Solar System Alerts in Year 1 of LSST

The Effects of Template Generation

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Rubin LSST Survey Strategy Optimization Focus Issue:
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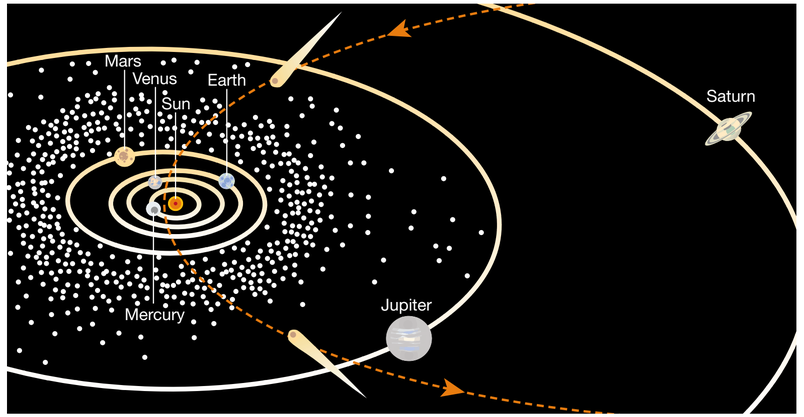
Solar System Science with LSST

- Depth and discovery - order of magnitude increase in known objects
- Number of observations - enables phase/light curve analysis
- Multiple filters *ugrizy* - colour characterisation
- Rapid "real-time" alerts (60s) - followup opportunities



Traditional view of asteroid and comets (Yeomans 2000)

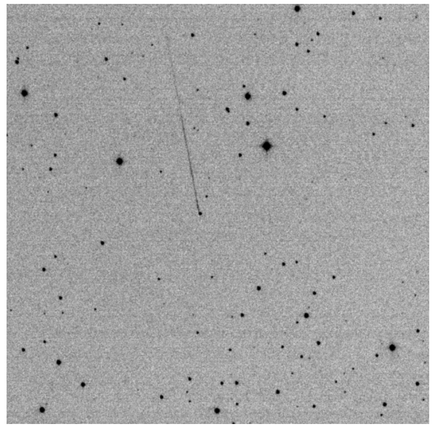
	Currently Known	LSST Discoveries	Typical number of observations
Near Earth Objects (NEOs)	~20,000	200,000	(D>250m) 60
Main Belt Asteroids (MBAs)	~650,000	6,000,000	(D>500m) 200
Jupiter Trojans	~7000	280,000	(D>2km) 300
TransNeptunian Objects (TNOs) + Scattered Disk Objects (SDOs)	~3000	40,000	(D>200km)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

LSST Science Book Ch.5

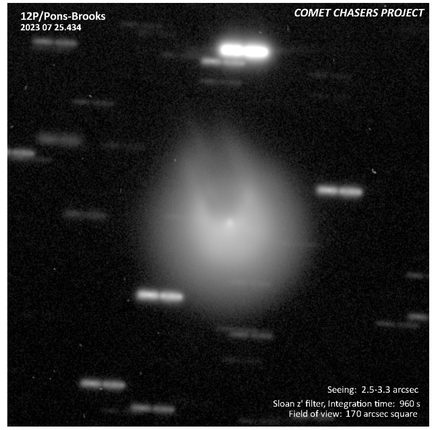
Rapid Solar System Science

Certain Solar System Objects (SSOs) will benefit from rapid discovery and followup:

- Interstellar Objects (ISOs) - limited observation window
- Near-Earth Objects (NEOs) - impact hazard and characterisation of small SSOs
- Active Objects - transient periods of activity/ outburst

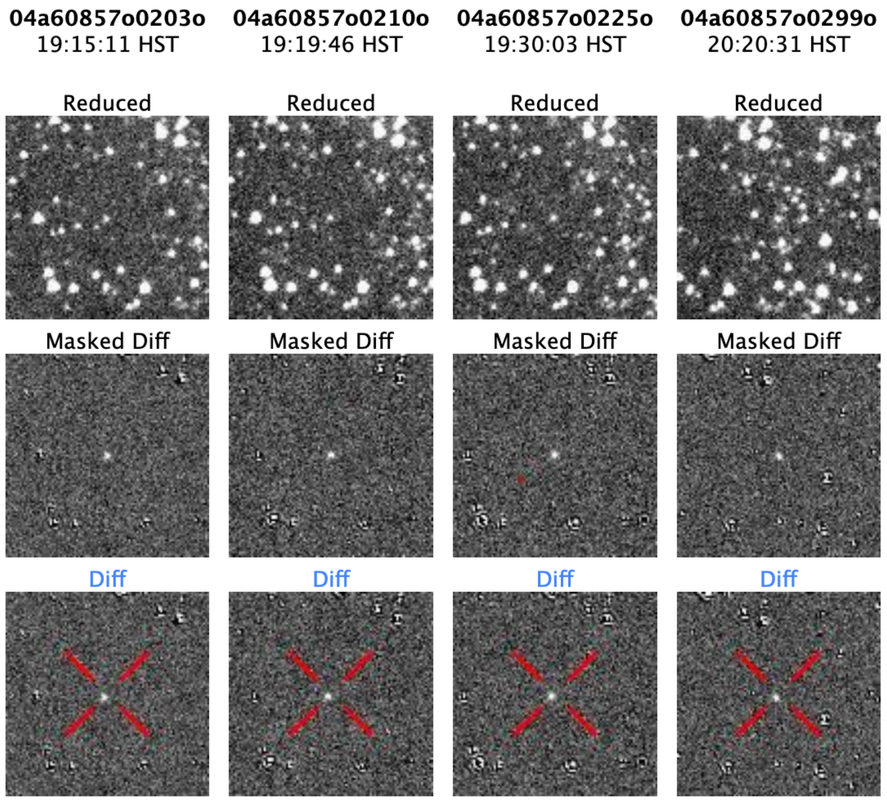


Final detection of impacting NEO 2024 BX1
L. Buzzi, G. V. Schiaparelli Observatory

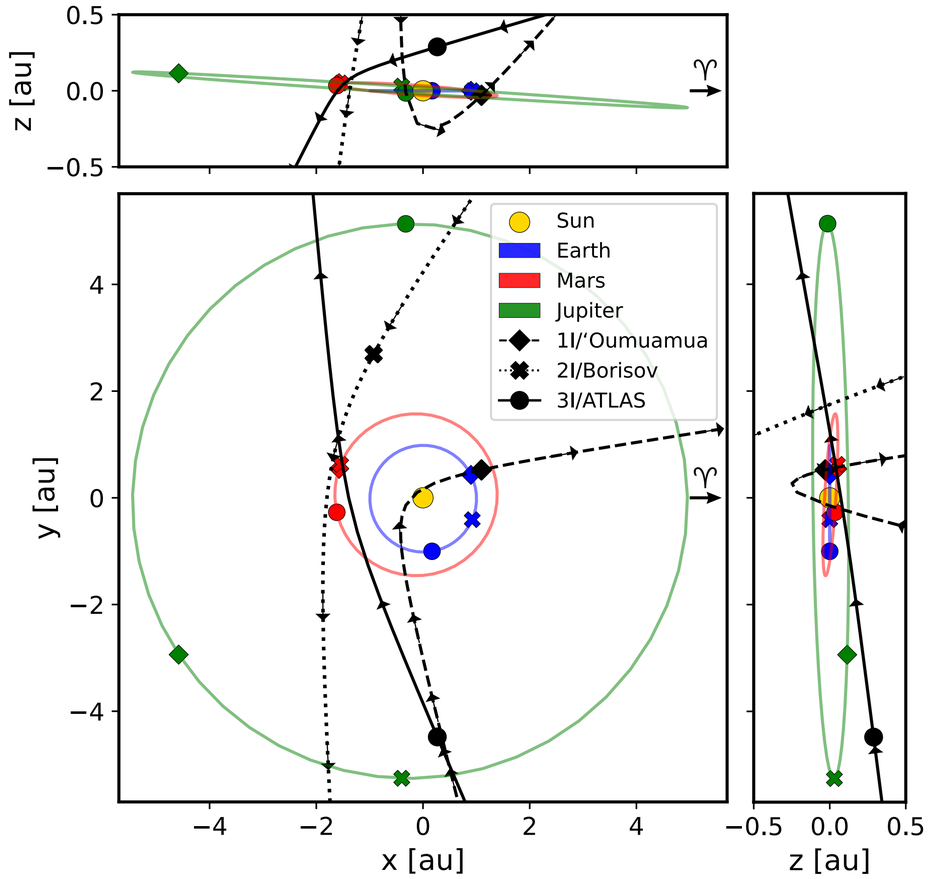


Comet 12P outburst
Comet Chasers/LCO

3I/ATLAS = C/2025 N1 (ATLAS)



