A wide-scale search for solar system objects with **DECam** in the NOIRLab Source Catalog

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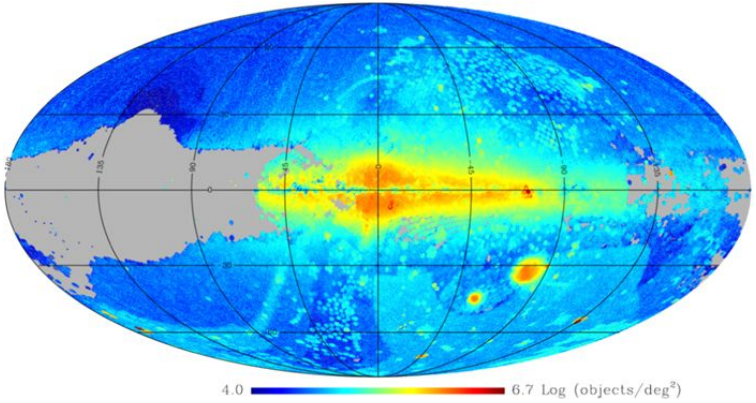
Our Project

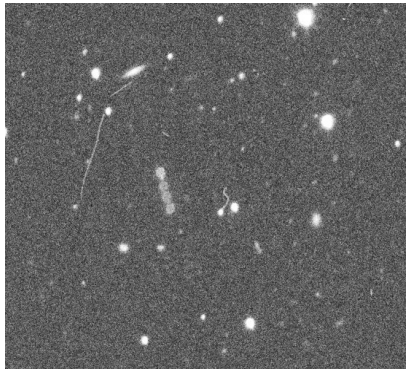
With public data in the NOIRLab's Astro Data Archive, largely taken by the **Dark Energy Camera (DECam)**, we are performing a comprehensive search of the **NOIRLab Source Catalog (NSC)** for **solar system objects (SSOs**).

Outline:

- NSC Data Release 1 (DR1, 2018) and DR2 (2021), planned updates
- SSO detection in the NSC



SSOs identified by high proper motion (μ)



NOIRLab Source Catalog

Photometric catalog of 68 billion sources from the **publicly available exposures in the NOIRLab Astro Data Archive**, taken with ground-based instruments (Nidever *et al.* 2018, 2021)

Table 1. Instrument Specifications and coverage in NSC DR2

Instrument	Observatory	Coverage(MMYYYY)	N_{exp}	FOV (°)	CCDs	pixel spacing (″)	bands
DECam[a]	CTIO Blanco 4m	092012–112019	340952	3	62	0.26	$ugrizY, VR$
Mosaic-3[b]	KPNO Mayall 4m	012016–082017	41561	3	4	0.26	z
90Prime[c]	Steward Bok 2.3m	112015–022019	29603	1	4	0.45	g,r

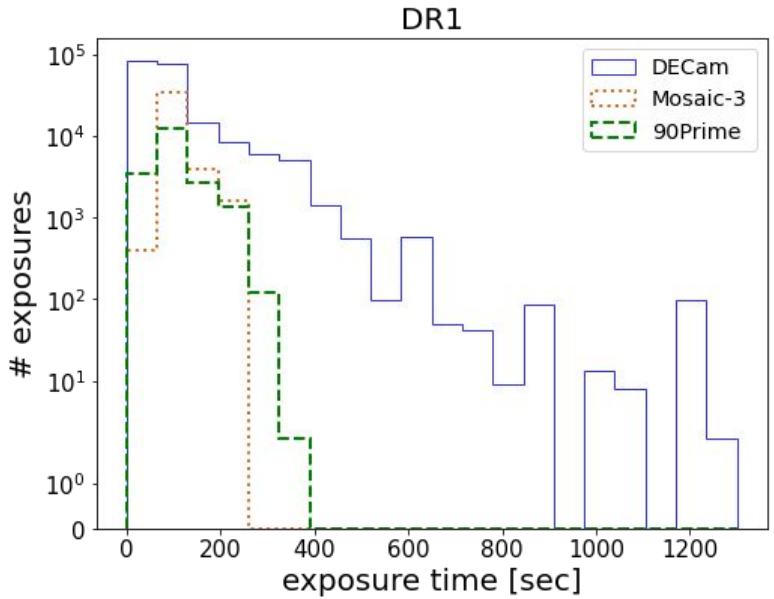
[a] Dark Energy Camera Dey et al. (2019); http://www.ctio.noao.edu/noao/node/1033

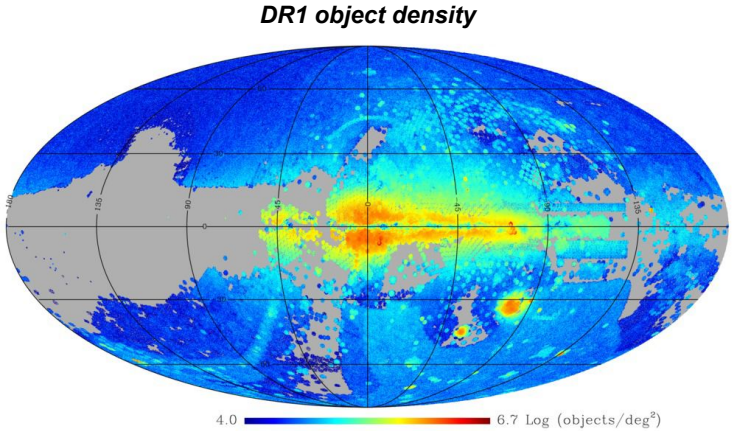
[b] Mosaic-3 Wide Field Imager Dey et al. (2016a); https://www.noao.edu/kpno/mosaic/

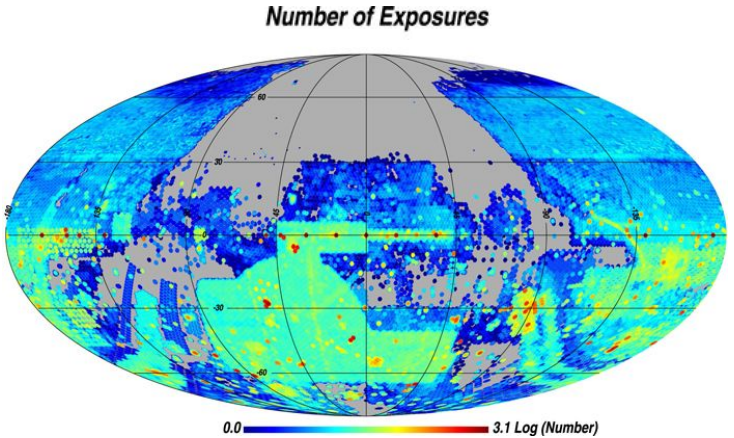
[c] Prime Focus CCD Mosiac Camera Zou et al. (2017)

