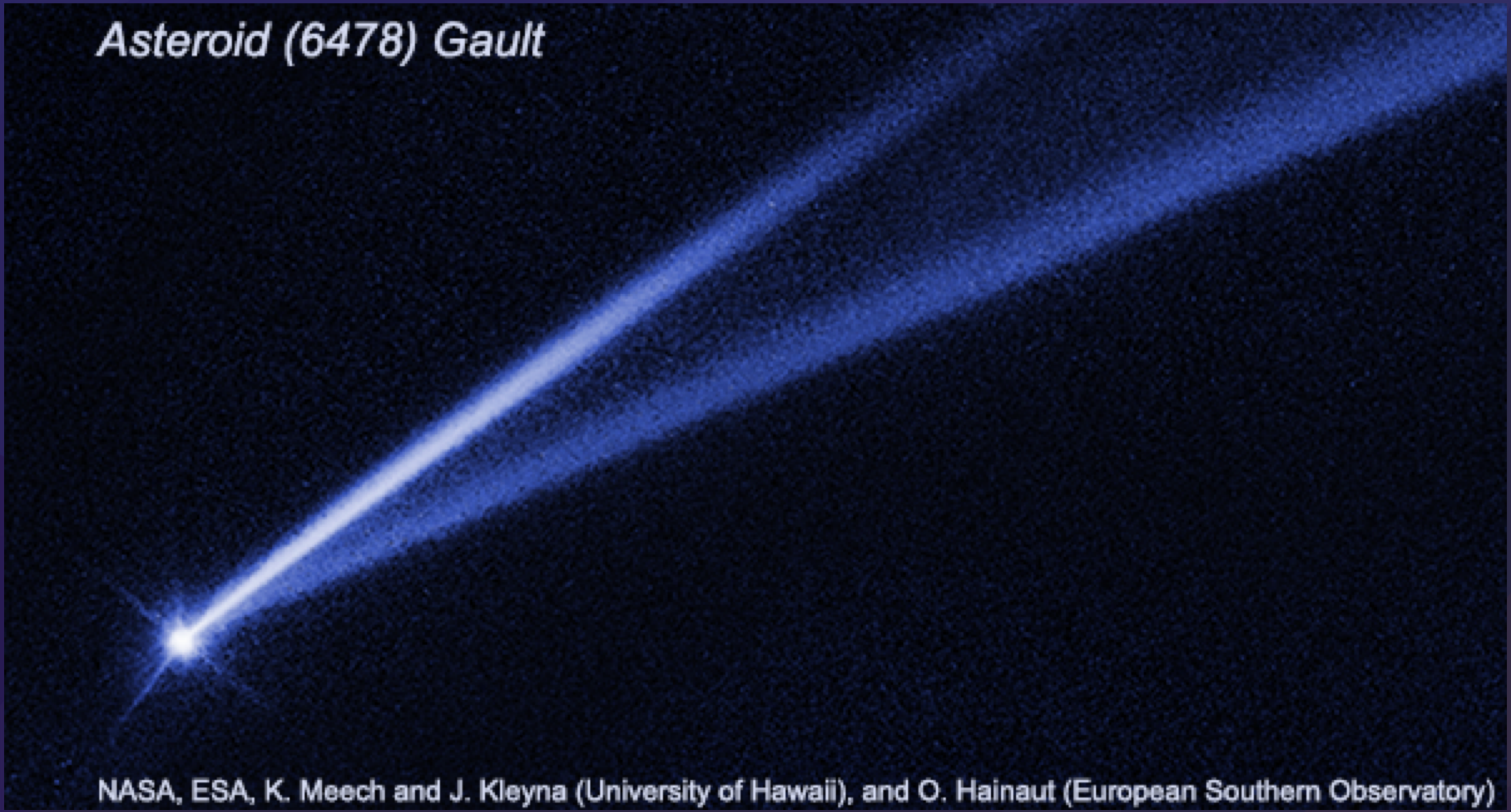
3. Detecting Comets and Active Asteroids