ATLAS discovery cutouts



Seligman et al. 2025

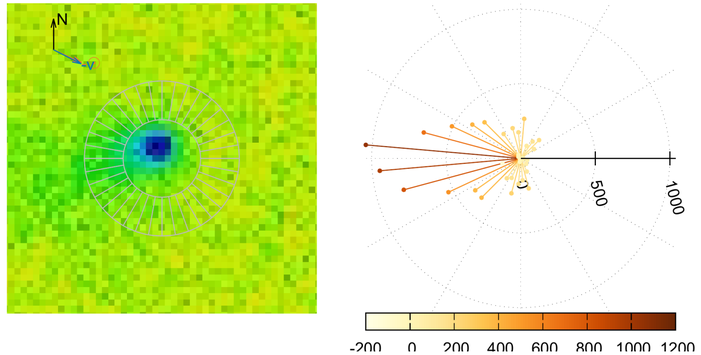
See also Dorsey et al. 2025 for LSST ISO predictions

SSO Activity

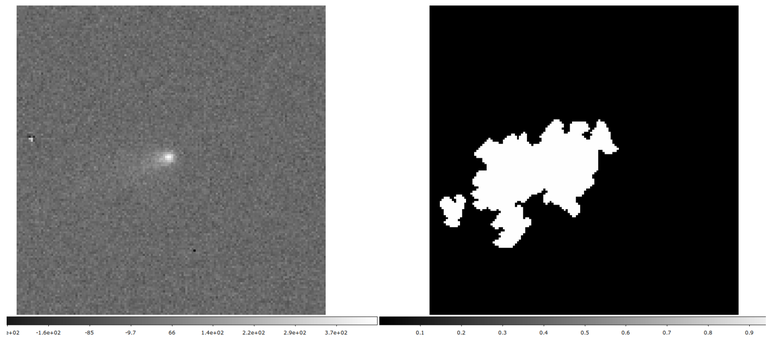
Adler GitHub:

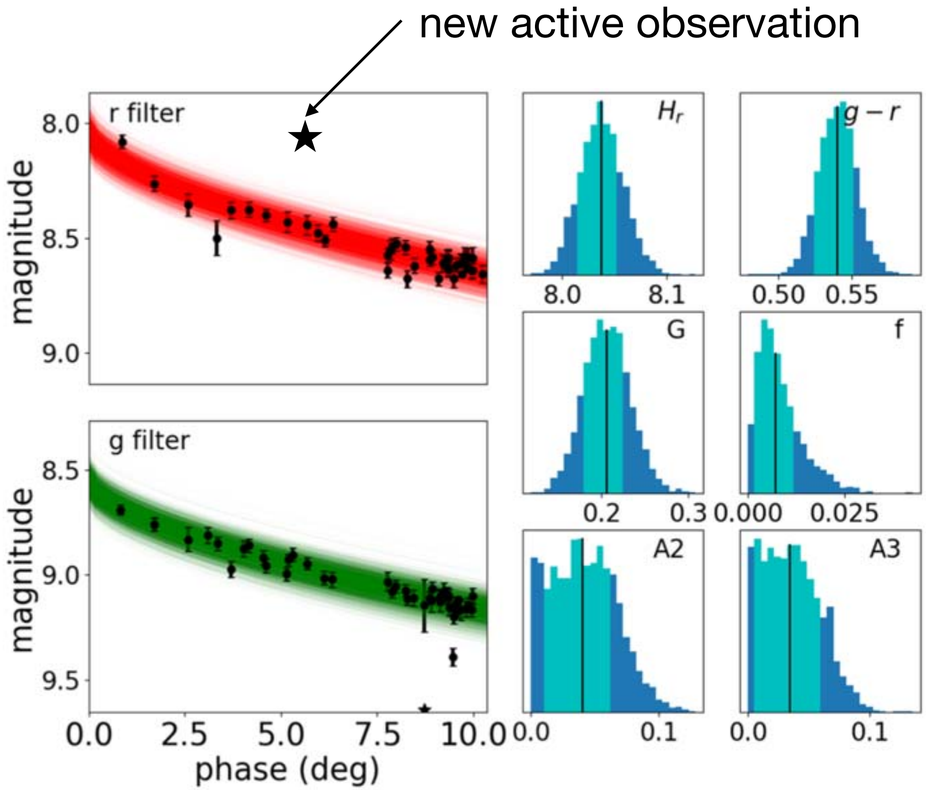
- LSST alerts - Extendedness, trailed source, predicted mag
- **LSST:UK Adler** - additional routines for phase curve photometry and cutout analysis
- Modular set of tools, to be run locally/Rubin Science Platform/alert broker (Lasair)

Wedge Photometry



Noisechisel (Gnuastro)



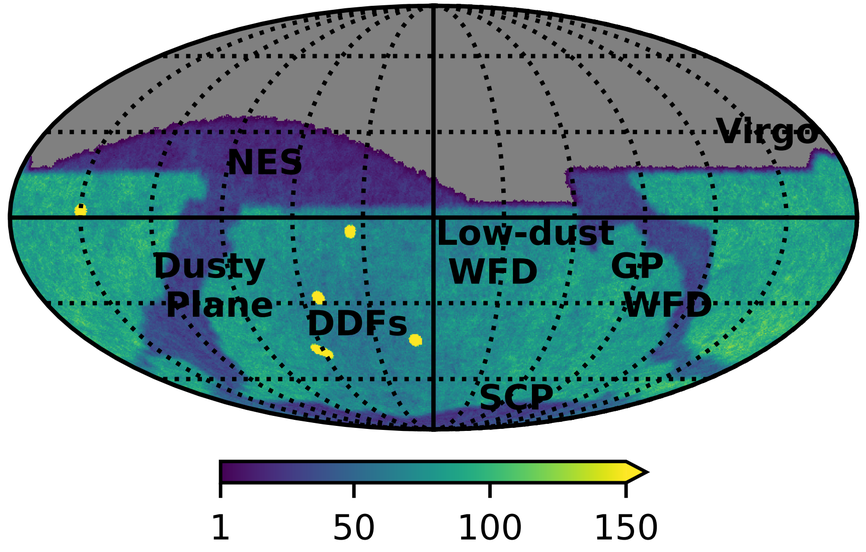


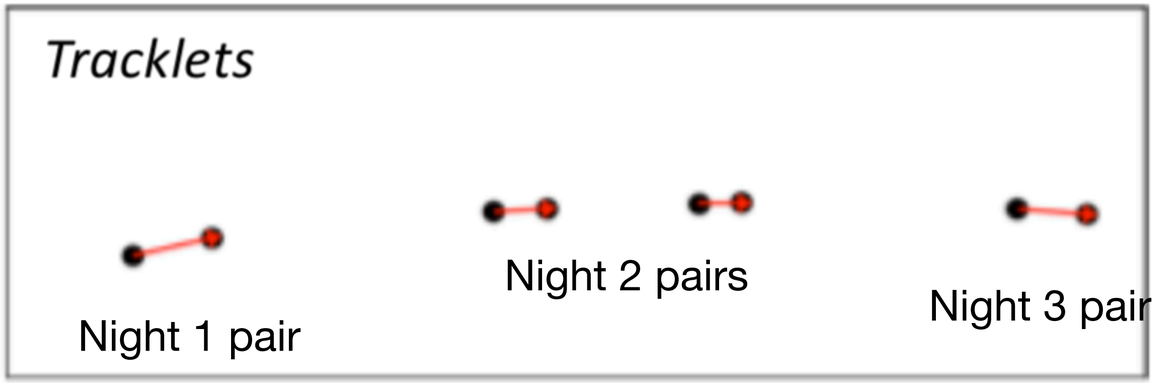
Rotational likelihood phase curve model (Schemel & Brown 2021), see also sHG1G2 (Carry et al. 2024)

LSST Alerts

- The Rubin Prompt Processing pipeline requires a template image of a visit sky area (in the same filter) to perform difference imaging and generate alerts
- Solar System Processing builds discovery tracklets from alerts - without alerts there can be no SSO discoveries
- Subsequent data releases will reprocess all images - alerts are not lost, they just aren't real-time