NOIRLab Source Catalog

DR1 - 34 billion detections of 2.9 billion unique objects



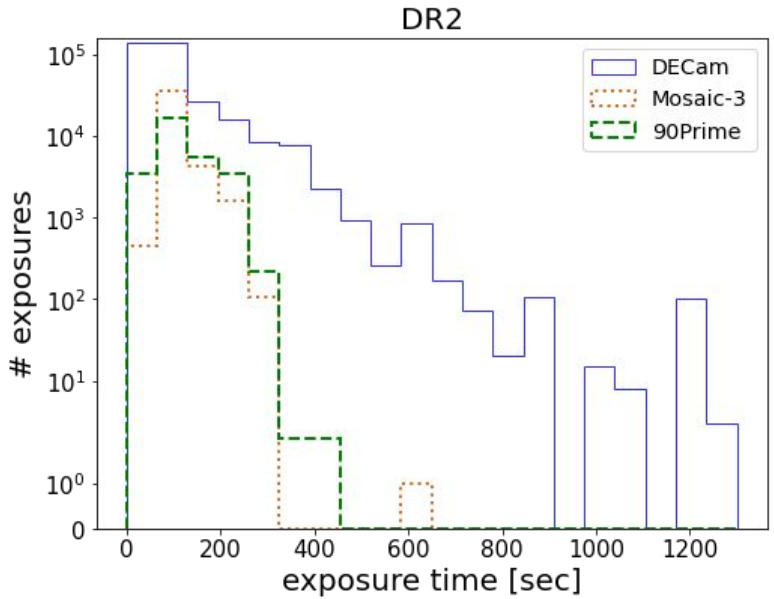


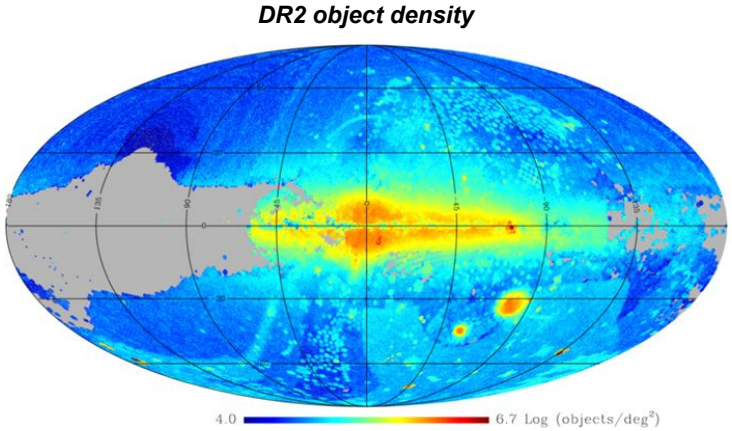


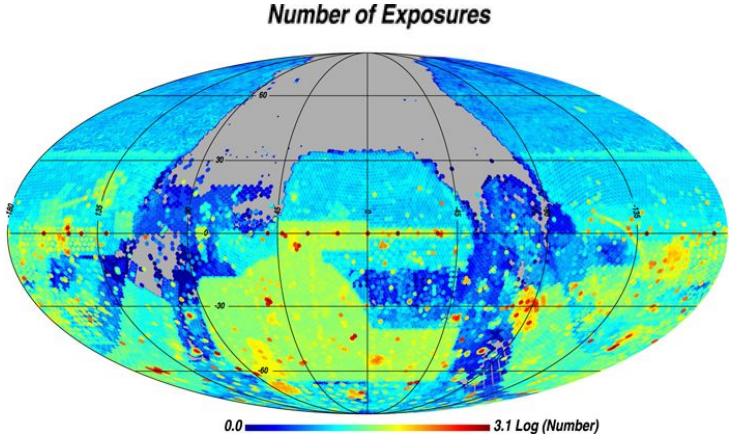
Nidever *et al.* 2018, Fasbender & Nidever 2021

NOIRLab Source Catalog

DR2 - 68 billion detections of 3.9 billion unique objects

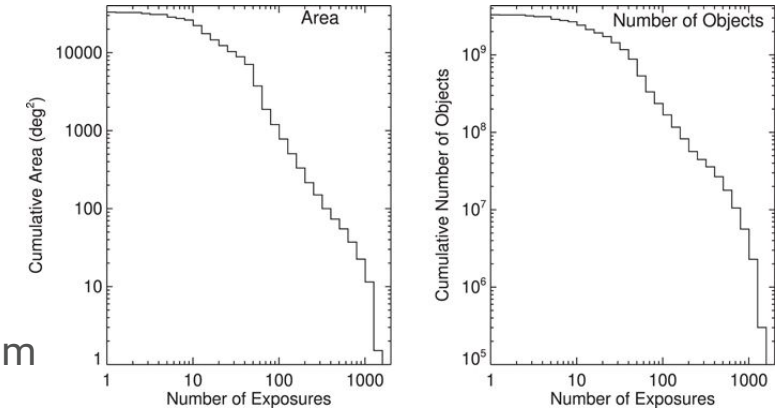






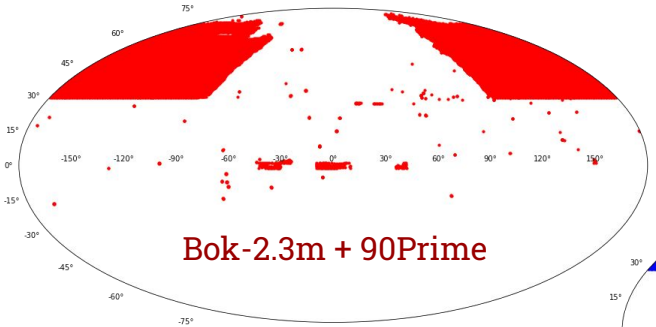
Nidever *et al.* 2021

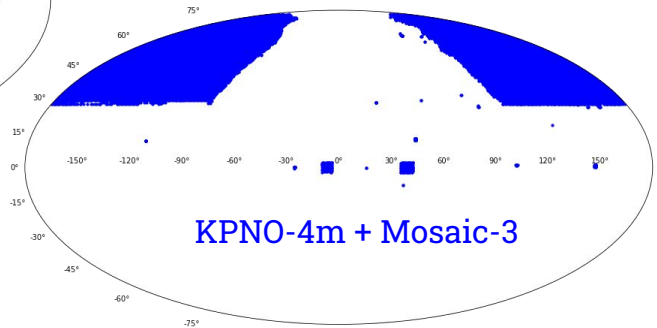
NOIRLab Source Catalog

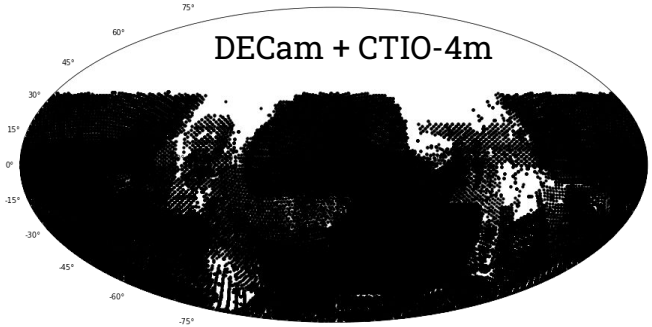


~80% of the exposures included in the NSC are from DECam

- **Data Release 1** (DR1, Nidever *et al.* 2018): 195,489 out of 255,454 total exposures taken by DEcam
- **DR2** (Nidever *et al.* 2021): 340,952 of 412,116 exposures
- **DR3** (*in development*): estimated 400,000 of 500,000 exposures