Active Asteroids

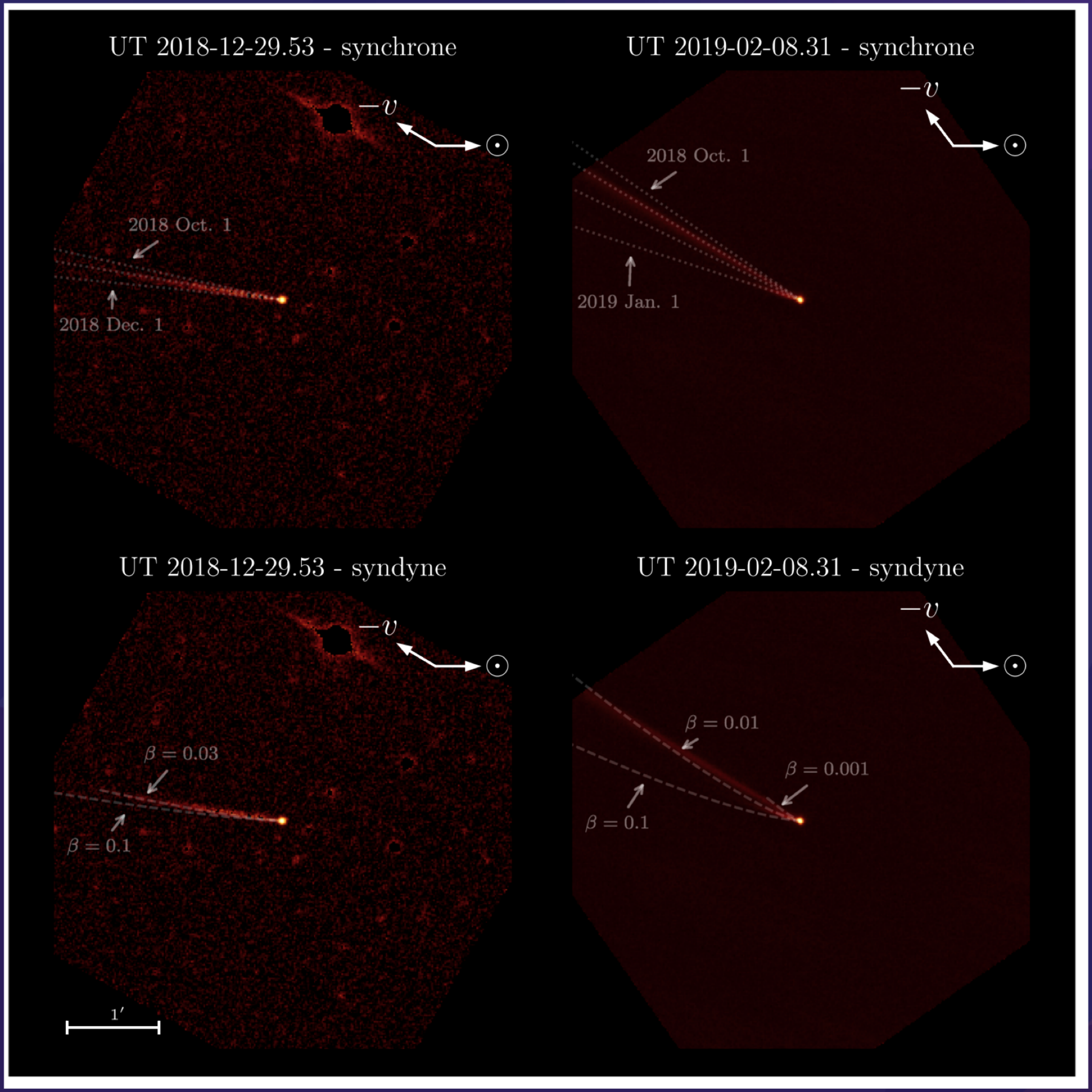
- Those "ejecting dust, producing transient, comet-like comae and tails." (Jewitt, Hsieh and Agarwal, 2015)
- First discovery: 133P/Elst-Pizarro (the first "main belt comet")
- Two more discovered in 2006 (Hsieh and Jewitt)
- Around ~30 are known today.

- Potential causes: impact disruption, sublimation of sub-surface ices, or YORP spinup

Note: Henry Hsieh (SSSC) is the world expert on these & can tell you more!



https://hubblesite.org/contents/news-releases/2019/news-2019-22.html


UT 2018-12-29.53 - synchrone
$-v$
2018 Oct. 1
2018 Dec. 1
UT 2019-02-08.31 - synchrone
$-v$
2018 Oct. 1
2019 Jan. 1
UT 2018-12-29.53 - syndyne
$-v$
$\beta = 0.03$
$\beta = 0.1$
1′
UT 2019-02-08.31 - syndyne
$-v$
$\beta = 0.01$
$\beta = 0.001$
$\beta = 0.1$

Ye et al. (2019)

What Will LSST Do?

- LSST computes a number of shape-related features for each DIASource
  - PSF model fit
  - Trailed model fit
  - Aperture magnitude
  - Dipole fit
  - Adaptive moments
- It will also compute the predicted positions and magnitudes for known SSOs
- These can be used to detect when the object is non-point source like, is significantly offset from predicted position, or is unexpectedly bright or faint.

Large Synoptic Survey Telescope

Low Surface Brightness Photometry on DiffIms

- Comets (& AAs) have diffuse extended comas with lots of changing substructure (filaments, outbursts, etc.)
- These would ideally be characterized on DiffIms
- We'd benefit from LSB-photometry algorithms in presence of correlated pixel noise, artefacts
- And then the same, shift-and-stacked…

Summary

- Nearly all Solar System science in LSST will be coming from image differencing.
- The DIA data products have been designed with features enabling the end-user to select potentially interesting SSOs
- But there are areas open for improvements:
  - No streak-detection algorithm; we will lose the faintest fast objects (which are almost guaranteed to be PHAs (or satellites)).
  - No deep shift-and-stacking in DRP
  - Doing low-surface brightness photometry on DiffIms (bonus points: on shift-and-stack coadds of diffims!)