Year 1 Survey Footprint





Mario Jurić

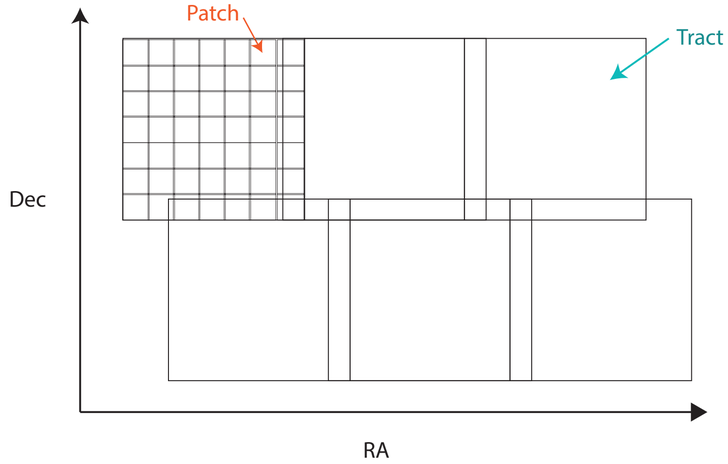
Simulating template generation

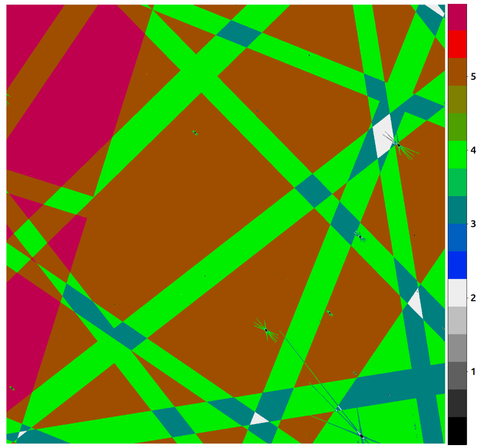
- Consider templates for one_snap_v4.0, nside = 256 healpixels (~14 arcmin scale, comparable to patch size) using Rubin Metric Analysis Framework (MAF; Jones et al. 2014)
- Pick timescale for template generation (every Δt = 3, 7, 14, 28 days)
- Consider all visits (in given filter) up to template generation night $t_n = t_0 + \Delta t * n$ (year 1 only)
- A healpixel has a template on night t_{n-1} if >=4 visits (of sufficient quality) were available and will generate alerts in the period $t_{n-1} < t < t_n$
- Consider the year 1 visit database in cumulative chunks ($t <= t_n$) and record metrics for healpixels with templates

Template Image Requirements

seeing/min(seeing) < seeing ratio = 2

(max(fiveSigmaDepth) - fiveSigmaDepth) < fiveSigmaDepth range = 0.5

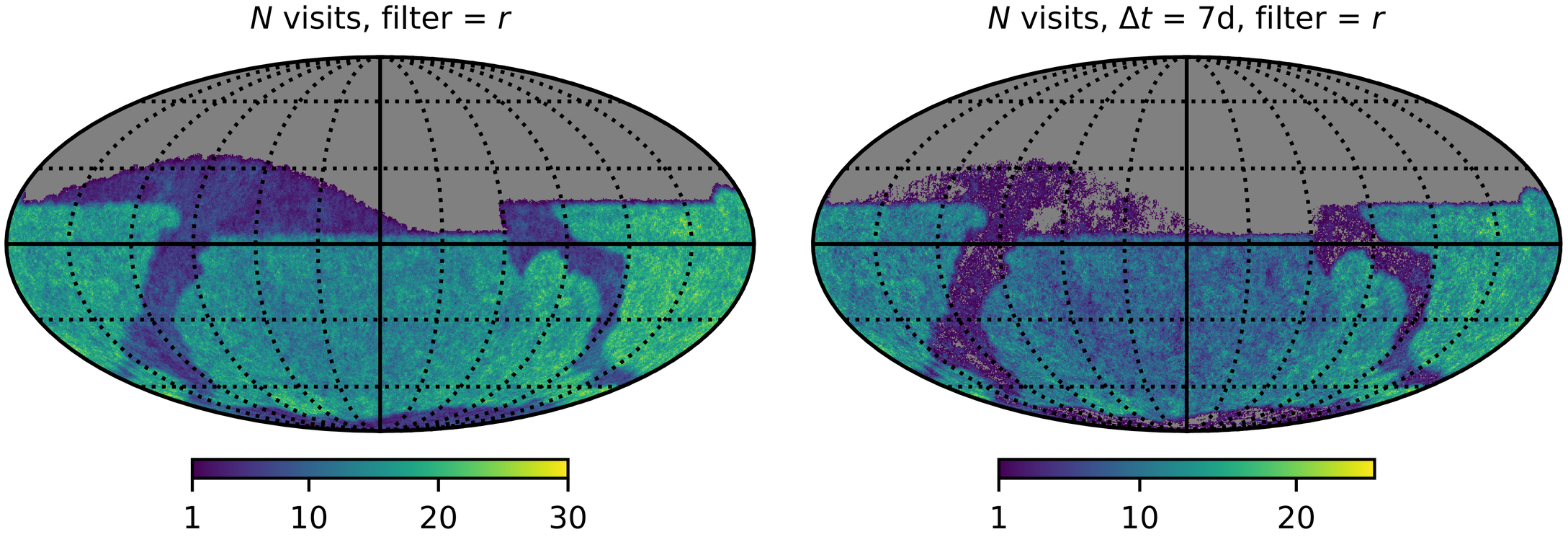




Coverage of a random patch (John Parejko)

Thank you to Lynne Jones and Peter Yoachim for the notebooks to start this work!

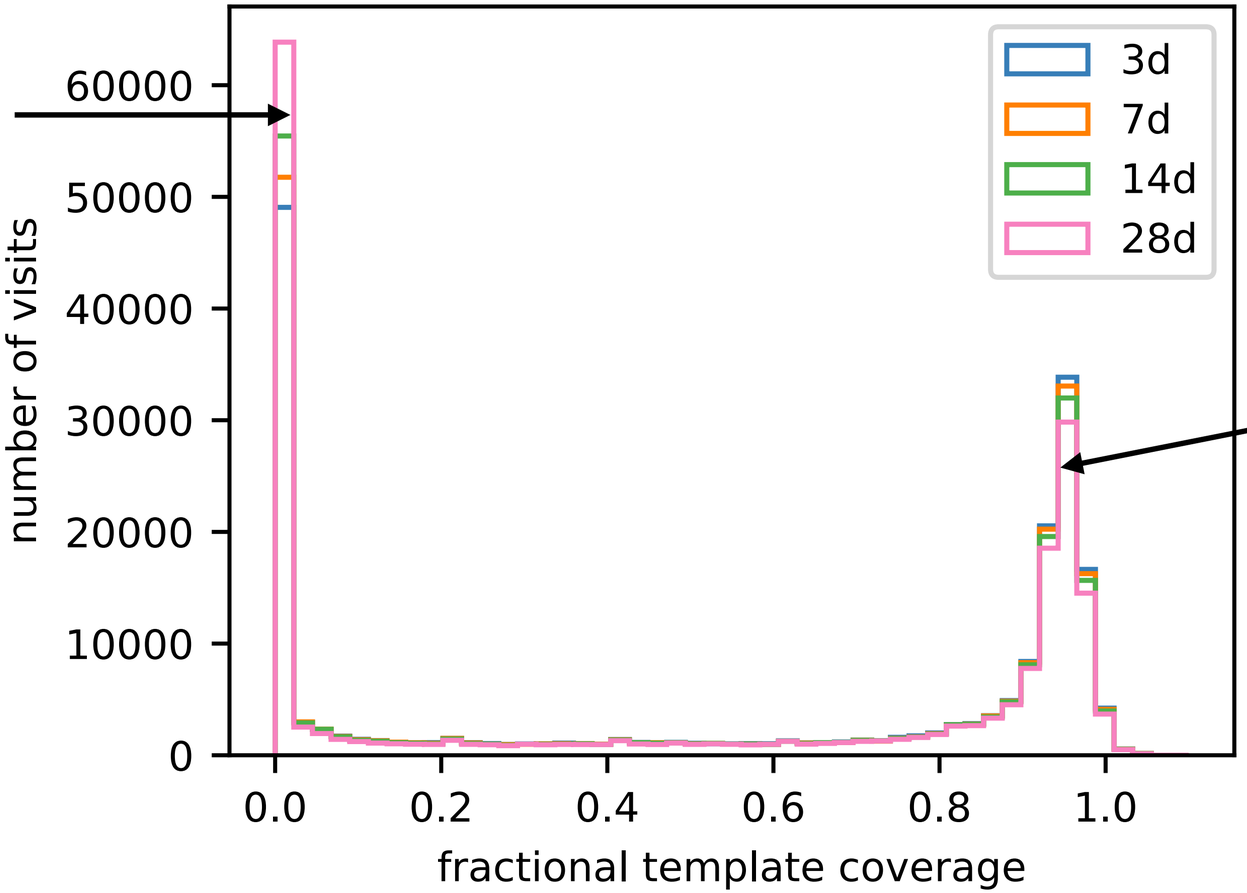
Template Coverage



Template generation reduces number of visits producing alerts, with patchier coverage (Robinson et al. 2025)