Nidever *et al.* 2021

Table 2
General Information for the 11 Top Contributing Surveys in NSC DR1, Expanded from Nidever et al. (2018) Table 1

Survey Name	Instrument	PI	$N_{exposures}$	Bands	Depth (mag)	PSF FWHM (″)
DES[a]	Blanco/DECam	Friedman	58,546	*grizY*	24.5, 24.3, 23.5, 22.9, 21.7	1.2, 1.1 ,1.0, 0.9, 0.9
Legacy Surveys:[b]						
DECaLS[c]	Blanco/DECam	Schlegel & Dey	17,533	*grz*	24.0, 23.5, 22.5	1.3, 1.2, 1.1
BASS[d]	Bok/90Prime	Zou & Fan	19,741	*gr*	23.7, 23.1	1.6, 1.45
MzLS[e]	Mayall/Mosaic-3	Dey	40,224	*z*	22.6	1.01
NEO[f]	Blanco/DECam	Allen	11,800	*VR*	23.0	~1
DECaPS[g]	Blanco/DECam	Finkbeiner	7590	*grizY*	23.7, 22.8, 22.2, 21.8, 21.0	~1
Bulge Surveys:						
BDBS[h]	Blanco/DECam	Rich	3849	*ugrizY*	23.5, 23.8, 23.5, 23.1, 22.5, 21.8	~0.8–1.8
DSSGB[i]	...	Saha	3837	*ugriz*	...	...
Light Echoes[j]	Blanco/DECam	Rest	7622	*rVR*	...	...
SMASH[k]	Blanco/DECam	Nidever	6645	*ugriz*	23.9, 24.8, 24.5, 24.2, 23.5	1.2, 1.1, 1.0, 1.0, 0.9
BLISS[l]	Blanco/DECam	Soares-Santos	3049	*griz*	...	...
NSC DR1	...	Nidever	255,454	*ugrizYVR*	23.1, 23.3, 23.2, 22.9, 22.2, 21.0, 23.1	1.4, 1.3, 1.2, 1.0, 1.0, 1.0, 1.2

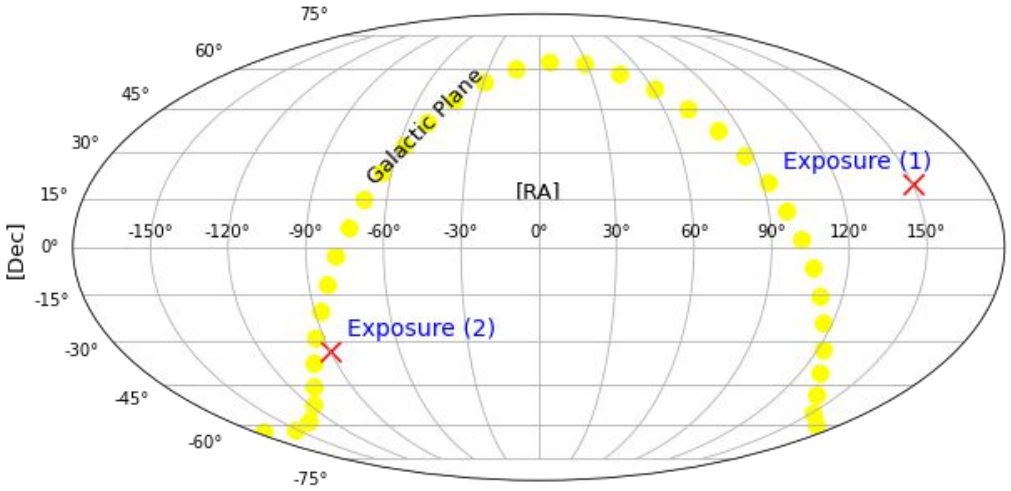
Notes.
[a] Dark Energy Survey (Dark Energy Survey Collaboration et al. 2016); https://www.darkenergysurvey.org.
[b] Dey et al. (2019); http://legacysurvey.org.
[c] DECam Legacy Survey; http://legacysurvey.org/decamls/.
[d] Beijing-Arizona Sky Survey (Zou et al. 2017).
[e] Mayall z-band Legacy Survey (Dey et al. 2016).
[f] DECam Near Earth Object survey (Allen et al. 2016).
[g] DECam Plane Survey (Schlafly et al. 2018); http://decaps.skymaps.info.
[h] Blanco DECam Galactic Bulge Survey (Rich 2015, Johnson et al. 2020).
[i] Deep Synoptic Study of the Galactic Bulge.
[j] Light Echoes of Galactic Explosions (Rest et al. 2015).
[k] Survey of the Magellanic Stellar History (Nidever et al. 2017); http://datalab.noao.edu/smash/smash.php.
[l] Blanco Imaging of the Southern Sky.

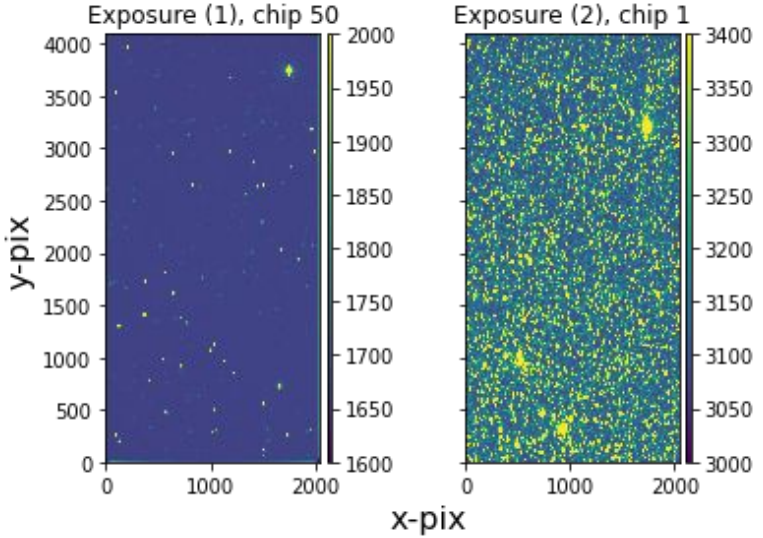
Look at NSC DR2: https://datalab.noirlab.edu/nscdr2