Template Coverage

Visits likely to be used for templates

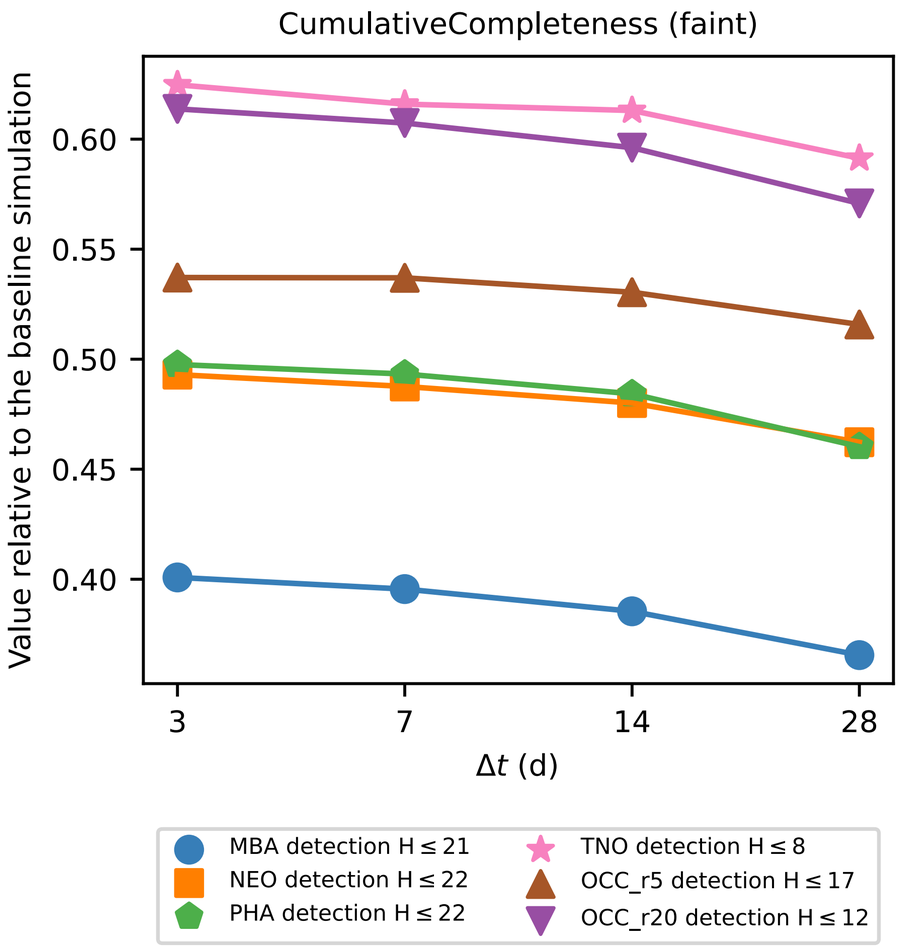


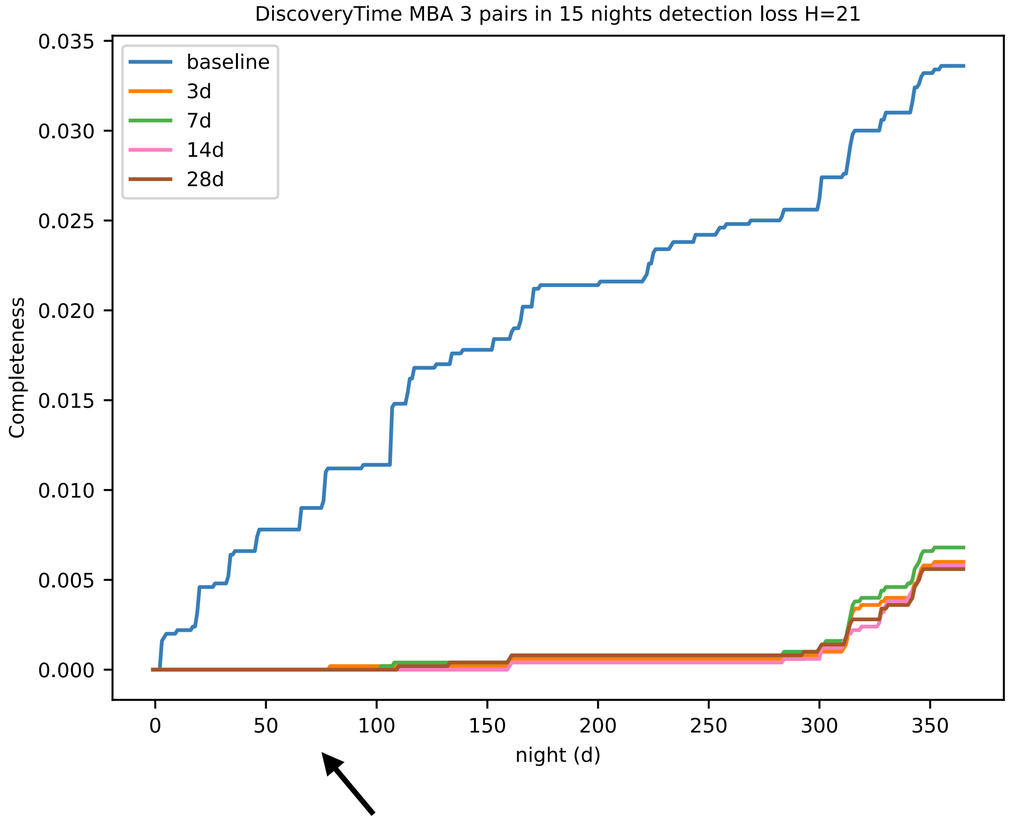
Visits likely to produce alerts

Visits (~183 healpixels) generally have 0% or >90% template coverage

SSO Discoveries

Drop in discoveries depends on population:
Main Belt Asteroids (MBAs)
Near-Earth Objects (NEOs)
Potentially Hazardous Asteroids (PHAs)
Trans-Neptunian Objects (TNOs)
Oort Cloud Comets (OCC)

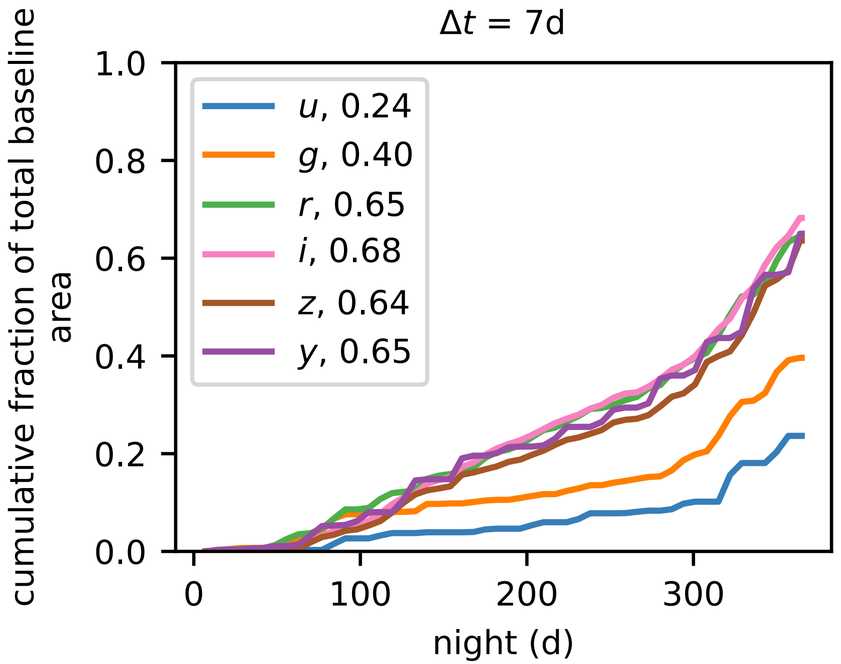




~50 day time delay

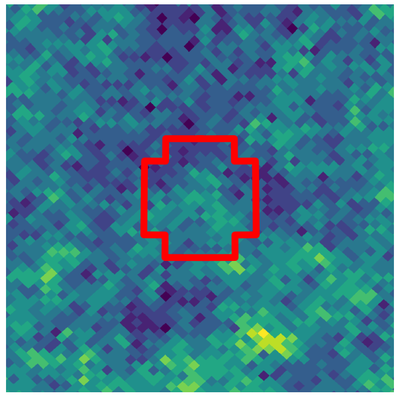
*results calculated for visits with >90% template coverage only

Problem Filters/Areas



u and g lag

1



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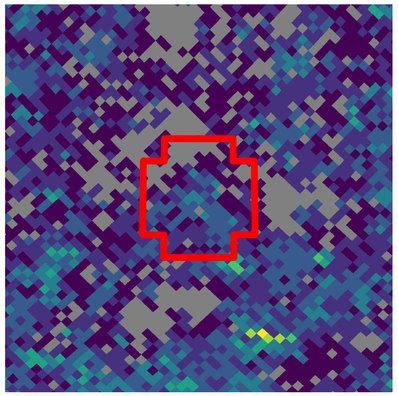

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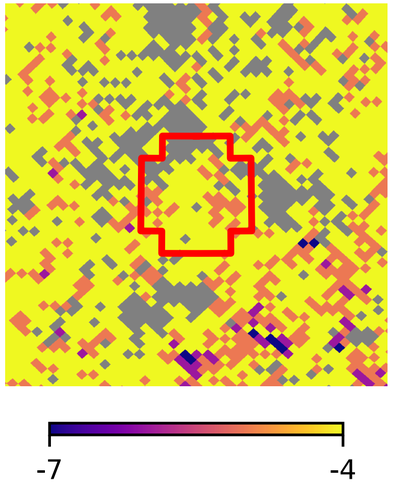


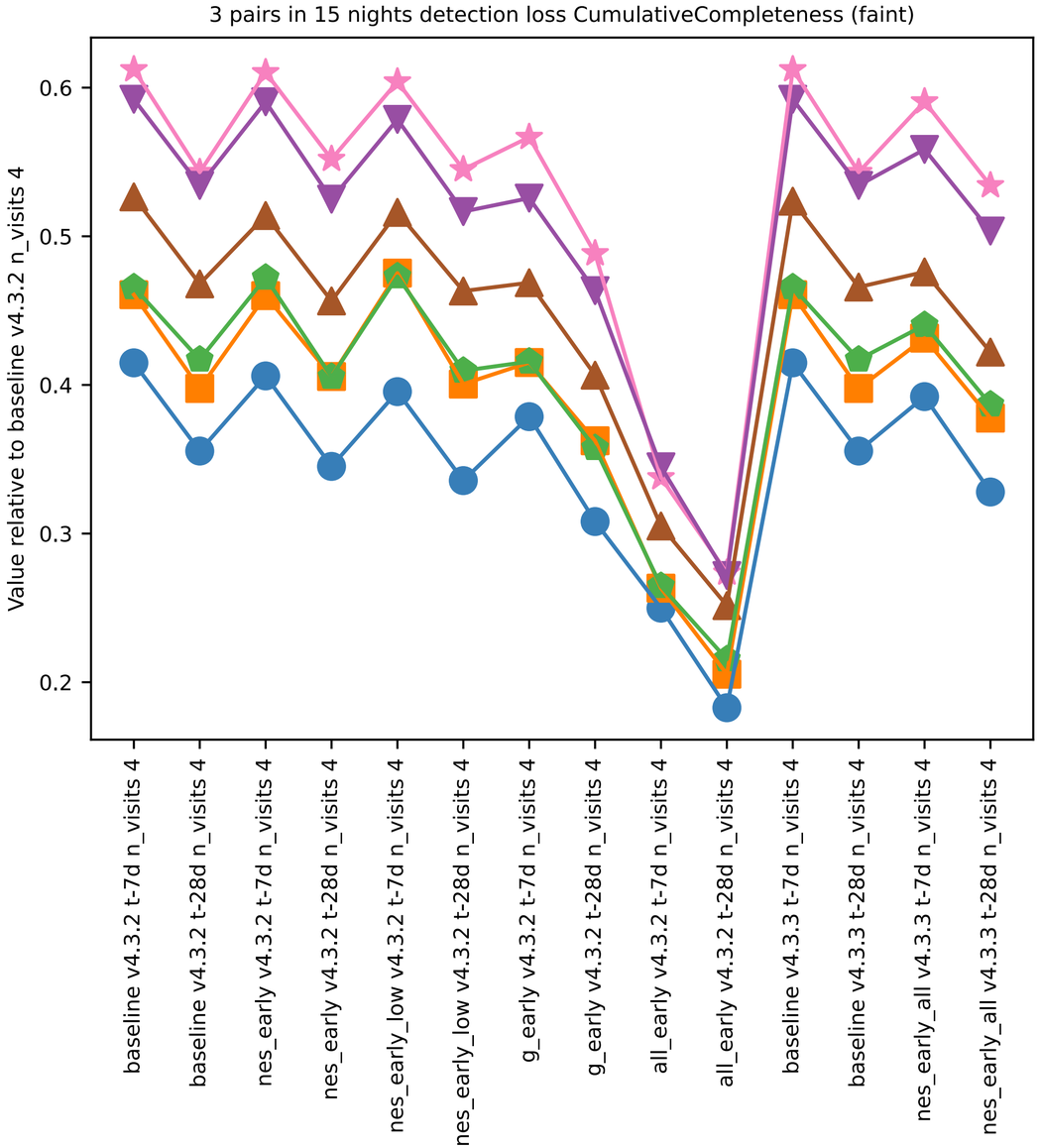
Filters or sky areas with low coverage in one_snap v4.0 are impacted more strongly by template generation. Important for:

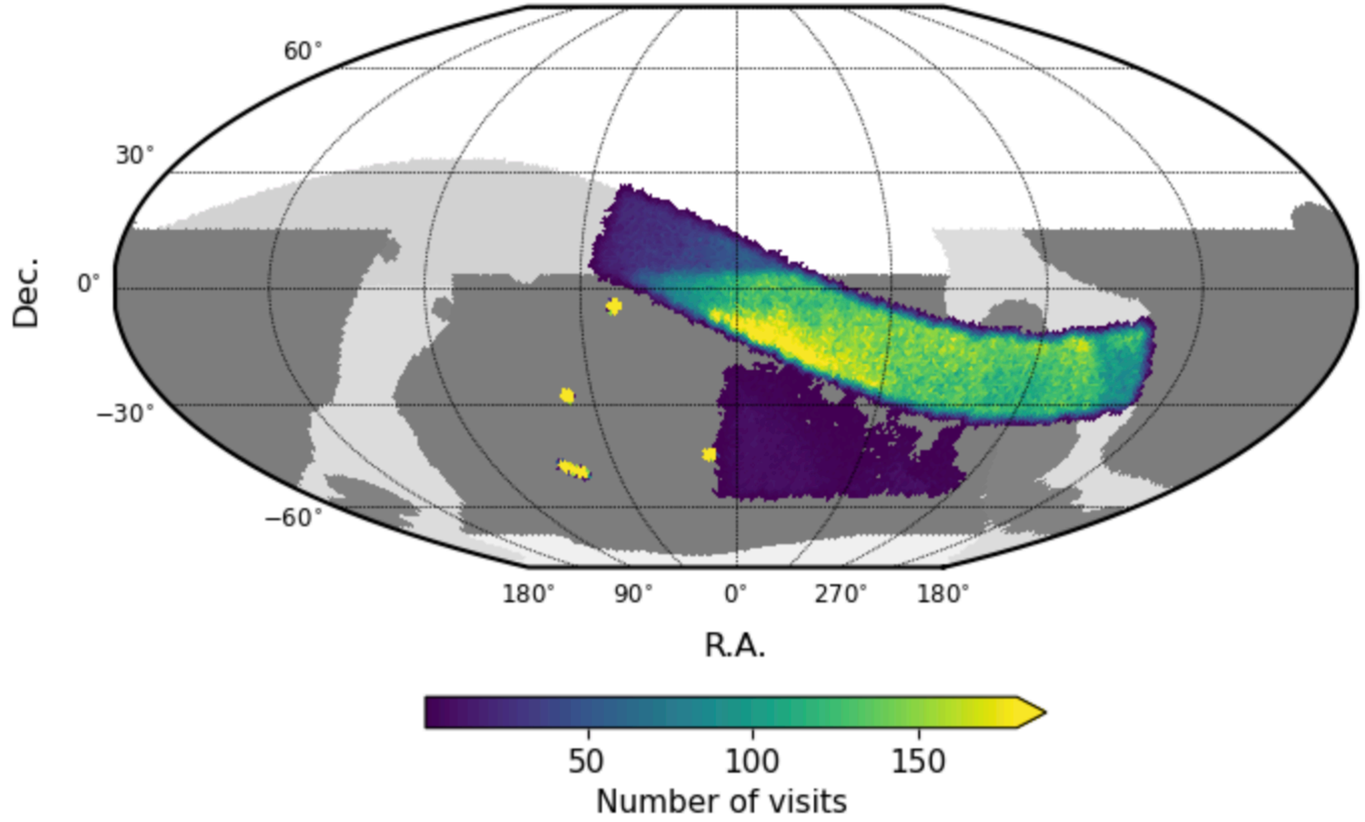
- colour measurements
- spatially dependent populations