Fasbender & Nidever 2021

NOIRLab Source Catalog

Upcoming developments to NSC DR3: (expected 2023)

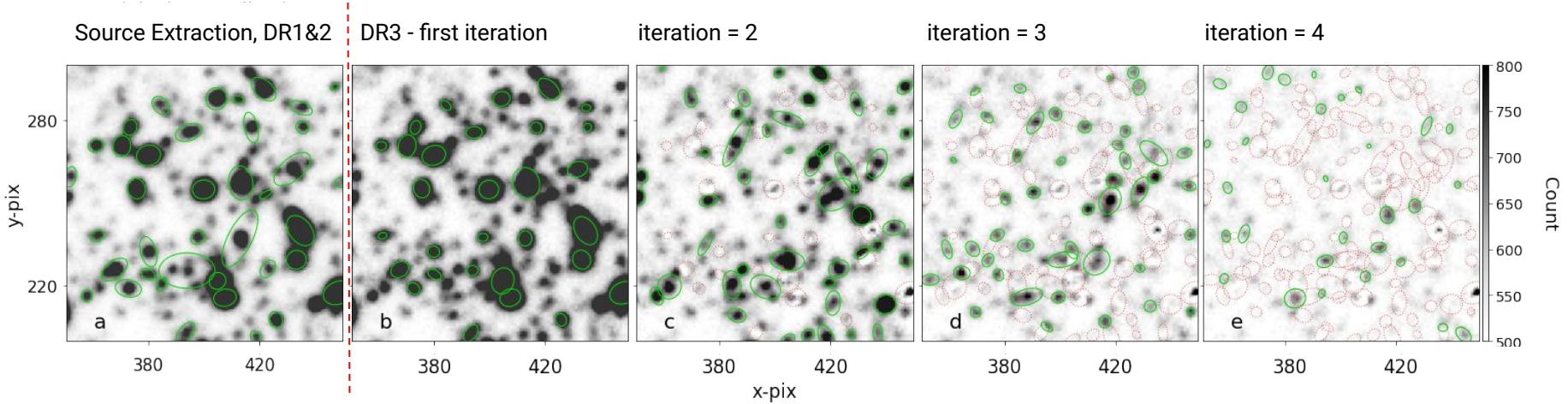




NOIRLab Source Catalog

Upcoming developments to NSC DR3: (expected 2023)

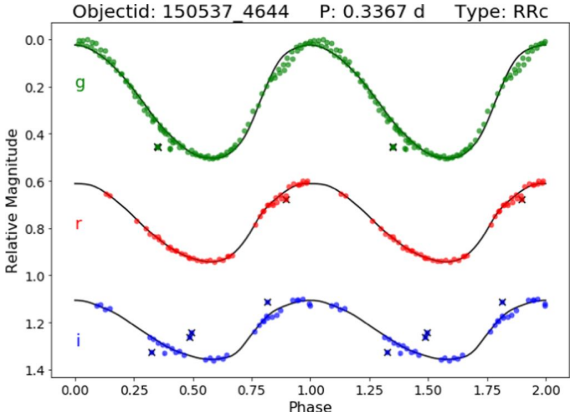
- Improved detection with Source Extractor (Bertin & Arnouts 1996)
- New photometric measurements with DAOPHOT (Stetson 1987)
- Calibration with Gaia DR3, ubercalibration (based on work in Magnier *et al.* 2020)

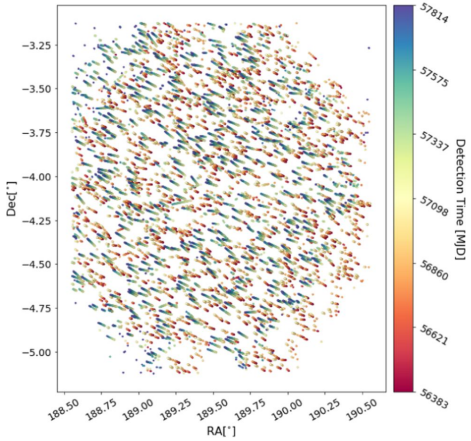


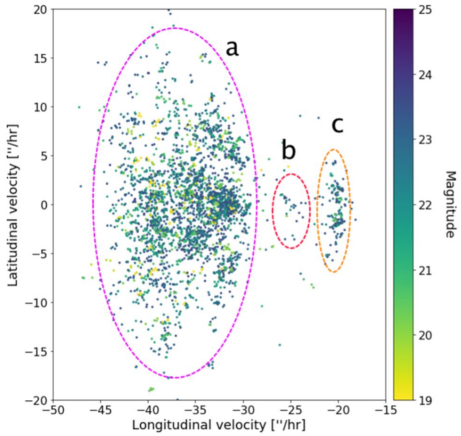
Science with the NSC

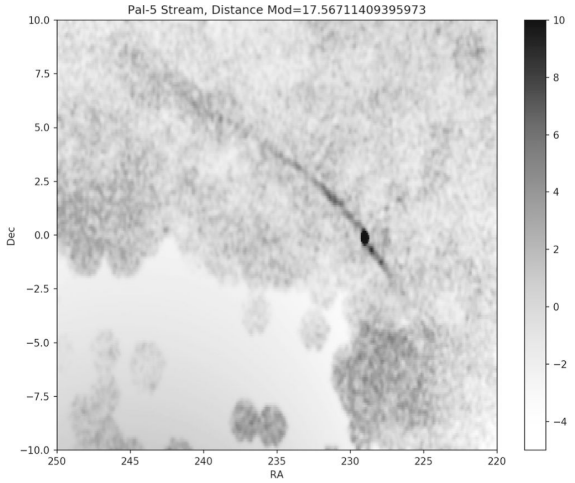
Examples: (Nidever et al. 2021)

- Stellar streams
- Milky Way satellite dwarf galaxies
- Variable stars
- **Solar system objects**



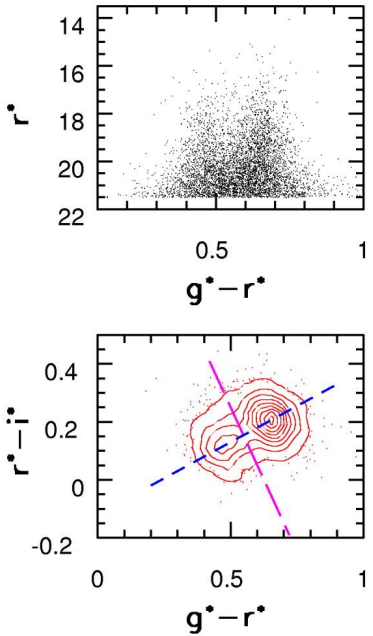






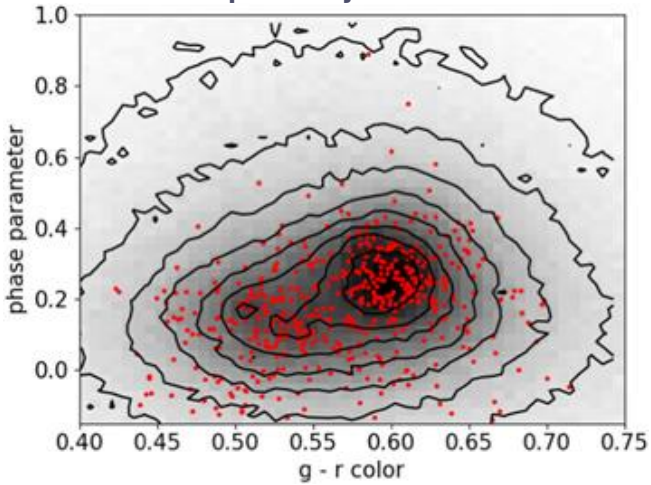
Solar System Objects - an overview

Bimodality in MBA Colors



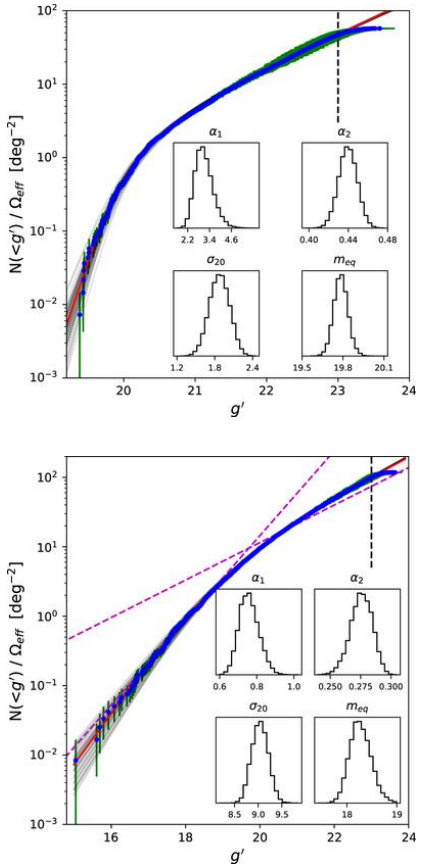
Ivezic *et al.* 2001

Jupiter Trojan Colors



Schemel & Brown, 2021

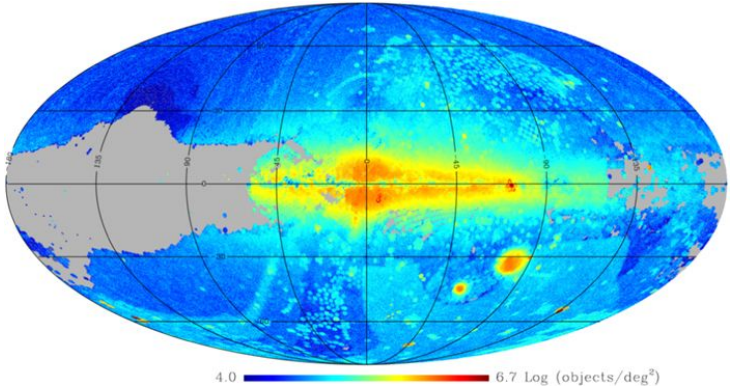
MBA Size Distribution

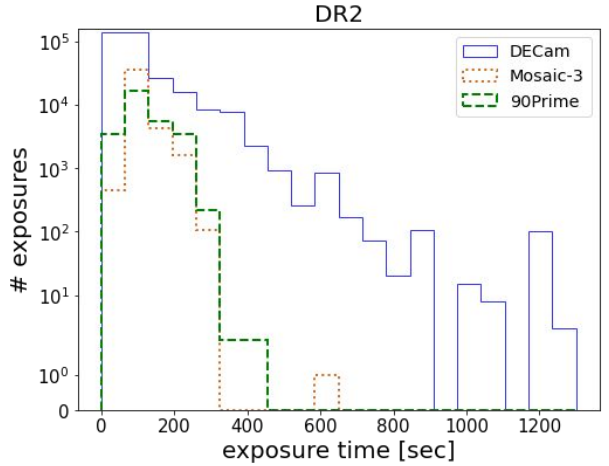


Peña *et al.* 2020

SSO Detection in the NSC

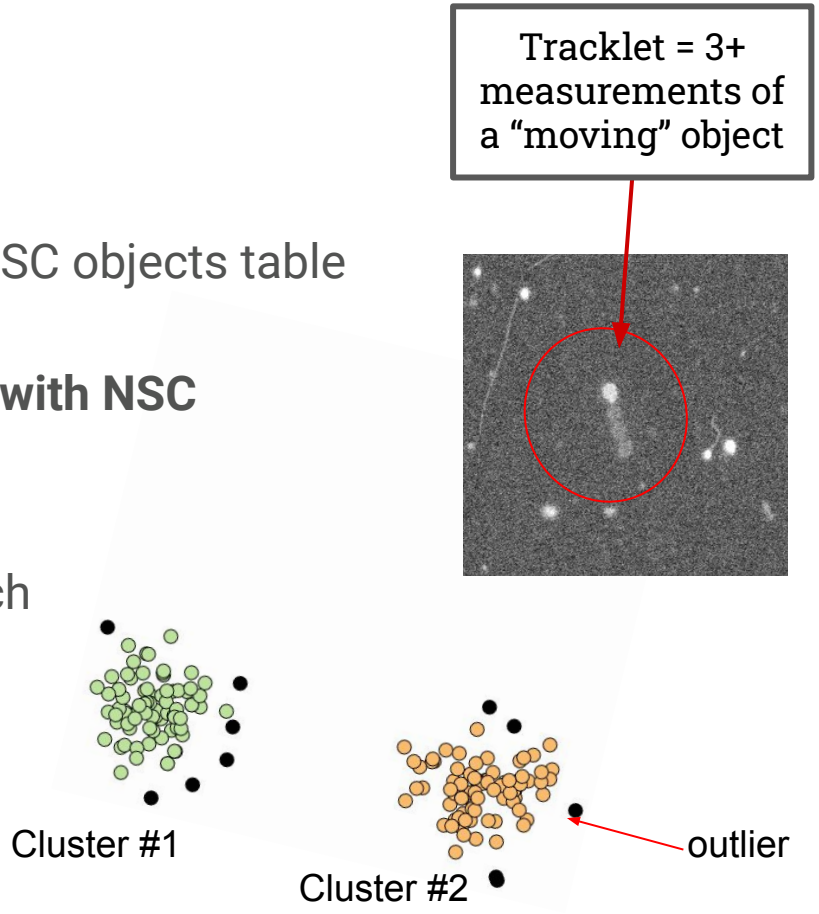
- Good **coverage** (35,000 deg^2, 2012-2019)
- Median depth **~22 mag** in all seven photometric bands
- All exposures analyzed with the same method = **uniformity** in data across sky
- Much **diversity in data** (exposure time, spatial/temporal coverage patterns, multiple filters, crowded/sparse fields, etc.)
- **Diverse NSC data = cast a wide net**