Sample North Ecliptic Spur (NES) region in the r filter:

1. one_snap v4.0
2. template generation (Δt = 7d)
3. Difference between 2 and 1

New Baselines and Science Validation





new baselines on community forum:

SV info: SITCOMTN-005

Conclusions

- **Template generation is relevant to any science case that requires real-time alerts in year 1**
- Template generation reduces the sky area capable of producing alerts - SSO discovery & characterisation in year 1 is greatly impacted (up to 50% loss)
- Generating templates as soon as sufficient images are available maximises alert production
- Possible tweaks to year 1 strategy? Assign more time to low coverage areas/filters? We have assumed no commissioning data for templates
- **The new year 1 cadence simulations need to be assessed for impact on LSST science goals**
- More info at lsstc.slack.com #incremental-template-generation and Focus Issue paper

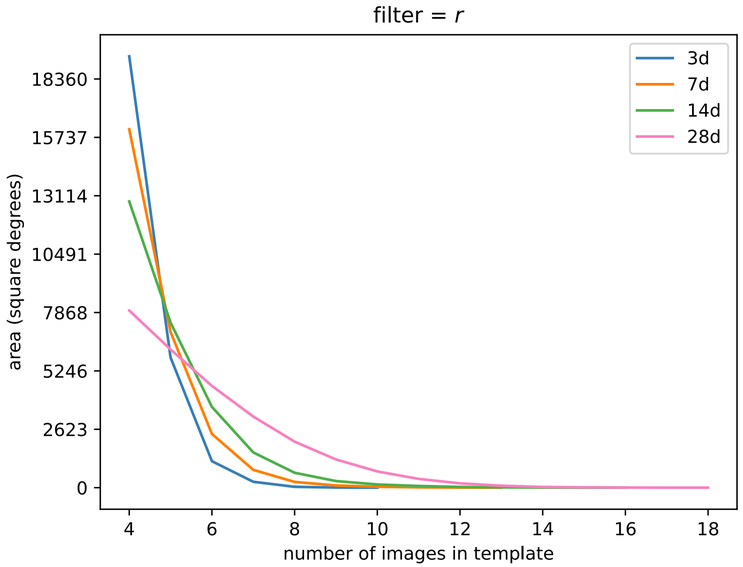
References

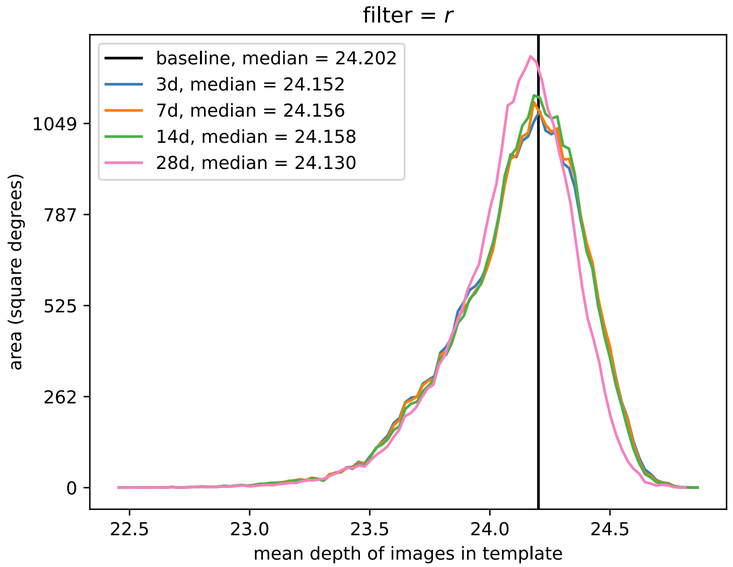
- Carry, B., J. Peloton, R. Le Montagner, M. Mahlke, and J. Berthier. ‘Combined Spin Orientation and Phase Function of Asteroids’. arXiv, 29 March 2024. http://arxiv.org/abs/2403.20179.
- Dorsey, Rosemary C., Matthew J. Hopkins, Michele T. Bannister, Samantha M. Lawler, Chris Lintott, Alex H. Parker, and John C. Forbes. ‘The Visibility of the Ōtautahi-Oxford Interstellar Object Population Model in LSST’. arXiv, 23 February 2025. https://doi.org/10.48550/arXiv.2502.16741.
- Jenniskens, P., M. H. Shaddad, D. Numan, S. Elsir, A. M. Kudoda, M. E. Zolensky, L. Le, et al. ‘The Impact and Recovery of Asteroid 2008 TC3’. Nature 458, no. 7237 (March 2009): 485–88. https://doi.org/10.1038/nature07920.
- Jones, R. L., Peter Yoachim, Srinivasan Chandrasekharan, Andrew J. Connolly, Kem H. Cook, Željko Ivezic, K. S. Krughoff, Catherine Petry, and Stephen T. Ridgway. ‘The LSST Metrics Analysis Framework (MAF)’. edited by Alison B. Peck, Chris R. Benn, and Robert L. Seaman, 91490B. Montréal, Quebec, Canada, 2014. https://doi.org/10.1117/12.2056835.
- LSST Science Collaboration, Paul A. Abell, Julius Allison, Scott F. Anderson, John R. Andrew, J. Roger P. Angel, Lee Armus, et al. ‘LSST Science Book, Version 2.0’. arXiv, 1 December 2009. https://doi.org/10.48550/arXiv.0912.0201.
- Meech, Karen J., Robert Weryk, Marco Micheli, Jan T. Kleyna, Olivier R. Hainaut, Robert Jedicke, Richard J. Wainscoat, et al. ‘A Brief Visit from a Red and Extremely Elongated Interstellar Asteroid’. Nature 552, no. 7685 (December 2017): 378–81. https://doi.org/10.1038/nature25020.
- Seligman, Darryl Z., Marco Micheli, Davide Farnocchia, Larry Denneau, John W. Noonan, Toni Santana-Ros, Luca Conversi, et al. ‘Discovery and Preliminary Characterization of a Third Interstellar Object: 3I/ATLAS’. arXiv, 3 July 2025. https://doi.org/10.48550/arXiv.2507.02757.
- Schemel, Madeline, and Michael E. Brown. ‘Zwicky Transient Facility Observations of Trojan Asteroids: A Thousand Colors, Rotation Amplitudes, and Phase Functions’. The Planetary Science Journal 2, no. 1 (1 February 2021): 40. https://doi.org/10.3847/PSJ/abc752.
- Schwamb, Megan E., R. Lynne Jones, Peter Yoachim, Kathryn Volk, Rosemary C. Dorsey, Cyrielle Opitom, Sarah Greenstreet, et al. ‘Tuning the Legacy Survey of Space and Time (LSST) Observing Strategy for Solar System Science’. The Astrophysical Journal Supplement Series 266, no. 2 (May 2023): 22. https://doi.org/10.3847/1538-4365/acc173.
- Yeomans, Don. ‘Small Bodies of the Solar System’. Nature 404, no. 6780 (April 2000): 829–32. https://doi.org/10.1038/35009193.

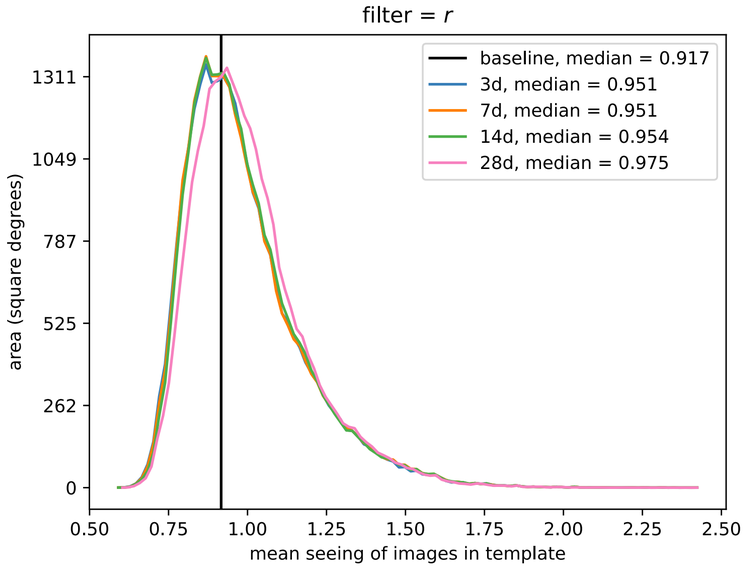
Extra Slides

(baseline v3.4 but similar enough to one_snap v4.0)