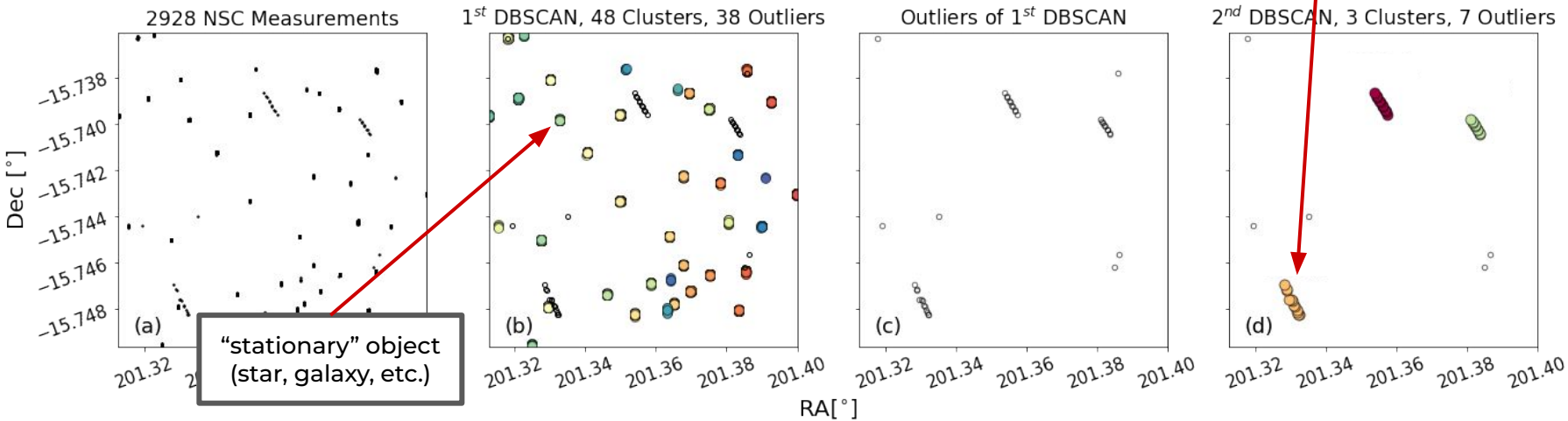
Detection

- Measurement spacing Δs < 0.5” - NSC objects table
- 0.5” < Δs < 11” - **iterative clustering with NSC measurements table**
- Δs > 11” - Hough transform approach

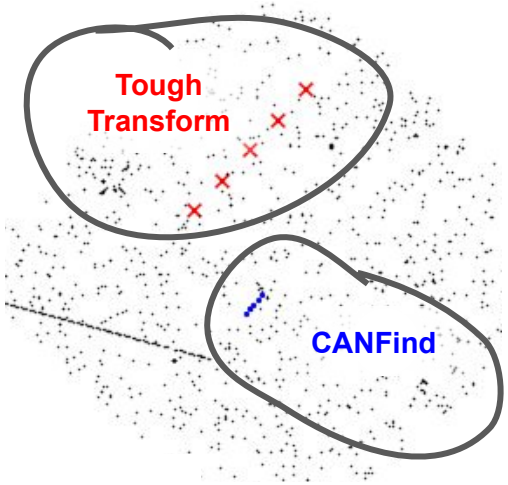


Detection

Iterative clustering approach (CANFind - the Computationally Automated NSC tracklet Finder)



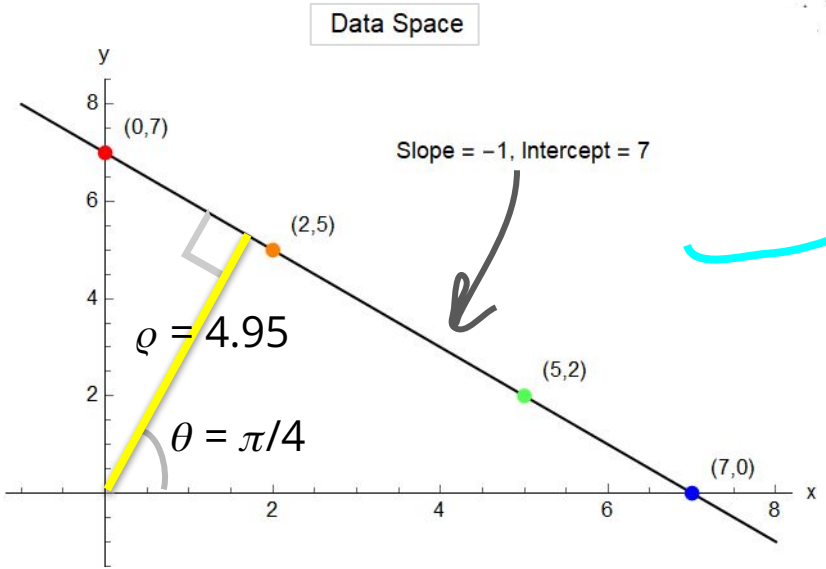
Detection

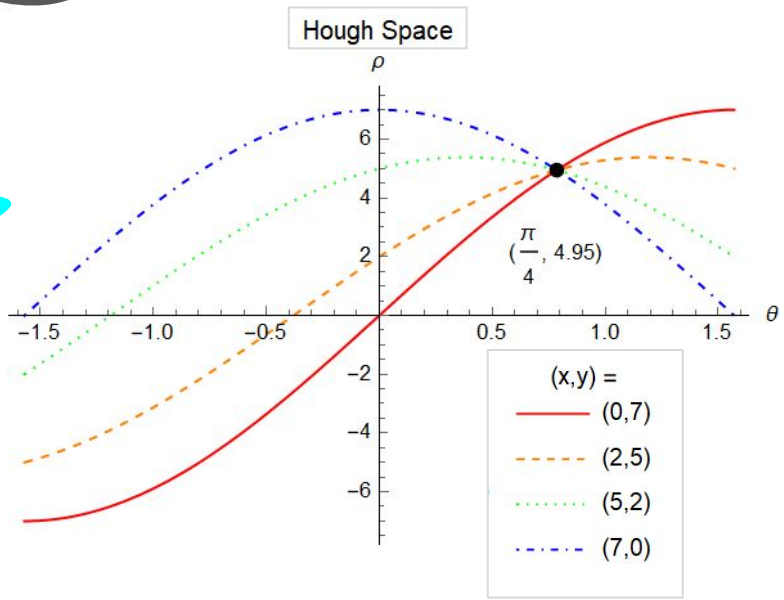


Diverse NSC data =

cast a wide net

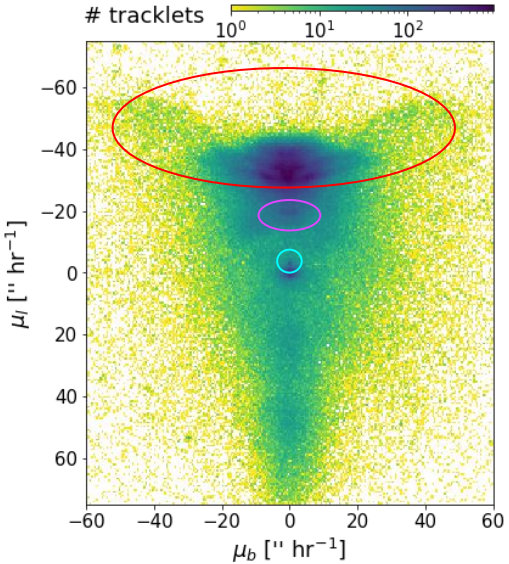
Tough Transform - adapted from Hough/Radon Transform (Duda & Hart 1972, Radon 1917)





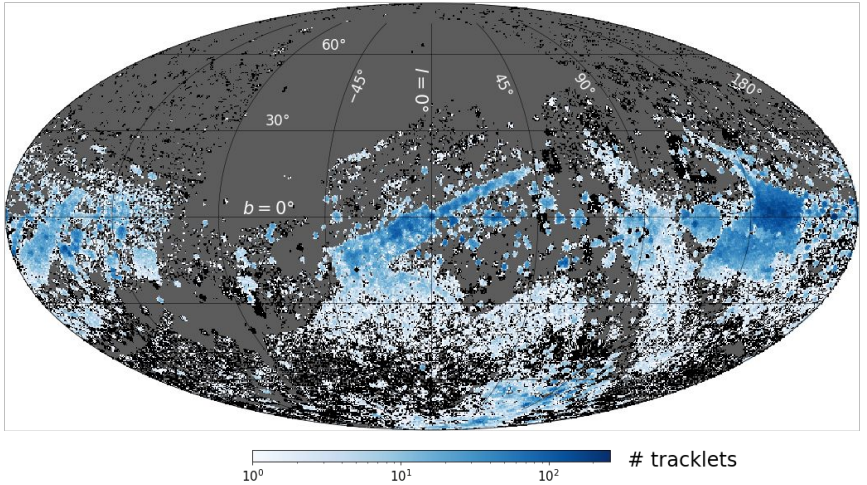
SSO detections in the NSC

600,000+ detections

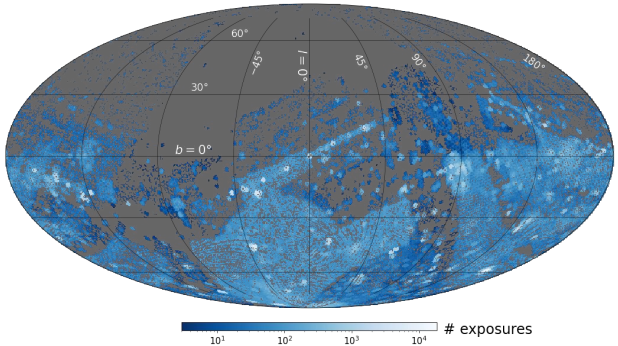


Color	# Tracklets	Multicolor	# Tracklets
g–r	107,604	*g + r + i*	50,222
r–i	70,557	*r + i + z*	16,323
g–i	70,161	*g + r + z*	9518
i–z	30,706	*g + i + z*	8505
g–z	13,335	*i + z + Y*	2806
r–z	22,563	*r + i + Y*	940

Moving objects in the NSC (ecliptic coordinates)