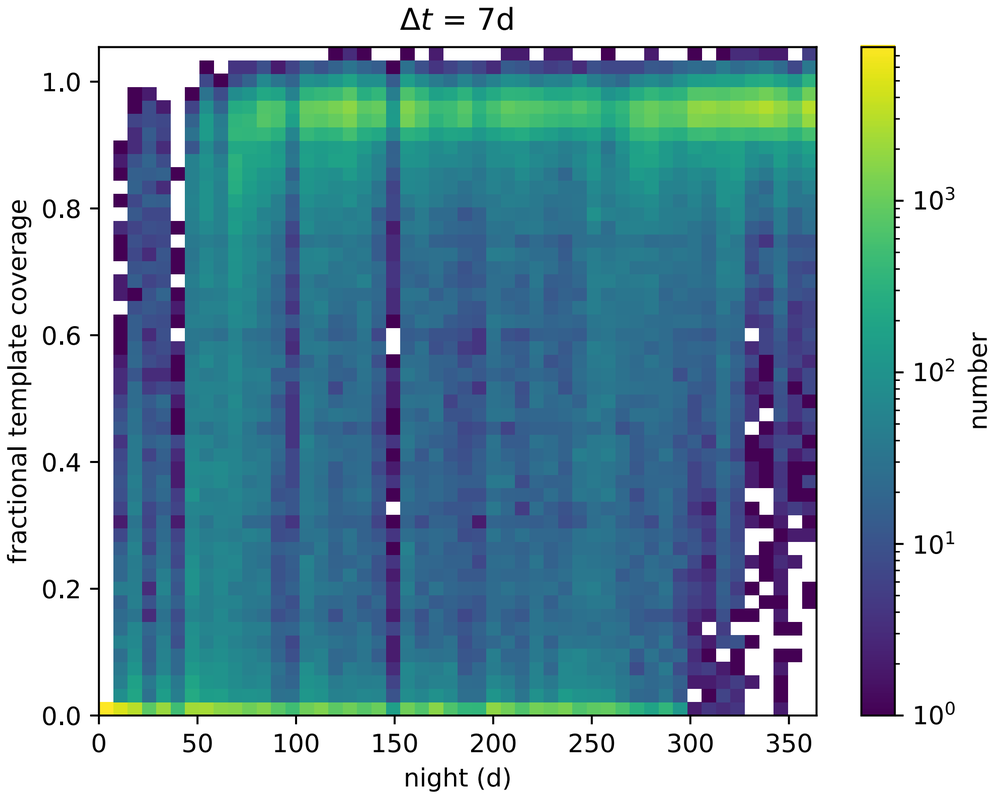
Template image quality

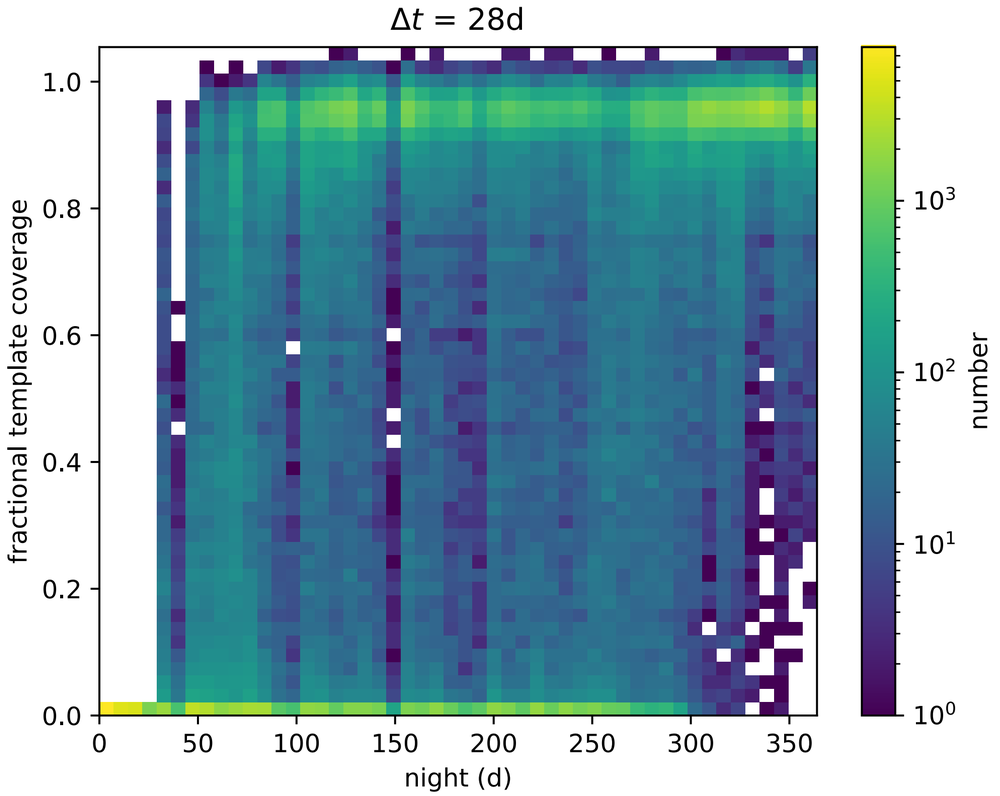




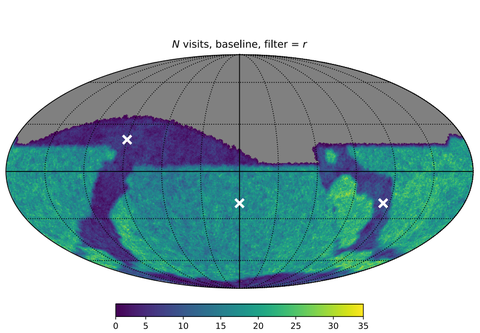


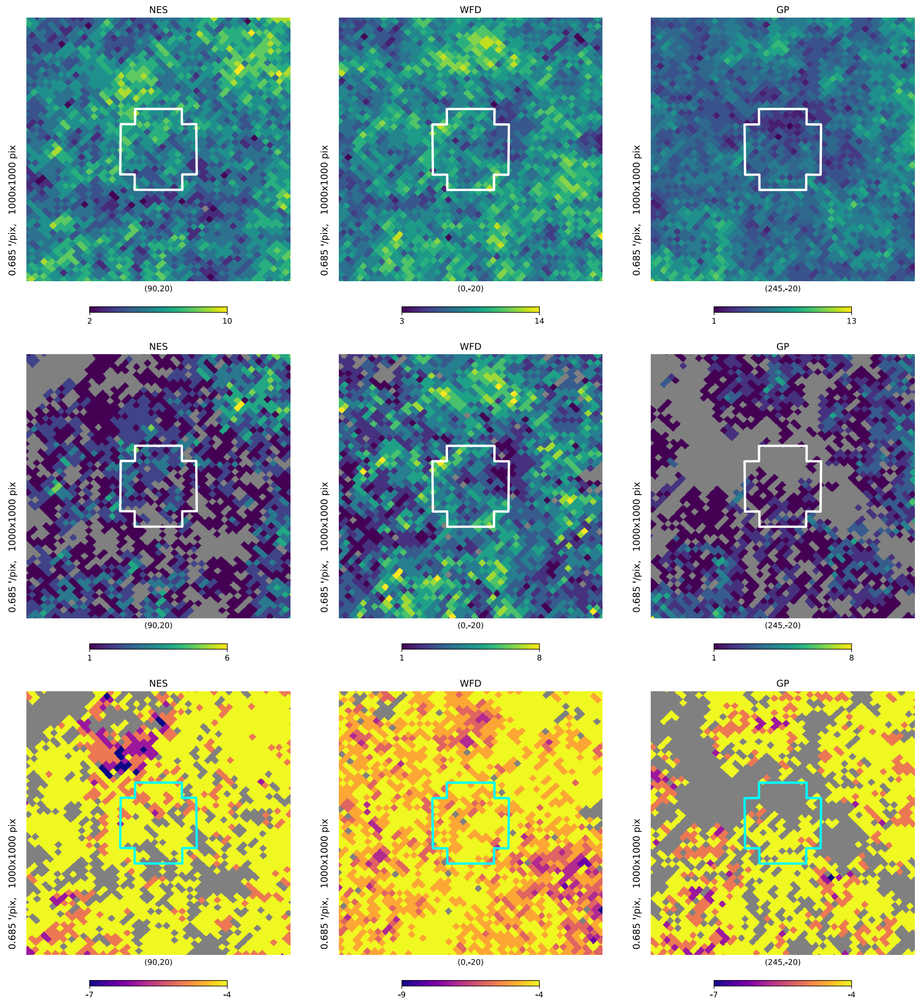
Visit template coverage



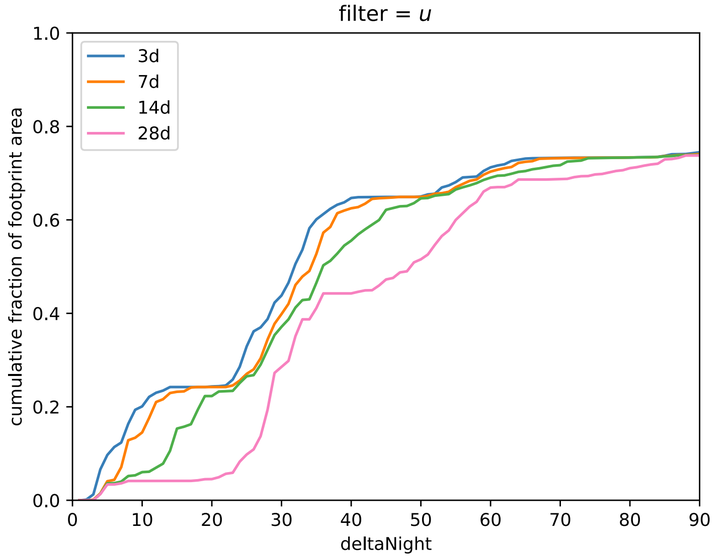


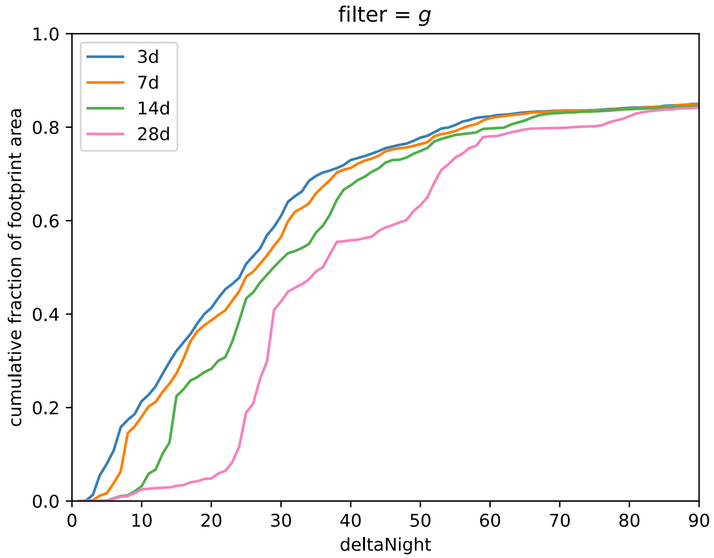
Low coverage areas

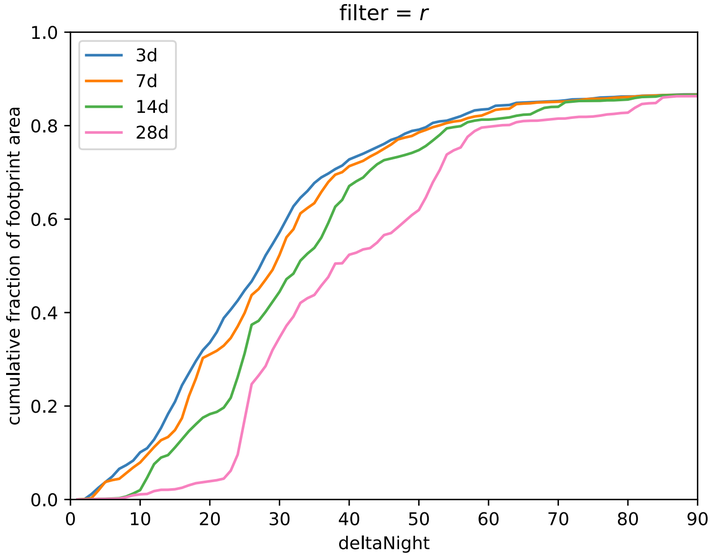




deltaNight

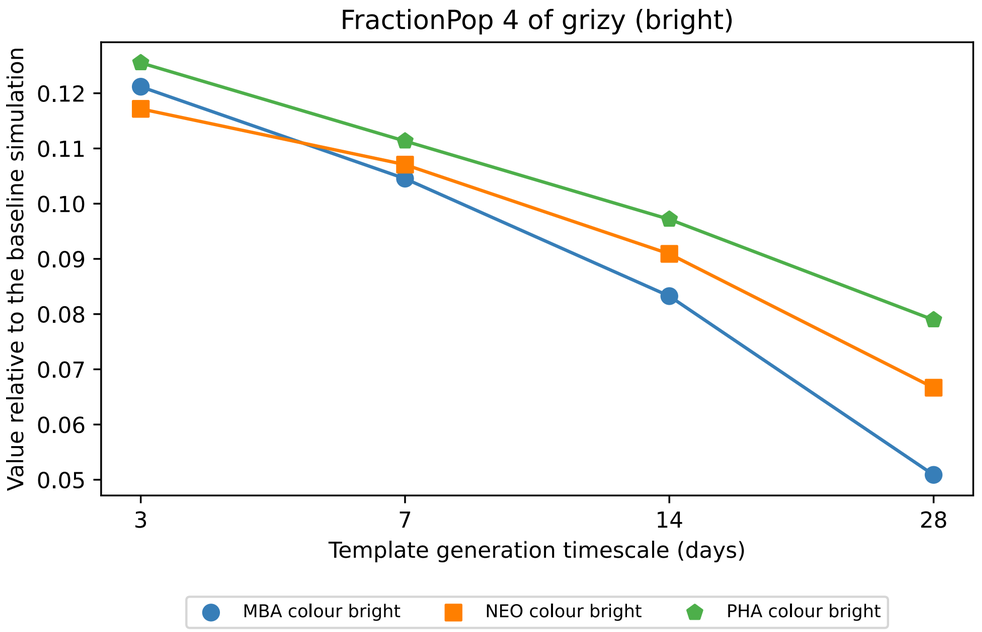


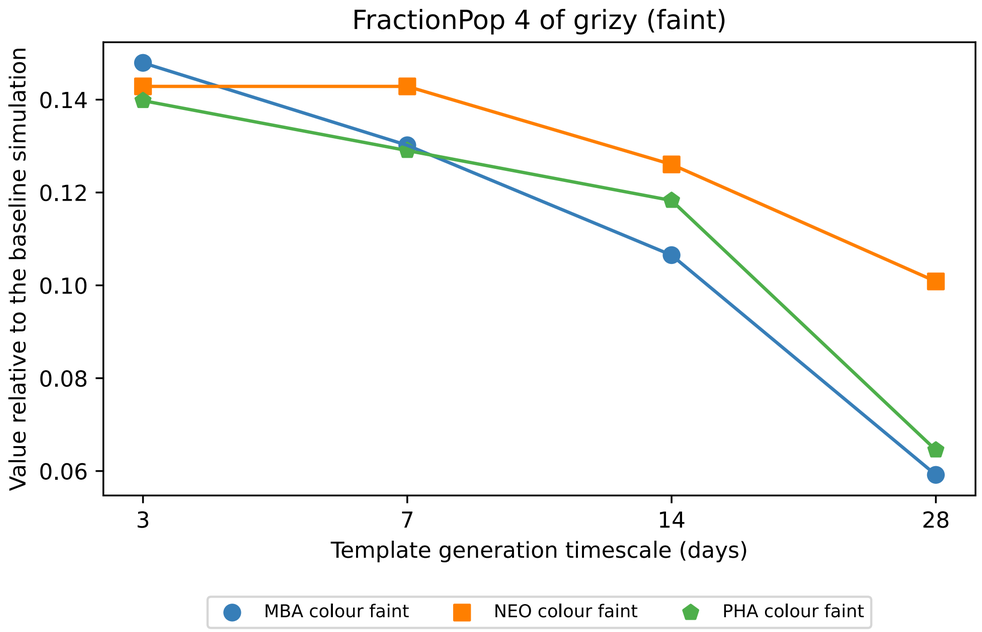




Number of nights between first visit to healpixel and its template generation

SSO Colours


FractionPop 4 of grizy (bright)
Value relative to the baseline simulation
0.12
0.11
0.10
0.09
0.08
0.07
0.06
0.05
3
7
14
28
Template generation timescale (days)
MBA colour bright
NEO colour bright
PHA colour bright


FractionPop 4 of grizy (faint)
Value relative to the baseline simulation
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0.12
0.10
0.08
0.06
3
7
14
28
Template generation timescale (days)
MBA colour faint
NEO colour faint
PHA colour faint