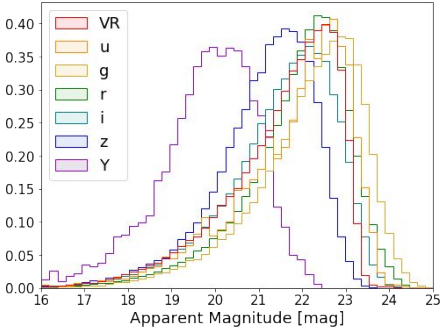
Exposure coverage of searched areas

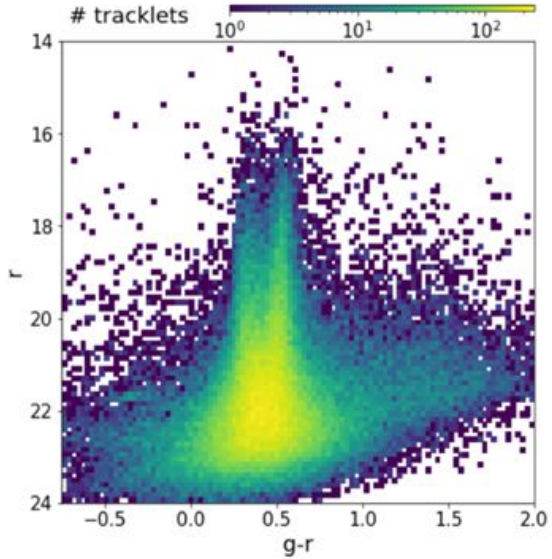


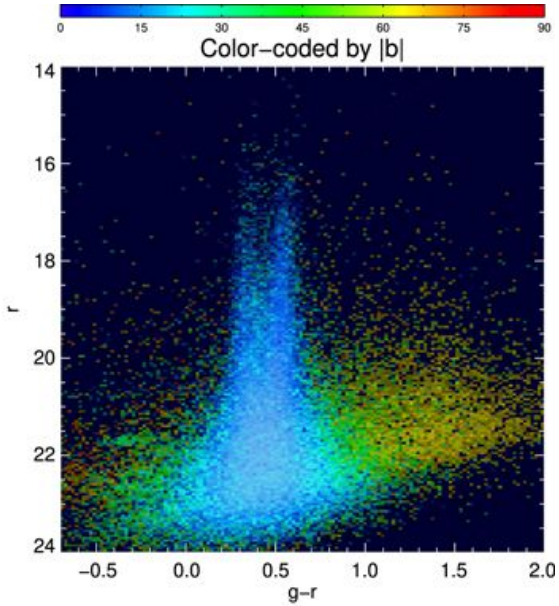
Fasbender & Nidever 2021

SSO detections in the NSC

Median tracklet magnitude = 21.9 mag





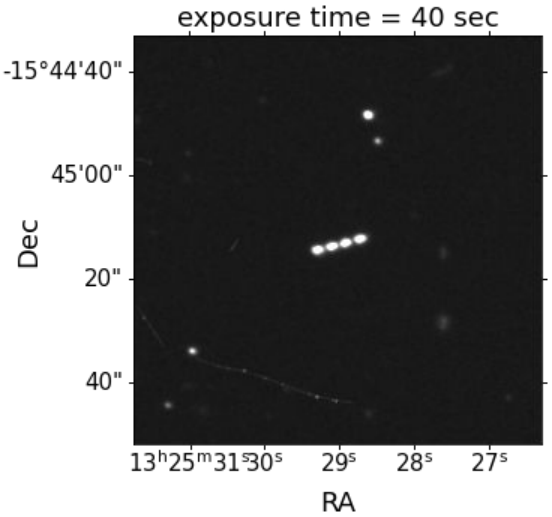


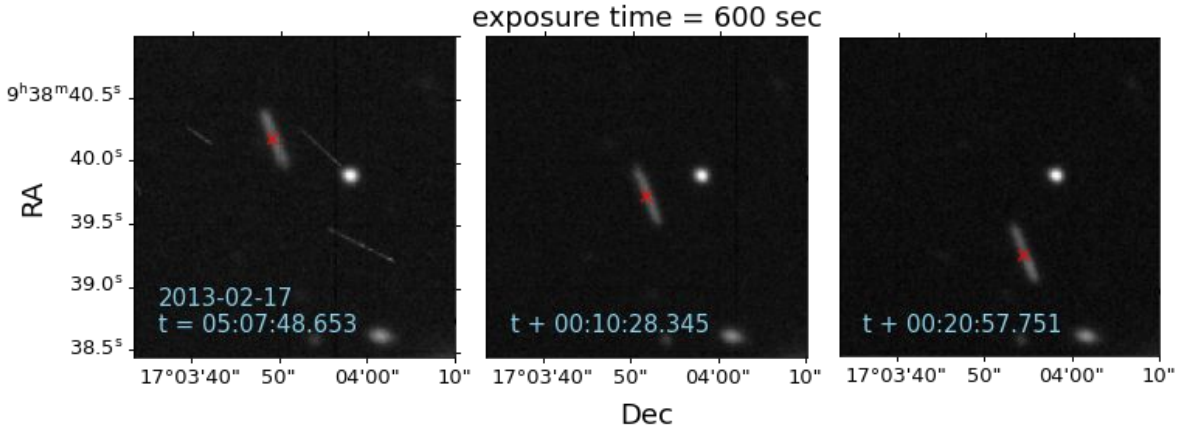
band	# tracklets
u	5,400
g	138,903
r	161,229
i	129,610
z	47,948
Y	7,570
VR	192,178

Fasbender & Nidever 2021

SSO detections in the NSC

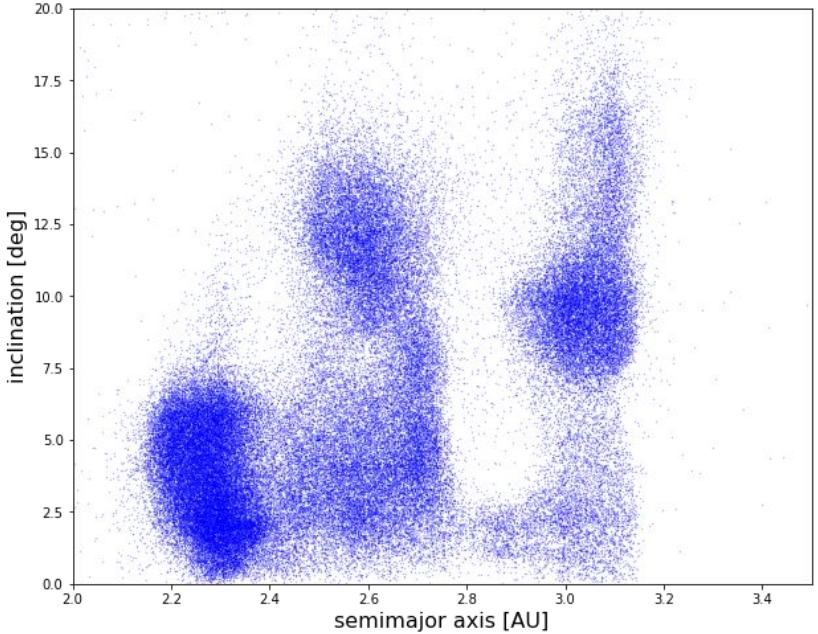
Streaked SSO detections identified as individual sources in NSC DR1&2 - Data Release 3 will include source photometry

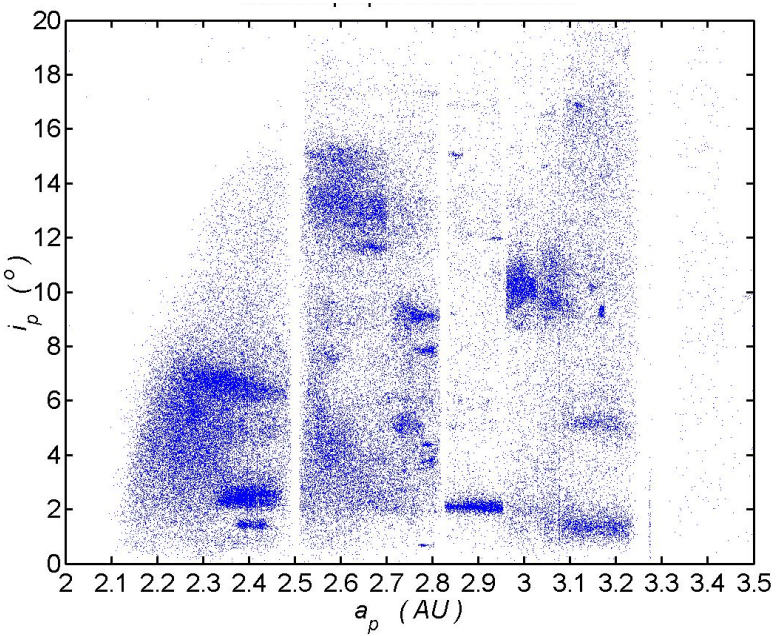




Initial Orbits

NSC short-arc (<1 day) MBAs vs well-known objects





Summary

- The All-Sky NOIRLab Source Catalog, largely comprised of DECam images, is a valuable and public photometric catalog with multiple science uses

- Detections of solar system objects from a wide range of solar distances are represented in NSC DR1&2; the third data release will have improved measurements and added photometry

Thank you to the community!

Acknowledgements

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